Studies of Electric Match Sensitiveness

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ABSTRACT

The sensitiveness of a collection of ten electric match types, from four suppliers, was determined under conditions intended to reflect their actual use to ignite fireworks displays. The measurements included determinations of impact, electrostatic discharge (ESD), friction, and thermal sensitiveness. The ESD tests considered discharges both through the bridgewire and from the bridgewire through the composition to ground. When safety shrouds were provided by the manufacturer, additional impact and ESD (through the composition) testing was performed with the safety shrouds left in place on the electric match tips. (Note that users often remove the protective shrouds for convenience during use.) To simulate conditions during use, additional impact and friction testing was performed with Black Powder prime composition in the presence of match tips.

It was found that there was a wide range of electric match sensitiveness, that the presence of the shrouds provided significant decreases in sensitiveness, and that the presence of Black Powder prime did not significantly affect sensitiveness.

Keywords: electric match, e-match, impact sensitiveness, friction sensitiveness, thermal sensitiveness, electrostatic discharge sensitiveness, ESD, sensitiveness testing

Introduction

Although more expensive and time consuming to set up, when compared to traditional reloaded and manually ignited fireworks displays, electrically fired displays have become increasingly common. For the most part, this is because they offer the potential for greater artistry, through the use of intricate display choreography often synchronized to music. However, electrically fired displays also offer the potential for greater display crew safety by requiring a smaller number of firing crew members and by separating them from the mortars and the occasional malfunctioning aerial shell. Unfortunately, too often the full potential for increased crew safety has not been achieved, with the crew sometimes trading accidents caused by aerial shell malfunctions for those caused by the accidental ignition of electric matches during transportation, set-up and disassembly.

A study of electric match (e-match) sensitiveness was completed for ten different match types from four suppliers, and brief summaries of the results have been reported in a series of short articles in *Fireworks Business*.[1] The present article was written to allow full presentation of the data and a number of photographs, as well as to allow a more complete comparison of the results. Table 1 lists the various suppliers and e-match types. Table 1 also presents the abbreviated designations of the e-matches used in many of the data tables throughout this article.

Table 1. List of Suppliers and Types of E-Matches Tested.

Supplier	Product Designation	Abbreviation Used
Aero Pyro[2]	none	AP
Daveyfire[3]	A/N 28 B	DF-B
	A/N 28 BR	DF-BR
	A/N 28 F	DF-F
Luna Tech[4]	BGZD	LT-B
	Flash	LT-F
	OXRAL	LT-O
Martinez Specialties[5]	E-Max	MS-EM
	E-Max Mini	MS-EMM
	Titan	MS-T

More than 1500 individual tests and measurements were performed during this study. However, it is important to acknowledge that, because of the large number of different combinations of e-match types and test configurations used, this sensitiveness testing must only be considered a screening study. For the most part, this is because only a limited number of individual tests were performed during each sensitiveness determination. Also note that the standard sensitiveness tests were often modified in an attempt to better characterize the e-matches in the environment of their use in fireworks displays. Accordingly, the statistical precision achieved is only sufficient to approximately characterize and rank the sensitiveness of the various e-matches, and then only under the specific conditions of this testing. For e-matches producing similar results, had additional numbers of matches been tested or had the conditions been somewhat different, it is possible that slightly different results would have been found. Nonetheless, additional tests or somewhat different test conditions would not be expected to produce substantially different results.

As a consequence of these only being considered screening tests, discussion of the results is often couched in terms indicating a significant lack of certitude. For example, terms such as “it is likely”, “it would seem”, “it is thought”, etc. are frequently used.

The e-matches for these tests were supplied in late 1999. Accordingly, it is possible that current production e-matches from these same suppliers have been modified in some way, which may have caused them to have sensitiveness results different than those reported herein.

Background

Figure 1 is an illustration of a typical electric match. It most commonly consists of an electrically insulating substrate with copper foil cladding, somewhat similar to that used for printed electrical circuits. The size of the e-match tip is often approximately 0.4 inch long by 0.1 inch wide by 0.03 inch thick (10 by 2.5 by 1 mm), exclusive of the pyrotechnic composition. Copper leg wires, used to attach the e-match to the firing control system, are soldered to the copper cladding. Completing the electric circuit within the e-match tip is a thin, high-resistance bridgewire (nichrome) soldered across the end of the substrate. The tip of the e-match is dipped into one or more heat sensitive pyrotechnic compositions, typically depositing about 40 mg of material. Then a protective lacquer coating covers the pyrotechnic composition. For the most commonly used e-matches, when an electric current of approximately 0.5 ampere is passed through the e-match, the relatively high-resistance bridgewire heats sufficiently to cause the ignition of the pyrotechnic composition. This produces a small burst of flame that is used to cause the ignition of a firework. (There are some significant differences in the construction and performance of the ten e-match types studied. However, a proper presentation and discussion of this is well beyond the scope of the present article. Accordingly, information on the construction and performance characteristics of these e-matches must be deferred to a subsequent article.[6])

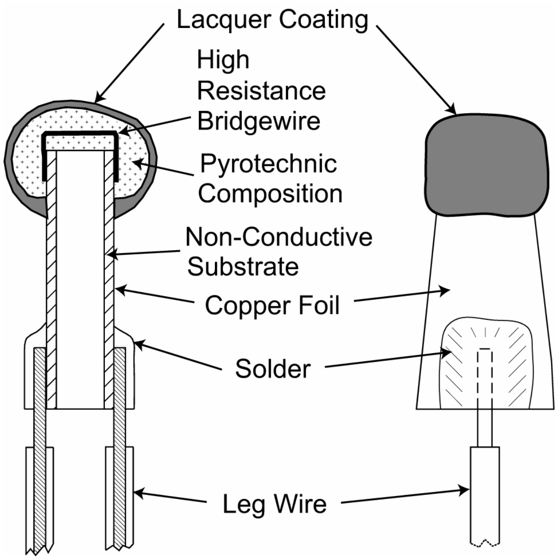

Figure 1. Illustration of a typical electric match in cross-section (left) and viewed externally after rotating 90° (right).

Figure 2 is a series of photographs of some of the types of e-matches tested in this study. Two views of each e-match are shown (rotated 90° from each other), as well as one view with a cut-away safety shroud when that was provided by the manufacturer. Some e-match types were not included in Figure 2 because they are similar in appearance to those shown. The Aero Pyro e-matches and Daveyfire A/N 28 B e-matches are similar to the Daveyfire A/N 28 BR e-match shown. However, the Daveyfire A/N 28 B e-match has somewhat less pyrotechnic composition than the A/N 28 BR, and the Aero Pyro e-matches were not supplied with safety shrouds. The Luna Tech BGZD e-match appears identical to their Flash e-match except for a different color coating. The Martinez Specialties E-Max e-match is virtually identical in appearance to their Titan e-match.

Pyrotechnic compositions are said to be metastable, meaning that they are stable under normal conditions, but when supplied with sufficient activation energy, they react to release their store of chemical energy,[7] typically in the form of a flame. For an e-match, the activation energy is intended to be the thermal energy produced by an electric current passing through the high-resistance bridgewire. However, the activation energy can come from other unintended sources, such as mechanical energy from impact or friction, or the electrical energy from an electrostatic spark, etc. When there is an unintended ignition of an e-match, too often this is the initiating cause of a significant accident, sometimes with the most serious of consequences.

In general, hazards are managed by reducing the probability of the accident occurring, reducing the consequences of the accident should it occur, or preferably by reducing both the probability and consequences.[8] In the case of e-matches, the probability of having an accidental ignition is reduced by taking measures to limit the unintentional delivery of energy to the pyrotechnic composition. This can be accomplished using measures as simple as educating workers to take care not to forcefully crush the e-match, or not to allow the forceful rubbing of the e-match against an abrasive surface. In addition, for e-matches used in situations where accidental crushing or rubbing might be expected, some manufacturers provide soft plastic safety shrouds to help protect the e-match tips. Clearly, the firing crew should be instructed to leave the safety shrouds in place and not to remove them during use (as is often done for convenience).

