Reaction propagation between fireworks shells and compositions confined in steel pipes

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Abstract: *This study presents the experimental results on the ignition of linear arrays of fireworks articles and bulk stars and describes their propensity to mass explode. Star and report shells, roman candles, and bulk cylindrical and spherical stars were functioned in steel pipes through initiation with a small black powder charge or an explosives booster. Continuous velocity of detonation probes was used to monitor the rate of reaction among the pyrotechnic components and the resultant fragmentation of the steel pipe was used to rate the violence of the reaction. All pipes fragmented and the measured reaction rate ranged from 170 to 870 m s*$^{-1}$*. Based on fragmentation, the violence of reaction increased from the star shells, to the roman candles, to the report shells, and then to the bulk stars.*

Keywords: *explosion, steel, mortars, fragments, reports*

Introduction

In an attempt to determine the reaction rate within a pile of fireworks, tests were performed with pyrotechnic composition and firework shells confined in steel pipes. The justification and applicability of such tests including unconfined burns and height-to-detonation tests were presented previously.[1] Fundamentally, the intent of the tests was to confine the samples to such an extent that maximum reaction rates would be achieved.

In a recent series of trials,[2] attempts were made to determine the shell-to-shell reaction rate with report and star shells. The 76, 102, and 127 mm shells were placed, in contact, end-to-end, in 3 m long Schedule 40, open-ended, steel pipes of corresponding nominal inside diameters of 3, 4, and 5 inches. A commercial explosive booster was used as initiator. It was found that complete, shell-to-shell communication within the pipe did not occur. Although most of the shells usually exploded, live and video observations indicated that some shells were ejected intact and/or burning from both ends of the pipes. Except for the small fragments produced by the booster, pipe fragments were large and fragmentation was very localized.

It was found that the commercially available coaxial-cable-type velocity of detonation (VoD) probe used to monitor the reaction rate over the length of the pipe was not sufficiently sensitive to detect all reactions/explosions. The records obtained indicated reactions/explosions occurring along the length of probe from which reaction rates could be determined. An example of such a record is shown in Fig. 1. It does not show a staircase-shaped trace as would be expected from the discrete amounts of energetic material in each shell exploding at the shell location. Such a trace, as explained in reference 2 could have been produced by non-sequential explosions of shells coupled with possible shell movement within the pipe. Non-sequential explosions would generate poor reaction rate records that could be used to determine average reaction rate values over the length of the pipe. On the other hand, had the shells been in motion within the pipe when they exploded, then the reaction rate calculated would be incorrect. The values of the reaction rate for the shells tested in the 3 m long pipe configuration ranged from 35 to 750 m s^{-1}.

Other researchers (Link *et al.*,[3] Downs,[4] Kennedy,[5] Kosanke *et al.*[6]) investigated the Bray Park accident (May 20, 2000, in Australia) where 50 mm roman candles placed in steel tubes exploded and ruptured the steel tubes. The investigators experimentally reproduced the accident and through modeling considered scenarios where the pyrotechnic

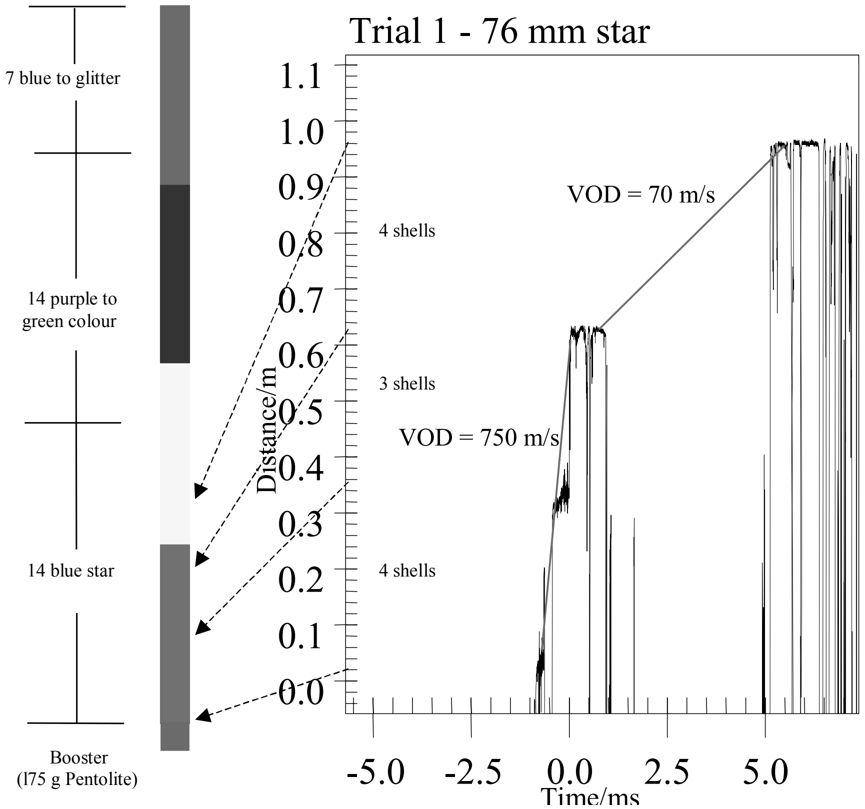

Figure 1. *Example of reaction rate record for 35, 76 mm star shells loaded in a steel pipe*

