An earlier version appeared in *American Fireworks News*, No. 254, 2002.

Pyrotechnic Burn Rate Measurements: Strand Testing

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Background

Burn rate is one of the most fundamentally important properties of pyrotechnic materials. While burn rate may be measured as a mass burn rate (mass of pyrotechnic composition consumed per unit time, e.g., g/s), linear burn rate is most commonly used. Linear burn rate can be defined as the distance the burning surface of a pyrotechnic composition advances inwardly (perpendicular to the burning surface) per unit time, and typically would be reported as inches per second (or mm/s). Even for a specific pyrotechnic material with a defined composition (including prescribed particle size and shape) there are a number of factors that will effect its burn rate.[1] Generally the most important factors, ranked roughly in order of importance, are: ambient pressure, loading pressure (composition density), temperature, and burning surface area. Accordingly, for burn rate measurements to be most useful, they must take each of these additional factors into consideration.

During World War II, B. L. Crawford, et al. developed the *strand burner* (sometimes also called the Crawford Bomb) for making linear burn rate measurements of propellants under suitably controlled conditions.[2–4] The strand was a thin column of pyrotechnic, typically about 1/8 inch (3 mm) in diameter and about 7-inches (180-mm) long. Today the strand is often 1/4-inch (6-mm) thick and may be square in cross section. The test strand is held in the burn chamber of the strand burner, which is a pressure vessel that is maintained at constant gas pressure for the duration of the test. The temperature of the strand during the test is the same as that of the strand burner and is held reasonably constant by the flow of gas (usually nitrogen or argon) through the burn chamber. When temperatures other than ambient are needed, the strand burn chamber and gas supply can be heated or cooled to the desired temperature.

Prior to loading into the strand burner, a series of small diameter holes are drilled through the strand at precisely determined points along its length; thin, easily-fused wires are then threaded through the drilled holes. The number of fuse wires may be as few as two, but it is common to use more. Typically the wires are made of lead and are about 0.01 inch (0.25 mm) in diameter. The outer surface of the strand will usually have been coated (painted) with a suitable flame-resistant inhibitor, to cause the strand to only burn inwardly from one end, in a cigarette-like fashion, rather than along its outer surface. (See Figure 1.)

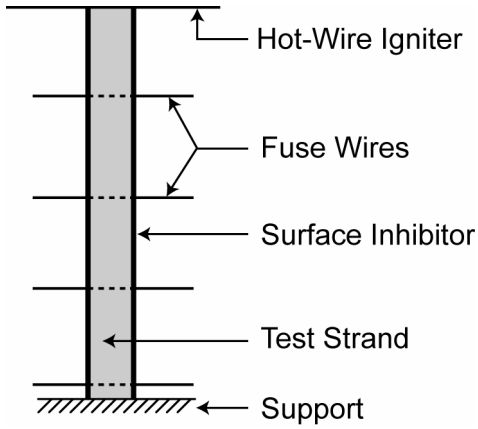

Figure 1. Illustration of a strand prepared for burn rate testing (not to scale).

After being placed in the burn chamber, the strand is ignited from one end using a hot-wire igniter. Then, as the strand burns, the heat fuses (melts) each wire as the burn front passes. The fusing of the first wire is used to provide the 'start' signal for the burn rate measurement, and then each successive wire fusing provides a 'stop' signal to indicate the progress of the burning. Knowing the time of the wire fusings and the spacing between the wires, the linear burn rate can be calculated.

Table 1. Sample Data from a Study of the Effect of Nano-Molybdenum as a Burn Rate Catalyst.[8]

Oxidizer →	Ammonium Perchlorate (80%)		Potassium Perchlorate (71%)		Potassium Chlorate (74%)		Potassium Nitrate (80%)	
Fuel →	Shellac (20%)		Sorbitol (29%)		Sorbitol (26%)		Charcoal (20%)	
	No Cat.[b]	Cat.[b,c]	No Cat.	Cat.[c]	No Cat.	Cat[c]	No Cat.	Cat[c]
Burn Time[a] (s)	8.63	6.73	20.10	16.60	5.27	2.67	6.33	5.20
	9.73	6.57	21.00	17.20	6.57	2.67	5.73	5.53
	8.17	7.43	20.63	16.47	6.00	2.50	6.50	5.50
	9.47	6.87	19.40	15.20	6.07	2.53	6.23	5.77
Ave. Burn Time (s)[d]	9.0	6.9	21.3	16.3	6.1	2.6	6.2	5.5
% Increase[e]	—	30%	—	30%	—	135%	—	15%

a) Time to burn 1.4 g of composition (including approximately 3 mg of oil to aid compaction) pressed at 4000 psi (30 MPa) in a paper tube with an internal diameter of 5/16 inch (8 mm) and a wall thickness of 3/32 inch (2.5 mm).

