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Hypotheses Regarding "Star-Shell-Detonations"

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ABSTRACT

Fireworks star shells occasionally explode upon firing while they are still inside the mortar. Most often, this occurs with approximately the same level of violence as when the shell explodes after having left the mortar, and often even relatively weak mortars survive the experience intact. While unnerving to the firing crew, this represents relatively little hazard for crew or spectators. However, on rare occasion, the in-mortar star shell explosion achieves a level of violence substantially greater than normal. These more powerful explosions represent a potentially life-threatening hazard for both the firing crew and spectators. Unfortunately, the cause for these more violent explosions has not been definitively established, and without knowing the cause, relatively little can be done to prevent them from happening. In this article, two hypotheses are suggested as possible explanations for these dangerous malfunctions. Basic information and some empirical evidence are presented in support of two potential theories.

Keywords: aerial shell explosion, aerial shell malfunction, in-mortar explosion, flowerpot, star-shell-detonation, VIME

Preface

A large number of explanatory notes are included in this text. These are indicated in the text using superscript letters. (Literature references are designated by superscript numerals.) Hopefully putting the supporting and supplemental information at the end of the article will make the text easier to read by allowing readers to skip this information if they wish.

Introduction

Occasionally upon firing, a fireworks aerial shell explodes while it is still within the mortar. Of course, when the shell in question is a salute (maroon), the result is always a powerful explosion, generally with the potential to fragment even a steel mortar. However, for star shells, the vast majority of in-mortar explosions produce the malfunction generally known in the US as a flowerpot. This results in a relatively mild explosion with an eruption of the burning contents of the shell projected upward from the mouth of the mortar. Typically, for small diameter, single-break shells the mortar remains intact and produces a display appearing much like a fireworks star mine. For large diameter, single-break star shells, depending on the strength of the mortar,[a] the display may again appear much like a normal star mine. (However, if a relatively weak mortar fails to withstand the explosive forces, a mortar failure may allow some of the burning stars to proceed in directions other than primarily upward.)

For star shells, another more malevolent in-mortar explosive malfunction may occur, fortunately only on fairly rare occasions. In this case, the power of the explosion is much greater than that produced by a flowerpot, and most mortars will fail to withstand the explosive force, thus potentially producing dangerous mortar fragments. Traditionally, the accepted term for this malfunction is a *star-shell-detonation*. However, it is unlikely such explosions technically are detonations in the true high explosive sense. In recognition of this, some pyrotechnists are beginning to refer to this malfunction as a VIME (violent in-mortar explosion). In an attempt to be more generally correct, that usage has been adopted for this article. It is generally believed that the reason for the great power of these explosions is that most of the pyrotechnic content of the star shell is consumed in a much shorter span of time than is the case when the same type of shell flowerpots.[b] Because the shell's stars are apparently consumed in producing the explosion, they are not seen as a display being projected from the explosion.[c]

Some information in the literature[3,4] suggests that the cause of star shell flowerpots is the fairly catastrophic failure of the shell's casing upon firing, due to the reactive forces produced by the shell's rapid acceleration.[d] Unfortunately, however, little information suggesting the cause of VIMEs has appeared in the literature. There is the important suggestion by Brock,[6] based on research conducted in the late 19th century, that at least one cause for VIMEs was the result of using "badly made" ("crumbly") stars made with a chlorate oxidizer. The implication that chlorate-based stars can contribute to the cause of VIMEs is consistent with much of the speculation regarding their cause even today. Potassium and barium chlorate oxidizers decompose exothermally, a property shared with explosives in general.[e] Further, potassium chlorate has been used to produce truly detonable explosives in simple combination with small percentages of organic fuels.[f]

In contrast to potassium and barium chlorate, the decomposition of potassium perchlorate is approximately energy neutral, and the decomposition of potassium, sodium, barium and strontium nitrate are all substantially endothermic.[7] Nonetheless, there have been anecdotally reported VIME incidents thought[g] to have been produced by shells containing stars made using potassium perchlorate, and still other incidents were thought to have involved stars made using a nitrate oxidizer with a metal fuel. Accordingly, while chlorates may make it somewhat more likely that a mild in-mortar explosion (flowerpot) may transition into a much more violent explosion (VIME), it would seem that the presence of a chlorate is not essential.

