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# Relation between Metal Properties and Historical Incidents: A Demonstration of Metal Burning and Cooling Experiments

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**Abstract** We have described a demonstration to introduce the relation between metal properties and historical incidents through metal burning and cooling experiments. In the demonstration, three different metals are burned in an oxygen atmosphere to test the theory that the high combustion heat of aluminum may have increased the fire-induced damage on a warship in the Falklands war. Based on the observations of the metal burning experiments, the relation between the heats of formation of materials and the fire-induced damage on the warship can be discussed. Three metal wires are then cooled using dry ice to demonstrate the relation between the low temperature-induced brittleness of carbon steel and the sinking of cargo ships in World War II. Following the metal cooling experiments, the brittleness and its relevance to crystal lattice structures of metals can be discussed.

***Keywords:*** *demonstration, general chemistry, heat of formation of materials, crystal lattice structures of metals*

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## 1. Introduction

A number of excellent books dealing with the role of chemistry in world history have been published, attracting broad public interest [1,2,3,4]. Some of these books are quite interesting and have been used as supplementary material for conventional lectures to enhance interdisciplinary understanding of chemistry [5,6]. To make these lectures more exciting, we propose the inclusion of lab demonstrations. Herein, we describe a simple demonstration focusing on the properties of metals, which is suitable for first year undergraduate and high school students. In this demonstration, the relation between metal properties and historical incidents are discussed, based on observations from metal burning and/or cooling experiments.

### 1.1. Historical Incidents and Conventional Views

#### 1.1.1. A Warship in the Falklands War

In 1982, a British warship (HMS Sheffield) involved in the Falklands hostilities was struck by missiles, causing it to subsequently burn and sink. It was rumored that the bridge of HMS Sheffield was constructed from aluminum and that the extremely high heat from its combustion amplified the fire-induced damage, causing the subsequent destruction of the vessel. After an extensive literature review, we can confirm that HMS Sheffield was built from either aluminum or steel [1,7,8,9].

#### 1.1.2. Steel Cargo Ships in World War II

In the 1940s, during the Second World War, hundreds of American cargo ships serving in the North Atlantic sank due to cracks in the hull. It has been suggested that the welded steel hulls of these ships became brittle and lost flexibility as a result of the low temperature of the Atlantic [1,10]. Since the 1940s, there have been extensive studies on the effects of low-temperature-induced metal brittleness [1]. As such, this theory is now widely accepted.

## 2. Experimental

This demonstration comprises two main parts, each requiring approximately 20 min to complete. In the first part, the instructor conducts metal burning experiments and discusses the results with respect to the fires on HMS Sheffield in the Falklands war. In the second part, the instructor conducts metal cooling experiments and explains the possible implications with regard to steel cargo ships in World War II. All demonstrations should be performed in a well-ventilated area.

### 2.1. Technical Terms

Before beginning this demonstration, students should understand the following concepts.

1) General properties of metals
2) Heat of formation
3) Crystal lattices

The instructor may need to introduce the following term to students.

1) α-Ferrite: A solid solution of carbon in BCC iron, which is soft and pliable.

2) Cementite: An intermetallic compound, $Fe_3C$, in steel alloys, which is very hard and brittle.

3) Pearlite: An iron alloy phase consists of alternating layers of α-ferrite and cementite, which is hard and strong.

## 2.2. Burning Experiment (A Warship in the Falklands War)

### 2.2.1. Materials and Apparatus

Aluminum foil (12 $cm^2$ 0.002 mm thick), steel wool (ca. 0.2 g), copper foil (12 $cm^2$, 0.003 mm thick), an oxygen canister (0.5 L), ignition stick, and three glass bottles (0.5 L).

### 2.2.2. Hazards

Instructor should wear dark or opaque goggles and leather gloves during this demonstration to block any possible sparks or debris emitted from the burning metal specimens. Exercise caution when handling lit ignition sticks, as they can cause burns. Do not touch the sides of the glass bottle once burning is initiated. Smoke released by burning metal can be harmful if inhaled.

### 2.2.3. Procedure

Place one of the metal samples in a 0.5 L glass bottle and fill with oxygen gas. The oxygen gas must be introduced slowly so as not to tear or mobilize the thin metal foil sample. The metal can then be ignited inside the bottle using a lit ignition stick. Repeat this procedure for all metal samples.

### 2.2.4. Possible Problems

1) The thin metal foil crumbles easily, so it should be treated carefully.

2) The thin metal foil is easily torn or blown away from the tweezers, so the oxygen should be introduced slowly.

3) Incense sticks quickly burn out in pure oxygen, so a new or long one should be used when igniting the metals.

4) The thin copper foil burns with a very weak flame even in pure oxygen, so students may miss the burning.

## 2.3. Cooling Experiment (Steel Cargo Ships in World War II)

### 2.3.1. Materials and Apparatus

Aluminum wire (1.2 mm diameter, 20 cm length), steel wire (ca. 0.8% carbon content, 1.2 mm diameter, 20 cm length), copper wire (1.2 mm diameter, 20 cm length), and dry ice (ca. 1 kg).

