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Pyrotechnic Burn Rate Measurements: Interstitial Flame Spread Rate Testing

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*[**Authors' note:** This article includes a number of notes with ancillary information. This information is not essential to the primary purpose of this article. Accordingly, it is suggested that the reader might wish to initially ignore the notes, and then subsequently, if additional information is desired, read any notes of interest.]*

Background

There are two general types of burning, sometimes described as *parallel burning* and *propagative burning*.[a] In the previous article in this series,[2] a method for determining parallel burn rate was discussed (*strand testing*), and a simplified method of testing under ambient conditions was suggested. In the current article, a method for determining one type of propagative burn rate (*interstitial flame spread rate*[b]) is discussed.

Knowledge of interstitial flame spread rates can be quite important in producing consistent pyrotechnic actions. For example, even though modern artillery uses smokeless powder as their primary propellant, it is common for these propellants to be ignited using an initial, centrally located, charge of Black Powder. This is because the proper functioning of the smokeless propellant in artillery rounds requires its rapid and controlled ignition under conditions of low initial pressure.[3,4] Black Powder accomplishes this rapid and controlled flame spread at near atmospheric pressure.[c,d] Similarly, the rapidity of flame spread at low pressure plays an important role in Black Powder's ability to successfully propel aerial shells high into the air, whereas smokeless powder and Pyrodex® are ineffective.

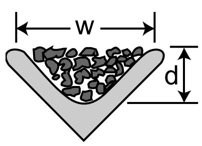
The methods used to determine the interstitial flame spread rate of powders range from quite simple to very complex. The procedure can be as simple as measuring the time to burn a trail of powder (e.g., burning 16 grams [6.6 oz] of Black Powder laid in a straight line on a flat surface and timing the burning with the aid of a video camera[7]). On the other hand, the hardware and procedure can become much more involved when performance is measured in the actual assemblies in which the powder is to be used. This can involve the use of multiple light and pressure sensors, special ignition methods, and a machined powder container mounted in a pressure vessel.[3]

One problem with interstitial flame spread testing is that many factors, other than the intrinsic nature of the pyrotechnic composition, can substantially affect flame spread rate. Probably foremost among these are what might be described as geometric effects. These include such things as the test powder's average grain size and the range of grain sizes present.[e] For example, if the same exact same pyrotechnic composition is used to produce two slightly different size granules, the flame spread rates of those granulations will differ. A more important geometric effect is the configuration of the powder during the test.[f] For example, even in the simplest configuration, such as a trail of powder burned in the open, the depth and width of the powder that is laid down will significantly affect the flame spread rate. However, despite the potential for uncertainties in making flame spread measurements, because of the simplicity of the method, this can be quite useful for comparing the performance of pyrotechnic powders.

Simplified Method

The simplified method suggested in this article is only slightly different than the "burn a trail" method described above. The primary difference is the use of a pre-made form (tray) that shapes and holds the powder trail. A convenient form is common steel angle iron. The use of this is illustrated in Figure 1, first shown in cross-section, where the powder has been laid into the "V" groove formed by the angle iron. The approximate dimensions of the powder trail formed using a "small" tray made from 1/2 × 1/2 × 1/8-inch

(13 × 13 × 3-mm) angle iron and a “large” tray made from 3/4 × 3/4 × 1/8-inch (19 × 19 × 3-mm) angle iron are shown in the accompanying table in Figure 1. Having two sizes of the apparatus can be useful; the smaller is perhaps better suited for fine-grained powders or if the amount of powder is limited. The amount of powder held by the smaller tray is approximately 40 grams (1.5 oz) whereas the larger tray requires approximately 130 grams (4.5 oz). The complete apparatus as seen from the side (at a reduced scale) is also shown in Figure 1. Here, a four-foot [1.2 m] length of material was used; however, end stops were inserted to provide a powder trail length of 39.4 inches (1 meter). When testing slower burning powders, or to save on the amount of powder consumed, the end stops can be moved closer together. Two common U-bolts are used to hold the end stops in place and provide support legs that keep the angle iron oriented upright. A small hole (not shown in the drawing) has been drilled into one end stop. This holds the electric match used to ignite the powder being tested. This hole is slightly below what will be the top of the powder in the V-channel of the apparatus.[g]



Size	Dimensions (in.)			
	w		d	
	in.	mm	in.	mm
Small	0.51	13	0.23	5.8
Large	0.85	22	0.38	9.7

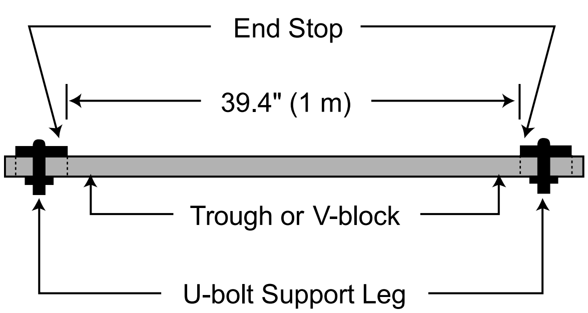


Figure 1. Illustration of a simple interstitial flame spread test apparatus.