As is generally true for pyrotechnics, the consequences of having an accidental ignition of an e-match can be reduced by limiting the amount of fireworks in the immediate work area. Work should be performed in a manner such that, in the event of an accidental ignition, only one item will ignite and that it is unlikely that anyone will be seriously injured by that single

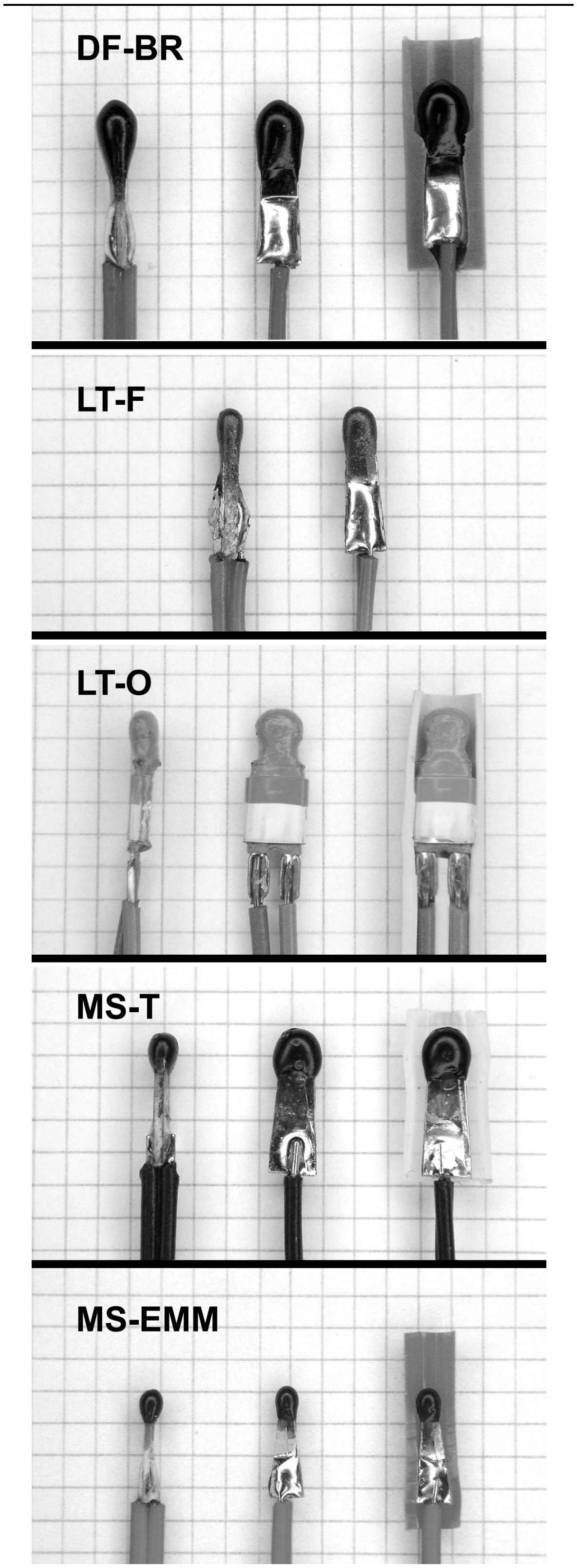

Figure 2. Photographs of some of e-matches studied. (Each background square is 0.10 inch, 2.5 mm.)

ignition. For example, consider the case where an aerial shell has been loaded into its mortar before inserting an e-match into its shell leader and wiring the e-match into the firing circuit. In the event of an accidental ignition of that shell, it is likely that only the one shell would ignite and that it should fire relatively harmlessly into the air. (Of course, that assumes care was taken to not have any body parts over the mortar while working.)

In this study of electric match sensitiveness, it was found that the various e-matches demonstrate a wide range of sensitivity to accidental ignition. However, it is important to note that none were found to be so sensitive as to preclude their safe use, provided appropriate levels of care are taken. Further, it is a general principle of pyrotechnics that materials that are less prone to accidental ignition also tend to be more difficult to ignite intentionally. Thus, it should not automatically be assumed that the least sensitive e-match is the best choice for every application.

Impact Sensitiveness

Normal Configuration

The impact sensitiveness apparatus was of a standard drop-hammer (fall-hammer) design; however, because of the relatively high sensitiveness of e-matches, lighter than normal drop hammers were used. In these tests, a one-half kilogram drop hammer was used with the more sensitive e-matches and a one-kilogram drop hammer was used with the less sensitive e-matches. An additional modification was made in an attempt to better simulate the use environment of the e-matches. Typically, impact sensitiveness testing is performed by placing a sample between two steel anvils that are then forced together by the impact of the drop hammer. However, in this case, the match tips were inserted inside a fold of 0.010-inch (0.25-mm) thick paper card stock (see Figure 3) and the drop hammer was allowed to fall directly on the assembly. Also, because the solder connections on some of the e-match tips were thick enough to have absorbed some of the impact energy, the solder connections of the e-matches were cut off and only the very end of the match tips, with the pyrotechnic composition, were used in the tests. The e-match tips were oriented such that their wide dimension was parallel to the impact surfaces. For these tests, any shrouds supplied with the e-matches had been removed. (Because almost all of the impact energy was absorbed inelastically, no measures were taken to keep the drop hammer from bouncing.)

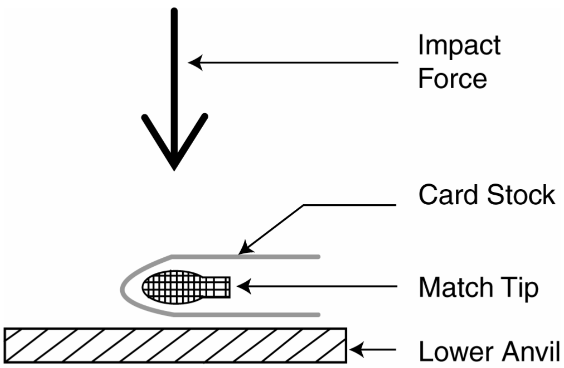

Figure 3. Illustration of the "normal" impact test sample configuration.

For each e-match type, approximately 20 were impact tested using the standard stair-step (Bruceton) method.[9] The results from testing using the *normal* configuration, as shown in Figure 3, are indicated in the "Test" column of Table 2 as "N-1/2" or "N-1", depending on whether the 1/2 or 1 kg drop hammer was used. The individual test results are reported as a pair of numbers, indicating the number of ignitions and non-ignitions, respectively, for each drop height used. The sensitiveness results are the Bruceton calculated heights that caused ignitions 50% of the time and are reported to the nearest inch. When the one-kilogram drop hammer had been used, the reported results were doubled (i.e., normalized to the corresponding half-kilogram drop hammer heights). (There is some concern that such drop-hammer normalization may not be completely correct. However, it was done to allow an easy comparison of results using the two different mass drop hammers.)

Based on these limited results, it would seem that the Aero Pyro, Daveyfire A/N 28 B and A/N 28 BR, Luna Tech BGZD, and Martinez Specialties E-Max Mini e-matches were all approximately equally sensitive, falling in the most sensitive group (50% sensitiveness height of seven to ten inches or 180 to 250 mm). A little less sensitive were the Luna Tech OXRAL and Marti-

Table 2. Results of Impact Sensitiveness Testing.

E-Match Type	Test[a]	Drop Height (inches)[b]											Impact Sens.[c]	BP Sens.[d]
		6	9	12	15	18	21	24	30	36	42	48		
AP	N-1/2	0/4	4/6	7/0									10	4/6
DF-B	N-1/2	0/6	7/3	4/0									8	4/6
	S-1			0/1		1/6		6/3	3/1	1/0			S 44	
DF-BR	N-1/2	0/2	2/6	7/1	2/0								10	2/8
	S-1					0/4		7/4	4/0				S 46	
DF-F	N-1								0/1	1/1	0/2	1/5	>96[e]	7/3
LT-B	N-1/2	0/3	4/4	7/0	1/0								9	8/2
LT-F	N-1											0/6	>96[e]	0/5
LT-O	N-1/2			0/2	1/3	3/3	3/0						18	5/5
	S-1					0/1		0/6	4/5	3/1	1/0		S 62	
MS-EM	N-1/2		0/3	2/4	5/3	3/0							14	3/7
	S-1					0/1		1/5	6/3	4/1	1/0		S 60	
MS-EMM	N-1/2	0/9	9/0										7	4/6
	S-1					0/3		3/6	5/1	1/0			S 60	
MS-T	N-1										0/4	5/5	≈ 96	0/5

a) In column 2, "N" indicates the use of the set-up as shown in Figure 3. "S" indicates testing with the safety shroud in place. "1/2" indicates use of a 1/2-kg drop hammer and "1" indicates use of the 1-kg drop hammer.

b) For conversion of drop height to SI units, 1 inch = 25.4 mm. Reported are the number of ignitions and non-ignitions that occurred at this height. For example, "6/2" would indicate there were 6 ignition and 2 non-ignition events recorded at this particular drop height.

c) This is the height, reported to the nearest inch, that was calculated using the Bruceton method[9] to produce ignitions 50% of the time (i.e., it is the 50% impact sensitiveness). Those entries prefaced by an "S" indicate the result is for an e-match with its safety shroud in place.

d) This is an indication of the effect of the presence of Black Powder prime. It is the number of ignitions and non-ignitions that occurred in the presence of Black Powder, in tests performed at the 50% drop height found previously during testing without Black Powder present.

e) The practical impact height limit for the instrument being used was 48 inches. For a 1 kg hammer mass, this approximately corresponds to an equivalent 96 inches (2.4 m) had a 1/2 kg mass hammer been used. The sensitiveness of these e-matches fell below the limit of the instrument using a 1-kg drop hammer.

nez Specialties E-Max e-matches (50% height of 14 to 18 inches or 360 to 460 mm). The Daveyfire A/N 28 F, Luna Tech Flash, and Martinez Specialty Titan e-matches were all much less sensitive (50% height of ≥96 inches or 2.4 m). (Note that the practical impact height limit for the instrument being used was 48 inches (01.2 m). For a 1-kg hammer mass, this approximately corresponds to an equivalent 96 inches (2.4 m) for a 1/2-kg mass hammer.)