material either reacted instantaneously as a constant volume event or the roman candle's discrete pyrotechnic material exploded sequentially, in an effort to predict pipe rupture. The conclusion was that an ignition caused a deflagration-to-detonation transition (DDT) in one of the comet charges of the roman candle, which in turn initiated the rest of the energetic material of the roman candle by a shock-to-detonation transition process. The ability of an ignition-to-deflagration-to-detonation crossover was facilitated by the very sensitive and reactive nature of the comet composition and the confining effect of the steel pipe. A finite element code used to model the process predicted that pressures exerted on the pipe wall from detonating comet charges exceeded 500 MPa.

On a related topic, Kosanke and Kosanke[7,8] explain shell malfunctions in mortars, flowerpots, muzzle breaks, in-mortar "detonations" or, using the more acceptable term, violent in-mortar explosion (VIME). The term VIME, usually associated with firework mortar bursts, is used because it is usually unknown whether a detonation actually occurred. The authors suggest that the malfunctions can be due to the high pressure from the lift charge causing shell-casing failure, structural damage of the timing fuse (fuse driven into shell casing), and/or premature ignition through inertial setback. Flame from the lift charge then spreads through the damaged shell pyrotechnic components, accelerating due to the confining effect of the mortar and ambient pressure loading from the lift charge being consumed. Andoh and Kubota[9] have proven similar behaviour with solid propellants drilled with different size holes and subjected to ignitions at pressures ranging from ambient to seven atmospheres. They showed that flame penetration and propagation rates increased with open-ended holes. The flame paths within stars in fireworks shells can be considered as being open-ended holes.

As a reference to mortar bursts, Takishita *et al.*[10] report that bursting 82 mm star shells, can project individual stars at speeds of 70 m s^{-1}, and that a pressure of 5.6 MPa is reached in 3 ms within the shell and causes the shell to burst. This magnitude of pressure can quite easily rupture paper and plastic fireworks mortars. On the other hand, Takishita *et al.*[11] also report the time required for communication between the acceptor shell and a donor shell, both contained in a cardboard container, as 5 s. This is ignition and shell explosion through the time delay element (normal function) and not ignition through structural deformation or rupture of the shell. In reference 11, Takishita *et al*. conclude that the "heat transfer process by the hot gases and/or by the hot fragments plays a dominant role on the prevention of accidental bursts of shells. It is suggested that ignition prevention caps be placed on the end of each delay fuse of the shells." This is plausible in low confinement scenarios and deserves further investigation beyond the few tests performed by Takishita *et al.* to investigate mitigation methods for preventing communication. Then, Takishita *et al.*[11] qualify their proposed ignition and corresponding mitigation method by stating that "No mechanical damage is suffered by neighboring shells as long as each shell is separated physically by a paper barrier when an accidental burst of a shell occurs."

This paper presents and discusses a series of tests where the same report shells and similar star shells to those used in the study with the 3 m long pipes,[2] roman candles, and bulk fireworks stars were loaded in 1 m long Schedule 40 steel pipes capped at one or both ends. This configuration was designed to restrain the shells and prevent them from moving during their initiation and communication process.

Since the performance of the tests presented herein, similar pipe tests have been carried out under the CHAF[12] program in Europe. At this time not all the data have been analyzed but some information and results are given in Work Reports WP5, WP6 and WP7, which are available from their web site.[12] Their pipe test configuration is referred to as the 1D (one-dimensional) test. Initiation was through the use of a report shell initiated with an electric match. The shells were instrumented with trigger wires that "sensed" the shell bursting. The pipes were also fitted with piezo-type pressure transducers, which recorded the pressure profile within the steel pipe. The wall thickness of these pipes was twice that of the pipes used in this study and the CHAF program reports no pipes as bursting. Therefore, no fragments were produced.

Figure 2. *Array of fireworks shells on cardboard (Test 1)*

Experimental Set-up

Four series of tests were performed, the first with star shells (35 g burst charge and 60 g stars), the second with report shells (35 g burst), the third with roman candles, and the fourth with bulk fireworks stars contained in 76 mm (nominal 3 inch Schedule 40) steel pipe, 90 cm long. In the first and second series of tests, 76 mm shells, with their lift charge removed, were rolled in a single layer of single-sided corrugated cardboard (Fig. 2). A continuous velocity of detonation probe (VoD) was placed in one of the corrugations. The assembly was then inserted into a steel pipe that was sealed on one or both ends with cast iron pipe caps. In this configuration, with the cardboard packaging fitting snugly against the inside surface of the pipe, the void volume consisted mainly of that between the shells in the linear array (Fig. 2) and it was estimated to be in the range of 25–30%. Note that the void volume refers only to that between the pyrotechnic packaging and the confines of the steel pipe. It does not, for example, include the voids among the stars or that among components within a roman candle tube.