Another clue to a possible cause of VIMEs was revealed recently during the investigation following a serious fireworks accident. During the course of testing, the open burning of some large comets occasionally produced powerful explosions.[10,11] These comet stars had previously been radiographed to confirm that they were composed of a single, substantially solid block of pyrotechnic composition (i.e., they did not contain internal explosive elements such as might be present in an intentionally exploding comet such as a crossette). The explosion of these comets while burning completely unconfined, and in particular the violence of these explosions, was quite unexpected. While attempting to formulate an explanation for these observations, an additional possibility regarding possible causes of VIMEs was formulated.[11]

These two possible causes of VIMEs are presented below, along with brief supporting discussions. About 10 years ago, the necessary test equipment and rough protocol for testing the first of these hypotheses were developed; however, to date, time constraints and other research projects have prevented pursuing this project. In addition, current research interests make it unlikely that the causes of VIMEs will be studied in this laboratory in the near future. Accordingly, and in the hope that someone else may be encouraged to pursue such a study, this article was written.

Weak Star Collapse Hypothesis

Most commonly, the individual particles in a fireworks star composition adhere to one another as a result of a binder that has been activated by the addition of a suitable solvent.[h] As a practical matter, all fireworks stars contain void spaces between the individual grains of the components in the mixture.[i] Figure 1 illustrates the porosity of two typical fireworks stars. The upper micrograph is of a rolled spherical color star; below that is a pressed aluminum comet star. Even though the two stars are substantially different in both their composition and method of manufacture, note the grain structure and void spaces (dark recesses) in both.

If something were to happen that would suddenly collapse these void spaces, the gas within the spaces would increase in temperature as a result of the mostly adiabatic compression.[j] (This is the same process that causes the ignition of the fuel in the cylinder of a diesel engine.) If the increase in void gas temperature were great enough, it is possible for this high temperature gas (*local hot-spot*) to cause an ignition of at least some of the surrounding pyrotechnic material.[k]

During the collapse of the star, frictional forces (shear) could also contribute to thermal

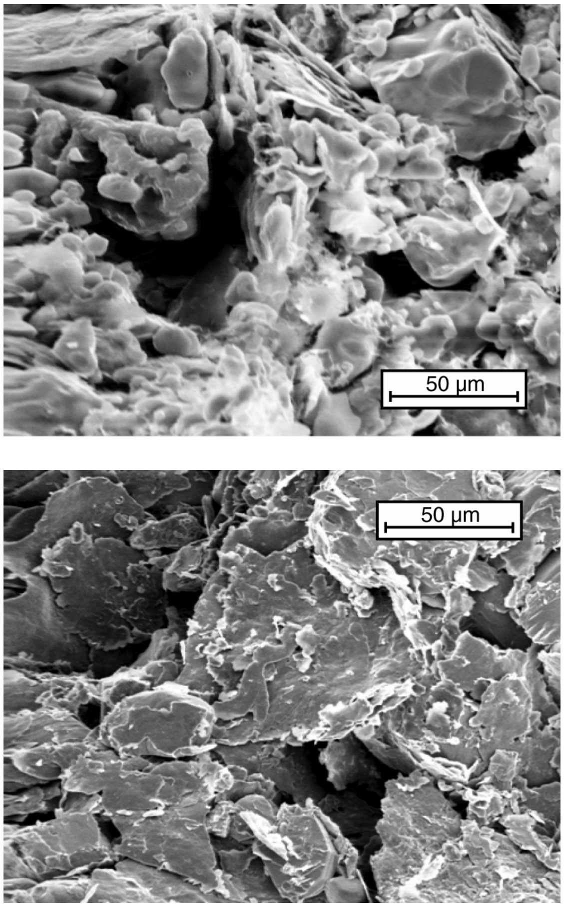

Figure 1. Electron micrograph of the internal structure of two substantially different firework stars. (Upper: rolled color star. Lower: pressed aluminum comet star.)

ignition as the grains of composition grind against each other. In addition, the penetration of burning gases from the burst charge, as the star is collapsing under the extreme pressure, must also contribute to the internal ignition of the star composition. In that way, the combination of adiabatic heating of void gas, plus the frictional heating from shear, plus the penetration of burning gas, might reasonably produce nearly simultaneous ignition of composition throughout much of the volume of the star.

