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Quick Match — A Review and Study

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ABSTRACT

Several factors affect the burning of quick match. A brief study was conducted to determine the general magnitude of the effects produced by those factors, singly and in combination. For high quality quick match, under the conditions of these tests, it was determined that tight string ties, damage to the Black Powder coating and exposure to high humidity had the potential to slow the burning of quick match. However, no single performance risk factor was observed to be sufficient to produce either a significant hang fire or a failure of the quick match to propagate. To the contrary, however, typically a synergistic effect was produced by combinations of risk factors. For example, combinations of two risk factors produced short hang fires, and combinations of all three risk factors produced occasional misfires.

An examination of the extent to which moisture is gained by the materials used to make quick match suggested that the use of synthetic (plastic) string could significantly reduce moisture adsorption. This should reduce the degradation of the performance of quick match that has been exposed to high humidity. Also long duration hangfires could possibly be eliminated because this string does not tend to smolder like cotton string. Finally, there was a brief examination of the time taken for the strings in black match to lose their strength after the flame front had passed. It was found that it may occasionally be possible for one shell firing in a chain to pull apart the fusing of the next shell in the series.

Introduction

Although some interesting new fusing technologies have recently been introduced (No-Match™[1] and Sticky Match™[2]), quick match continues to be widely used in fireworks, mostly for aerial shell leaders. While many in the fireworks trade have extensive practical knowledge regarding the performance of quick match, relatively little quantitative information has been published. Several years ago, a study was conducted to investigate quick match burning under various conditions. This article reports those results, specifically: the effectiveness of methods used to slow the burn rate of quick match, the effect of risk factors (such as powder loss and exposure to high humidity) on its performance, how a combination of risk factors can account for its failure to function properly on occasion, some suggestions for possible improvement of quick match, and the length of time its strings retain significant strength after the fuse burns. However, before presenting those discussions, this article sets the stage by discussing the construction and manner of functioning of quick match.

Construction and Manner of Functioning

Typically quick match consists of black match within a thin loose fitting sheath of paper. (However, on occasion other materials such as plastic tube or even metal tubing are used). Generally the paper sheath is called the “match pipe” and sometimes quick match is called “piped match”. See Figure 1 for the appearance of black match and quick match. The match pipe can be pre-made and a length of black match slipped into it. Although this works well

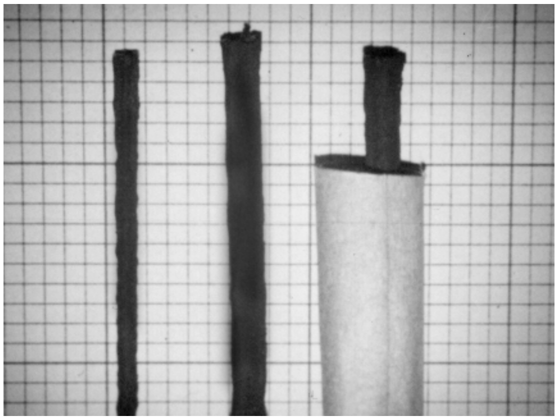

Figure 1. Two examples of black match (left) and an example of quick match (right).

for making short lengths of quick match, such as needed for shell leaders, longer lengths, such as needed for fusing lancework, would need to be spliced together. As an alternative, and the method most commonly used commercially in the US, the match pipe is formed in a continuous process around a very long length of black match. Traditionally, the match pipe included an inner wrap of thin wax-impregnated paper for moisture protection of the black match core. More recently, some manufacturers have used plastic laminated paper,[3] plastic-covered tape[4] or other similar means to provide a greater level of moisture protection.

Black match most commonly consists of a collection of thin strings, usually cotton or cotton / polyester blends that have been coated with a slurry of Black Powder with a binder in water. Manufacturers may use commercial meal Black Powder, a mixture of commercial powder and rough (handmade) powder, or rough powder alone. Typically, the individual strings are pulled over a number of rollers immersed in the slurry, then brought together as a bundle and pulled through a funnel shaped orifice to remove the excess Black Powder mixture. The wet black match is usually wound on a frame for drying before it is used to make quick match. However, some oriental manufacturers use wet, or at least damp, black match to make their quick match. One variation in making black match is to apply a dusting of meal powder to the black match while the match is still wet. This so-called "dusted" match is reputed to ignite easier and burn faster when made into quick match.

Black match typically burns at approximately one inch per second (25 mm/s). The same black match, when loosely sheathed to make quick match, typically burns more than 100 times faster, at 10 to 20 feet per second (3–6 m/s). The authors have heard three explanations for the accelerated burning of black match when wrapped to make quick match, specifically:

1) The black match burn rate increases because of its being starved for oxygen under the paper wrap.
2) The increase in black match burn rate is the result of burning under increased pressure because of the paper wrap.
3) The burn rate increase is the result of contained gases traveling along the enclosed space between black match and the paper (i.e., in essence a transition from parallel burning to propagative burning induced by the presence of the paper wrap).

In large part, the first explanation can be quickly dismissed on theoretical grounds; there is no scientific basis for pyrotechnic burning accelerating because of a deficiency of oxygen. Clearly Black Powder is not dependent on atmospheric oxygen for burning. Moreover, atmospheric oxygen is a more energetically favored source of oxygen than potassium nitrate. Thus, if anything, its availability can only serve to increase burn rate. However, the main reason for rejecting this explanation is that it is contrary to common experience. For example, consider a case where a thin trail of fine (mixed particle size) commercial Black Powder is burned on a surface. The rate of burning will be inches per second (100's of mm/s). However, when this same powder is tightly wrapped with threads to make visco fuse or when well compacted into a casing as a rocket motor, its burn rate falls to less than half an inch per second (about 10 mm/s). This slowing is contrary to the prediction of accelerated burning when Black Powder is starved for oxygen by encasing it.

The second explanation for high burn rates of quick match at least has a potential theoretical basis to support it; burn rate generally accelerates in response to increasing ambient

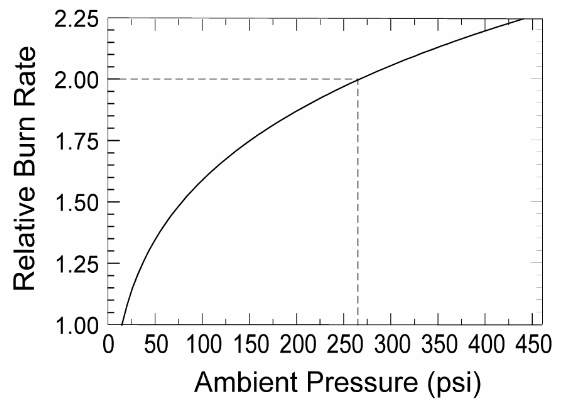

Figure 2. Graph of Black Powder burn rate as a function of ambient pressure (note that 1 psi = 6.9 kPa).