To use the apparatus, first an electric match is inserted through the hole in the end stop such that its head (tip) protrudes approximately 1/8 inch [3 mm] into what will be the powder trail. Then the powder to be tested is added to the V-channel such that it completely fills the space of the channel without extending significantly above the top of the channel. (A small paper card can be useful for forming and smoothing the top of the powder trail.) To initiate the test, the electric match is fired.

For slow burning powders, it may be possible to measure the time for the fire to advance to the end of the unit simply using a stopwatch. However, to make a permanent record of the test and to much more accurately time the burning, a simple home video camcorder can be used. When this is done, the tape can be played back counting the number of 1/30 second frames (or 1/60 second fields, available from some VCR’s). In the testing done by the authors, the light sensitivity of the video camera must generally be reduced such that the light from the burning powder does not overwhelm the camera. The first video frame (field) that documents a slight reduction of the light produced upon the flame front reaching the approximate end of the powder trail is taken as the indication that the end of the powder trail has been reached.[h,i] Typically, at least, three measurements are made for each powder type, and an average burn time is calculated. To demonstrate the use of the simple flame spread measurement method, a series of Black Powder samples were tested. The results are listed in Table 1.

Some useful inferences and conclusions can be drawn from even the limited amount of test data presented in Table 1.

- The three Goex powders were tested using both the small and large tray, and they serve to demonstrate the effect that even relatively small differences in the powder’s configuration have on the interstitial flame spread rate. Note that the flame spread rate using the larger tray is 20 to 35 percent higher than when using the small tray.
- The average particle size of the three types of Goex powder are approximately 14, 22 and 60 mesh for the 3FA, 2Fg and 4Fg powders, respectively. Note in Table 1 that the 4Fg (finest mesh) powder did not have the greatest interstitial flame spread rate. This would seem to be an indication that, for these three powders in the configuration used in these tests, the 2Fg powder has the optimum effective fire path cross-sectional diameter.[e]
- For the powder samples and configurations tested: the Wano brand powder (4Fg in the

Table 1. Results of Flame Spread Rate Measurements of Black Powder Samples.

Powder Description	Tray Size[(a)]	Burn Time (video fields, 1/60 s) 1	2	3	Average Burn Time (s)	Flame Spread Rate (in./s)	(m/s)
Goex™ – 3FA	Small	68	74	76	1.21	32.6	.83
	Large	60	59	54	0.96	41.0	1.04
Goex™ – 2Fg	Small	58	53	59	0.94	41.9	1.06
	Large	39	40	42	0.68	57.9	1.47
Goex™ – 4Fg	Small	63	57	55	0.97	40.6	1.03
	Large	45	41	43	0.72	54.7	1.39
Wano™ 4Fg	Small	58	58	59	0.97	40.6	1.03
Chinese Military 2Fg	Large	52	63	54	0.94	41.9	1.06
Elephant™ 2Fg	Large	42	41	46	0.67	58.8	1.49
Hobbyist 4FA[(b)]	Small	51	53	(c)	0.87	45.3	1.15
Pyrodex™ RS 2Fg[(d)]	Large	300	262	266	4.60	8.6	.22
Clean Shot™ 2Fg[(d)]	Large	138	127	128	2.18	18.1	.46
Black Canyon Powder™	Large	86	86	82	1.41	27.9	.71
Bullseye™ Pistol (Red)	Small	1106	920	1138	16.94	2.3	.06

a) The small tray was made of 1/2 inch (13 mm) angle iron 1/8 inch (3 mm) thick and 39.4 inches (1 meter) long. The large tray was made of 3/4 inch (19 mm) angle iron 1/8 inch (3 mm) thick and 39.4 inches (1 meter) long.

b) This powder was handmade, unglazed, of moderately low density, and made with handmade charcoal.

c) There was only enough of this powder to allow two flame spread rate tests using the small tray.

d) These powders were marked by their manufacturers as being equivalent to 2Fg Black Powder; however, their actual grain sizes were somewhat larger.