As a point of comparison, rough Black Powder harvested from some Horse Brand black match was recently found to have a 50% impact sensitiveness height (using steel anvils) that was roughly comparable to that of the least sensitive electric matches (Daveyfire A/N 28 F, Luna Tech Flash, and Martinez Specialty Titan). In this configuration, without safety shrouds, all of the other e-match types are five to ten times more sensitive to accidental ignition from impact. Accordingly, such e-matches must be treated with much care and respect.

One additional point should probably be raised regarding these impact sensitiveness results. In performing the testing on completed e-match tips, it appears there may be an effect due to the physical size of the mass of composition. Note that the sensitiveness of the Martinez Specialties E-Max Mini e-match is significantly greater than that for the E-Max e-match. It is possible that this is an effect of a difference in the size of the two e-match tips (see again Figure 2) with the impact force being more concentrated on the smaller e-match tip. It is possible that a similar effect is seen for the Daveyfire A/N 28 B and A/N 28 BR e-matches, where results suggest that the larger A/N 28 BR e-match is a little less sensitive.

Effect of Black Powder

It has been speculated that some e-match compositions may be more sensitive to accidental ignition when in the presence of Black Powder, perhaps because of the sulfur contained therein. Accordingly, the matches in this study were subjected to impact sensitiveness testing in the presence of Black Powder. The normal test configuration was modified slightly, as illustrated in Figure 4. In these tests the inside surface of the piece of card stock around the e-match was heavily painted with a slurry of Black Powder (bound with 5% dextrin) and allowed to dry thoroughly before testing. However, to conserve on the number of individual tests performed, a full set of Bruceton impact tests was not performed. Instead, for each e-match type, a series of just ten individual impacts were used, each time using the 50% impact sensitiveness height found previously in the testing without Black Powder. If the presence of Black Powder had no effect on impact sensitiveness, the number of ignitions should be roughly five out of the ten tests. The results of this testing are presented as a pair of numbers in the final column of Table 2, indicating the number of ignitions and non-ignitions, respectively.

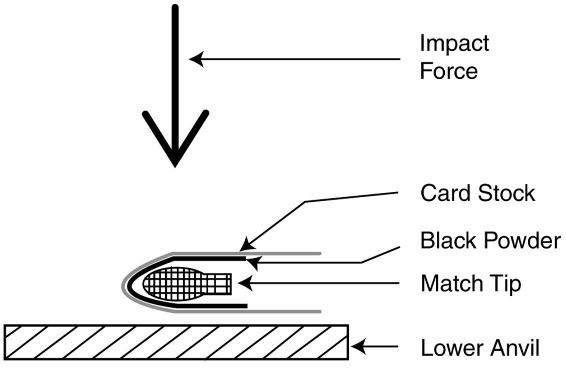

Figure 4. Illustration of the impact test sample configuration, with Black Powder prime present.

Within the precision limits of this testing, for a finding of three to seven ignitions, it must be concluded that any effect due to the presence of Black Powder is probably relatively small. Based on the testing, most of the e-match types are in this category. However, it is fairly likely that a finding of eight or more ignitions indicates added sensitiveness as a result of the presence of the Black Powder. The only e-match falling in this group was the Luna Tech BGZD e-matches. Because these e-matches were already found to be fairly sensitive to impact—even without the presence of Black Powder, it might seem that this is a matter of particular concern. However, it must be recognized that the Luna Tech BGZD matches are intended for use in stage effects where it is significantly less likely to be subjected to impact, than if they were being used in fireworks displays. Further, it is even less likely that they will be subject to a significant impact in the presence of Black Powder.

The Daveyfire A/N 28 F and Luna Tech Flash e-matches had been found to have 50% impact sensitiveness heights *without* the presence of Black Powder that exceeded 96 inches (2.4 m) (as corrected for using a 1/2-kg drop hammer). These e-matches were retested using the same impact (1-kg drop hammer at 48 inches or 01.2 m) with Black Powder present. For the Daveyfire A/N 28 F e-matches in the presence of Black Powder, there were now seven ignitions in ten tests, whereas without Black Powder there had been only one ignition in 6 tests. Accordingly, it would seem that there is an added sensitiveness due to the presence of Black Powder. However, since these e-matches are among the very least impact sensitive e-matches, it is thought not to be of significant concern. For the Luna Tech Flash e-matches, there were zero of six ignitions at 96 inches (1.2 m) without Black powder and zero of five ignitions in the presence of Black Powder. (In both cases the testing was terminated early because more definitive results seemed unlikely.) Accordingly, it is not possible to speculate on the possibility of their being more impact sensitive in the presence of Black Powder; however, they were the least impact sensitive of all the e-matches tested.

In one case, the impact results suggest that there might have been a reduction in the sensitiveness observed. It seems likely that this is an artifact of the test method. It is suspected that the presence of Black Powder provided more material over which the force of the impact was distributed. For that reason it might have been expected that reduced sensitiveness would be found. (This is similar to the size effect discussed above for the E-Max and E-Max Mini matches.)

Effect of Safety Shroud

Some e-match suppliers, in particular those whose customers are likely to use the e-matches to ignite fireworks, supply safety shrouds for their e-matches. (Safety shrouds are a soft plastic covering for an e-match.) These are either pre-installed or available for customer installation. (See Figure 5 for an illustration of a typical e-match and shroud configuration.) Suppliers of e-matches for use in proximate audience pyrotechnics typically do not supply shrouds, or they offer them as an optional feature. In the proximate audience use environment, it is often necessary to install e-matches through small holes in hardware (e.g., into flash pots and concussion mortars) or into small preload devices. Such installation often precludes the use of shrouds and tends to obviate the benefits of safety shrouds because of their use in a more physically protected environment.

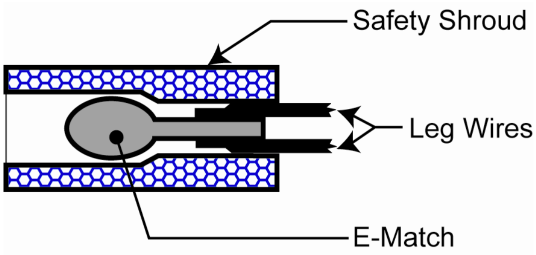

Figure 5. Illustration of a typical e-match with its molded safety shroud in place (not to scale).

While the safety shroud acts to direct the combustion products of the e-match ignition out its open end, it is generally thought that the primary purpose of the shroud is to protect the e-match and thus reduce its sensitiveness to accidental ignition. Accordingly, the e-matches in this study that were supplied with safety shrouds were subjected to impact sensitiveness testing with their shrouds in place.

The safety shrouds found on the Daveyfire e-matches and the Luna Tech OXRAL e-match are specially molded, similar to that shown in Figure 5. The soft plastic appears to be polyethylene, and although removable, the matches were supplied with the shrouds already in place. The shrouds for the Martinez Specialties e-matches were short lengths of soft plastic or rubber tubing (apparently a type of silicone or Tygon tubing) and needed to be installed on the e-matches by the user when desired. Because of the e-match's somewhat arrowhead shape, this was fairly easy to accomplish and the safety shrouds tended to stay in place reasonably well.

The shrouded e-match impact sensitiveness testing was conducted using much the same method as used in the testing without the presence of safety shrouds. However, those e-match types not supplied with shrouds were not retested. One modification to the test configuration was that the e-matches were held in place on a piece of card stock (0.010 inch) using a small piece of cellophane tape. (See Figure 6.) This was to help hold the shrouded e-matches in the same orientation as in the testing without shrouds. In the shrouded e-match tests, there were generally approximately 20 separate test impacts for each e-match type, again using the stair-step (Bruceton) method.[9] The results of the testing are also presented in Table 2, with the data designated as "S-1", where "S" indicated that the e-matches had their shrouds in place, and the "1" indicated that the 1-kg drop hammer was used.

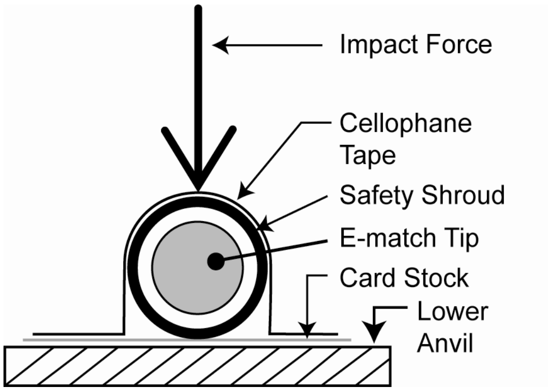

Figure 6. End-on, cross-sectional illustration of the configuration used for shrouded e-match impact testing.