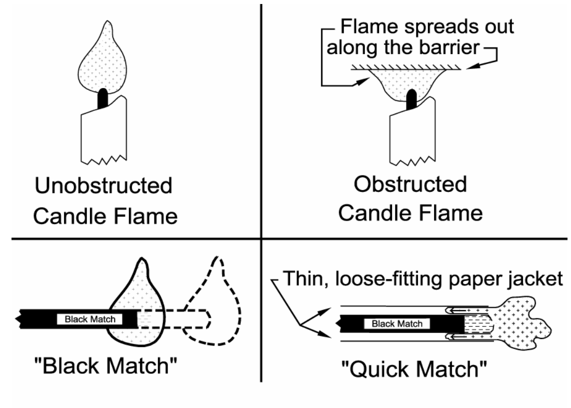

Figure 3. The analogous burning of a candle and black match without and with the presence of an obstruction.

pressure. This is expressed in the burn rate or Vieille equation:[5]

$$R = A\ P^B$$

where R is linear burn rate, P is ambient pressure, and A and B are constants.

For Black Powder, burn rate increases with pressure as shown in Figure 2 (based on the constants given by Shidlovskiy[5]). Two things should be noted in Figure 2: first, ambient pressure must rise to approximately 265 psia (1.8 MPa) for the burn rate of Black Powder to double; and second, the effectiveness of rising pressure to increase burn rate lessens with increasing pressure. Obviously, the pressure increase needed to even double the burn rate for black match is much greater than could ever be contained by the paper match pipe, let alone the horrendous pressure increase needed for a 100 fold increase in burn rate. Accordingly, this second possible explanation for the increased burn rate of quick match must also be rejected.

In essence, the third explanation for the accelerated burn rate of quick match is that there is a transition from parallel to propagative burning. This explanation was presented by Shimizu,[6a] without specifically using the terms parallel to propagative burn type transition. (For a more complete discussion of these terms, see reference 7.) Shimizu's explanation uses the analogy of a candle flame. When a barrier obstructs a candle flame, see Figure 3, the flame tends to spread out along the barrier. He likens the unobstructed candle flame to the burning of black match. When the black match has burned to the start of the match pipe, the pipe at least temporarily obstructs the flame. Some of the flame is deflected out the end of the match pipe, but some flame is also deflected into the "fire path" between the match pipe and black match. The flame entering the match pipe causes the ignition of an additional amount of Black Powder on the surface of the black match. Because more black match has ignited, additional flame is produced. Some of this flame exits the match pipe, and some penetrates further into the match pipe igniting still more black match, thus producing even more flame. The process continues to accelerate as the flame races through the fire path between the black match and match pipe. In the process, the pressure inside the match pipe does increase slightly, but much less than that needed to explain even a small fraction of the increase in the rate of burning. Nonetheless, the increase in pressure has important ramifications. The acceleration of the burning of black match can only increase to the point where the internal pressure exceeds the strength of the match pipe, at which time the pipe ruptures and further acceleration of burning ceases.

In addition to there being a sound physical basis for believing Shimizu's explanation, he conducted supporting experiments. In these tests, the paper match pipe was replaced with thin metal tubes.[6a] As expected, the burn rate increased beyond that found for paper-piped quick match because of the higher pressures

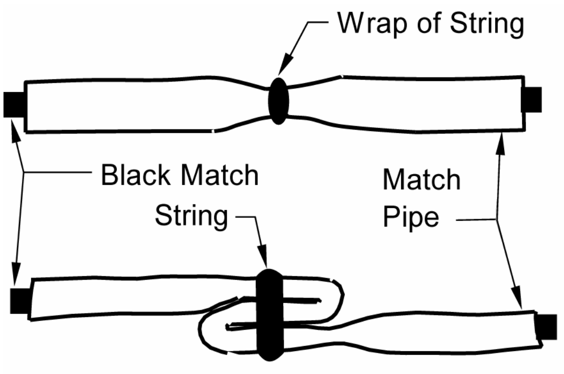

Figure 4. Illustration of two common methods used to slow the burn rate of quick match.

tolerated by the metal tubes before their rupturing. Further, the authors' studies of quick match reported in this article support or are consistent with Shimizu's explanation.

Methods to Slow Quick Match Burning

Lengths of quick match typically burn at 10 to 20 feet per second (3–6 m/s). However, sometimes this is faster than desired, such as when firing a barrage of chain-fused aerial shells. Quick match burns rapidly because fire (burning gas) races down the "fire path" between the black match and the loose fitting match pipe, and therein lies the answer to slowing its rate of burning. Whenever the fire path in quick match is tightly closed, its burning must temporarily transition back from propagative burning (fast) to parallel burning (slow). Ofca[8] calls such delays "choke delays".

A number of similar methods are used to close the fire path of quick match. Probably the most common is simply to tie a string (or light cord) very tightly around the quick match at the point where a momentary slowing is desired. The string collapses the paper match pipe compressing it tightly against the black match. Accordingly, the quick match burning propagates rapidly along its fire path until the point where it is tightly closed by the string. At that point it must burn slowly, layer by parallel layer under the string and compressed match pipe. Then, when the fire path re-opens, the burning again propagates rapidly. For this method of slowing