small tray) appears to be approximately equivalent to the Goex powder in terms of interstitial flame spread rate (approximately 40.6 and 40.6 inches/second (1.03 m/s) average burn rates, respectively). Similarly the Elephant brand powder (2Fg in the large tray) was approximately equivalent to the Goex powder (approximately 58.8 and 57.9 inches/second (1.49 and 1.47 m/s) average burn rates, respectively), whereas the Chinese military powder (2Fg in the large tray) had a distinctively lower flame spread rate than did the Goex powder (approximately 41.9 and 57.9 inches/second [1.06 and 1.47 m/s] average burn rates, respectively). Although 4FA powder from Goex was not tested, based on the granulations that were tested, it would seem likely that the flame spread rate in the unglazed and somewhat dusty hobbyist 4FA powder produced what would have been a higher flame spread rate than the commercial powder of the same granulation.

- In strong contrast to the interstitial flame spread rates of Black Powder under the conditions of these tests, the flame spread rates of the Black Powder substitutes and the smokeless powder were significantly to dramatically lower. This performance difference serves as an indication as to why these powders generally are poor substitutes for of Black Powder in propelling fireworks aerial shells from their loose fitting mortars.

Conclusion

When it is sufficient to perform interstitial flame spread rate testing at atmospheric pressure under mostly unconfined conditions, the simplified method described in this article can be employed. Certainly the precision afforded in these measurements is sufficient for screening tests, and in some cases such testing might be employed as part of a quality control program.

Acknowledgments

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Notes

a) In parallel burning, the burn front proceeds inward, into the solid mass of pyrotechnic composition, burning layer after layer as it proceeds, with each layer approximately parallel to the burning surface. The primary mechanism of energy feedback from the reacting (burning) layer to the pre-reacting (about to burn) layer is thermal conduction. This is in contrast to propagative burning of granular powders, where fire races down *fire paths* between individual grains of pyrotechnic composition, driven by the pressure of the gases being produced in the burning process. The primary mechanism of energy feedback, from burning grains to about-to-burn grains, is the convection of hot gas. (For more information about these two types of pyrotechnic burning see reference 1.)

b) In this article, these tests have been called "interstitial" flame spread rates, to emphasize that it is the collective rate of flame spread along the numerous fire paths between a large number of individual grains of powder. In the jargon of the trade, these and similar tests are sometimes referred to as *V-block tests*.

c) It is the combination of both rapid and controlled flame spread in Black Powder that is needed in the ignition of smokeless propellant in artillery. Clearly many pyrotechnic materials have the characteristic of rapid flame spread (e.g., flash powder). However, while under some conditions the flame spread in flash powder may be nearly as low as granulated Black Powder, under only slightly different conditions the flame spread in the same flash powder may be quite explosive. Thus the flame spread rate in flash powders is often unpredictable (i.e., it is not easily controlled or regulated).

d) In addition to Black Powder's rapid interstitial flame spread, another important characteristic is that it burns to produce a relatively high percentage of non-gaseous combustion products. Based on thermodynamic modeling using the CEQ code, the flame of burning Black Powder produces approximately 30% non-gaseous (liquid) reaction products.[5] As the flame cools, approximately another 25% of the reaction products condense (for a total of 55%).[6] Then as cooling continues these molten products may proceed to solidify. These non-gaseous, condensing and solidifying reaction products are much better than permanent combustion gases at carrying and transferring the heat energy needed to cause the ignition of other materials. Accordingly, it is the combination of Black Powder's rapid and controlled interstitial flame spread at near atmospheric pressure and its high proportion of non-permanent gaseous reaction products that make it so effective in the ignition of the smokeless powder in artillery rounds.

e) Average grain size and the range of grain sizes in the powder being tested act to determine the average or typical space between the individual powder grains. This is important because the spaces between the grains constitute the fire paths through the powder, and the effective cross-sectional diameter of the fire paths determines their effectiveness in producing high interstitial flame spread rates.[8] This is illustrated in Figure 2, in which burn rate is presented as a function of fire path diameter for a hypothetical pyrotechnic composition. In that figure, when there are no effective fire paths (i.e., the fire path diameter is zero) such as for a very tightly compacted pyrotechnic composition, the rate of burning is just that of the inward burning into the composition (R_I). This corresponds to parallel burning and is the burn rate that is measured in the surface inhibited strand testing as discussed in the previous article.[2] As the fire path diameter increases from zero, the burn rate increases until a maximum value is reached (R_M) corresponding to the most effective fire path diameter (D_M) for that composition under the conditions of the tests (temperature, pressure, etc.). Thereafter, as the fire path diameter continues to increase, the burn rate falls until it eventually reaches the burn rate approximating what would be measured across the surface (R_S) of a large compacted mass of composition.