For those e-match types for which previous impact tests without a shroud produced a 50% impact sensitiveness height of at least 96 inches (equivalent for the 0.5 kg drop hammer) no testing was performed with safety shrouds in place. This is because it was thought that the impact sensitiveness of these matches was already so low as not to present a significant potential impact hazard during normal use. (In addition, any e-matches that were not supplied with shrouds were not tested.) As expected, for the five e-match types that were tested, it was found that the presence of the shroud provided a substantial decrease in impact sensitiveness. The decrease ranged from a factor of three to eight and averaged a factor of a little more than five. That is to say, with the shrouds in place approximately five times greater impact energies were required to produce an ignition. Obviously, the presence of the safety shrouds on those e-matches that were fairly sensitive to impact stimulus affords a substantial safety benefit, and display crews should be instructed to leave them in place.

Electrostatic Discharge (ESD) Sensitiveness

In these tests, ESD sensitiveness was determined for two configurations. In the first series of tests, the electric discharge current was passed through the e-match bridgewire in much the same fashion as the intended firing current. This is illustrated in the upper drawing of Figure 7. In the second series of tests, the discharge current passed from the bridgewire through the pyrotechnic composition to ground, as illustrated in the lower drawing of Figure 7.

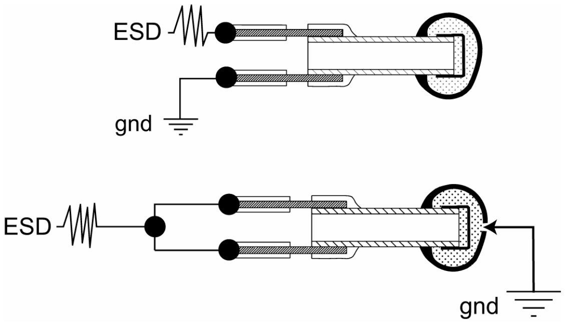

Figure 7. Illustration of the two basic ESD test configurations used in this study.

The high voltage discharge current used in this testing was provided by an instrument whose basic circuit diagram is shown in Figure 8. Each of the three main circuit components (R_c, R_s, and C) are removable so that their values can be selected as appropriate for the specific testing being performed. For these e-match tests, the charging resistor (R_c) was always 3.3 megohms, the series resistor (R_s) was always 100 ohms, and the charge storage capacitor (C) was varied between 0.001 and 0.25 microfarads depending on the ESD sensitiveness of the particular type of e-match being tested. In each case, to assure the full charging of the storage capacitor, the instrument was operated such that the charging time was at least 10 RC time constants. The maximum high voltage available from the power supply used in these tests was 6 kilovolts. In the first test configuration (ESD passing through the bridgewire), solid electrical connections were made directly to the individual e-match leg wires. For each e-match type, approximately 20 individual discharge tests were performed, using the standard stair-step (Bruceton) method.[9]

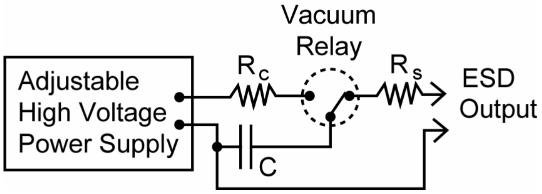

Figure 8. Circuit diagram for the ESD test apparatus used in this study.

While it is more typical to perform ESD sensitiveness testing using a higher voltage (up to 25 kV) than was used in these tests, it is thought that the lower voltages were a somewhat more realistic limit to the charge potential that might be developed on persons working at a fireworks display site in typical summer humidity. Another modification from more typical ESD testing conditions was the use of a series resistance of only 100 ohms as opposed the commonly used value of 500 ohms,[10] (or even 5000 ohms as used in some military ESD testing[11]). For human induced discharges, the series resistor is intended to be a substitute for a contact resistance person delivering an ESD to an e-match. The choice of this lower resistance value was somewhat arbi-

Table 3. Electrostatic Discharge Sensitiveness Test Results.

E-Match Type	Test(a)	Cap. (μF)(b)	Min. (V)(c)	Step (V)(d)	Individual ESD Test Data(e)							Sens. (mJ)(f,g)
					0	1	2	3	4	5	6	
AP	TBW	0.01	4000	250	0/1	0/3	2/6	7/0				120
	TC	0.001	500	250	0/1	1/1	1/3	4/4	5/1	1/1	1/0	0.7
DF-B	TBW	0.01	3500	250	0/7	8/2	3/0					70
	TC	0.001	500	250	0/3	2/4	4/3	3/2	1/1			0.5
DF-BR	TBW	0.01	3500	250	0/5	5/3	3/1	1/1	1/0			70
	TC	0.001	1000	250	0/5	4/4	4/2	2/0				0.8
DF-F	TBW	0.1	2000	250	0/7	7/2	3/0					240
	TC	0.001	1750	250	0/1	1/1	1/3	4/1	3/4	5/1	1/0	3
LT-B	TBW	0.01	4000	250	0/1	0/6	6/4	4/0				100
	TC	0.01	500	500	0/2	2/2	2/6	5/4	4/2	2/1	1/0	20
LT-F(h)	TBW	0.25	3500	250	0/1	0/9	9/9	8/3	4/0			2300
	TC	0.01	500	250	0/2	2/3	5/3	3/1	1/2	2/1	1/0	6
	TBW	0.25	3000	300	0/5	6/5	6/0	1/0				1400
	TC	0.01	400	400	0/7	7/4	5/7	7/4	4/3	4/0		8
LT-O	TBW	0.01	4500	250	0/4	3/4	3/3	3/0				120
	TC	0.001	1500	250	0/4	3/3	3/2	2/1	1/1	1/0		2
MS-EM	TBW	0.01	3500	250	0/3	3/6	7/0					70
	TC	0.001	1250	250	0/2	2/2	3/4	5/0				2
MS-EMM	TBW	0.01	3750	250	0/4	4/4	5/1	2/0				80
	TC	0.001	1750	250	0/2	2/5	4/3	3/0				2
MS-T	TBW	0.1	2000	250	0/2	1/8	9/0					260
	TC	0.25	1000	1000	0/4	4/2	2/2	2/5	4/3	2/0		1000

a) Two test configurations were used. TBW indicates the *through-the-bridgewire* configuration, and TC indicated *through-the-composition* configuration, the upper and lower configurations shown in Figure 7, respectively.

b) This is the value of the storage capacitor (in micro Farads–μF) labeled "C" in Figure 8.

c) This is the minimum voltage used during the testing of this type of e-match using the configuration listed.

d) This is the step size used (i.e., the voltage difference between adjacent stimulus levels).

e) These are the number of ignitions and non-ignitions that occurred at this ESD test voltage. For example, "6/2" would indicate there were 6 ignitions and 2 non-ignitions at this particular voltage. The voltage is equal to the minimum voltage (c) plus the product of the step size (d) and the number of steps.

f) This is the ESD energy that produced an ignition approximately 50% of the time. Because of the limited precision of these results, the energy values for through-the-bridgewire test configuration (TBW) are reported to the nearest 10 mJ, or two significant figures, whichever is less precise.

g) Because of the additional uncertainty associated with the removal of the protective coating, the energy values for through-the-composition test configuration (TC) are reported to only one significant figure.

h) Because of some concern regarding the accuracy of the initially collected data, some additional trials were conducted using a second production lot of the Luna Tech Flash matches.

trary; however, measurements involving a heavily sweating person confirmed that body resistances of no more than approximately 100 ohms are common.

The choice of series resistance for these tests is an important parameter, in that it determines the partitioning of energy between that delivered to the series resistance and that delivered to the item under ESD test. Ignoring impedances other than resistance, the ESD energy being provided divides proportionally between the two resistances (in this case, between the series resistor and the e-match). Accordingly, with a 2-ohm test item and a 100-ohm series resistor, approximately 2% of the ESD energy is delivered to the test item. However, had a 500-ohm series resistor been chosen, only 0.4% (or 1/250) of the ESD energy would have been delivered to the test item. In addition to the 100-ohm body resistance being more likely, it was felt that using a 500-ohm series resistor in these tests might have given the reader a false sense of security regarding the ESD sensitiveness of e-matches under conditions typical of their use at fireworks displays.

Through-the-Bridgewire Test Configuration

The ESD sensitiveness test conditions and results for the *through-the-bridgewire* test configuration are presented in Table 3 with the designation of "TBW" in the column labeled "Test". The value of the charging capacitor for this test configuration ranged from 0.01 to 0.25 micro Farad (μF) depending on the approximate sensitiveness of the e-matches and is given in the column labeled "Cap." The lowest ESD voltage used for each type e-match and the voltage increment between the steps used for that e-match are given in the next two columns of Table 3, labeled "Min." and "Step", respectively. The next series of columns present the data from the individual test firings, where each pair of numbers is the number of ignitions and non-ignitions, respectively. The first of this series of columns, labeled "0", has the data obtained using the minimum test voltage. The succeeding columns, labeled "1" through "6", have the data obtained using stepwise increasing voltages. The final column of Table 3, labeled "Sens.", presents the sensitiveness results given as the discharge energies that produced ignitions in approximately 50% of the tests. (Note that some degree of caution is necessary in interpreting these results, because the test conditions used in these tests were significantly different from those often reported in the literature. Accordingly, the values reported in Table 3 must not be compared with values reported elsewhere, unless an adjustment is made to account for those significant differences in test conditions.)