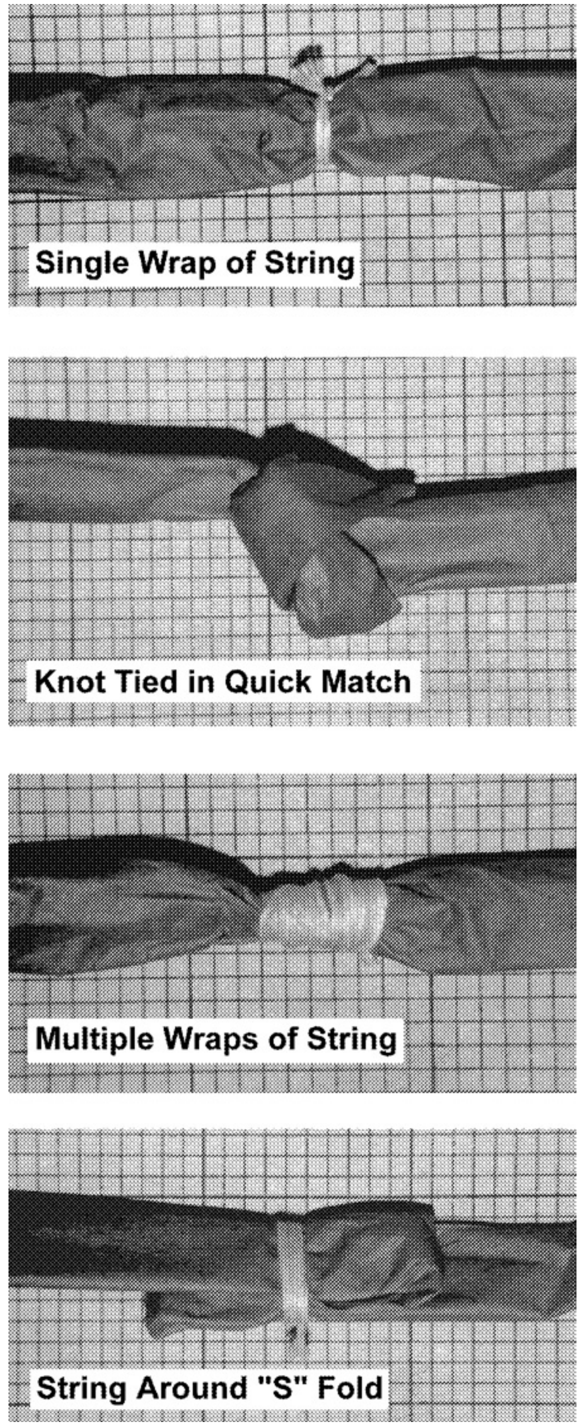

Figure 5. Photos of common methods used to slow the burning of quick match.

to be successful, the fire path must be totally closed. Otherwise some fire will race through any small gap between the black match and match pipe, and there will be much less slowing of the burning.

Table 1. Quick Match Delay Times.

Condition	Burn Times (seconds/60)[a]			Average[b]
	Longest	Shortest	Average	Delay Time (s)
Unaltered	21	17	19	≡ 0.0
Single string tie	45	21	33	0.2
Quick match knot	52	30	44	0.4
"S" tie	79	26	48	0.5
Cable tie	100	24	47	0.5
½" string wrap	109	42	65	0.8

(a) Burn times are in video fields, each 1/60 of a second.

(b) Because of the large variations observed in burn times for the same conditions, the reported averages (in seconds) must be seen as approximate values and are only reported to the nearest 0.1 second.

Several common methods to close the quick match fire path are illustrated in Figures 4 and 5. Instead of tying a string tightly around quick match, other items such as plastic electrical cable ties can be used. Another method is simply to tie the quick match itself into a tight knot. If a longer delay is desired, more than one tie can be made around the quick match, or a long continuous wrap of string can be used, or the quick match can be tightly tied in the shape of an "S" with string.

Unless noted to the contrary, the same method of measuring burn times was used throughout this study. In each case, three measurements of burn time were made for each condition being tested. Approximate burn times were determined by videotaping the burning of quick match sections and counting the number of 1/60-second video fields, while viewing the tape in slow motion. Each 16-inch (400 mm) long test section of quick match had an additional 4 inches (100 mm) of black match exposed on the end for ignition. Timing started with the first indication that burning had propagated to the inside of the match pipe (i.e., when the flame from the burning black match became distorted by the paper match pipe). Timing stopped at the first sign of fire or significant sparks projecting from the other end of the quick match section. Unless noted to the contrary, the quick match used in these tests was produced by Valet Manufacturing,[9] which had been stored for more than a month at 75 ºF and 35% relative humidity. The reason for choosing Valet quick match was that it is generally believed to be of high-quality and because a moderate quantity was available in the lab for testing. However, because more testing was performed than originally anticipated, the supply of quick match from Valet was exhausted and quick match from Primo Fireworks (now out of business) was substituted.

The results of the tests of quick match slowing methods are reported in Table 1. In each case the longest, shortest, and average times of three separate tests are reported. The relative unpredictability of these slowing methods can be approximated by comparing the longest and shortest burn times for the various methods. In part the differences must be the result of variations in the length of tightly compressed match pipe around the black match. Further, the variability was probably exacerbated to some extent by the low relative humidity, causing the match pipe paper to be relatively stiff and unyielding, making it difficult to achieve a tight closure of the match pipe around the black match.

The subject of humidity will be specifically addressed below; however, humidity can affect the amount of delay commonly achieved using the various quick match slowing methods. For quick match that has been subjected to high humidity for a few days, the delays reported in Table 1 can be twice as long. Another factor affecting the amount of delay achieved using the various methods is the quality of the quick match. Quick match that is fiercely burning,

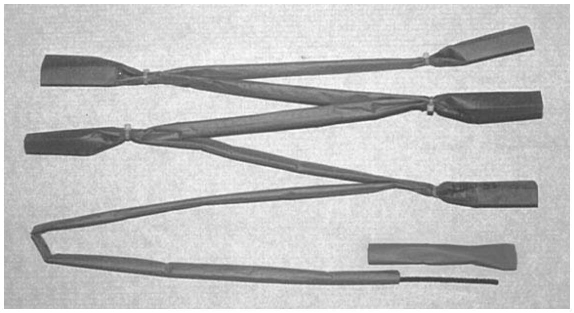

Figure 6. Photo of a short "finale chain", shown with "buckets" for attaching shell leaders.

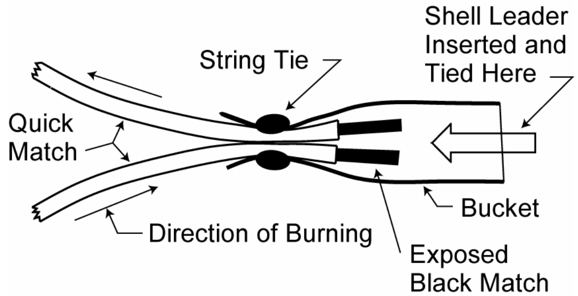

Figure 7. Cut away illustration of one "bucket" in a finale chain.

with a heavy powder coating and a thick match pipe, is the most difficult to slow.

To some extent, an operator can control the speed of a finale during the chaining operation. Figure 6 shows a short finale chain with paper wraps (often called "buckets" and made from coin wrappers) that are used for attaching the quick match to the leaders of shells in the chain. Figure 7 shows a cut away illustration of one bucket. At the chain end of each bucket (left in Figure 7), if the string is tied VERY tightly, a brief delay will be introduced (such as suggested in Table 1). Whereas, if the buckets are only tied tight enough to minimally hold the fusing together, there will be significantly less delay at each tie point. Note: To secure such a connection, some operators augment the string tie with a small amount of glue between the match pipe and bucket.