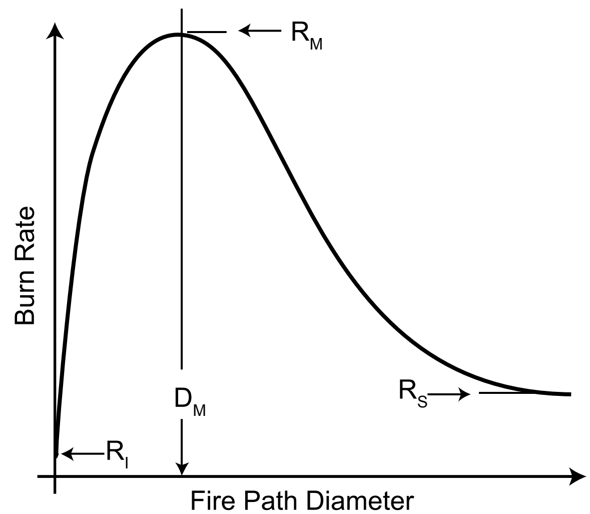

Figure 2. Illustration of the relationship between burn rate and fire path diameter for a hypothetical pyrotechnic composition.[8]

f) One important way in which the configuration of the powder during an interstitial flame spread measurement affects the burn rate is by limiting the ease with which the combustion gases can escape from the burning powder to the atmosphere. This is because any escaping gas will be lost for the purpose of traveling along fire paths to ignite additional powder. As an example of this effect, consider a demonstration in which one trail of powder is burned on a smooth flat surface, whereas a second trail of the same powder is burned after being loaded into an open-ended tube. When this is done for commercial Black Powder, it will be found that the same powder burns roughly 20 times faster in the open-ended tube than it does as a powder trail. This much greater rate of interstitial flame spread can easily be enough to produce an explosion of the open-ended tube.

g) On occasion the firing of the electric match may blow the powder away from it, without igniting the powder. This is not a significant problem as the match can simply be replaced and the test completed. However, on rare occasion (because of the force of the electric match ignition) some of the ignited powder can be seen to be propelled a few inches down the length of the apparatus. This is more problematic and is the reason that: generally at least three tests are repeated for the same powder, the length of the powder trail in the apparatus is fairly long, and the results are only considered to be approximate. If it is necessary to eliminate this occasional source of small error, one could simply use a hot wire igniter rather than a vigorously functioning electric match.

h) Shortly after ignition of the powder, as the flame front advances along the powder trail, the amount of powder burning at any instant is approximately constant, and thus the light output is also approximately constant. When the flame front reaches the end of the powder trail, no additional powder is ignited. Thus, the amount of powder burning starts to decrease and the amount of light produced also decreases. Accordingly, the first indication of light reduction as the flame front approaches the end stop, serves as a reliable indicator that the flame has reached the end stop.

i) Using a video camcorder to measure the rate of interstitial flame spread along the apparatus is the method most often described in the literature.[3,4] Nonetheless, other methods, such as fuse wires, could be employed. However, this requires the use of timing electronics. More importantly, for fast burning powders, producing relatively low flame temperatures, the uncertainty introduced because of variations in the time taken for these wires to fuse is on the same order as the uncertainty in using the video method.

References

1) K. L. and B. J. Kosanke, "Parallel and Propagative Burning", *Pyrotechnics Guild International Bulletin*, No. 79, 1992; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 2 (1980 through 1992)*, Journal of Pyrotechnics, 1995.

2) K. L. and B. J. Kosanke, "Pyrotechnic Burn Rate Measurements: Strand Testing", *American Fireworks News*, No. 254, 2002; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 6 (2001 and 2002)*, Journal of Pyrotechnics, 2005.

3) N. A. Messina, L. S. Ingram, M. Summerfield and J. C. Allen, "Flamespread Propagation Rates of Various Black Powders Using

the PCRL-Flamespread Tester", *Proceedings of the 7th International Pyrotechnic Seminars*, 1980.

4) K. J. White and A. W. Horst, "Black Powder Flamespreading Characteristics", *Proceedings of the 7th International Pyrotechnic Seminars*, 1980.

5) W. Meyerriecks, private communication, 1999.

6) T. L. Davis, *The Chemistry of Powder and Explosives*, 1943, reprinted by Angriff Press, p 43.

7) R. A. Sassé, *A Comprehensive Review of Black Powder*, Technical Report BRL-TR-2630, 1985.

8) T. Shimizu, *Fireworks, From a Physical Standpoint, Part I*, reprinted by Pyrotechnica Publications, 1981, p 16.