Regarding ignitions produced by an ESD through the bridgewire, the e-matches can be roughly divided into four groups. Based on these limited results, it would seem that the Daveyfire A/N 28 B and BR, and the Martinez Specialties E-Max and E-Max Mini fall in the most sensitive group (70 to 80 mJ). A little less sensitive are the Aero Pyro, Luna Tech BGZD and OXRAL e-matches (100 to 120 mJ). Significantly less sensitive are the Daveyfire A/N 28 F and Martinez Specialties Titan e-matches (240 to 260 mJ). Substantially less sensitive still are the Luna Tech Flash e-matches (1900 mJ).

As a point of comparison, consider that the approximate maximum ESD energy that can be developed on a typical person (200 pF and 25 kV)[12] is on the order of 60 mJ. However, note that there are conditions under which a person can act as a conduit passing much greater ESD energy, from other objects that may be capable of storing considerably larger charges than a human body stores.

E-Match Tip Protective Coating Evaluation

The e-matches examined in this study all have a protective coating over their pyrotechnic composition. This coating provides a level of protection from physical damage during handling and use, as well as possible damage from exposure to moisture. The coatings also provide a significant degree of electrical insulation, which generally limits the ability to cause an ESD from the bridgewire through the composition (and its coating). However, imperfections are occasionally observed in the e-match coatings, such that discharges through the composition can potentially occur. These imperfections can occur as a normal consequence of manufacturing methods or as a result of the e-match tip being physically damaged (from crushing or abrasion) during handling and use. A close examination of e-match tips from each of the suppliers, revealed occasional visible imperfections (apparent voids or holes) in their coatings. Figure 9 is a collection of electron micrographs of such imperfections observed for each of the various suppliers' e-matches. (It should be mentioned that only one example of a coating imperfection was found for the Aero Pyro matches, shown in Figure 9. Further, because those matches are apparently coated twice, and the imperfection was only in one of the coating layers, thus even in that one case there was ample ESD protection.)

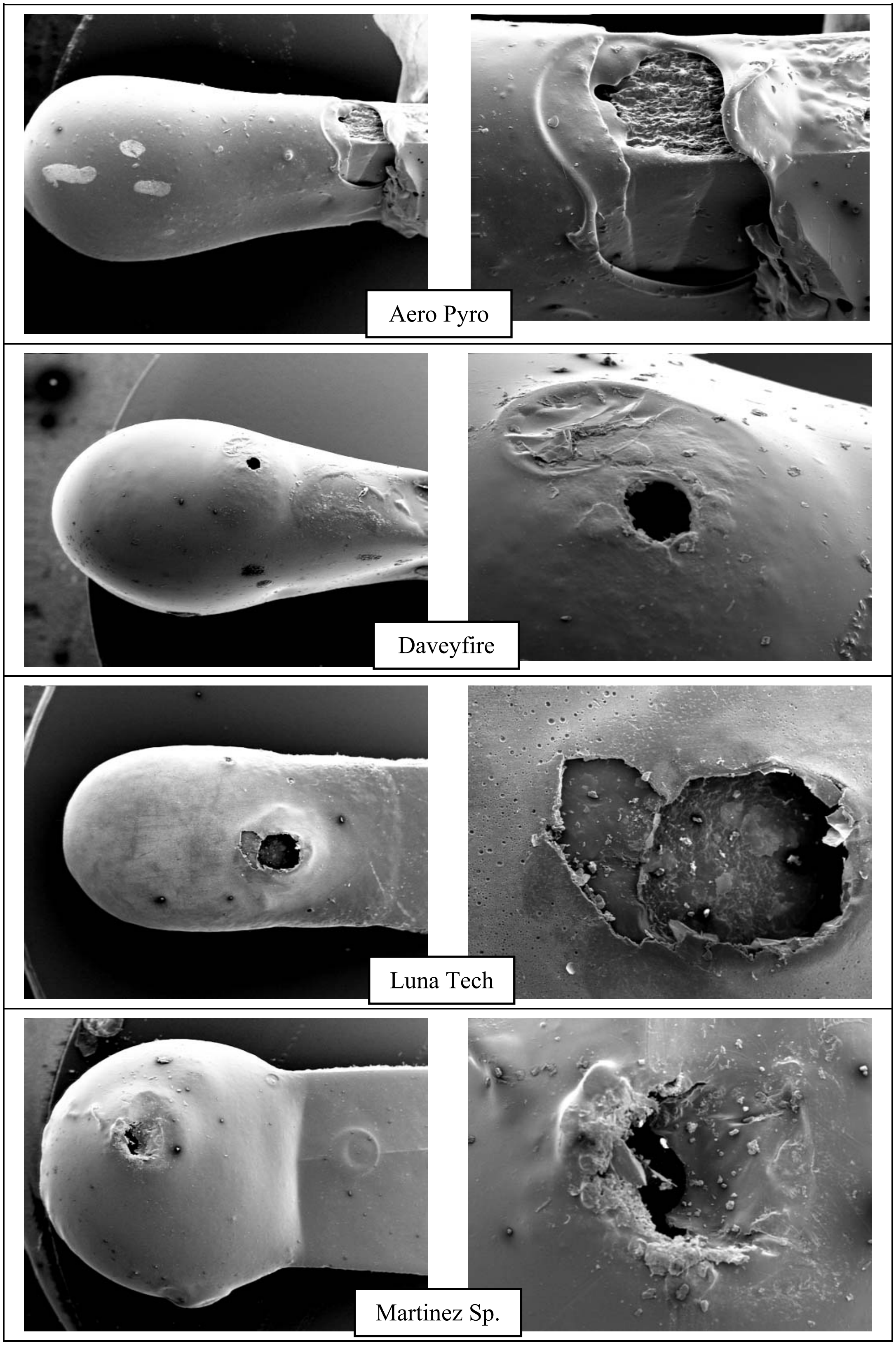

Figure 9. A collection of electron micrographs of imperfections found in some of the e-match tips from the various suppliers, with the image on the right being a close-up view of the imperfection.

Table 4. Minimum E-Match Tip Coating Resistance Measurements.(a)

E-Match	Lowest Resistance of Each E-Match Tip (MΩ)(b)										Lowest Resistance (MΩ)	
Type	1	2	3	4	5	6	7	8	9	10	Of Any(c)	Average(d)
AP	500	500	500	500	500	500	500	500	500	500	>500	>500
DF-B	70	50	500	500	500	500	10	20	500	500	10	300
DF-BR	40	500	500	50	500	500	500	500	500	500	40	400
DF-F	500	500	1	20	500	500	500	500	500	500	1	400
LT-B	<1	3	4	2	3	<1	1	4	2	2	<1	2
LT-F	<1	<1	<1	2	<1	1	<1	3	2	<1	<1	<1
LT-O	20	40	30	60	20	30	60	40	40	<1	<1	30
MS-EM	500	500	500	500	500	500	500	500	500	500	>500	>500
MS-EMM	500	50	300	300	500	500	100	100	500	500	50	300
MS-T	60	<1	2	20	1	3	500	3	<1	<1	<1	60

a) Because of a fairly large uncertainty in the resistance measurements, all values are reported to only one significant figure.

b) This is the lowest single point resistance, in megohms (MΩ), found on each of ten individual e-matches of this type. The reporting of a value of 500 means that at no point on the surface of the e-match tip was the resistance found to be less than 500 MΩ.

c) This is the lowest single point resistance value found on any of the ten individual e-match tips.

d) This is the average of the lowest single point resistances for the collection of ten e-matches. When the lowest resistance value for an individual e-match was >500 MΩ, a value of 500 MΩ was used. When the lowest resistance value was <1 MΩ, a value of 0 was used.

To evaluate the nature of the e-match coating imperfections, a megohm meter, specifically designed to make high resistance measurements, was used to measure coating-to-bridgewire resistances. In stark contrast to typical resistance measuring instruments, this instrument applies a test voltage up to 200 volts (but with very limited current). The intention is that these higher voltages would induce dielectric breakdowns in imperfect e-match tip coatings similar to those produced during an ESD event. One terminal of the instrument was connected to the e-match leg wires, and a test probe—with a small rounded tip—was connected to the other terminal of the instrument. The probe was moved over the e-match tip looking for points with relatively low resistance. (Only those areas of the match tip where pyrotechnic composition was present were investigated.) In most instances, the coatings on the e-matches were found to provide a resistance of more than the maximum instrument reading, 500 megohms (MΩ); however, a fair number of e-match tips had one or more points on their coating where relatively low resistance values were found. The point on the e-match tip found to have the lowest resistance value was noted for each of a collection of ten e-matches of each type. Table 4 has those individual resistance values, plus both the minimum point resistance observed for any e-match tip in each group of ten tips of the same type and the average of the minimum resistance values for each set of ten e-matches. (For comparison, note that the resistance of unglazed Black Powder grains (20 mesh) was found to be in excess of 500 MΩ, and the resistance of glazed Black Powder grains was found to be less than 1 MΩ.) Because of a fairly large uncertainty in the resistance measurements, all values in Table 4 are reported to only one significant figure. (Further, given the nature of dielectric breakdown, the resistance values are expected to depend on the measurement voltage.)