When longer delays are needed, it is possible to add a length of time fuse such as shown in Figure 8. Here a length of time fuse has been cut, punched and cross-matched (usually with thin black match). The length of time fuse between the cross-matched points determines the amount of delay that will be produced. The piece of time fuse is inserted into a very thin-walled paper tube, typically made with two or three turns of Kraft paper. The time fuse is tied into place near both of its ends. To install the delay element, first cut the quick match to be slowed into two pieces and expose its black match by tearing back the match pipe roughly one inch (25 mm). Then insert the two ends of quick match into the two ends of the delay element and tie them securely. It is important that the string ties on the time fuse are quite tight to keep fire from passing under the strings and skipping around the time fuse.

As one gains experience with a particular supplier's quick match and the methods of slowing quick match burning, it should be possible to control its burn rate to accomplish most needs, providing a high degree of timing precision is not essential.

Effect of Powder Loss

Damage to the Black Powder coating on the black match is reputed to degrade the performance of quick match. Further, severe damage is sometimes given as a reason for quick match failure (a hangfire or misfire). One example of how such powder loss might occur would be the result of extreme and repeated flexing of the quick match in one area, such as from very rough handling. For these tests, damage to the black match coating was introduced by repeatedly drawing approximately 2 inches (50 mm) of its length (near the middle of the quick match

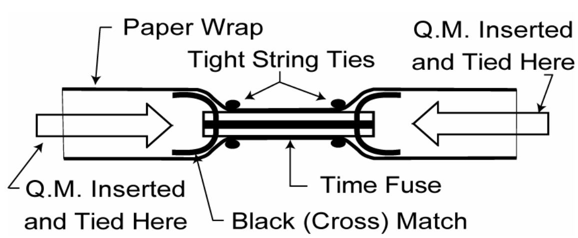

Figure 8. Cut away illustration of method for attaching a length of time fuse to quick match (Q.M.= quick match in illustration).

Table 2. Burn Times of Test Segments of Quick Match Suffering Serious Powder Loss.

Condition	Burn Times (seconds/60)[a]			Burn Time Change[b]
	Longest	Shortest	Average	
Undamaged	21	17	19	≡ 0%
2" Damaged	16	15	16	–15%
6" Damaged	17	13	15	–20%
Undamaged[c]	24	19	21	≡ 0%
2" Washed[c]	26	20	24	15%
6" Washed[c]	37	34	36	70%

(a) Burn times are in video fields, each 1/60 of a second.

(b) Because of the variations observed in burn times for the same conditions, the reported average percentage change must be seen as approximate and are only reported to the nearest 5%.

(c) Quick match was from Primo Fireworks.

test segment) over a 0.25 inch (6 mm) diameter mandrill. After each pass, the direction of the bending was changed by rotating the quick match approximately 90°. The process continued until the paper match pipe was so distressed that its tearing was imminent. (Note that this amount of damage to the black match core is more than would be expected from even the roughest handling of aerial shell leaders.) After this treatment, the length of quick match was held vertically and repeatedly tapped to cause as much as possible of the loosened black match coating to fall out of the match pipe. On average, approximately 0.3 g of powder was removed from each damaged quick match segment. A second set of test samples were similarly prepared, except that approximately 6 inches (150 mm) of its length was damaged by being drawn over the mandrill. In this case, approximately 0.7 g of powder was removed from each test segment. The results from these tests are shown in the top half of Table 2, along with burn times for undamaged quick match segments.

Because the observed differences in burn time were small, one cannot be quantitatively certain of these results. Nonetheless it seems likely that the damaged quick match segments actually burned slightly faster than undamaged quick match. Certainly, the damage did not cause the segments to burn significantly slower; even though the damage was severe and much of the loosened powder had been removed. In these tests, it seems obvious that sufficient powder remained attached to the black match for it to function well. If there actually was a burn rate increase, it may be the result of a residue of loosened powder coating the black match and the inside of the match pipe, or an increase in the ease of ignition of the black match coating because the remaining powder had been broken into small pieces.

In another series of tests, this time using quick match manufactured by Primo Fireworks, the effect of even more extreme black match powder loss was studied. In these tests, quick match segments were prepared in which there was a complete loss of black match coating for approximately 2 and 6 inches (50 and 150 mm). This was accomplished by first sliding the length of black match out of the match pipe. The black match coating was then removed from a length of the match, initially by crumbling off a much as practical, and then by washing the strings. Care was taken to prevent wash water from contacting the rest of the black match and to limit the migration of water into the black match through the strings. The lengths of black match were then dried at approximately 70 °F (21 °C) and 35% relative humidity for a week, before being reinserted into the match pipe. The burn testing proceeded as normal, with the results reported in the lower half of Table 2.

While there was a slowing of the burning, under the conditions of the tests, it is apparent that the flame front successfully jumped the lengths of string with no coating. However, it is expected that having an open end to the match pipe aided the propagation of flame over the uncoated sections of the black match.[6b] Accordingly, it should not be assumed that such severe removal of the black match coating would necessarily result in successful propagation in a length of quick match that has a closed end such as is normal for shell leaders. Nonetheless, that the segments of quick match with 2-inch (50-mm) lengths of washed string propagated fire with only a slight increase in burn time, and that the segments with 6 inch (150 mm) of washed string propagated fire with less than a doubling of the burn time are interesting observations.

The results from these two series of tests seem to be convincing evidence that for otherwise excellent quality quick match, as a single factor, it is unlikely that even the most severe physical damage to the black match coating will cause the failure of the match to propagate fire. However, it is important to note that this is not to say that such damage, in conjunction with other problems, does not contribute to failures of quick match (a situation that is investigated later in this article).

Effect of Humidity

Absorbed moisture has the potential to reduce the burn rate of quick match because thermal energy is wasted in heating and vaporizing the moisture. (See reference 10 for a more complete discussion of the factors affecting burn rate.) A series of tests were conducted to determine the effect on the burn rate of exposure of unaltered quick match to higher humidities. Also examined was the approximate length of time of exposure needed to reach a steady state condition.

The constant humidity chambers (hygrostats) used in this study were simply constructed using plastic containers approximately 14 by 10 by 6 inches (360 by 250 by 150 mm) purchased from a discount store. These boxes were chosen because their lids fit well and the seal could be made fairly tight by placing weight on the lid. For humidity control, two small trays were placed inside each plastic box. Each tray was filled with a saturated aqueous solution of either ammonium nitrate, sucrose (table sugar) or potassium sulfate. At the temperature of the lab (≈65 °F or ≈18 °C), the theoretical relative humidity maintained by these solutions should have been approximately 66, 85 and 97%, respectively.[11,12] (For more complete information on this method of producing constant relative humidity environments, see reference 13.) The quick match segments to be subjected to the various humidities were placed into the chambers.