When a star shell bursts (explodes) normally in the air, the peak internal pressure reaches a fairly high level before the casing fails and the contents are projected outward. However, based on the observation that most fireworks stars exit a bursting aerial shell in one piece, this peak pressure is obviously one that most well-made stars successfully withstand without being crushed.[l] If, instead, the shell explosion takes place within a mortar, the additional confinement provided by the mortar, must result in significantly greater pressure being produced within the exploding star shell. If this greater pressure is sufficient to cause the collapse of some of the stars in the shell, this might trigger a VIME. (This is the combined effect of the adiabatic heating of the gas in the pore-spaces, the frictional energy of the grains of composition grinding against one another, and the penetration of burning gases from the shell's burst charge into the interior of the stars.) As a result of the essentially simultaneous ignition of the entire mass of a few stars, the total pyrotechnic energy of those stars might then be released in a matter of milliseconds, instead of their normal several-second burn time. As a consequence of the additional, near instantaneous, release of energy from the collapse of a few stars, still greater pressures could result, which might then induce other stars to collapse, increasing the pressures even further, causing still more stars to collapse. In such a manner, essentially all of the stars in the shell might fail in a small fraction of a second, adding substantially to the power of the explosion, thus producing a VIME.

Weak Star Collapse Discussion

As explained above and in the notes, there is at least a theoretical basis to believe that the weak star collapse hypothesis could be one explanation for VIMEs. Further, the star collapse theory is consistent with Brock's observations about "crumbly" stars, along with anecdotal accounts of non-chlorate stars being capable of producing these powerful explosions. In considering the likelihood of an in-mortar star shell explosion producing a VIME, in addition to those things affecting a star's tendency to collapse, all of the other factors affecting pyrotechnic ignition and propagation must be considered. For example, ignition temperature, friction sensitiveness, heat of reaction, the degree of acceleration of burn rate with pressure,[m] etc., all are expected to play a role in determining whether an in-mortar shell explosion will be a flowerpot or a VIME.

With the weak star collapse theory as background, a couple of related areas deserve a little more attention. One topic relates to voids. The size of voids is important. This is because larger voids contain a greater mass of gas, thus offering the ability to produce and transfer more heat to the surrounding composition and in turn offering a greater potential for the internal hot-spot ignition of the collapsing star.[n] Larger voids also offer greater potential for frictional heating and ignition upon collapse. This is because, for a star with larger void spaces, there will be greater internal movement as the star collapses.

While the size of voids is a prime consideration, attention must also be directed toward the pressure acting to cause the star's collapse. With greater pressure, the amount of adiabatic heating, the shear forces, and the extent of penetration of burning gas from the burst charge will all be greater. Accordingly, smaller voids, under greater pressure, should produce similar results. In much the same way, the number of voids should be relevant, with a large number of voids offering a greater combined ability to produce and transfer heat. Accordingly, with both the size and number of voids as concerns, probably it is porosity (the percent void space) that is most important.

For cut stars, probably the amount of water present in the composition and the degree of consolidation of the *loaf* (block of moistened star composition) collectively play a role in determining the porosity of the stars. In this case excess water and poor consolidation would be expected to produce high porosity stars. For pressed stars, while the amount of moisture added must have an influence on porosity, the loading pressure (compacting force) is expected to have the greatest effect, with low loading pressure producing high porosity stars.

For rolled stars, the amount of water used must be kept fairly low, to keep the stars from sticking together during their manufacture. Nonetheless, there is a range of moisture content that is possible and that should also result in a range of porosities. Further, the degree of consolidation of rolled stars seems to depend on the amount of water being used, the amount of star composition added in each layer of the star, and the amount of time the stars tumble between additions of composition.[o]

This star collapse hypothesis is based on the premise that the cause of VIMEs may be the result of sufficiently weak stars with sufficiently great porosity. Accordingly, another topic deserving discussion relates to the structural strength of stars. The crush strength of the star will depend on both the type and amount of binder, as well as the solvent, used. Obviously, when too little binder is used, the star will be weak as a result of the individual particles not being well secured to one another. While the strength of the binder is important, and certainly not all binders are equally strong, there is little useful information in the pyrotechnic literature on this subject. Also the nature of the solvent used to activate the binder will affect star strength. For example, for water-soluble binders, sometimes a water and alcohol mixture is used to decrease the time needed for star drying. However, while drying times are reduced, it is suspected that using a water and alcohol mixture may result in reduced structural strength of the star because of a reduced effectiveness of the binder.

