Modern Rack and Mortar Designs for Professional Fireworks Displays

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ABSTRACT

Professional fireworks displays, as well as those performed by volunteers, have for many years relied on equipment designs and techniques that were established before the turn of the century. The use of steel mortars, the hand firing of individual aerial shells and the use of wooden racks for chain firing of finale effects have until recently been the industry standard. These techniques and designs are adequate for the use intended, as long as the shells function normally, but if a color shell "detonates" or a salute explodes in a mortar, the results can be catastrophic. Since these designs and techniques first came about, the severity of the legal repercussions from accidents at displays has increased to the point where such an event, however unlikely, now represents an unacceptable legal risk to the display company. In this article, designs are presented for finale racks and single shot mortars (for use in "dense-pack" style rack systems) that were developed at Night Musick Inc., and which significantly reduce the risk of catastrophic equipment failure in the event of a shell malfunction.

Keywords: overpressure, shell detonation, dense pack, finale rack, matrix rack, chain fusing

Introduction

Fireworks display operators, both professional and volunteer, have for many years accepted the risks associated with using equipment designed simply to perform as required under normal circumstances. Accidents involving shells that explode while still in the mortar are seldom catastrophic, since they are more likely to involve a color shell than a salute (there are usually many more color shells than salutes in a display), and these devices will generally flowerpot without causing serious damage to reasonably constructed and maintained equipment. The risk of salutes exploding in a mortar rack or color shells detonating* in a mortar rack are usually ignored, perhaps because the operator is ignorant of these possibilities (as may be the case with some "ship show" recipients), or because they are accepted as an inherent part of performing displays.

Display Equipment Failure Analysis

Equipment failure of the type discussed in this paper is the result of a primary failure of a fireworks shell. Equipment failure during normal operation that is the result of poor workmanship or materials is beyond the scope of this article.

It can be argued that equipment that is destroyed because of a shell malfunction has not "failed;" it has merely exceeded its design criteria. While it is true that the cause of this type of incident is the shell, it is also true that the display operator will in all probability bear the brunt of any legal repercussions if subsequent events result in injuries to the audience or the crew. In an ideal situation, there would be no need to anticipate the occasional shell malfunction and no need to limit its destructive effects. However, in reality shells do malfunction, and the responsible display company must anticipate this event and attempt to minimize the resulting damage.

* "Detonation" as it is used here refers to a color shell in which the normal combustion rate is accelerated to approximately flash powder reaction velocities when it explodes in a mortar. It does not refer to supersonic combustion rates as in the case of high explosives.[1]

Of primary concern to the display operator are the types of accidents that can result in serious injury to the audience or the crew. Foremost among these accidents is the catastrophic loss of structural integrity of a mortar support system which repositions adjacent mortars in unsafe directions. If for any reason these mortars continue to fire, either from chain fusing or burning debris in the air, there is great potential for serious injury (or death) resulting from shells exploding in close proximity to the audience or the crew.

To avoid this situation, a mortar support system must be designed that can withstand the explosive force of the most powerful shell that the operator might use. Even if a support system is designed that meets this criterion, the additional problem of collateral damage to adjacent mortars and their unfired rounds must also be considered. If blast pressure and fragments from the primary explosion penetrate a nearby mortar, the shell it contains may also explode, adding to the net effect of the first shell failure. Further, this process could conceivably continue rendering what would otherwise be an adequate support system (one which could contain the effects of a *single* shell explosion) useless in the face of a more powerful event. Therefore, consideration should be given to mortar construction as well, especially where the support system is of the "dense-pack" design (i.e., a matrix of mortars tightly clustered together for firing).

Design Criteria

As the previous discussion indicates, the primary design criterion for a successful mortar support system must be its survivability in the face of a powerful "in-tube" shell explosion. It must not allow adjacent mortars to become repositioned, and it must not be able to fall over, or cause other racks to fall over, as a result of this type of shell failure. It is obviously impractical to test every shell that an operator may fire in a prospective system (and impossible, to date, to reliably reproduce the detonation effect seen in some star shell explosions), therefore a suitable "worst case scenario" must be used. For the purposes of this paper's designs, a cylindrical 4-inch (102-mm) salute will be used as a maximum explosion for testing dense-pack mortar systems and a cylindrical 3-inch (76-mm) salute for the finale rack system.