The relative humidity in the lab during the period of the measurements was about 35%. Because the chamber lids were removed to load and remove the samples, and because the lids on the chambers did not provide perfect seals, the relative humidities maintained inside the chambers were less than their theoretical values and they varied somewhat during the course of each day. The relative humidities actually maintained within the chambers were measured using a digital hygrometer (Davis Instruments, model 4080). Those values averaged approximately 64, 78 and 90% for the three chambers.

The results of burn tests of these humidity-conditioned quick match segments are reported in Table 3. As can be seen, the range of values for the same conditions is quite wide as compared to the effects being measured (i.e., statistical precision is limited). Nonetheless some things are certain under the conditions of these tests. In all cases the quick match segments successfully propagated fire. However, exposure to high levels of humidity significantly slowed the burning of quick match, and greater slowing was produced as the level of humidity exposure was increased. Also, for these short open ended segments, the effect of the exposure apparently reaches a steady state within approximately 5 days.

Table 3. Burn Times of Unaltered Quick Match Segments Exposed to High Humidity.

Relative Humidity	Burn Times (seconds/60)[(a)]			Burn Time Percent Change[(b)]
	Longest	Shortest	Average	
35%, > 30 days	21	17	19	≡ 0
64%, 2 days	22	17	20	10
64%, 5 days	30	14	24	30
64%, 7 days	28	16	23	20
78%, 2 days	37	22	31	60
78%, 5 days	32	22	29	50
78%, 7 days	34	21	28	50
90%, 2 days	39	28	34	80
90%, 5 days	50	29	40	110
90%, 7 days	48	31	41	120

(a) Burn times are in video fields, each 1/60 of a second.

(b) Because of the very wide variations observed in burn times for the same conditions, the reported percentage differences in burn time must be seen as approximate and are only reported to the nearest 10%.

Effect of Combined Risk Factors

In earlier sections of this article, methods for slowing quick match burning (by fire path closure) and the effects of powder loss and humidity exposure were reported. In some respects, these are each potential risk factors for the proper performance of quick match. This section presents information on the effects of some combinations of these individual risk factors.

In the current tests, the same constant humidity chambers described above were used. In all cases, unless otherwise noted, the humidity exposure was for at least 5 days. Two of the techniques for slowing the burning of quick match were reexamined for quick match exposed to high humidity. The first technique was that of tying a knot in the quick match. This was chosen because the stiffness of the low humidity quick match segments had made tying a tight knot difficult, and thus possibly less effective than it might have been. The second technique was that of tying a string tightly around the quick match. This was chosen because it is probably the most commonly used method to slow the burning of quick match and because the normal use of quick match for shell leaders commonly requires tying string around the quick match. Burn times from the previous tests (35% relative humidity) and for the high humidity (78% relative humidity) tests are presented in Table 4 (“Knot in Quick M.” and “String Tied”).

Exposure to 78% relative humidity was previously observed to increase quick match burn times by approximately 50% (see Table 3). In the present test, the slowing produced for humidity-exposed quick match tied in a knot was approximately 40%, essentially what might be expected. However, the extreme increase in burn time, approximately 300% (> 1.5 s), observed for the string tie method was surprising. This is approximately six times the magnitude of the effect that might have been expected from combining the separate effects. This observation is especially significant because such string ties are commonly used (in securing shell leaders to cylindrical aerial shells, bags of lift powder, and finale chain buckets) and because exposure to such levels of humidity is quite common. Thus, it seems clear that short delay hangfires can be produced by nothing more than prolonged exposure to moderately high humidity and any tight string ties normally around shell leaders.

Previously, the effect of the loss of some or all of the black match coating was investigated. In one series of tests, the black match coating

Table 4. Burn Times of Quick Match in Various Conditions upon Exposure to High Humidity.

Condition and Humidity	Burn Times (seconds/60)[a] Longest	Shortest	Average	Burn Time % Change[b]
Knot in Quick M., 35%	52	30	44	≡0
Knot in Quick M., 78%	87	41	62	40
String Tied, 35%	45	21	33	≡0
String Tied, 78%	162	103	137	320
6" Damaged, 35%	17	13	15	≡0
6" Damaged, 64%	30	18	22	50
6" Damaged, 78%	32	25	27	80
2" Washed, 35%[c]	26	20	24	≡0
2" Washed, 78%[c]	74	36	50	110
6" Washed, 35%[c]	37	34	36	≡0
6" Washed, 78%[c]	∞[d]	68	71[e]	100[e]
String Tied, 35%	45	21	33	≡0
2" Dam., S. Tied, 35%[f]	65	30	45	40
2" Dam., S. Tied, 64%, 2 D.	69	34	52	60
2" Dam., S. Tied, 64%	∞[d]	44	107[e]	220[e]
2" Dam., S. Tied, 78%, 2 D.	∞[d]	89	115[e]	250[e]
2" Dam., S. Tied, 78%	∞[d]	∞	∞	∞
2" Washed, S. Tied, 35%	∞[d]	∞	∞	∞

(a) Burn times are in video fields, each 1/60 of a second.

(b) Because of the large variations observed in burn times for the same conditions, the reported average percentage differences must be seen as approximate and are only reported to the nearest 10%.

(c) The quick match was from Primo Fireworks.

(d) The infinity symbol (∞) was used to indicate that the burning did not propagate to the end of the segment.

(e) The average difference in burn times was calculated using only the results from the two tests in which the burning successfully propagated to the end of the segment.

(f) Two inches (50 mm) of damaged black match in the quick match, around which a string is tightly tied, was exposed to 35% relative humidity. (Note that listings below also indicate when there were only two days (2 D.) of exposure at the higher humidities.)

was loosened from 6 inches (150 mm) near the middle of the quick match segment. This was accomplished by repeatedly drawing the quick match over a mandrill, followed by removal of the loosened powder. The results of the original tests, and the results for identically prepared segments conditioned in the humidity chambers, are reported in Table 4 (labeled as "Damaged"). As expected, there was an increase in the burn times of the quick match segments. However, the amount of increase for the humidity exposed segments (found to be 50% and 80%) was nearly twice that previously found for humidity exposure alone (which was 20% and 50%).

Also previously, the complete loss of short lengths of black match coating was investigated. To accomplish this total loss of powder from a portion of its length, the black match was removed from the match pipe, some of the coating was removed by physically crushing the black match, and then the strings in that area were thoroughly washed and then dried for a week. For the additional testing reported here, quick match segments were initially prepared as before, but were then conditioned by placing them into the humidity chambers. The quick match used in these tests was from Primo Fireworks. The results for these tests are reported in Table 4 (labeled as "Washed"). Exposure to high humidity increased the burn times of the quick match segments, and again the increase in burn time (≈100%) was approximately twice that previously found for humidity exposure alone (50%). However, note that on one occasion the burning of a humidity-conditioned quick match segment was incomplete, failing to propagate past the washed section.