As indicated in Fig. 3, a hole was drilled in the wall of the pipe for the purpose of inserting initiator wires in the tests where the pipe was capped at both ends. In this configuration, initiation of the samples was either with a 175 g Pentolite booster initiated with detonating cord or with approximately 15 g of 5FA black powder initiated with an electric match. In the tests where the pipe was only capped at one end, the initiator was placed at the open end. A 4 mm hole was drilled in the cap

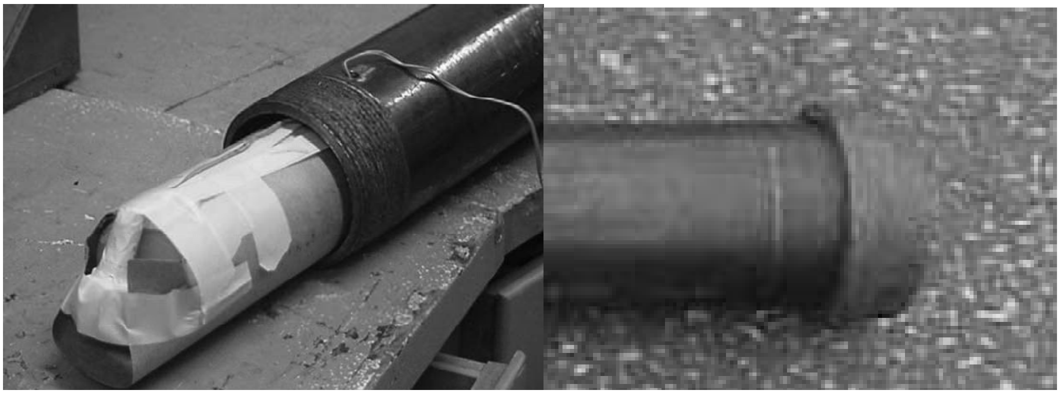

Figure 3. *VoD probe signal wires and capped-end of pipe*

located at the end opposite to the initiator end of the pipe to accommodate the VoD probe.

In the third series of tests, candles were inserted in Schedule 40 pipes. In the first test, an eight-shot, blue star candle was used. It contained approximately 120 g of pyrotechnic composition in the form of the black powder lift charges and stars. The stars were housed in plastic shells. The 30 mm candle, with an outside diameter of approximately 38 mm was inserted into a nominal 2 inch pipe (outside diameter 6.05 cm, wall thickness 3.8 mm, burst pressure approximately 60 MPa[13]), with a nominal inside diameter of 5.26 cm. No additional packaging was used. Therefore there was a 7.3 mm air gap between the candle and pipe. The candle was 850 mm long and assuming that only 60% of the candle length is filled and the remainder forms the muzzle end, the candle occupies a volume of approximately 580 cm^3. The candle was placed in a 92 cm long pipe having an internal volume of approximately 2000 cm^3. Then the void volume within the pipe is 70%. If only the length of pipe equal to the length of candle containing composition is considered, then the void volume within that length of candle and pipe is approximately 50%.

In the second test, an eight-shot, two-colour, 60 mm candle containing approximately 430 g of energetic materials (lift charge and stars) was used. The stars were contained in a spherical paper shell slightly smaller in diameter than the candle inside diameter. The 1000 mm long candle, with an outside diameter of approximately 71 mm was placed inside a nominal 3 inch pipe (outside diameter 88.9 mm, wall thickness 5.6 mm, burst pressure approximately 45 MPa[14]), whose inside diameter was 77.7 mm. Again, with only 60% of the candle length being filled and the remainder forming the muzzle end, the candle occupies a volume of approximately 2.4×10^6 mm^3. Therefore there was a 3.4 mm air gap between the candle and pipe. The steel pipe was 1150 mm long, with a volume of 5.4×10^6 mm^3, so that the void volume was approximately 55% of the total pipe volume. If only the length of pipe equal to the length of candle containing composition is considered, then the void volume in that length is approximately 15%.

In the fourth series of tests, red stars removed from fireworks shells were placed inside a cylindrical tube, formed with two layers of kraft paper. A VoD probe was inserted between the layers of kraft paper and the assembly was placed inside the steel pipe. Two tests were performed with spherical stars and one with cylindrical stars. The components of this configuration, with the pipe capped at only one end, are shown in Fig. 4. Initiation of the samples was with a 175 g Pentolite booster initiated with detonating cord placed at the open end

Figure 4. *Components of fireworks star tests*

of the pipe. The booster was placed tightly against the package of stars so as to minimize the void volume between the kraft paper tube and steel pipe, estimated to be approximately 5%. Note that the void volume among the stars is approximately 20%, less than the theoretical 25% for equal size spheres, correcting for the fact that the stars are approximately of the same diameter.