Strong Star Explosion Hypothesis

Imagine a situation where one has a fairly large star that is constructed such that the particles adhere to one another with great strength, producing a star that is quite hard and structurally very strong. In addition, assume that the star has features that under the right circumstances could produce fire paths to its interior. Such features might be the star having marginal permeability, such that its pore spaces are not sufficiently well connected to constitute effective fire paths to its interior when ignited under the pressures[l] experienced within a normally exploding aerial shell (i.e., when the shell is not exploding while still within a mortar). In that case, when the star is ignited on its exterior surface it will burn normally (non-explosively). However, if that same star is ignited during an in-mortar shell explosion, and if the greater pressures are now sufficient to force open the connection of the pre-existing void spaces, those void spaces might then become effective fire paths leading to the interior of the star. In that case, very quickly fire will race down the fire paths into the interior of the star producing ever increasing internal star pressure. Given the great structural strength of the star, the resulting internal burning might then be sufficient to cause the explosion of the star when the internal pressure finally exceeds the structural strength of the star. Further the power of the star's explosion will be greater if the star composition is sufficiently fast burning or if it has a sufficiently large pressure exponent,[m] such that the gas pressure inside the star rapidly accelerates to catastrophic (explosive) levels.

Strong Star Explosion Discussion

As explained above and in the notes, there is at least a theoretical basis to believe that the strong star explosion hypothesis might be another explanation for VIMEs. Further, this theory seems to be supported by some of the testing performed following a recent accident, wherein a number of incredibly violent comet star explosions were observed to occur during their unconfined burning.[10] A close examination of the interior of these comet stars revealed a level of porosity perhaps sufficient to be consistent with this strong star explosion theory. In addition, when properly functioning (non-explosive) comets were modified by increasing their permeability by drilling tiny channels into the center of the star, the stars exploded violently upon their unconfined ignition.

If the fire paths within a star such as described above are sufficiently well developed so as to allow the powerful explosion of the star when burning unconfined at one atmosphere, then it would surely do so under the conditions of a normal (not-in-the-mortar) shell explosion. Thus, it would not require the additional high pressures that must occur during an in-mortar shell explosion, and it would not seem to be a potential explanation of VIMEs. However, if the degree of permeability is not sufficient under these normal shell explosion pressures but could become sufficient during an in-mortar shell explosion, then it remains a potentially viable explanation. There would seem to be at least two ways this might happen.

The first way would be if the connection between the pre-existing pores is marginally blocked, such as might be caused by a relatively thin film of binder at various points along the length of the channel, see the upper illustration in Figure 2. If that were the case, the pores might not function as fire paths under the normal shell functioning pressures. However, under the higher in-mortar shell explosion pressures, these thin barriers to gas penetration might be breeched to then become continuous (fire paths), see the lower illustration in Figure 2. If so, these stars could behave properly during normal shell explosions but might still be the cause of VIMEs. Note that this scenario becomes more likely as the pressure exponent of the composition increases towards unity. This is because there would be a rapid further increase in pressure inside the channels themselves. As a minimum, this could act to force even greater penetration of fire into the star. Further, in general, the