In another series of tests, the combined effect of having the quick match segments suffer the loss of some of its black match coating (using the method described previously), tightly tying a string around the quick match in the area where the powder coating was damaged, and subjecting the segments to high humidity was studied. The results are listed in Table 4 (labeled as "Dam., S. Tied"). For these tests, the burn time for dry undamaged quick match segments with a string tied tightly around them was chosen for reference. As reported earlier, when the only factor was partial black match powder loss, there actually was an average 15% decrease in the burn time. However, in the current study, the burn time for the combination of the string tie and coating loss increased by 40%. When the effect of high humidity was included, the effect was extreme (> 200%), and there were numerous propagation failures.

Finally, reported in Table 4 (labeled as "Washed, S. Tied") are results for another test, wherein segments with 2-inch (50-mm) washed sections were tested after tightly tying a string around the quick match in the area of the washed section. Under these extreme conditions, it was expected that there would be a consistent failure to propagate.

Under the conditions of tests reported earlier in this article, it would seem that high quality quick match can generally suffer any of the individual performance risk factors (closure of the fire path, powder loss, or high humidity) without a serious loss of performance. However, combinations of the risk factors apparently act synergistically to cause much greater loss of performance, sometimes including a total failure of quick match to propagate fire. Of course, one reason this is significant is the hazards posed when aerial shells hangfire or misfire.

Hangfires and Misfires

Probably the most notable malfunctions of quick match, especially when used as aerial shell leaders, are hangfires and misfires.

> *Hangfire - A fuse ... which continues to glow or burn slowly instead of burning at its normal speed. Such a fuse may suddenly resume burning at its normal rate after a long delay. ... If the hangfire goes completely out (is extinguished), it is termed a misfire.*[14a]

An aerial shell hangfire is hazardous because of its unpredictability. The shell could fire at any time, up to a limit reputed to be 30 minutes or more. An aerial shell misfire is a problem because of the necessity to eventually unload the mortar. It is not the purpose of this article to discuss how these malfunctions should be handled once they occur, but rather to suggest some things that might be done by the shell manufacturer and display operator to reduce the likelihood of their occurrence. If the results reported earlier in this article are generally applicable, a solution to hangfires and misfires is to eliminate situations where multiple risk factors could occur, and even the individual risk factors as much as practical.

In the normal course of its use, it is necessary to make connections to lengths of quick match, for example, when attaching shell leaders to the top of cylindrical shells or to plastic bags of lift powder, and when chain-fusing aerial shells. Typically, string or other ties are used around the quick match for attachment. The strength of the attachment (that keeps the connection from pulling apart) is a result of the tightness of the string tie. It was determined above that a tight tie at a point where there is serious damage to the coating on the black match can cause a malfunction (especially when the quick match has also been exposed to high humidity). However, there are measures that can be taken to limit this potential problem.

Some manufacturers[15] insert an additional short length of black match into the end of the quick match where a tie will be made (or use two strands of black match the whole length). This accomplishes two things. Assuming the inserted black match is in good condition, it is assured that at least that piece of black match will have a good powder coating where the tie is made. Also, with two side-by-side pieces of black match, it is nearly assured that even a tight tie will not completely close the fire path between them.

Some manufacturers do not rely on a single tight tie to hold quick match to finale chain buckets or top-fused aerial shells. Rather they use multiple moderately snug ties, or a combination of a moderately snug tie and a small amount of adhesive applied to the paper at the point of connection. In addition to reducing the likelihood of completely closing the fire path of the quick match, this provides a strong and reliable connection (not likely to be pulled apart accidentally). Note that a strong coupling can have important safety ramifications. By itself, an undetected partial slippage of the shell leader from the its point of connection to a top-fused aerial shell could cause a hangfire or misfire. Similarly, if a finale chain pulls apart while firing, it may cease firing, typically causing someone to approach and re-ignite the chain.

During the summer months, exposure to high humidity may be inescapable. With high quality materials and manufacturing techniques, high humidity alone is unlikely to cause quick match malfunctions. However, exposure to high humidity has serious deleterious effects when combined with other quick match performance risk factors. Thus, as a minimum, nothing should be done to exacerbate the situation. For example, magazines should be kept as dry as practical. This is particularly important if the aerial shells are not of the highest quality and may already have other performance risk factors present. At the display site, measures should be taken to limit exposure to high humidity. For example, boxes of aerial shells should not be placed directly on the ground for long periods of time, and most certainly they should not be placed directly on the ground and then covered with a tarp, thus trapping the shells in a high humidity environment.

The testing performed for this article, used only high quality quick match. Thus the results reported can not be assumed to apply to lower quality material. For example, it was observed that even severe damage to the powder coating on the black match, in the absence of exposure to high humidity, did not result in propagation failures. It is likely that this is a result of one characteristic of high quality quick match—its black match is made using multiple strands of string, each of which is well coated with composition before being drawn together to form the black match. To the contrary, in recent years some of the aerial shells imported from China have used a single coarse cord for the black match, which is only coated on its outside, and to which there is rather poor adhesion of the powder to the cord. This product would not be expected to be nearly as forgiving with respect to rough handling, especially in conjunction with any other risk factors.

Moisture Absorption by Quick Match Components

It had been observed that moisture absorption as a result of humidity exposure can seriously affect the performance of quick match. Accordingly, it seemed appropriate to examine the moisture absorption problem more closely by testing the materials used to make quick match. For this, the same constant humidity chambers were employed; however, three additional relative humidities were used. The chemical solutions in these additional chambers were saturated solutions of sodium chloride, potassium nitrate, and barium chlorate. At the temperature of the lab (≈65 °F or ≈18 °C), the theoretical relative humidities for these solutions would be approximately 75, 93, and 94%, respectively.[10,11] Under actual conditions, the relative humidities were measured as averaging approximately 72, 86, and 88%, respectively.

The test samples for this study were either lengths of black match harvested from various manufacturers' quick match or the individual materials used in making quick match. The black match samples had been stored for an extended period of time at approximately 35% relative humidity and were not dried further

Table 5. Percentage Weight Gain of Various Sources of Black Match Exposed to Increasing Relative Humidities.