During the test program it was found that the commercially available copper VoD probes were too rugged and were not responding. Therefore, trials were also performed with custom-made aluminum VoD probes. The pipes were prepared and then hung inside a blast chamber where they were initiated via an electric firing system. Testing inside the chamber allowed recovery of the fragments but prevented video recording.

Figure 5. *Test 1: 8 star shells*

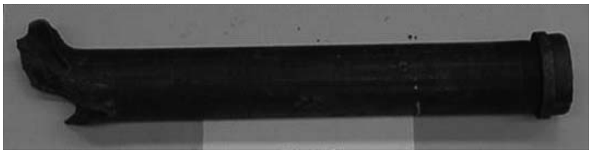

Figure 6. *Test 2: 8 star shells*

Test Results

Two methods of initiation were used in these tests, a booster initiated with a short length of detonating cord and a small amount of black powder ignited with an electric match. The small booster will itself contribute to fragmentation more than the black powder charge, but its fragmentation effect will be limited to a very short distance of the initiated end of the pipe. Comments relating to fragments will refer to those produced over the whole length of the pipes.

Figures 5, 6, 8, 9, and 11 to 15 show the fragmentation of the pipes resulting from the various configurations. Only two rate-of-reaction traces were obtained and they are shown in Figs. 7 and 10. Table 2 summarizes the results and quantifies the fragmentation.

Except for Tests 2 and 5, the damage to all pipes was substantial. Fragmentation of the pipes with star shells resulted in quite different results when initiated with a booster than with the black powder charge, with the booster initiation resulting in more than twice the number of fragments.

In Test 1 with the star shells, the pipe suffered damage mostly at the initiated end and the far end. A section approximately 10 cm long remained undamaged. The pipe in Test 2 was capped at both ends and as a result, even though initiation was with a black powder charge (inside pipe), the initiating end suffered localized damage. A rate-of-propagation was recorded in Test 2 with the continuous copper VoD probe indicating a rate of approximately 160 m s^{-1}.

Tests with the report shells, Tests 3 and 4 produced 3 to 4 times more fragments than those from the star shells. The interesting occurrence with these two tests is that Test 3 with a pipe capped at one end and with booster initiation resulted in about 25% fewer fragments than the pipe in Test 4, which was capped at both ends but was initiated with a black powder charge. Both pipes suffered similar damage with the additional number of fragments in Test 4 being primarily due to the fragmentation of the second cap. Note that this result indicates that the two different initiation methods resulted in the same type of response from the shells. A reaction rate trace was obtained for Test 4, where a continuous aluminum VoD probe was used. The measured rate ranged from 700 m s^{-1} to 870 m s^{-1}. This coincides with the upper range of values determined from the 3 m long pipe tests reported in reference 2.

The third series of tests, Tests 5 and 6, was performed with roman candles. One was an eight-shot candle, 30 mm by 850 mm long and the other was an eight-shot candle, 60 mm by 1000 mm long.