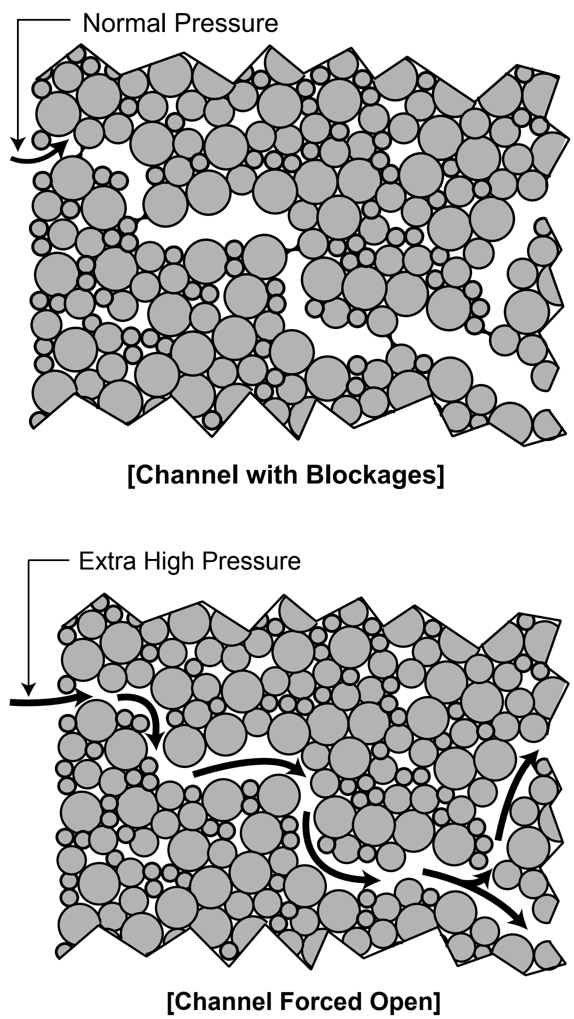

Figure 2. Illustration of a possible star interior that initially (upper) has its pores blocked by thin films of binder, but which are forced to open (lower) upon exposure to the high pressures during an in-mortar shell explosion.

higher the pressure exponent, the less pressure is required to initiate explosive burning.

The second way stars might have such a dual mode of functioning has to do with the effectiveness of fire paths as a function of their diameter. Shimizu reports that the effectiveness of fire paths is a maximum for some diameter, but decreases to approach a constant value for large diameter fire paths,[p] and decreases to zero as the diameter of the fire path approaches zero,[15] see Figure 3. Based on general physical principles, a developing pressure gradient accelerates flame propagation down a fire path. Accordingly, consider the case where pores are minimally connected via tiny paths so narrow that they are ineffective as fire paths at the normal shell explosion pressures. However, the same minimally connected pores might serve as effective fire paths at the higher in-mortar explosion pressures. Note that a similar argument might be made for stars that have microscopic cracks in them, perhaps produced during drying or curing.[q]

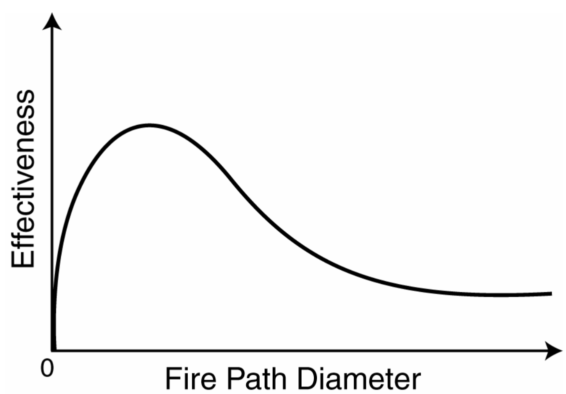

Figure 3. The effectiveness of fire paths as a function of diameter.[14]

Conclusion

Fortunately, VIMEs are considerably less common than the substantially less explosive (and thus less dangerous) flowerpot malfunctions. Nonetheless, because they can produce such powerful explosions, apparently rivaling those from salutes and salute containing shells, VIMEs continue to be a serious display crew and public safety concern. It is hoped that this article will provoke further discussion of the causes of VIMEs, possibly resulting in research to identify the actual causes of VIMEs.[r] Once the causes are determined, it should be possible for manufacturers to eliminate these most horrific of star shell malfunctions.[s]

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Notes

a) The pressure safety margin for many large diameter mortars is less than for small diameter mortars made of the same material. For example, the most commonly used 3-inch high density polyethylene (HDPE) mortars, firing typical spherical shells, have a pressure safety margin estimated to be perhaps as much as a factor of 16, whereas 12-inch (300-mm) HDPE mortars may have a pressure safety margin of no more than 2.[1]

b) Power is equal to the amount of energy produced during a given time interval. Thus, if roughly the same energy is produced, but it is produced in a much shorter period of time, this corresponds to much greater power. For a flowerpot, much of the pyrotechnic energy is produced over a number of seconds as the stars continue to burn after the explosion. For a VIME, while the duration of explosion has not been measured, it appears to be on the order of no more than a few tens of milliseconds (and possibly only a very few milliseconds). Accordingly, if the same total amount of pyrotechnic energy is produced by both the flowerpot and the VIME, the power contributed by the stars in the VIME will be on the order of at least 100 times greater than that from the stars in a flowerpot. (Presumably, the power produced by the shell's burst and lift charges will be mostly unchanged.)

