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IGNITION AND COMBUSTION OF METALS IN OXYGEN

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IGNITION PROPERTIES OF METALS

During the oxidation of metals that precedes ignition, the products adhere to the metal surfaces as solid oxide coatings. If the oxide coatings are tough and impervious to oxygen, they can inhibit further oxidation and subsequent ignition of metals. For example, the ignition temperatures of metals have been observed to remain unchanged or even increase as oxygen pressure is increased (ref. 151). Oxide coatings can affect the ignition temperatures of metals by changing the overall oxidation kinetics of the metals and/or acting as a physical barrier separating the unreacted portions of the metal from the surrounding oxygen (ref. 152).

The effects of oxide coatings on the oxidation of metals are complex, and entire texts have been written on the subject (refs. 153 and 154). Laurendeau (ref. 151) categorized oxide coatings as either being protective or nonprotective. Oxidation rates for metals that form protective coatings are dependent on electric field-induced transport of metal ions through n- or p- oxide coating, oxygen diffusion along pores in oxide coatings, and other mechanisms (ref. 155). Metals that form nonprotective oxide coatings act as if they have fresh metal surfaces, and the oxidation rates are dependent on physical and/or chemical adsorption of oxygen on the metal surface. In general, oxidation rates for metals that form protective oxide coatings are slower and less dependent on pressure than oxidation rates for metals that form nonprotective oxide coatings (refs. 152 and 155).

In the case of oxide coatings acting as physical barriers, the ignition properties of zinc provide an excellent example. The oxide coating produced by zinc encapsulates the unreacted zinc, separating it from the surrounding oxygen. As the temperature is increased in a static system, the vapor pressure of zinc will eventually exceed the strength of the oxide coating. The oxide coating fails, releasing zinc vapor, which immediately ignites with the surrounding oxygen. Increasing the surrounding oxygen pressure requires a greater vapor pressure or temperature to fail the oxide coating, which results in an apparent increase in the zinc ignition temperature. In a static system, aluminum will ignite when the melting temperature of its oxide is achieved. The ignition temperature of aluminum as oxygen pressure is increased remains essentially constant, since the melting temperature of the oxide is independent of pressure.

Dynamic conditions that are characteristic of many ignition situations can compromise the protectiveness of the oxide coatings and cause a decrease in the temperatures or energy inputs required for ignition. For example, the ignition temperature of aluminum determined in static bomb tests was approximately 2100 K (ref. 151), whereas, in frictional heating tests where samples of aluminum were rubbed together, aluminum ignited at temperatures below 700 K (ref. 156). Another example is aluminum samples that were impacted with single stainless steel particles (ref. 157). The total kinetic energy of the particles was less then 0.8 J, and only a small portion of this energy was converted to heat. The results indicated that aluminum ignited at bulk temperatures below 650 K. It is believed that during the impact process thin fibers of fresh aluminum metal were produced, which ignited and caused combustion of the entire samples. Thus, it is important that the source of the energy stimulus be carefully considered to ascertain the effects the stimulus will have on the protectiveness of oxide coatings.

An increase in oxygen pressure has, for many years, been viewed as causing an increase in the potential for metals to ignite. Tests conducted at the NASA White Sands Test Facility (WSTF), in which metals were rubbed against themselves in oxygen, have revealed that increasing oxygen pressure does not always increase the potential for ignition. It is believed that there exists specific pressures, above which, convective heat loss due to the higher oxygen density will overcome the potential increase in the oxidation rate afforded by the increase in oxygen pressure. Test results have shown that, once a specific oxygen pressure was exceeded, greater rates of frictional energies were required for ignition of metals as pressure was increased (ref. 156). Other test results have indicated that as oxygen pressure was increased during the rubbing process, the bulk sample equilibrium temperatures decreased. These results support the belief that increases in convective heat loss as pressure is increased can raise the energy requirements for ignition of metals or lower their ignition potentials. Testing has also indicated that, when metals were exposed to a rubbing process and oxygen pressure was increased, metals such as carbon steel exhibited a decrease in their bulk ignition temperature, whereas other metals such as Monel showed bulk ignition temperatures independent of pressure. It is believed that these results reflect the ability of certain metal oxides to retain their protectiveness even under dynamic conditions. A test effort at WSTF is presently being conducted to determine if similar pressure effects observed in the frictional heating tests are also characteristic of other ignition sources, such as ignition of metals by impact of particles entrained in flowing oxygen at high velocities.

COMBUSTION PROPERTIES OF METALS

Metals can burn as either vapors or liquids. This appears to be related to the boiling points and flame temperatures of metals. A comparison of these properties is listed in table I for aluminum that burns as a vapor and iron that burns as a liquid. The flame temperatures of metals are limited by enthalpy considerations at the metal oxide boiling points (ref. 152).