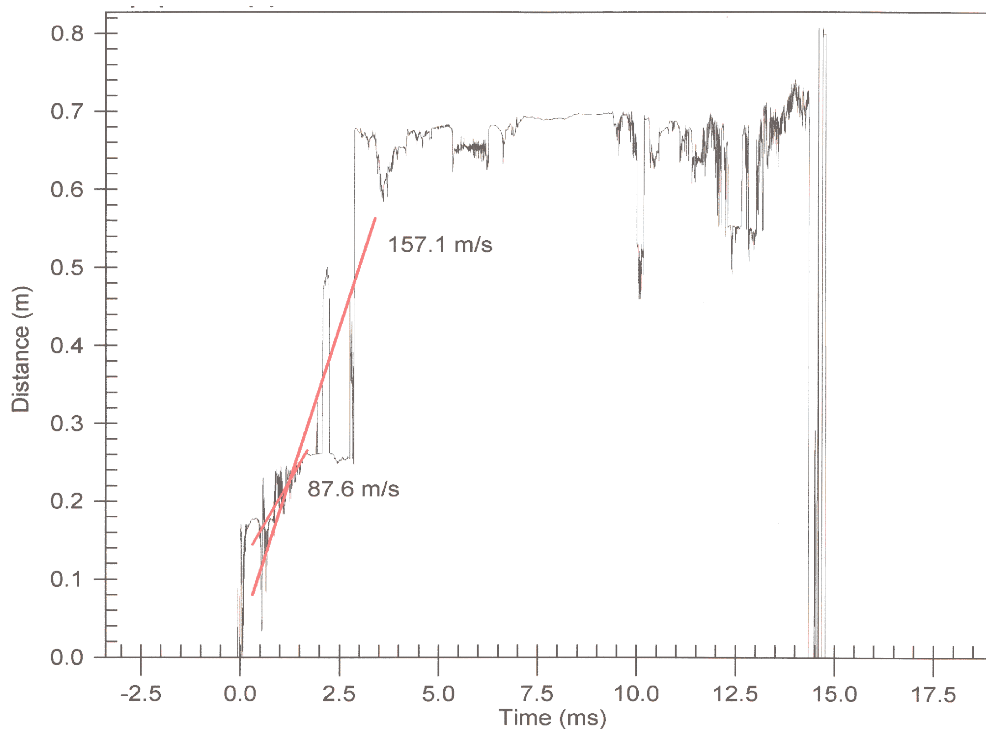

Figure 7. *Record from Test 2 Average rate of propagation 157 m s*$^{-1}$

Figure 8. *Test 3: report shells (booster initiated)*

Both tests made use of pipes capped at one end and both candles were initiated with a booster. The smaller, 30 mm candle was the only sample tested in a smaller diameter steel pipe (2 inch Schedule 40), in an attempt to keep the void volume low. It still had the highest void volume of all the tests at approximately 70% while the volume over the length of the candle containing energetic material was only approximately 50%. This combined with the relatively low mass of energetic material per unit length resulted in very low fragmentation of the pipe, as low as the star shells initiated with the black powder charge. The larger candle was tested in a pipe with a welded base, instead of a threaded cap, to better simulate the Bray Park accident set-up. With a void volume of approximately 55% and slightly higher energetic material per unit length, the resulting explosion caused fragmentation equivalent to that of the star shells initiated with a booster. Again, note that the void volume over the length of the candle containing energetic mate-

Figure 9. *Test 4: report shells (15 g black powder initiated)*

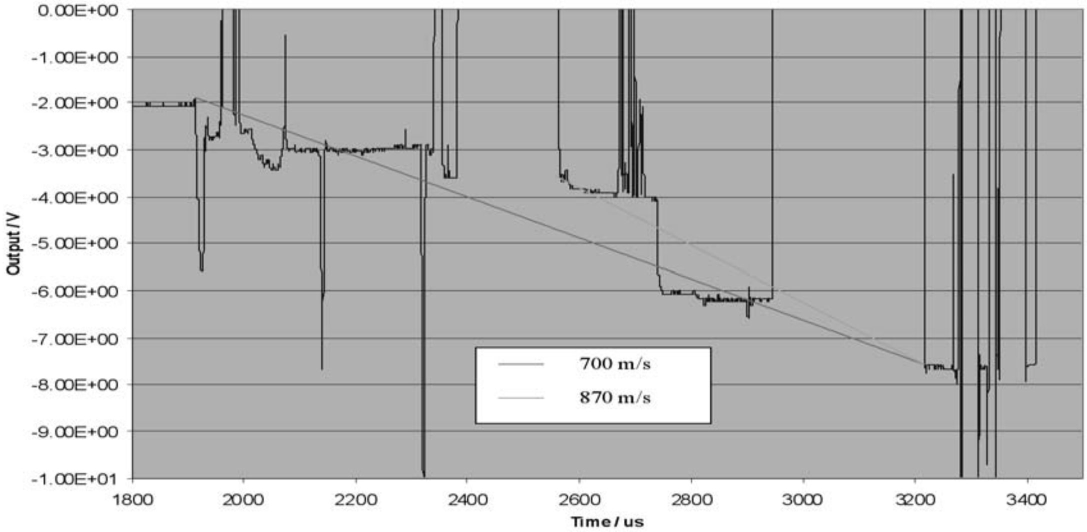

Figure 10. *Record from Test 4 - Average rate of propagation 700 m s^{-1}, Maximum rate of propagation 870 m s^{-1}*

Figure 11. *Test 5: One 30 mm Ø × 85 cm roman candle*

rial was only approximately 15%. The capped end of the pipe was undamaged because it housed the top, empty part of the roman candle. Both candles were totally consumed in these tests but no rates of propagation were obtained, as the VoD probes did not respond.

The last series of tests was with bulk stars. Considering the extent of fragmentation, the highest of all the trials, it was surprising not to obtain a response from the VoD probes. The high fragmentation was obviously due to high energetic material (star composition) mass per 10 cm length (250 g) but even at this loading density, less than twice the number of fragments were produced than those caused by the report shells which had an energetic material (flash composition) mass values per 10 cm length of only 40 g. No large distinction was noted in fragmentation caused by the cylindrical and spherical stars.