Table 5. Additional Through-the-Composition ESD Test Results.

E-Match Type	Number of Ignitions in 10 trials[a]				
	Without Shroud[b]		With Shroud – 18 mJ[c]		
	18 mJ	180 mJ	g/BP[d]	u/BP[e]	Air[f]
AP	0	2	—	—	—
DF-B	4	(g)	4	1	1
DF-BR	2	(g)	3	0	0
DF-F	6	(g)	3	0	0
LT-B	1	4	—	—	—
LT-F	0	5	—	—	—
LT-O	10	(g)	10	9	10
MS-EM	2	(g)	2	0	1
MS-EMM	7	(g)	7	0	0
MS-T	0	2	0	0	0

a) These tests were performed at 6 kV. To store an ESD energy of 18 mJ, a 0.001 μF charging capacitor was used. To store an ESD energy of 180 mJ, a 0.01 μF capacitor was used.

b) For those e-matches supplied with safety shrouds, they were removed for these tests.

c) These tests were only performed for the e-matches with safety shrouds, and they used the lower stored ESD energies of 18 mJ. The "—" symbol is meant to indicate those e-matches not supplied with safety shrouds, which were not tested.

d) The "g/BP" column is the number of ignitions that occurred when the end of the safety shroud was filled with *glazed Black Powder*.

e) The "u/BP" column is the number of ignitions that occurred when the end of the shroud was filled with *unglazed Black Powder*.

f) The "Air" column is the number of ignitions that occurred when nothing filled the end of the shroud.

g) These e-match types were not tested at the higher ESD energy because there were at least two ignitions at the lower energy.

Through-the-Composition Test Configuration

A limited number of *through-the-composition* ESD sensitiveness tests were conducted. This was accomplished by connecting the positive terminal of the ESD test apparatus to the shunted pair of leg wires of an e-match, connecting the negative terminal of the ESD tester to a steel post, causing the e-match tip to be held in loose contact with the metal post, and applying the ESD energy. As might have been expected, the stair-step (Bruceton) method of testing produced highly variable results. When the e-match tip was well coated, there were no ignitions even with high discharge energy. When there was a significant imperfection(s) in the e-match tip coating, there were ignitions even at low discharge energies. To that extent, the testing served as more of an indicator of when there was a significant coating imperfection as opposed to being purely an indication of the ESD sensitiveness of the e-match composition.

Accordingly, the test was modified from the normal stair-step method. Instead, a collection of ten e-match tips of each type were a tested using a relatively high voltage but storing only a relatively low energy (6 kV with a charging capacitor of 0.001 μF to store energy of 18 mJ). In most cases, when the test produced no ignition of the e-match composition, the ESD spark passed harmlessly over the coated surface of the match. Whenever the first discharge produced no ignition, the same e-match was subjected to two more discharges of the same energy. (On several occasions, an ignition did occur on the second or third discharge. When this happened, it was considered the same as if it had occurred with the first discharge. This was done even though the previous ESD events could have acted to damage the coating to some extent.)

The results of this testing are presented in Table 5 in the column titled "18 mJ", as the number of ignitions in ten trials. Of the ten tests of e-matches of each type, when less than two of them ignited using the 18 mJ stored ESD energy, the test was repeated using a higher discharge energy. In this case, another set of ten e-matches was subjected to ESD energies of 180 mJ (6 kV using an 0.01 μF capacitor). The results of these tests are also reported in Table 5, in the column titled "180 mJ", as the number of ignitions out of ten trials. (Note that in those cases where the manufacturer had provided e-matches with safety shrouds, those shrouds were removed prior to testing.) (It must be expected, under the conditions of these tests, that only a fraction of the energy stored in capacitor C in Figure 8 was successfully delivered to the ESD event.)

Based on the observation of e-match coating imperfections, low coating resistances and the e-match ESD test results reported in Table 5, it seems obvious that coating imperfections afford the ability for ESD events to pass from the bridgewire through the pyrotechnic composition of the match tip. Further, it must be expected that at least on some occasions, damage to e-match tips during use might be sufficient to introduce discharge paths through the composition of e-matches initially with perfect coatings. (Shrouded e-match tips must be significantly less prone to being damaged during use, but in extreme cases, even they could be damaged.) Accordingly, since the ESD protection offered by the e-match coatings can be, or can become compromised, it was decided to perform additional tests to determine the ESD sensitiveness of the exposed e-match compositions themselves.

For these tests, a small portion of the protective coating on the tip of each test e-match was intentionally removed with emery paper before testing. This was done in an attempt to simulate a significant imperfection in the e-match coating or the damage that might occur during prolonged or rough handling and use. In this test series, one terminal of the ESD apparatus was connected to the shunted pair of e-match leg wires, the other terminal of the ESD tester was connected to a metal post, the match tip was held in loose contact with the metal post, and the ESD energy applied. For each e-match type, approximately 20 individual discharge tests were performed, using the standard stair-step method.[9] The data and results of these *through-the-composition* e-match sensitiveness tests are also presented in Table 3, where the test configuration is indicated as "TC". The sensitiveness is reported as the discharge energy that produced an ignition in approximately 50% of the tests. (Note that in those cases where the manufacturer had provided e-matches with safety shrouds, those shrouds were removed prior to testing.)

Regarding ignitions produced by an ESD from the bridgewire through the pyrotechnic composition when the coating is imperfect or damaged (and without safety shrouds), the e-matches can be roughly divided into four groups. Based on these limited results, it would seem that the Aero Pyro and Daveyfire A/N 28 B and BR e-match compositions fall in the most sensitive group (0.5 to 0.8 mJ 50% ignition energy). Somewhat less sensitive (2 to 6 mJ 50% ignition energy) are the Daveyfire A/N 28 F, Luna Tech Flash and OXRAL, and Martinez Specialties E-Max and E-Max Mini e-match compositions. Still less sensitive (20 mJ 50% ignition energy) are the Luna Tech BGZD e-matches. Surprisingly, less sensitive yet (1000 mJ 50% ignition energy) are the Martinez Specialties Titan e-matches.

As a point of comparison, consider that these through-the-composition (TC) ESD ignitions were produced using roughly 100 times less energy than those occurring through the bridgewire. Accordingly, through the composition discharges represent a much greater risk of accidental ESD ignition. Further, shunting the e-matches has no effect in reducing this hazard. Finally, note that most of these 50% ESD ignition energies are a small fraction of the approximate maximum ESD energy (approximately 60 mJ) that can be developed on a typical person (200 pF and 25 kV).[12]

Effect of Safety Shroud and Black Powder

The appearance and design of the safety shrouds, for those e-matches supplied with them, were illustrated above in Figures 2 and 5. The ESD sensitiveness testing with shrouds in place was conducted using much the same method as the through-the-composition testing without shrouds. However, only those e-match types supplied with safety shrouds were tested. The e-matches were used as supplied (i.e., without altering the protective coating over the pyrotechnic composition). One point of electric contact was the shunted leg wires of the e-match, and the other point of electric contact was a flat piece of metal placed across the end of the shroud. In each test, a stored energy of only 18 mJ was used (6 kV stored in 0.001-μF capacitor and discharged through a 100-ohm series resistance).

To test for a variety of possible use conditions, three test configurations were used. In one series of tests, the safety shroud was filled with fine-grained glazed Black Powder (20 mesh). In a second series of tests, the shroud was filled with fine-grained unglazed Black Powder. (Recall that the resistance of unglazed Black Powder grains was found to be in excess of 500 MΩ, and the resistance of glazed Black Powder grains was less than 1 MΩ.) In the third series of tests, the shroud was left empty. In each configuration, a total of ten e-matches were tested. The results of the testing are presented in the last three columns of Table 5.

When filling the safety shroud with glazed Black Powder, note that the presence of the safety shroud apparently provided no decrease in ESD sensitiveness; compare column 4 ("g/BP") with column 2 ("18 mJ" "without shrouds") of Table 5. It would seem the reason is that glazed Black Powder is fairly conductive because of its graphite coating, thus allowing the discharges to gain access to the e-match tips and any imperfections in their coating. In contrast, note in column 5 ("u/BP") that when unglazed Black Powder was used to fill the shroud, there was nearly a total elimination of ignitions (for all but Luna Tech's OXRAL e-matches). Given that the typical grain resistance of unglazed Black Powder exceeds 500 MΩ, such a reduction in the number of ignitions was expected. Finally, in column 6 ("Air") the test with empty (air-filled) shrouds produced virtually the same results found for the tests using unglazed Black Powder.