Source[(a)]	Percentage Sample Weight Gain at Humidities Listed					
	64%	72%	78%	86%	88%	90%
Mantsuna	1.3	1.3	1.4	1.5	2.1	2.5
Wandar	2.1	2.4	3.3	3.5	4.1	5.2
Angel Brand	1.9	2.1	3.1	4.1	---	5.4
Temple of Heaven	2.5	2.9	3.0	3.7	5.2	5.6
Primo (dusted)	2.7	3.0	3.9	4.8	5.1	5.8
Horse Brand	3.1	3.3	4.8	4.9	5.4	5.8
Onda	2.6	2.8	4.0	5.1	---	6.2
Yung Feng	3.1	3.3	4.8	5.6	6.0	6.7
Val-Et	3.1	3.3	4.3	5.0	5.3	7.1
Primo (undusted)	3.0	3.6	4.1	4.7	5.7	7.1
Average Gains	2.5	2.8	3.7	4.3	4.9	5.7

(a) All quick match samples dated to approximately 1992.

prior to testing. About 5 grams of sample material was weighed and placed into the constant humidity chambers. The samples were weighed daily to monitor their absorption of moisture as a function of time. For most materials, there was little absorption after the first full day and no further absorption after 2 days. However, the total time of exposure in the humidity chambers was always at least 4 days. In a few cases (e.g., where the samples liquefied) absorption continued for several days and the time of exposure was extended appropriately. Once data collection was completed at one humidity, the sample was placed into the next higher relative humidity chamber, and the measurements continued.

The samples of black match were harvested from aerial shell leaders that were available for use in the laboratory in 1994; some of the shells were then already several years old. Certainly it cannot be assumed that the black match samples used in this study are representative of what that manufacturer may have been using on all of their products or are using today. The percentage weight gains for the test samples of black match, exposed to the various relative humidities, are presented in Table 5. As can be seen, most samples gained between 5 and 7% at the highest relative humidity examined. Note that the Mantsuna black match gained less than half that of any other sample. (The reason for this will be discussed later.)

The average sample weight gain as a function of relative humidity exposure is graphed in Figure 9. Note that the weight gained is an accelerating function of humidity as it approaches 93% relative humidity. This is the humidity at which potassium nitrate becomes deliquescent and liquefies as a result of drawing extreme amounts of moisture from the air.

To study the weight gains of the individual materials used to make quick match, sample materials were dried for 24 hours at approximately 175 °F (80 °C) then humidity conditioned in the same manner as the black match

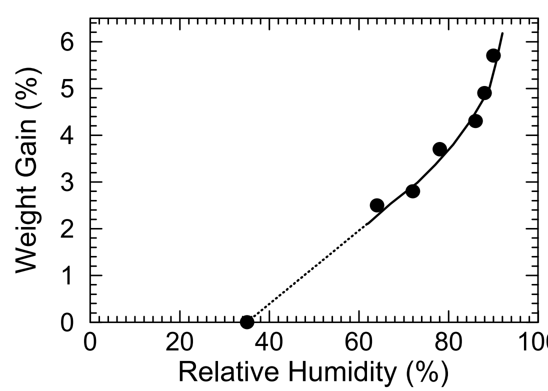

Figure 9. Average percentage weight gain as a function of relative humidity exposure above 35% relative humidity.

Table 6. Percentage Weight Gain of Various Materials Used To Make Quick Match When Exposed to Different Relative Humidities for Five Days.

	Percentage Sample Weight Gain at Humidities Listed					
Material	64%	72%	78%	86%	88%	90%
Goex Meal Powder	1.2	1.2	1.2	2.1	2.3	2.8
Hand Mixed Meal	1.0	1.0	1.2	2.1	2.1	2.6
Charcoal + Sulfur(a)	3.4	3.6	3.8	4.2	4.3	4.8
Potassium Nitrate, AR(b)	0.0	0.0	0.0	0.0	0.0	0.0
Potassium Nitrate, w/AC(c)	0.0	0.0	0.2	0.9	1.3	1.8
Potassium Nitrate, K-P(d)	0.2	0.2	0.3	1.5	2.1	2.2
Dextrin	8.9	11.2	14.0	22.3	(e)	(f)
Gum Arabic	11.8	13.9	15.7	16.8	(e)	(f)
CMC(g)	21.5	26.5	35.5	52.7	(e)	(f)
PVA(h)	5.7	7.9	10.4	16.8	(e)	18.5
HCE(i,j)	12	17	26	38	(e)	(e)
SGRS Waxy(i,k)	11	13	16	20	(e)	(e)
SGRS Quick(i,k)	12	14	16	19	(e)	(e)
Cotton String	5.4	5.9	7.2	9.5	10.0	10.8
Synthetic String(l)	0.0	0.0	0.0	0.0	(e)	0.0
30# Kraft Paper	6.7	7.8	10.3	13.2	(e)	15.1

(a) Air float charcoal and sulfur in a weight ratio of three to two. Supplied by Service Chemical.[17]

(b) Potassium nitrate analytic reagent grade.

(c) Potassium nitrate with anticake, as supplied by Service Chemical.[17]

(d) Agricultural grade potassium nitrate, "K-Power".

(e) Data not taken for this relative humidity.

(f) Sample liquefied.

(g) Sodium carboxymethylcellulose, a water-soluble, thixotropic binder.

(h) Polyvinyl alcohol, a water soluble binder.

(i) The relative humidities to which these samples were exposed were slightly different from those of the other data in this table. The reported percentage weight gain was adjusted slightly by the authors in an attempt to correct for this humidity difference.

(j) Hydroxyethylcellulose, a modestly water-soluble, thixotropic binder.

(k) Soluble glutinous rice starch (SGRS), supplied in two varieties, "Quick" and "Waxy".

(l) The synthetic string had the physical appearance of cotton string. Unfortunately, the type of plastic used to manufacture the string is not known.

samples. These weight gain results are presented in Table 6. Both Goex[16] Black Powder and the rough mixed ingredients, gained essentially the same amount of moisture, approximately 2.5% at the highest humidity. Given that the mixture of air float charcoal and sulfur constitute one fourth of Black Powder, they account for about half of the moisture absorbed by the samples of Black Powder and rough powder (1/4 of 4.8% = 1.2%). High purity (Analytic Reagent grade) potassium nitrate was not observed to gain any moisture. The less pure grades of potassium nitrate, the commercial grade with anticake and the agricultural grade, absorbed about 2% moisture.

Manufacturers of black match in this country usually add dextrin or starch (binders) to the Black Powder or rough powder used to make black match. As can be seen, both dextrin and two rice starches absorb a significant amount of moisture. In this study, six other binders were examined for their tendency to absorb moisture. The other binders were gum Arabic (more commonly used in the past in fireworks), sodium carboxymethylcellulose (CMC, a thixotropic binder that is occasionally used in manufacturing black match), polyvinyl alcohol (PVA, occasionally used in fireworks), hydroxyethylcellulose (a thixotropic binder, potentially useful in fireworks), and two forms of soluble glutinous rice starch (SGRS, commonly used in products manufactured in the far east). If the goal is to make black match that is less sensitive to high humidity, it would seem that PVA and gum Arabic might be considered as an alternative binder. However, neither offers much improvement considering that only small amounts of binder are typically used.