Figure 12. *Test 6: One 60 mm Ø × 100 cm roman candle*

Figure 13. *Test 7: Loose cylindrical red stars 12 mm Ø × 19 mm (2.6 kg)*

Figure 14. *Test 8: Loose spherical 12 mm Ø red stars (2.8 kg)*

Figure 15. *Test 9: Loose spherical 12 mm Ø red stars (2.6 kg)*

Discussion

Possible Ignition/Reaction Propagation Mechanisms

There are essentially five probable reaction propagation mechanisms for fireworks confined in a steel pipe. In these tests, the initiation stimulus is either from an explosive booster or a quantity of black powder. This stimulus fractures part of the initiating end of the pipe and the first and possibly the second shell thereby igniting their contents either through shock, mechanical, and/or flame initiation. The following five possibilities then exist:

1. Failure: the contents of the shell(s) do not explode en masse, in which case the pipe will not be damaged. It is possible that other shells further along the column ignite (out of sequence ignition) and burn (see scenario 5), resulting in the jetting of flame or ejection of shells from the open end of the pipe as seen in the 3 m long pipe tests and possibly causing some damage to the pipe.

2. Detonation: this is typical of high explosives where a supersonic pressure wave (shock) travels through an energetic material. The pressure generated by the shock causes the rapid reaction of the materials (pyrotechnics) behind the shock front. This reaction generates its own pressure wave, which coalesces with the shock front, thereby maintaining it. Detonation would be expected to occur promptly after initiation of the stimulus.

3. Shock initiation: the contents of the shells explode and the adjacent shell is sufficiently shock sensitive that it too explodes. This process repeats along the linear array of shells in the pipe until all shells are consumed. Reference 8 suggests that conditions can exist for hot spot initiation through adiabatic compression of entrained air bubbles (voids) within the star composition. Another possibility is that of shear band heating. High pressures, as those from the detonation of the booster, acting on dislocations, imperfections or microcavities within the star composition, can generate shear slip planes with associated shear band heating.[15,16] Ignition points, either due to hot spots or shear banding, will then cause an increase in pressure through coalescence of the shocks from each site and can result in a transition to an explosion/detonation. This initiation-to-explosion process was identified as the cause of the catastrophic

Table 2 – Test results (Nominal 3” diameter, Schedule 40 steel pipes)

Test	No. of Capped Ends	Sample				Initiator	VoD Probe Type	Number of Fragments		
		Type	Mass /kg	Size /mm	No.			> 1 kg	< 1 kg	Total
1	1	SS	0.095	76	8	Booster	C	3	13	16
2	2	SS	0.095	76	8	EM+BP	C	1	5	6
3	1	RS	0.035	76	12	Booster	A	7	31	38
4	2	RS	0.035	76	12	EM+BP	A	5	43	48
5*	1	RC	0.15	30Nx850	1	Booster	C	4	3	7
6**	1	RC	0.43	60Nx1000	1	Booster	C	12	20	32
7	1	CBS	2.6	12Nx19	---	Booster	C	10	51	61
8	1	SBS	2.8	12 N	---	Booster	C	8	59	67
9	1	SBS	2.6	12 N	---	Booster	C	7	65	72

* – Nominal 2” diameter, Schedule 40 steel pipe, ** – 115 mm long pipe with one end sealed with a welded steel plate

EM – Electric Match, BP – Black powder, C – Copper VoD probe, A – Aluminum VoD probe, RS – Report shell, SS – Star shell, RC – Roman candle, SBS – Spherical bulk stars, CBS – Cylindrical bulk stars

propellant explosion that resulted in the death of 26 people on the USS Iowa in 1989.[17] The propellant exploded when it was being rammed into the gun. Interestingly, it was found that the propellant grains were only sensitive to this type of initiation when sheared across the extrusion axis. The CHAF[12] program included the gap sensitivity of flash composition. It was found that the flash composition could be initiated with pressures ranging from 350 to 400 MPa.

4. Deflagration-to-detonation transition (DDT): the contents of the fireworks articles behave more like a propellant confined in light casing, their reaction rate is related to the local pressure. The high pressures generated by the booster will cause ignition and structurally damage the stars. In so doing, the flame is exposed to very large surface areas of the star composition so that convective heating can quickly accelerate, thereby increasing the pressure and continued flame progression under the confinement provided by the pipe. As the local pressure increases due to the production of reaction products, the reaction rate increases until either the pipe bursts or the pressure reaches a critical value causing the reaction to transition to detonation. References 5, 8 and 9 support this argument. The voids found among the stars in the pipe can be envisaged as being similar to those among propellant grains of the same form. In Reference 18, Bernecker *et al.* indicate that the stages of a DDT mechanism for porous charges are; 1. Pre-ignition, 2. Ignition/conductive burning, 3. Convective burning, 4. Compressive (“Hot spot”) burning, 5. Shock formation, 6. Compressive burning, 7. Detonation.

5. Normal function: the flame from the booster or black powder channels around the shells igniting them through their normal initiation train. In this scenario, the shells are expected to be ejected from the open end of the pipe in a sequential fashion. With the pipe closed at both ends, this mode of ignition could result in a mass explosion, as the burning rate of the delay fuses would increase under the pressure built-up. An individual shell could also function first, possibly causing the explosion of the remaining shells. Pipe rupture would be expected in either case. As with the previous work with the 3 m long pipes,[2] results indicate that the sequence of ignitions within a linear array of shells is not clear. Shell movement, flame channeling between shells and the pipe wall, and pipe break-up can result in scenarios where a second or third shell ahead of the linear array ignites before the first. High-speed video of tests in the CHAF[12] program, where shells were placed in plastic tubes, also indicate that flame channeling was occurring and shells were exploding out of sequence.