In the test results for safety shrouds filled with unglazed Black Powder and for empty shrouds, the Luna Tech OXRAL e-matches standout as a notable exception to the reduction in the number of ESD ignitions produced. The apparent reason for this is the limited distance between the end of the e-match tip and the end of the shroud. Typically, this distance is only approximately 0.03 inch (0.75 mm) for the OXRAL e-matches and, under the conditions of these tests, was short enough to allow a discharge to take place even without partially conductive material filling the shroud. (See again Figure 2.) In contrast, the typical distance for the Daveyfire e-match types was approximately five times greater (approximately 0.15 inch or 3.8 mm) and sufficiently great to usually prevent a 6 kV ESD from taking place. In the case of the Martinez Specialty matches, which use short lengths of tubing as safety shrouds to be installed by the user, it is possible to install the shroud with a range of distances between the end of the e-match tip and end of the shroud. For these tests, the e-match tips were installed so that the widest end of the e-match tip (its leg wire end) was pushed just slightly inside the length of tubing supplied.

Additional ESD Discussion

It is perhaps worth reiterating that an ample and well-applied protective coating can offer a high degree of ESD protection. Note that the Aero Pyro e-matches apparently have a double protective coating. Accordingly, while their composition is among the most ESD sensitive, these e-matches tied for producing the least number of intact e-match tip ignitions (zero in ten tests). They equaled the performance of the Martinez Specialty Titan e-matches, which use a composition with approximately a thousand times less ESD sensitiveness. (See again Tables 3 and 5.)

At the time of this writing, it was unclear why two of the Titan e-matches ignited with only 180 mJ of energy in the intact e-match tip ESD tests when the 50% ignition energy was found to be more than five times higher. Laib[13] has suggested that this might be caused by a particularly high percentage of conductive metal particles in the composition. If so, when the coating is intact, the spreading of the discharge energy across numerous potential conductive paths is inhibited by the presence of surface dielectric, whereas the discharge is thus relatively confined to fewer discharge paths in the vicinity where dielectric breakdown through the coating occurs. When the coating is damaged,

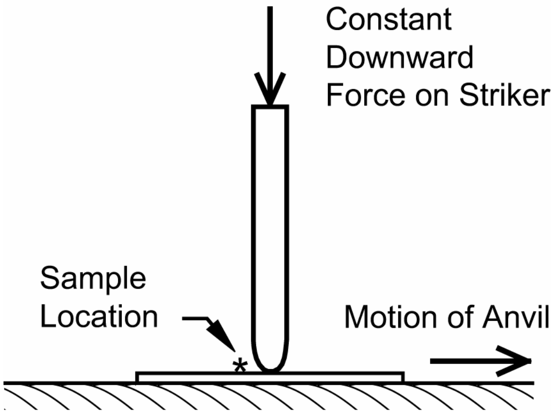

Figure 10. Simplified illustration of a typical friction test apparatus.

more surface conductors are available along with more numerous paths through the material, thus reducing the average ohmic heating available per path, leading to higher required energies.

In interpreting the ESD sensitiveness data presented here, some degree of caution is necessary. The reason is that the conditions for these tests were substantially modified from those commonly used. (This was done in an attempt more nearly to duplicate the typical conditions during use.) Accordingly, the results reported in this article should not be directly compared with other data reported in the general pyrotechnic literature, unless adjusting for the different test conditions being used.

Probably the most important conclusion to be drawn from this study is that, while there is a very wide range of sensitiveness to ESD ignition, under some conditions all of the e-match types could be ignited by an accidental discharge. (If not as a result of an ESD from a person through an e-match with a perfect coating, consider the possibilities of damaged e-match tips or something like a nearby stroke of lightning.) Further, in almost all cases the ESD energy capable of initiating an e-match by a discharge through the composition is very much less than that required for a discharge through the bridgewire. (Note that shunting the e-match leg wires provides no protection against such through the composition discharges.) Finally, some of these 50% ignition energies are so small that they are less than a typical person can feel.[12]

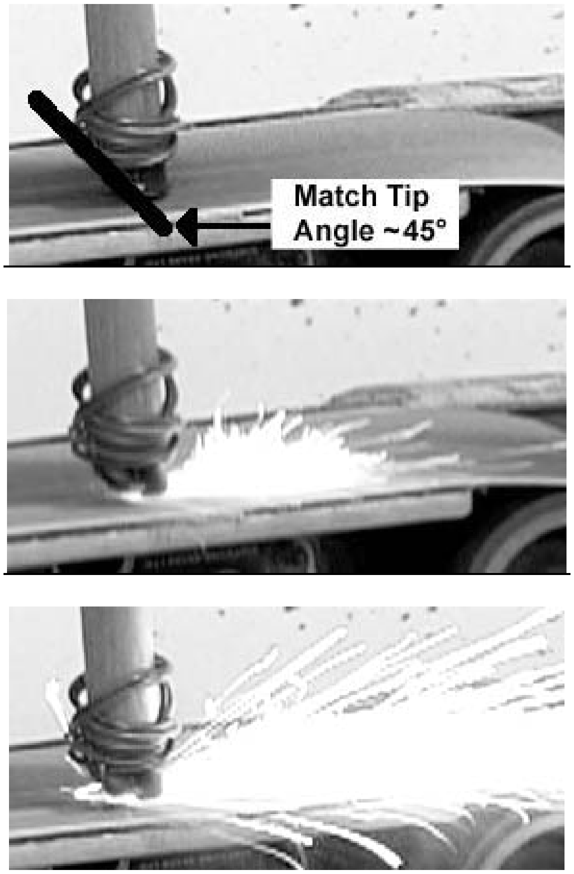

Figure 11. Photographs of the friction test setup as modified for e-matches. There is a time lapse of 1/60th second between images.

Friction Sensitiveness

Normal Configuration

The standard method of friction sensitiveness testing is illustrated in Figure 10. This method works well for loose powders; however, in this case, friction sensitiveness for the intact e-match tips was being sought. Unfortunately, during testing it was found that the standard method was mostly unsatisfactory for intact e-match tips. Often the e-match tips just slid loosely along the surface in front of the striker without ever being caught forcefully between the striker and the abrasive surface. Accordingly, the test setup was modified to use the e-match tip itself as the striker. The tip was supported from behind and held at an approximate 45° angle to a moving abrasive surface, #100 grit sand paper

Table 6. Results of Friction Sensitiveness Testing.

E-Match Type	Force (N)(a)	Time to Ignition w/o BP (s)				Time to Ignition w/ BP (s)			
		1	2	3	Average(b)	1	2	3	Average(c)
AP	1.5	0.37	0.25	0.23	0.28	0.23	0.38	0.25	0.29
DF-B	1.5	0.17	0.20	0.22	0.20	0.25	0.20	0.15	0.20
DF-BR	1.5	0.13	0.25	0.12	0.17	0.15	0.10	0.17	0.14
DF-F	6.0	n/i	n/i	n/i	n/i	n/i	n/i	n/i	n/I
LT-B	3.0	0.20	0.33	0.12	0.22	0.07	0.37	0.56	0.33
LT-F	6.0	n/i	n/i	n/i	n/i	n/i	n/i	n/i	n/i
LT-O	3.0	0.80	0.58	0.32	0.57	n/i	0.38	n/i	0.6(d)
MS-EM	1.5	0.12	0.12	0.10	0.11	0.13	0.28	0.13	0.18
MS-EMM	1.5	0.20	0.22	n/i	0.3(d)	n/i	0.12	n/i	0.2(d)
MS-T	6.0	n/i	n/i	n/i	n/i	n/i	n/i	n/i	n/i

a) This is the minimum applied force that produced an ignition during testing.

b) This is the average time-to-ignition for a set of three e-matches without the presence of Black Powder. “n/i” means no ignition(s) occurred.

c) This is the average time-to-ignition for a set of three e-matches in the presence of Black Powder. “n/i” means no ignition(s) occurred.

d) There were one or two non-ignition(s) observed. The average time to ignition was calculated using twice the longest time to ignition as the time for each e-match failing to ignite during the test. This value is reported to only one significant figure.

(see Figure 11). To configure the test to be somewhat consistent with anecdotal accounts of accidents, it was thought that the force holding the e-match tips against the abrasive surface should be fairly low and the rate of movement along the surface should be fairly high. The combination of a force of 0.33, 0.67 or 1.35 pounds (1.5, 3.0 or 6.0 N) at a rate of movement of 10 feet per second (3 m/s) was found to be reasonably effective for the range of e-match friction sensitiveness of the various e-match types. It must be acknowledged that the test conditions were quite severe (with the e-matches being quickly sanded into non-existence) and that some ignitions could have been produced as a result of frictional heating of non-pyrotechnic elements in the e-matches as they abraded away.