### 2.3.2. Hazards

Instructor should wear safety glasses and leather gloves during this demonstration. The hazards associated with dry ice include severe burns upon eye or skin contact and asphyxiation due to displacement of oxygen in confined spaces. Exercise caution when handling metal specimens as the sharp metal edges can cause serious injury.

### 2.3.3. Procedure

Insert a bent piece of metal wire into a block of dry ice for 30 seconds. Remove the frozen metal wire and straighten with gloved hands. Repeat this procedure for all metal samples.

### 2.3.4. Possible Problems

After cooling on dry ice, the bent piano wire should be straightened immediately, because the temperature of the wire rises rapidly.

# 3. Results and Discussion

## 3.1. Relation between Burning Experiment and Aluminum Warship in the Falklands War

In this experiment, aluminum foil, steel wool, and copper foil are ignited in pure oxygen. The heats of formation of the corresponding aluminum, iron, and copper oxides, as summarized in Figure 1, are negative values, indicating that the formation of metal oxides from their corresponding elements is an exothermic process. The intensity of the flame and stability of the metal oxide increase proportionally to the absolute value of the heat of formation.

Although aluminum is combustible, it is difficult to ignite in air as it generally has a natural passivation coating. However, once aluminum foil is ignited, it burns with an intense flame (Figure 1A). Following combustion, the glass bottle is filled with alumina ($Al_2O_3$) smoke, which the instructor should ask the students to identify. The intensity of the flame reflects the large heat of formation of $Al_2O_3$. The reaction between aluminum and oxygen releases significant energy in the form of light and heat, which indicates the high stability of $Al_2O_3$ and the inherent difficulty in reducing $Al_2O_3$ to produce aluminum metal.

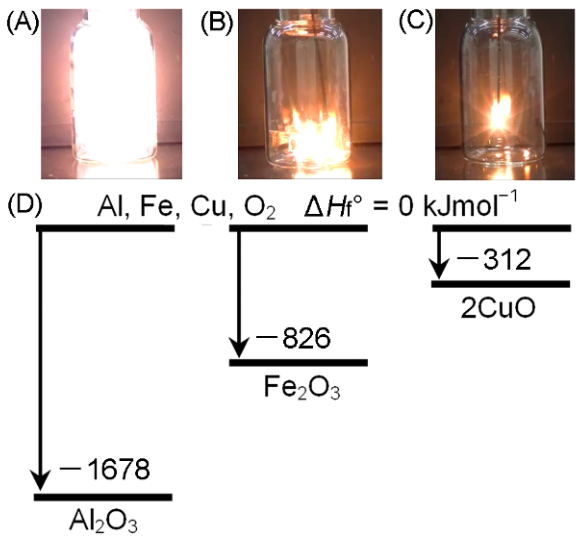


**Figure 1.** Metal burning experiments in an oxygen atmosphere: (A) aluminum foil, (B) steel wool, (C) copper foil, and (D) heats of formation ($\Delta Hf°$ (kJ $mol^{-1}$)) of the corresponding oxides [11]

Steel is an alloy that contains varying amounts of carbon and is harder and more resistant to oxidation than pure iron. In this experiment, we use steel wool rather than thin steel foil because it is less expensive. A mass of steel wool is ignited and burns slowly, emitting a crackling noise (Figure 1B). The intensity of the combustion reaction is less than that of aluminum, mainly due to the difference in the heats of formation of the corresponding metal oxides, i.e., $Fe_2O_3$ and $Al_2O_3$. Finally, a thin copper foil burns with a very weak flame even in pure oxygen (Figure 1C), which reflects the small heat of formation of CuO.

## 3.2. Relation between Cooling Experiment and Steel Cargo Ships in World War II

In this experiment, bent aluminum, steel, and copper wires are pressed against the surface of a block of dry ice for 30 s and then straightened. The aluminum and copper wires maintain their ductility both at room temperature and low temperature (Figure 2A–C). However, the steel wire simply breaks upon straightening at room temperature, as it becomes brittle at low temperature (Figure 2D–F).

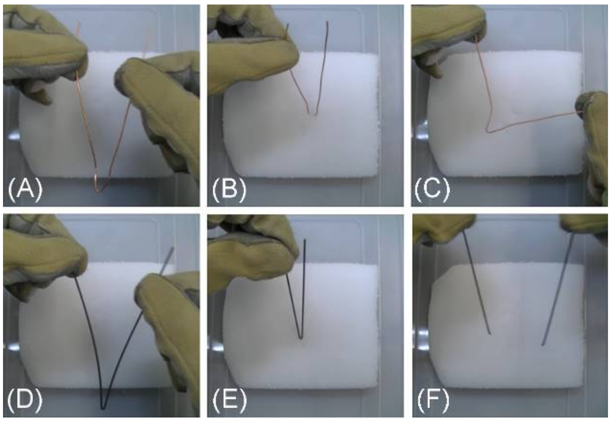


**Figure 2**. Cooling of metal wires on dry ice followed by straightening. Copper wire (A) before cooling, (B) pressed against dry ice, and (C) straightening after cooling. Steel wire (D) before cooling, (E) pressed against dry ice, and (F) breaking upon straightening

The difference in mechanical strength between aluminum, steel, and copper at low temperature can be explained in terms of the difference in their crystal structures. Aluminum and copper crystalize in a face-centered cubic (FCC) structure, wherein the metal atoms are closely packed (Figure 3A). In contrast, steel adopts a body-centered cubic (BCC) structure, wherein the Fe atoms are loosely packed (Figure 3B).