c) While it is generally assumed that all of the stars within a shell are consumed during a VIME, it is possible that some (many?) of the stars are not consumed, but rather are "blown blind" (i.e., traveling so fast that they are not capable of remaining ignited as they leave the area of the explosion).[2]

d) Calculations, based on simple physics and the measured pressures during the firing of aerial shells, indicate that the peak acceleration of a shell is approximately 1000 times the acceleration due to gravity.[5] Inertial forces in response to such high acceleration rates, produce large and partially unbalanced forces on the casings of aerial shells. These forces can produce a more or less complete failure of the shell casing.

e) The energy produced upon the decomposition of potassium and barium chlorate are 0.34 and 0.38 kJ/g, respectively.[7] The energy produced by the explosive decomposition of tritnitrotoluene (TNT) is 4.4 kJ/g.[8] Thus the decomposition of these chlorate oxidizers, on their own without any fuel, produce roughly 10 percent of the energy that is produced by a common high explosive.

f) The typical formulation of some of these chlorate explosives (called "Cheddites") was approximately 9 parts potassium or sodium chlorate and 1 part hydrocarbon (often paraffin), and they produced detonation velocities of approximately 3000 m/s.[9]

g) The reason for including the word "thought" is that rarely is one completely certain of the actual contents of an aerial shell. For example, often when an aerial shell malfunctions, it is not known with certainty what type of aerial shell was involved. Further, even when it is thought that the type if shell can be identified by recalling the identifying label, there is no guarantee as to the actual contents of the shell. That is to say, it is a common experience of those performing fireworks displays to find that Chinese shells have been incorrectly labeled (e.g., shells labeled as producing one color display are found to actually produce some other color display).

h) The most commonly used binder in the US is dextrin. It is present as approximately 5% of the star composition and is activated by the addition of water. The water dissolves the dextrin, which, upon drying, then holds together the other ingredient particles in the composition. However, the first hypothesis for VIMEs applies equally well to non-aqueous binders and to pressure activated plastic flow binders.

i) Based on measurements of typical fireworks stars, the density of a star may be approximately 1.6 g/cm^3, whereas its maximum theoretical density (MTD) might be 2.0 g/cm^3. This means that such a star has about 20% void space (porosity). Although not well reported in the literature, the average percent MTD of cut stars is probably the lowest for stars made using common manufacturing methods; while the MTD of rolled stars is somewhat greater. For pressed stars, the percent MTD probably ranges from as low as for cut stars to more than that for rolled stars, depending in how forcefully the stars are compressed.

j) The temperature of a gas heated by adiabatic compression is given by

$$T_2 = T_1 \left({P_2}/{P_1} \right)^{(\gamma-1)/\gamma}$$

where T is absolute temperature, P is pressure, γ is the heat capacity ratio for the gas (γ ~ 1.4 for air), and subscripts 1 and 2 refer to the initial and final states, respectively.[12] While this equation is most useful, it is only an approximation, in that it assumes the process of compression is thermodynamically reversible and that it is for an ideal gas.[13]

k) Based on the equation in Note j, compression from atmospheric pressure to about 10 atm is sufficient to raise the temperature of air to over 450 °C. While many star compositions would easily be ignited at this temperature, that is not to say that a small mass of gas could transfer sufficient heat to raise the much larger mass of surrounding star composition to this temperature. However, compressions ranging up to 50 to 100 atm should be capable of transferring sufficient heat to a few tiny particles of star composition to cause their ignition.

l) One published value for the peak pressure inside a hard breaking Japanese style spherical aerial shell is approximately 4 MPa[14] (about 600 psi). At this pressure, a fireworks star that was a 1-centimeter (about 0.4-inch) cube would experience a force of 400 N (about 100 lbs) on each surface of the cube. Note that this is likely to be somewhat different from just squeezing a star on its two opposing sides with a 400 N force. It seems likely that a star pressed equally on all six sides at once is likely to be able to withstand a somewhat greater force than if that force is only applied to its two opposing sides. Consideration also needs to be given to the rapidity with which the gas pressure is applied and to the permeability of the star. If the pressure is increased somewhat gradually, over a sufficiently long interval, and the permeability of the star is sufficiently high, the externally applied pressure and that within the voids will more nearly have a chance to equalize, and the star is not likely to collapse.

m) The burn rate equation (also called the Vieille equation) expresses the relationship between pyrotechnic burn rate and local pressure.

$$R = A\,P^b$$

where R is linear burn rate, P is the pressure in the vicinity of the burning surface, and typically A and b are approximately constant over a moderate range of pressures. (However, these "constants" themselves are commonly pressure dependent when considering a wide range of burning pressures.) Further, if b (the pressure exponent) is sufficiently large, the increase in burn rate with pressure may easily accelerate to catastrophic (explosive) levels, even under conditions of minimal confinement.