Each test consisted of a set of three trials of the same e-match type and same downward force. For those e-match types failing to ignite during the three trials with the applied force, the next greater force was used for another set of three e-matches. For different e-match types found to ignite with the same applied force, their times-to-ignition were used to discriminate between them in terms of sensitiveness. Ignition times were determined by video taping each test, then playing back the tape and counting the number of individual video fields elapsing before ignition occurred. The raw data from this friction sensitiveness testing and the results are presented in Table 6, with the ignition times in the set of columns labeled “w/o BP”, indicating the testing was performed *without Black Powder* being present. (Note that the testing was performed on bare e-matches without the safety shroud present.)

Friction sensitiveness of the e-matches was found to fall into three groups. In the most sensitive group were the Aero Pyro, Daveyfire A/N 28 B and A/N 28 BR, and the Martinez Specialty E-Max and E-Max Mini; all these e-matches ignited with an applied force of 1.5 N (0.33 lbf). Less sensitive were the Luna Tech BGZD and OXRAL e-matches, which required an applied force of 3.0 N (0.67 lbf) for ignition. Substantially less sensitive still (failing to ignite even with an applied force of 6.0 N (1.35 lbf) were the Daveyfire A/N 28 F, Luna Tech Flash, and Martinez Specialty Titan e-matches.

Configuration with Black Powder and Safety Shrouds

There are a number of anecdotal reports of accidental ignitions occurring when e-matches were being forcefully removed from aerial shell leaders where the e-match was in contact with the Black Powder coating on the black match fuse. Accordingly, it was thought to be appropriate to attempt to determine whether added friction sensitiveness resulted from the presence of Black Powder. In this case, each test e-match was coated with a slurry of Black Powder (fine meal powder bound with 5% dextrin) and allowed to dry thoroughly. (Note that the testing was preformed on bare e-matches without the safety shroud present.) In this series of tests, the same downward force was used as was found to be the minimum capable of producing ignitions without the presence of Back Powder. Using this force, the average time to ignition for a series of three Black Powder coated e-matches was determined. If the presence of Black Powder had little or no effect on friction sensitiveness, it would be expected that the average time to ignition would be roughly the same as found when testing without Black Powder. The raw data and results of this testing are presented in Table 6, with the ignition times in the set of columns labeled "w/ BP", indicating the testing was performed with Black Powder being present. Note that the average times to ignition are all essentially unchanged (i.e., for these test conditions, apparently no increased friction sensitiveness resulted for any e-match in the presence of Black Powder).

Additional friction sensitiveness testing was not performed with safety shrouds present on the e-matches. This is because, during normal use or even abuse, so long as the shrouds survived and stayed in place, it could not be imagined that an ignition would be produced due to friction.

Thermal Sensitiveness

The initial attempt at determining thermal sensitiveness of the complete e-match tips was to insert the various matches into a series of six small wells, 0.25-inch (6-mm) diameter and 0.5-inch (12-mm) deep, drilled into a block of aluminum that was heated electrically. See Figure 12 for an illustration of the thermal test apparatus. The temperature of the block was monitored using a thermocouple inserted into one of the six wells. The power to the electric heating element was adjusted to provide approximately a 5 °C per minute rate of temperature rise in the wells. In preparation for the test, five e-matches of the same type were loaded into the available wells (after cutting off their leg wires). Then, starting at room temperature, the block was heated, and the test continued until all of the test e-matches ignited or until a temperature of 300 °C was reached. Although the temperature of each ignition was noted, the lowest temperature at which any of five test e-matches ignited was considered an indication of their thermal ignition sensitiveness and is reported as "Ramp" ignition temperature in Table 7.

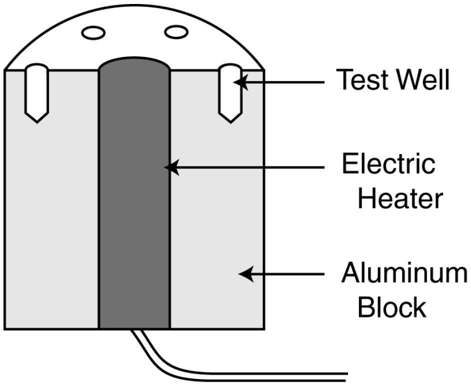

Figure 12. Illustration of the thermal sensitiveness test apparatus.

Even though the rate of temperature rise in the initial testing was fairly rapid (approximately 5 °C per minute), it was found that most of the e-matches being tested decomposed during the heating period without actually igniting. Accordingly, a second series of tests was performed. In these tests, the thermal block was pre-heated to a specific temperature. Then a single e-match tip (with leg wires removed) was placed into a well. The time taken for that e-match to ignite was noted; if the time exceeded 60 seconds, the test was terminated for that temperature. If the e-match did not ignite within 5 seconds, the temperature of the block was increased 20 °C, and the test was repeated using a new e-match tip. The data from this second series of thermal tests are reported in Table 7 as "Time to Ignition" at

Table 7. Results of Thermal Sensitiveness Testing.

E-Match Type	Ramp Ignition Temperature (°C)(a)					Time to Ignition (s) at the Indicated Temperature (°C)							5-Sec Temp. (°C)(b)
	1	2	3	4	5	180	200	220	240	260	280	300	
AP	170	178	192	208	232	19	12	6	2				225
DF-B	165	>	>	>	>	22	12	5					220
DF-BR	245	>	>	>	>	16	10	4					215
DF-F	>	>	>	>	>	>60		>60		>60		>60	>300
LT-B	217	>	>	>	>	>60		>60		9	6	5	300
LT-F	>	>	>	>	>	>60		>60		>60		>60	>300
LT-O	204	205	206	207	209	32		14		5			260
MS-EM	164	>	>	>	>	18		19		10	7	6	≈300
MS-EMM	159	161	162	162	>	29		11		7	5		280
MS-T	>	>	>	>	>	>60		>60		>60		43	>300

a) These are the ramp ignition temperatures for each of five e-match tips tested. Values are listed in order of increasing temperature. The ">" indicates that no ignition occurred below 300 °C.

b) The 5-second ignition temperatures were determined graphically and are reported to the nearest 5 °C.

the temperatures specified. These ignition times were plotted graphically to estimate the 5-second ignition temperature, which was reported in the final column of Table 7 to the nearest 5 °C.

The temperatures found to produce e-match ignitions in these tests are all sufficiently high as to seriously discount the possibility that accidental ignitions caused by thermal sources are likely to be encountered during use on a fireworks display site. Accordingly, it was not thought to be appropriate to rank the different e-match types based on their thermal sensitiveness.

It may be of interest to note that the American Pyrotechnic Association is party to an exemption (DOT-E 11685) allowing the shipment of previously approved fireworks combined with previously approved e-matches. However, one requirement of that exemption is that the e-matches "be certified by the manufacturer to be thermally stable at 150 °C for 24 hours". While a test for this was not conducted, it may be worth noting that, in the ramp temperature tests, several of the e-match types ignited at only slightly higher temperatures.

Additional thermal sensitiveness testing in the presence of Black Powder was not performed. This is because the exterior of the e-matches has a protective coating, and there is no opportunity for the e-match composition to have direct contact with the Black Powder. Accordingly, it is believed that the possibility of the presence of Black Powder having a significant effect on the thermal sensitiveness of e-matches is rather remote. For much the same reason, there was no thermal sensitiveness testing of e-matches with their safety shrouds in place.

Conclusion

Although a large number of individual tests were performed, it is important to recall that this sensitiveness testing was limited in scope and that it must only be considered a screening study. Further, many of the standard tests were modified somewhat in an attempt to better characterize the e-matches in an environment similar to their use for fireworks displays. Accordingly, the statistical precision achieved is only sufficient to approximately characterize and rank the sensitiveness of the various e-matches, and then only under the specific conditions of this testing. For e-matches producing similar results, had additional e-matches been tested or had the conditions been somewhat different, it is possible that slightly different results would have been found. Nonetheless, it is not expected that additional tests or somewhat different conditions would have produced substantially different sensitiveness rankings of the various e-match types.

One further caution is that the e-matches tested were supplied in late 1999. Accordingly, there is no guarantee that current production e-matches have the same sensitiveness characteristics as observed in the tests reported herein.

While there was a large range in sensitiveness observed for the different e-matches under various conditions, none was found to be so extremely sensitive as to preclude their safe use providing appropriate care and safety measures are taken during their use. One obviously appropriate safety measure is to leave the safety shrouds in place on e-matches to be used in any situation where they could be subject to physical abuse. However, probably the single most appropriate safety measure is to educate fireworks display crews of the potential for accidental ignition of electric matches, and the measures to take to minimize both the probability and the consequences of an accidental ignition.[8]

In selecting a supplier of e-matches, it is generally thought to be appropriate to use the least potentially dangerous materials that will successfully and reliably (and economically) perform the needed task. Unfortunately, this study has only reported on the sensitiveness and not on the performance of those e-matches studied. In an attempt to provide some of the additional information needed for users to make the best choice in their selection of e-matches, a second study is under way to characterize the performance of the same ten types of e-matches. As the individual testing is being completed, those results are being reported.[14] Eventually, following completion of the individual tests, a full report will be produced in a companion article to this one.[6]

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