In reality the effects observed in the tests involve a combination of these mechanisms. For example, with the use of a booster, the first few shells could be overdriven and respond as if they were shock initiated. However, they may not release sufficient energy for this type of reaction to continue the entire length of the pipe. On the other hand, the initial shock would likely cause some or all of the remaining shells to rupture exposing energetic material to flames. As a result, a large quantity of propellant may ignite nearly simultaneously resulting in rapid deflagration of the remaining material.

Without a means of directly recording the sequence of events inside a pipe, such as with flash X-ray or neutron radiography, the mechanism of reaction propagation inside the pipe must be interpreted indirectly. One possibility is through the number and size of the fragments produced. Typically, detonation inside a pipe results in small fragments with sharp, jagged, brittle-like edges, while an explosion/deflagration results in large fragments without the sharp edges. Thus, in the five scenarios described above, the fragments resulting from a failing reaction would include small fragments near the ignition end of the pipe, but the opposite end of the pipe would be essentially undamaged. Scenario 2 (detonation) would produce a large quantity of small fragments. Scenario 3 (shock initiation) would produce small fragments at the ignition end, larger longitudinal fragments in the middle and possible smaller fragments at the end if transition to detonation occurs. Scenario 4 (deflagration) would result in a few large fragments. Finally, Scenario 5 (normal function) could result in just small fragments at the initiating end if shells are ejected or small fragments at the initiating end and larger fragments from the remainder of the pipe if all the shells were to explode simultaneously.

These above explanations between the size of fragments and the reaction rate are not straightforward for fireworks articles but are complicated by the fact that the energetics in fireworks are rarely directly in contact with the pipe wall. They are decoupled, by air and blast attenuating material (packaging) between the energetics and the wall. The formation of fragments will depend on the distance separating the article from the pipe wall and packaging material.

A comparison of the number of fragments and the shape of the fragments produced in Tests 1 to 8 (Fig. 5, 6, 8, 9, 11–15) shows three different modes of response. The star shells and the small roman candle produced just a few very large fragments indicating a response similar to scenario 1 or 5 (Failure and Normal Function). As an example, in Test 2, only the centre of the cap was punched out. The pipe suffered no other damage. Again, this could only happen if flames from the original shell(s) explosions by-passed other shells to initiate shells along the column closer to the remaining capped end of the pipe. The explosion of a shell close to the cap would do damage to the cap and drive the remaining shells back toward the open end of the pipe, possibly initiating them in the process. The fact that pressure could be relieved from both ends would reduce the damage to the pipe. High-speed video of similar trials reported in Reference 2 indicated flame and shell ejection from both ends of the 3 m long pipes, and the pipes suffering little or no damage.

The larger roman candle and the report shells produced significantly more fragments, and if one disregards the brittle pipe caps, the fragments are primarily large longitudinal strips. The rate of propagation recorded for one of the report shell tests was six times higher than that recorded for a star shell test, 870 m s^{-1} *vs.* 150 m s^{-1}. Researchers in the CHAF[12] program found a similar trend between report shells and star shells recording propagation rates of 200 to 300 m s^{-1} for 55 mm report shells and 90 m s^{-1} (5 shells were consumed in 5 ms) for star shells. Based on the propagation rate and the size and number of fragments, the response of the larger roman candle and the report shells correspond most closely with the propagation mechanism proposed as Scenario 4 (Deflagration). The bulk stars on the other hand, produced many relatively small fragments more closely resembling Scenario 2 (Detonation), but the lack of the sharp jagged edges typical of those produced by a high explosive in contact with metal indicate that the reaction was not a detonation. Thus it is more likely that the propagation mechanism is that discussed in Scenario 3 (Shock initiation) or 4 (Deflagration initiation), and that the large number of fragments are the result from the large mass of energetic material in these tests, the large surface area exposed to flame, and the fact that the energetic material was coupled to the wall of the pipe.

The disparity in the number of fragments produced by the two roman candles demonstrates the effect of confinement on the reaction rate of energetic materials. The estimated void volume was 50%

for the smaller candle and 15% for the larger candle. In both tests a high explosive booster provided the initial stimulus. The larger candle produced 38 fragments while the smaller one produced only 7 fragments. An even more graphic example occurred in the Bray Park accident where a roman candle was placed in a relatively tight fitting steel mortar. Because of the tight fit the void volume was very low and thus there was a high level of confinement. The initial stimulus was provided by the normal ignition of the article, and in spite of this low energy ignition the roman candle is believed to have made the transition to detonation due to a very energetic composition.