In burning of bulk metals such as solid metal rods, measuring burn propagation rates (V) can aid in the understanding of the combustion properties of metals. Metal rods in a vertical position and ignited at the top (downward propagation) exhibit V's which were generally greater than V's for the same metal rods ignited at the bottom (upward propagation). The effect for the larger V's observed for downward propagations was attributed to hot molten mass (produced from combustion) that had dripped down the rods and preheated or ignited the unreacted portions of the rods (ref. 158). In the case of upward propagations, the hot molten masses attached themselves to the bottom of the rods and were held by surface tension. As the size of the molten masses increased, the weight of the molten masses eventually exceeded the force of the surface tension holding the molten masses to the rods. The molten masses detached from the rods and dropped away from the rods. Heat transfer required to support combustion of the rods was limited to the cross-sectional area at the molten mass/rod attachment points.

Much has been learned about the overall combustion process of bulk metals by studying the upward burn propagation of solid metal rods. The transfer of heat, required to support combustion of the rod, is believed to occur at the interface where the molten mass attaches itself to the rod. Temperature differences generated by the hot molten mass and the relatively colder solid rod are believed to cause convection currents in this region and provide the dominant mechanism for heat transfer (ref. 159). All other heat transfer paths such as radiation or conduction were considered to be negligible.

Detachment of molten masses from the rod appeared to have very little effect on the V observed for mild steel that burns as a liquid (ref. 160). However, in the case of aluminum, which burns as a vapor, V was observed to be highly dependent on the detachment of the molten mass (ref. 158). The V appeared to be at a maximum during the initial growth of the molten mass. At some point in the growth of the molten mass, V decreased to a smaller value and continued at this smaller value until detachment of the droplet again occurred; the cycle then repeated itself. The decrease in V was attributed to the formation of vapor aluminum bubbles as the molten mass temperature reached the boiling point of aluminum. These vapor bubbles were believed to have lowered the heat transfer coefficient at the molten mass/rod boundary layer. The formation of vapor bubbles probably also hastened the detachment of the molten mass by lowering the surface tension of molten mass.

As the diameters of the rod were increased, V decreased for metals that burn as liquids and vapors (refs. 158 and 161). The decrease in V was attributed to greater conductive heat loss through the rod as compared to the increase in heat generated by combustion as the diameter of the rods were increased.

The effects of increasing oxygen pressure on V again depended on whether the metals burn as liquids or vapors. Metals that burn as liquids exhibited increases in V as pressure was increased, and this was attributed to the increase in the oxidation rate (refs. 160 and 162). However, in the case of aluminum that burns as a vapor, V was observed to increase, decrease, and then increase as pressure was increased (refs. 158 and 161). Sato et al. (ref. 158) attributed this variation in V to the combination of an increase in the boiling temperature of aluminum and an increase in the heating rate of the molten mass. Both these effects will change the time required to reach the boiling point of aluminum.

POSSIBLE EFFECTS OF ZERO GRAVITY ON IGNITION AND COMBUSTION PROPERTIES OF METALS

The effects of zero gravity on the ignition characteristic of metals will probably be small, since many of the ignition sources observed in real systems involve dynamic conditions, such as frictional heating produced in rubbing processes, impact of particles, and adiabatic compression ignition of oil or soft-goods, which in turn ignite metals (kindling chain). Since the pre-ignition oxidation products are solids, convective mass transfer near the metal surfaces does not appear to be important in the oxidation kinetics in normal gravity, and thus the elimination of gravity should have no effect. However, in static systems where heat transfer due to free convection is important, changes in the ignition process may occur when gravity is eliminated.

Combustion tests performed in normal gravity may not be in some cases adequate for describing the combustion properties in zero gravity. In static systems under normal gravity, differences are observed for upward and downward burning of metals, and elimination of gravity will most likely produce large changes in these combustion properties. For example, in zero gravity, the molten mass will not detach and fall away from the rod as observed in upward propagation, and the molten mass will not drip down the rods as observed in downward propagation. In zero gravity, the molten mass will probably continue to grow at the surface of metal, and the effective area for heat transfer may increase from that observed in upward propagation in normal gravity. However, elimination of gravity will eliminate the convective currents at the interface boundaries, and heat transfer may have to occur by some slower mechanisms such as conduction or radiation. In the case of metals that burn as vapors, it is unclear at this time how the vapor bubbles in the molten mass will behave.

In dynamic systems, many of the effects that zero gravity may have on the combustion properties of metals may be small compared to the dominant effects the dynamic conditions will have on the combustion process.

When ignition and combustion of metals are compared, combustion appears to be inherently more susceptible to the effects of zero gravity; and, if testing in zero gravity is planned, combustion tests should be carried out first as opposed to ignition tests.

TABLE I. - COMPARISON OF METAL COMBUSTION PROPERTIES

	Aluminum	Iron
Metal melting temperature, K	932	1860
Metal boiling temperature, K	2720	3160
Oxide melting temperature, K	2323	1700 (FeO) 1900 (Fe_3O_4)
Oxide boiling temperature, K	3800	2070 (FeO) 3690 (Fe_3O_4)
Flame temperature, K	3300	3000