n) The volume, and thus the mass, of gas in a void space is proportional to the cube of the effective radius of the void. Whereas the mass of composition immediately surrounding the void is proportional to the square of its effective radius. Thus the ratio of gas to surrounding composition mass increases with increasing void size.

o) While measurements of rolled star porosity were not actually made, the statements about those factors affecting the porosity (density) of rolled stars is based on the authors' significant past experience manufacturing rolled stars.

p) For large diameter fire paths, the rate of flame propagation drops to the rate of propagation across a normally exposed surface.[15]

q) Some binders shrink upon setting. For example, based on recollections of work performed by the authors in the distant past, polyester resins typically shrink by about 6% upon curing. As a result, upon drying or curing, some stars could possibly develop microscopic stress cracks. It would seem that the production of such stress cracks may be more likely to occur for large stars, with their larger dimensions and greater aggregate shrinkage. Further, for large stars there is a greater potential for differential drying to occur, wherein the exterior portions of the star dry (and shrink) before the center of the star dries. Based on more recent star manufacturing experiences of the authors, differential drying was observed to occur and did act to greatly increase the burn rate of the stars.

r) It is not intended to imply that the two hypotheses are necessarily mutually exclusive. It is possible that both could be occurring to some extent at the same time or at different stages of the same VIME. Also, it is certainly possible that there are other explanations of VIMEs that have not occurred to the authors at this time.

s) Experience suggests that fireworks mine effects experience VIMEs at least as frequently as do star shells. There is little reason to think that the mechanisms suggested for star shell VIMEs would not also apply to mines. On the one hand, the in-mortar pressures produced by normally functioning mine effects must certainly be less than the pressure within star shells functioning inside mortars (flowerpots). This fact potentially makes mine VIMEs less likely. However, all mines function within their mortars, whereas relatively few star shells flowerpot. This fact makes mine VIMEs more likely. The net result seems to be that mine and star shell VIMEs occur with approximately similar frequency.

References

1) PyroLabs, Inc., unpublished results from the test firing of massive and over-lifted shells from HDPE mortars, ca. 1990.

2) K. L. and B. J. Kosanke, "Stars Blown Blind", *American Fireworks News*, No. 160, 1995; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 4 (1995 through 1997)*, Journal of Pyrotechnics, 1999.

3) B. Ofca, *Fireworks Safety Manual*, B&C Associates, 1991, pp 13 and 32.

4) K. L. and B. J. Kosanke, "Hypothesis Explaining Muzzle Breaks", *Proceedings of the Second International Symposium on Fireworks,* 1994; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 3 (1993 and 1994)*, Journal of Pyrotechnics, 1996.

5) K. L. and B. J. Kosanke, "Peak In-Mortar Aerial Shell Accelerations", *Journal of Pyrotechnics*, No. 10, 1999 ; also in *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 5(1998 through 2000)*, Journal of Pyrotechnics, 2002.

6) A. H. Brock, *A History of Fireworks*, George G. Harrap, 1949, pp 179–180.

7) A. A. Shidlovskiy, *Principles of Pyrotechnics*, reprinted by American Fireworks News, 1997, pp 22–23.

8) R. Meyer, *Explosives*, VCH Verlagsgesellschaft, 1987.

9) T. L. Davis, *The Chemistry of Powder and Explosives*, 1943, reprinted by Angriff Press, pp 357–364.

10) *Investigation Report - Bray Park Fireworks Tragedy*, Queensland Government, Department of Natural Resources and Mines, 2001.

11) K. L. & B. J. Kosanke, G. Downs and J. Harradine, "Roman Candle Accident: Comet Characteristics", *Fireworks Business*, No. 228, 2003.

12) F. P Bowden and Y. D. Yoffe, *Initiation and Growth of Explosion in Liquids and Solids*, Cambridge University Press, 1952, pp 33 & 35.

13) *Mark's Standard Handbook for Mechanical Engineers*, McGraw Hill, 1978, p **4**-10.

14) Y. Takishita, H. Shibamoto, T. Matsuzaki, K. Chida, F. Hosoya, and N. Kubota, "Burst Process of Spherical Aerial Shells", *Journal of Pyrotechnics*, No. 10, 1999, p 3.

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