In Table 6, note that the cotton string which is used in most high quality black match is another important contributor to moisture absorption. In contrast, notice that string made from synthetic (plastic) material, does not absorb moisture. This string appears identical to cotton string (but is noticeably stronger). Synthetic string can be identified by placing it near a flame, where unlike cotton string, it first melts before it burns with a sooty flame. The use of such non-cotton string, may pose a problem regarding difficulty in wetting the string during the black match coating process. However, the use of a small amount of surfactant in the slurry of composition should solve that problem. Recall that the test sample of black match from Mantsuna absorbed less than half the moisture of the other samples. This black match is made using such non-cotton (plastic) string and demonstrates that high quality match can be made using it. In addition to high humidity resistance, another even more important potential advantage of using non-cotton string is that it does not tend to smolder, or burn somewhat like a punk, as does cotton string. Of course, this is important because it should significantly reduce the likelihood of hangfires.

Considering the amount contained in quick match, Kraft paper was the component found to be the greatest absorber of moisture. However, that may only have a relatively minor effect on the performance of quick match in an unconstricted match pipe. This is because, unlike the string in black match, the paper is normally not in intimate contact with the black powder. Accordingly, when the black match composition burns, the moisture containing paper match pipe may not be as effective in wasting the thermal energy being produced. However, when string ties are made around the match pipe, there will be contact between the paper and black match. In that case, the damp paper could have a greater effect. For example, recall the much greater delay reported earlier in this article when a string was tied around quick match and exposed to high humidity.

Survival Time for Strings in Black Match

One reason given for the practice of securing finale chain fusing to mortar racks is that, as shells fire, their shell leaders may sometimes pull apart the fusing to yet unfired shells later in the chain. The only way this can occur is if there is sufficient physical strength remaining in the paper match pipe or in the string of the black match, for a short time after the burning of quick match. A brief study was conducted to determine approximately how long after quick match burns that the string in its black match retains significant physical strength.

There is a basis for believing that the black match strings survive for a short time after quick match burns. In the burning of quick match, a flame front races down the fire path formed between its black match core and its paper match pipe. In this process, a small amount of time is required for the black match coating to be consumed and the strings in the black match to be exposed. Accordingly, the strings are not immediately subjected to high temperatures, and they must retain a significant portion of their strength for a brief time after the flame front has passed.

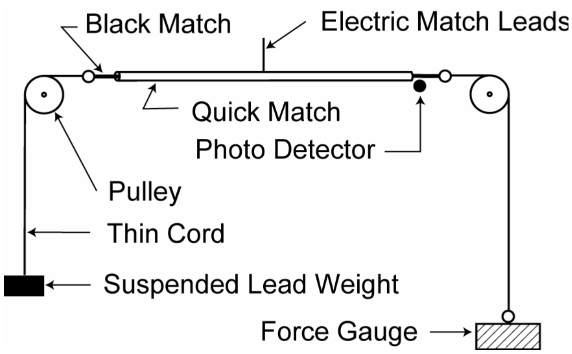

Figure 10. Illustration of the apparatus used to determine black match string failure times.

The apparatus for this study is illustrated in Figure 10. In the center is a 16-inch (405-mm) length of quick match, with approximately 2 inches (50 mm) of black match protruding from each end. Small loops were formed on the ends of the black match to attach thin cords used to apply tension to the black match. The thin cords were each run over small pulleys, where one cord was attached to a piezoelectric force gauge, and the other cord was attached to a suspended lead weight of approximately 2 pounds (≈1 kg mass). Accordingly, as long as the black match in the quick match remained intact, there was approximately a 2 pound (1 kg) tension being applied to the force gauge. The means of igniting the quick match was an electric match inserted through the match pipe at the approximate center of the quick match segment. At one end of the match pipe, a cadmium sulfide photo detector was mounted for the purpose of detecting when the flame front exited the match pipe. (Note that it is not clear whether the detector responded to visible light from the flame or infrared light from hot gases ahead of the flame front.)

A digital oscilloscope was used for timing the events during the tests. The oscilloscope was triggered by the application of current to the electric match. (The level of electric current had previously been determined to be sufficient to cause the firing of the electric match in less than 1 ms.) The outputs from the photo detector and the force gauge were recorded by the oscilloscope. The time of occurrence for each event was read from the oscilloscope traces by knowing the horizontal sweep rate.

The cotton string was found to be a significant absorber of moisture. Thus, it might be expected that the period of time after burning during which it retains its strength was a function of relative humidity exposure. Accordingly, for these determinations measurements were made for each of three humidity exposure conditions. The quick match used in these tests was manufactured by Primo Fireworks and had been stored for more than a month at 35% relative humidity. After being made up as test segments, some were conditioned for 5 days by being placed into humidity chambers at approximately 64 and 78% relative humidity. The test results are presented in Table 7.

For the segments conditioned at 35% relative humidity, the black match strings held the weight for approximately 1/3 second after firing the electric match. In this case, the average time difference between detecting fire exiting the match pipe and the strings failing was approximately 1/4 second. Consistent with what was found in earlier testing, exposure to higher humidity increased the burn time of the quick

Table 7. Black Match String Break Time as a Function of Humidity Exposure.

Measurement and Humidity	Time (s) Longest	Time (s) Shortest	Time (s) Average	Average Time Difference (s)
First Light, 35%	0.16	0.07	0.13	—
String Break, 35%	0.41	0.28	0.35	0.22
First Light, 64%	0.28	0.10	0.20	—
String Break, 64%	0.52	0.39	0.46	0.26
First Light, 78%	0.30	0.22	0.27	—
String Break, 78%	0.56	0.48	0.51	0.24

match (in this case there was an approximate doubling of burn time resulting from exposure to 78% relative humidity). However, exposure to higher humidity also increased the time before the strings failed; for both 64 and 78% relative humidity, the strings failed after about 1/2 second. However, each time, the net result was that the strings failed approximately 1/4 second after detecting fire exiting the match pipe.

Given the time taken for an aerial shell to exit a mortar,[18] the survival time of the black match strings after the burning of quick match may be minimally sufficient to occasionally allow a firing shell to pull apart the fusing of other yet unfired shells. However, a detailed discussion of this question is more complex than it might at first appear and is beyond the scope of this article.

Conclusions

The information about quick match performance presented in this article may be substantially more complete than has appeared elsewhere in print. Nonetheless, this study was limited in both scope and depth. There is much more that should be researched and reported about quick match and its occasional malfunctions (hangfires and misfires). Accordingly, great care should be taken in drawing definite conclusions from the information in this article. The results reported are reasonably accurate but may only be correct for the materials and conditions used in these studies.

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