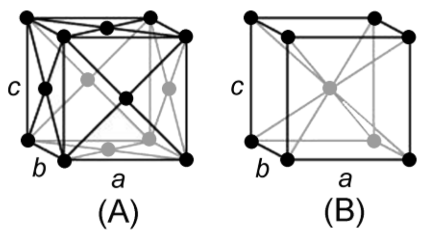


**Figure 3**. Cooling of metal wires on dry ice followed by straightening. Copper wire (A) before cooling, (B) pressed against dry ice, and (C) straightening after cooling. Steel wire (D) before cooling, (E) pressed against dry ice, and (F) breaking upon straightening

In the closely packed FCC metal (Figure 4), the slip distance of the plane is short, requiring relatively low energy. This causes the ductile nature of FCC materials, resulting in plastic deformation rather than brittleness (Figure 4A). For this reason, FCC metals can preserve their ductility even at low temperatures. In contrast, the loosely packed BCC structure exhibits reduced ductility upon cooling and becomes brittle as a result (Figure 4B). This phenomenon generally occurs over a narrow temperature range via a process referred to as the ductile-to-brittle transition. The ductile-to-brittle transition temperature (DBTT) is defined as the temperature at which the behavior of the metal is midway between its ductile and brittle states (Figure 5) [10], which is different from the thermodynamic phase transition temperature.

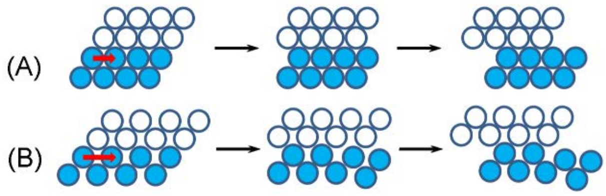


**Figure 4**. Shear planes in (A) closely packed FCC and (B) loosely packed BCC structures during applied stress. The length of the "slip distance" is represented by the red arrow

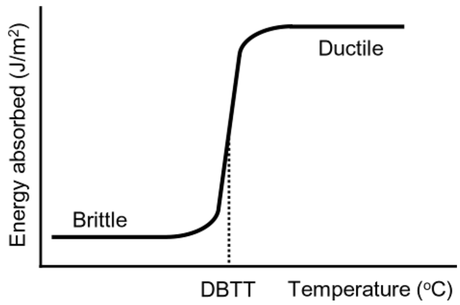


**Figure 5**. Ductile-to-brittle transition behavior in BCC metals

The steel wire employed in this experiment is an iron alloy with a pearlite microstructure and carbon content of ca. 0.8%. Pearlite is a lamellar structure comprised of alternating layers of α-ferrite (89 wt%), with a BCC structure, and cementite (11 wt%) [12]. The DBTT of carbon steel ranges from 130 to −50 °C; increasing with increasing carbon content [10] and decreasing with decreasing grain size [13]. The grain size of the steel piano wire used in this experiment is small, due to the shaping process. This is beneficial for the cooling experiment as it makes the transition to the brittle state easier to observe.

## 3.3. Suggested Discussion Points

The instructor introduces generally recognized causes for the historical incidents, and explains scientific grounds described in the text. During interpretations, the instructor can emphasize the following points, all of which are suitable for first year undergraduate and high school students.

### 3.3.1. Relation between Burning Experiment and Aluminum Warship in the Falklands War

1) What are the differences between the experimental and real world conditions, in terms of the form of the metal (foil or armor) and atmospheres (pure oxygen or air)?
2) Why should we recycle aluminum products?

3) Why was aluminum not isolated until the 19th century?

#### 3.3.2. Relation between Cooling Experiment and Steel Cargo Ships in World War II

1) What are the differences between the experimental and real world conditions, in terms of the form of the metal (wire or sheet), temperatures (dry ice or Atlantic seawater), time spans (ca. 30 seconds or several days) and load stresses?

2) One reason for the rapid sinking of the Titanic after collision with the iceberg was that her hull was made of welded steel and so became brittle and inflexible because of the low temperature of the Atlantic waters.

3) The results of various accident investigations have shown that steel is weakened at low temperature to a greater degree when it contains hydrogen atoms that have been inserted in the material during arc welding. Hydrogen atoms generated by arc welding are small enough to enter the interstitial spaces of the metal lattice, causing hydrogen brittleness.

## 4. Conclusions

Although neither the metal burning nor the cooling experiments are novel [14,15], this demonstration allows for them to be approached in a fresh way by relating them to historical incidents. This demonstration shows the relation between macroscopic phenomena (brittleness and ductility) and microscopic chemical concepts (atomic arrangements) illustrated in high school chemistry. It is important to note that these demonstrations do not attempt to explain the actual causes of the incidents, as it would be difficult to ascertain what truly happened in these instances.

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