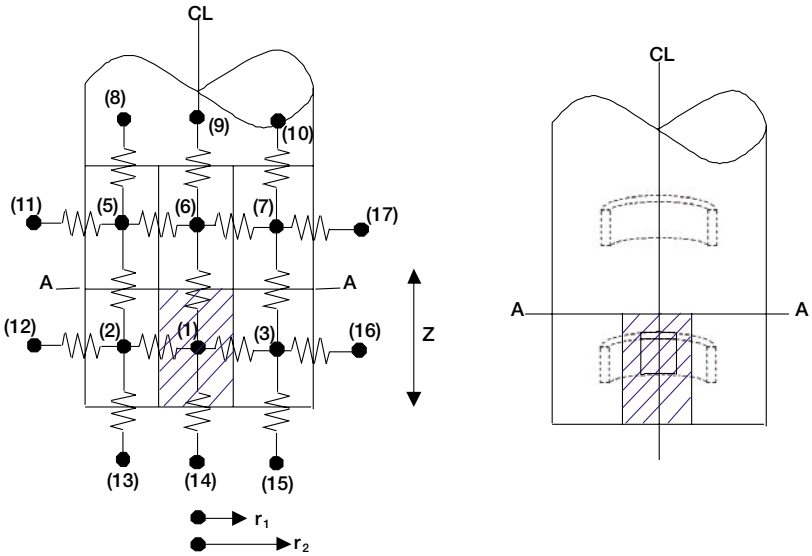
Modeling the Ignition of Large-Diameter Rods and Pipes in Flowing Oxygen

Miguel Maes, White Sands Test Facility,
Johnson Space Center

The recent Industry-Sponsored Metals Combustion Test Program 96-1 involved promoted ignition and burning of 316L stainless-steel rods (1.27-cm diameter) and Sch. 80 and XXS pipe (3.175-cm nominal diameter) in both static and flowing oxygen. These tests demonstrated difficulties igniting large samples in flowing oxygen. This work examined and modeled the ignition of metals based on the Standard Test Method for Determining the Combustion Behavior of Metallic Materials in Oxygen-Enriched Atmospheres (ASTM G124) configuration test. Appropriate mass and energy conservation balances were developed and validated against the experimental results of Phase I and II tests. Parametric studies demonstrated the effects of system pressure and flow on ignition. These results were compared to current theories of ignition and future work may be pending.



Cross-section view of large-diameter rods for combustion tests.

Wendell Hull & Associates, Inc. coordinated the Industry-Sponsored Metals Combustion Test Program 96-1 on behalf of several contributing companies. All design and testing was performed at Johnson Space Center's White Sands Test Facility (WSTF). Phase I of this test program studied the threshold pressure for propagation of burning 3.175-mm-diameter stainless-steel rods in static oxygen. Phase II testing studied the ignition and propagation of burning 12.7-mm-diameter stainless-steel rods and 31.75-mm-diameter pipes in flowing gaseous oxygen (GOX). The oxygen concentration for these WSTF GOX test systems is verified to be a minimum of 99.5 percent, which meets or exceeds the minimum specified in MIL-PRF-27210G for Aviator's Breathing Oxygen (ABO-grade). For the rod configuration, the sample was suspended vertically and the flow of oxygen was directed downward and around the outside of the sample along its longitudinal axis. For the pipe configuration, the sample was suspended vertically and the flow of oxygen was directed through its interior, thereby simulating a real piping system. The test sample configurations were chosen to replicate previous promoted ignition and burning tests, as well as to represent geometries and cross-sectional thicknesses common in industrial piping applications. The gas pressures and velocities for the test matrix were selected to generally compare with Compressed Gas Association (CGA) guidelines for the use of stainless steel in oxygen service (CGA G-4.4, Industrial Practices for Gaseous Oxygen Transmission and Distribution Piping Systems).

Test result comparison demonstrates differences in materials flammability between flow and non-flow oxygen conditions and between solid rod vs.

pipe sample configurations. While there is consistent agreement as to the qualitative description of the ignition event, there is no single robust mathematical model for metal ignition. This is because ignition, including the ignition source, is a system-dependent event. There are, however, good simplified models of gas phase ignitions, such as homogeneous exothermic gaseous reactions exchanging energy conductively or convectively with their surroundings, and occurring without depletion of reactants (Frank-Kamenetskii 1955). The difficulty in modeling efforts for metals ignition involves the heterogeneous nature of the metal system, the possible growth of a protective metal oxide layer, and the complex heat transfer that exists for a heterogeneous system. In addition, there exists the mass transfer of gaseous oxidizer to the reacting surface.

Previous metals ignition work has been based on concepts reflected in the Van Heerden plot (Froment & Bischoff 1979). These solutions are steady-state solutions (ignition is unsteady state). The applications come through the fact that SS1, SS3, SS4, and SS5 are stable and SS2 is unstable. Given recognition of the information on this type of diagram, a lumped-parameter model is useful as shown in the figure. After positive ignition (i.e., the continuous burning of the sample), both combustion products and melted sample are drained away by gravity; each mode is thus modeled by a mass and a momentum balance.

The model development resulted in the following equation:

$$\dot{Q}_{R5} = C_5 T_5 - C_{55} * f(T)$$

where $\dot{Q}_{R5}$ is the S-shaped curve for thermal energy generation, C5¬ is the varying slope on the heat exchange curve, and C55 is the intercept of this curve.

The results of the recent Industrial-Sponsored Test Program for promoted-ignition and burning of large-diameter 316L SS rods, Sch.80 pipe, and XXS pipe have been analyzed by a lumped-parameter model study. This analysis has focused on the 316L SS solid rod samples. Similar analyses are appropriate for both the Sch. 80 and XXS pipe, except flow is internal to the pipe instead of external. The effects of oxygen pressure and flow would be essentially the same. The results of the model analysis are consistent with experimental observations:

- Increased oxygen pressure in a flow environment increases the rate at which heat is transferred to the surroundings from the burning system.
- Flow increases heat transfer through forced convection, requiring a substantial increase in thermal energy input for promoted ignition testing. (NOTE: This is based on upward-propagation burning being opposed by the flow. Upward-propagating burning is enhanced by free convection.)
- Previous concepts used to describe ignition temperatures have been derived from steady-state solutions. A more appropriate phase-plane analysis of the promoted-ignition system should be undertaken.