The void volume, reactivity and the energy output of the compositions determine whether an ignition-to-explosion process will proceed to adjacent fireworks articles or composition. The maximum pressure of 5.6 MPa, measured by Takishita *et al.*[8] on the surface of a star shell exploding in free air, can be easily increased by providing confinement at the shell surface. This was noted in the CHAF[13] program where pressures for shells confined in steel pipes reached a maximum of 7.7 MPa. Pressures six to eight times higher must have been developed locally in the pipe tests reported herein to rupture the pipes which had burst pressures of 45 and 60 MPa for the nominal 2 and 3 inch schedule 40 steel pipes, respectively. Furthermore, steel is typically 20% stronger under dynamic loading than under static loading, as such it is possible that the pressure could have been 20% higher. Link[3] reports that pressure levels between 35-40 MPa would have been required to rupture the pipes (76 mm OD, 3.6 mm wall, 500 mm long) of the Bray Park accident. Calculation from reference 11 using static loads results in a 25 MPa pressure to rupture the pipe.

Conclusions

The intent of this test program was to determine the mechanism by which the reaction resulting from the ignition of a single fireworks article propagates to adjacent articles and results in a mass explosion. Because the testing of large masses of fireworks is prohibitively expensive, pipes where used simulate the confining effect of a large mass of fireworks.

It was found that the mechanism of propagation of a reaction inside the pipe was highly dependent on the packing configuration within the pipe. Parameters such as composition, packing density, ullage, area of contact between shells, strength and shock attenuating properties of packaging material, and confinement all play a substantial role in determine the rate of reaction. Because the design of a fireworks article is specific to each manufacturer there can be a great variation between the types of materials, the geometry and the composition in fireworks of the same type of article manufactured by different companies. This makes it very difficult to draw general conclusions from specific test results.

In this program, two or possibly three different levels of reaction violence were observed. The star shells and the small roman candle produced very few fragments, indicating that the reaction failed to propagate fully within the pipe while the pipe was still intact. This type of slow propagation was designated either a "Failure" (to propagate) or as propagation by "Normal Function". The other tests resulted in many more fragments, indicating a more complete reaction of the articles in the pipe before the pipe ruptured. This faster reaction propagation was attributed to a process involving first the damaging of the articles and exposing of the energetic material (in the case of bulk stars the material was already exposed) and then a rapid deflagration of the energetic material. This process was designated as "Deflagration". There was no evidence of a detonation in any of the tests. All pipes fragmented and the measured reaction rate ranged from 170 to 870 $m\ s^{-1}$. Based on fragmentation, the violence of reaction increased from the star shells, to the roman candles, to the report shells, and then to the bulk stars.

There are insufficient data here to prove that detonation is not possible in a mass of fireworks. Before this can be demonstrated further work would be required, particularly in the areas of the effect of confinement and packing density.

Acknowledgements

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References

1 E. Contestabile, "Applying Explosives Testing Techniques to Obtain Insight into the Explosion Phenomenon of Piles of Fireworks", *Journal of Pyrotechnics*, Issue 14, 2001.

2 E. Contestabile, R. Guilbeault, D. Wilson and B. von Rosen, "Fireworks Shells Subjected to a Modified Height-To-Detonation Test", *Journal of Pyrotechnics*, Issue 20, 2004.

3 Link, R.A., G. Delbridge, and D. V. Ritzel, "Computational Modeling of a Steel Tube Subjected to Internal Fireworks Explosion", 7th International Symposium on Fireworks, Valencia, Spain, 2003.

4 G. Downs (editor), *Investigation Report - Bray Park Fireworks Tragedy*, Queensland Government, Department of Natural Resources and Mines, 2001

5 D. L. Kennedy, *Bray Park Investigation: Explosive and Propellant Behaviour (Revision 2)*, Orica Explosives, March 2002.

6 K. L. Kosanke, B. J. Kosanke, G. Downs and J. Harradine, "Roman Candle Accident: Comet Characteristics"*, Fireworks News, Fireworks Business News*, Issue 225, 2002.

7 K. L. Kosanke and B. J. Kosanke, "Hypothesis Explaining Muzzle Breaks", Proceedings of the Second International Symposium on Fireworks, Vancouver, Canada, 1994.

8 K. L. Kosanke and B. J. Kosanke, "Hypotheses Regarding Star Shell Detonations", *Journal of Pyrotechnics*, Issue 14, 2001.

9 E. Andoh and N. Kubota, "Flame Penetration into Solid Propellant Holes", *Propellants and Explosives*, Vol. 6, 1981.

10 Y. Takishita, et al., "Experimental Studies on Spherical Burst - Aerial Shells", Proceedings of the 5th International Symposium on Fireworks, Naples, Italy, 2000.

11 Y. Takishita, et al., "Safety Characterization on Burst - Aerial Shells", Proceedings of the 5th International Symposium on Fireworks, Naples, Italy, 2000.