The secondary design criterion is practicality. There is any number of ways to achieve the primary design consideration stated above if this second requirement was neglected. These might include sinking mortars in solid high-strength concrete, making the walls several inches thick, using surplus military cannons, increasing the separation distance of the mortars by several feet, etc. All of these solutions would be effective; however, they would also be impractical to implement due to the cost and/or the inconvenience. The requirement of a practical solution is also a subjective one. It is up to individual display companies to decide if the designs presented here are practical for their situation.

These designs fulfill the above criteria for the specific situation at Night Musick. The explosion test results indicate a high degree of survivability for these types of equipment. We feel strongly that while these designs were developed for the operational environment at this company, they can, with few modifications, be utilized by others in the profession and result in an increase in display safety.

Finale Rack Design

The primary attribute of this finale rack design (and the dense-pack mortar system presented later) is that it maximizes structural integrity while minimizing surface area. The force that acts on any mortar support system for a given explosion pressure is directly proportional to the surface area exposed to the blast[2] (i.e., Force = Pressure × Area). Therefore a successful design would use as few structural members as possible, minimizing the aerodynamic, load-bearing surface area, while meeting the need for structural integrity.

A wooden finale rack is a good example of a design that does not possess these characteristics. The structural materials, wooden planks, are easily shattered by even modest applications of force. A three to five gram charge of flash powder (quite modest compared to the 70 gram charges found in 3-inch [76-mm] aerial salutes) can destroy 1 × 4 and 2 × 4 wooden boards (nominally ¾ × 3½ inch and 1½ × 3½ inch; or 19 ×

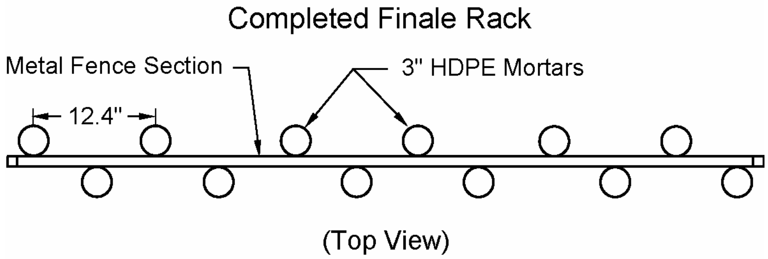

Figure 1. Top view drawing of Night Musick mortar rack design.

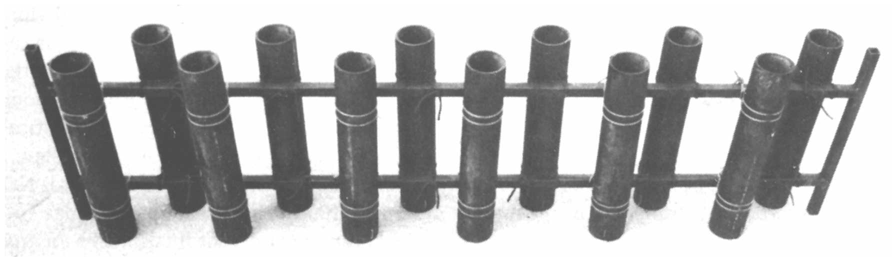

Photo 1. One section of a "fence-type" finale rack.

89 mm and 38 × 89 mm, respectively). Further, our testing has shown that a 3-inch (76 mm) aerial salute can totally destroy the average five-mortar wooden finale rack, no matter which mortar the shell is in, or where in the mortar the shell explodes. This destructive effect is achieved because this design possesses and exposes a large surface area to the explosion pressure and the structural integrity of the wood and the fasteners are not sufficient to withstand the resultant force.