b) These test items had a 3/32-inch (2-mm) diameter by 1/8-inch (3-mm) long indentation formed in the ignition end of the test strand when being pressed. This was done to provide some erosive burning to help sustain the burning of the test items.

c) Four percent molybdenum trioxide (MoO_3) as nano-particles was used as the catalyst.

d) To better reflect the uncertainty in the results, average burn times are only reported to one decimal place.

e) This is the percent increase in burn rate for the composition with the catalyst present. To better reflect the uncertainty in the results, increases in burn rate are only reported to the nearest 5%.

The dependence of burn rate on local pressure is especially important for propellants, in particular, gun propellants where the pressures can range to especially high values. The pressure dependence of the burning of a propellant (or a pyrotechnic composition) can often be characterized using the Vieille burn rate equation,[1]

$$R = a\,P^{\,b}$$

where R is linear burn rate, P is pressure, and a and b are constants. For example, in one series of strand tests of the burning of Black Powder, when R and P have the respective units of cm/s and atmospheres, the constants a and b were found to have the values 1.72 and 0.164, respectively.[5] (While the Vieille equation generally applies over a reasonably wide range of pressures, often more than one set of constants is necessary to fit the data over the entire pressure range.[6])

Simplified Strand Test Method

When simple comparisons between similar compositions are desired, it is often possible to make a number of simplifications to the strand burner test. For example, a series of tests was recently conducted to investigate the potential for nano-particle size molybdenum trioxide[7] to function as a useful burn rate catalyst. In these tests, simple comparisons were made between the burn rate of pairs of compositions made with and without the presence of a small amount of the potential catalyst. Accordingly, in these initial tests it was not necessary to determine burn rate as a function of pressure and temperature, and testing could be performed at atmospheric pressure and room temperature. Accordingly, a complex strand burner apparatus was not needed.

In the catalyst tests, each oxidizer was prepared by simultaneously ball milling two samples of the oxidizer, the first sample with 4% of the molybdenum trioxide added and the second sample without the catalyst. In this way the nano-catalyst was well mixed with the oxidizer without otherwise treating the two oxidizer samples differently. Following this, the fuel was mixed with each oxidizer sample. Finally, to aid in compacting the compositions a tiny amount of a light oil was added (approximately 2 mg per gram of composition). This was accomplished

by first dissolving the oil in acetone, then mixing the oil/acetone solution into the composition and continuing mixing until the acetone completely evaporated, leaving the trace of oil evenly distributed through the composition.

Once the test compositions were prepared, a series of eight test strands were prepared, four with and four without the catalyst added. Each test strand was made by pressing a series of small increments, totaling 1.4 g into a small paper tube, 5/16-inch (8-mm) ID by approximately 1-3/4-inches (44-mm) long. To further help produce a consistent composition density, the composition was compacted using a constant loading pressure of 4000 psi (30 MPa). The tubes provided a constant cross sectional area of composition and acted as the flame resistant surface inhibitor to cause the burning to proceed in a cigarette-like fashion. With consistent composition density and constant amounts of composition compressed into each tube, the length of each test strand was nearly the same [in this case approximately one inch (25-mm)]. Since each test strand was approximately the same length, it was only necessary to compare their burn times to determine whether and approximately how great a catalytic effect was produced.

In this case, burning of the test strands was initiated using a small torch flame applied to one end of the composition. Accurate burn times were measured using a video camera to make a record of each burn test, then playing back the tape one video field at a time, while counting the number of video frames (each 1/30 second) between the first sign of ignition and the first indication of fire from the other end of the tube (test strand). As a check on the results, for each composition, four separate burn tests were performed. See Table 1 for a sample of the catalyst data produced.

The test results exhibit a moderate amount of variability. This is thought to reflect somewhat of a lack of care in preparing the sample items, the relatively short length of the test strands, plus variations in ignition stimulus from the torch. For some purposes, such variation would not be acceptable; however, for simple screening tests as in this case, it is not a major concern. It seems clear that the nano-molybdenum trioxide does have the ability to act as a burn catalyst.

Conclusion

When it is sufficient to perform strand testing under ambient conditions, the greatly simplified method, as described for this initial study of the burn catalytic effect of nano-molybdenum trioxide, can be employed to produce reasonably useful screening data.

Acknowledgements

The authors wish to acknowledge D. Dillehay, D. Tanner and L. Weinman for commenting on an earlier version of this article. Also, the authors are grateful to L. Johnson for supplying a sample of nano-molybdenum trioxide for testing.

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