Figure 1 and Photo 1 show a completed Night Musick "fence type" finale rack using common high density polyethylene (HDPE) mortars.[3] It achieves the primary design criterion in three ways. First, it uses 14 gauge, 1-inch (25-mm) square tubular steel stock to make the "fence" section, see Figure 2. This material is very strong, easily obtained and comparatively inexpensive. Most importantly, a 3-inch (76-mm) cylindrical aerial salute placed in a mortar and exploded while in contact with this material will only result in a denting of the steel on the side facing the explosion. Also, when properly welded (four welds per connection) the same test explosive does not damage the joint when the rack is in a vertical position.

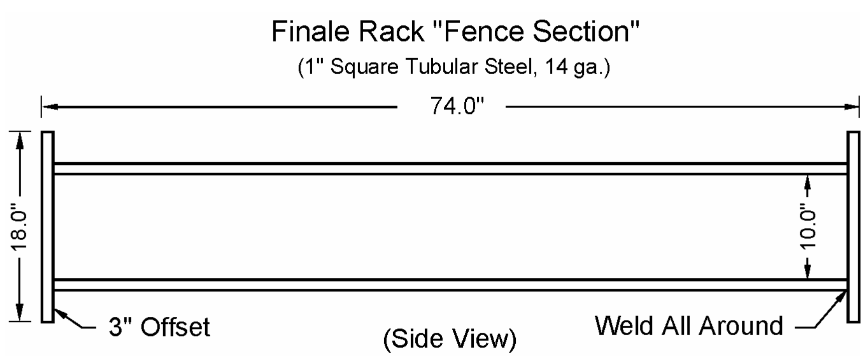

Figure 2. Side view drawing of "fence" section (back bone) of Night Musick mortar rack design.

Secondly, the attachment of the mortars to the rack is accomplished by tying them to the tubular steel fence section using 1/8-inch (3-mm) diameter, braided nylon parachute cord (see Photo 2). This method was selected for two reasons. The first is that the cord itself has a very small surface area when compared to other methods of attachment such as additional tubular steel. This significantly reduces the force that can act on the rack. The second reason is that the cord has very good shock loading ability (i.e., it can absorb large impulses without breaking, such as those experienced during parachute deployment, or, in this case, the shock experienced by nearby mortars when an adjacent mortar explodes). In fact, this material was so successful at absorbing this shock that on many occasions, shell failures (both deliberate and accidental) that totally destroyed a mortar have left the cord that attached the mortar to the rack completely intact (see Photo 3).

Finally, the rack maximizes the distance between mortars by "zigzagging" their location on the rack. As reported by Contestabile[4] the overpressure generated by an explosion decreases rapidly with the distance from the explosion. Therefore increasing the distance between mortars substantially reduces the force which can act on adjacent mortars.

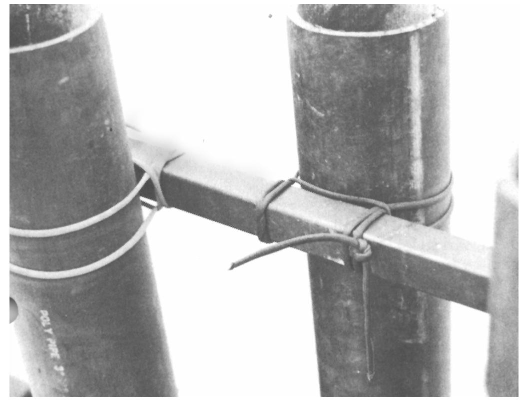

Photo 2. HDPE mortars attached to a "fence-type" finale rack using parachute cord.

This configuration meets our secondary design requirements for practicality as well. In fact, in many ways these racks are easier to use than their wooden counterparts. They are considerably lighter; the average crew member can carry two 12 round racks at once. Because the mortars are "zigzagged" they interlock when stacked on top of one another for transport, thereby saving valuable truck space. This stacked configuration is remarkably stable as well. The racks have been found to be extremely durable; they can sustain much more abuse than wooden racks. The cost of each rack is comparable to most wooden rack designs; approximately 15 feet of

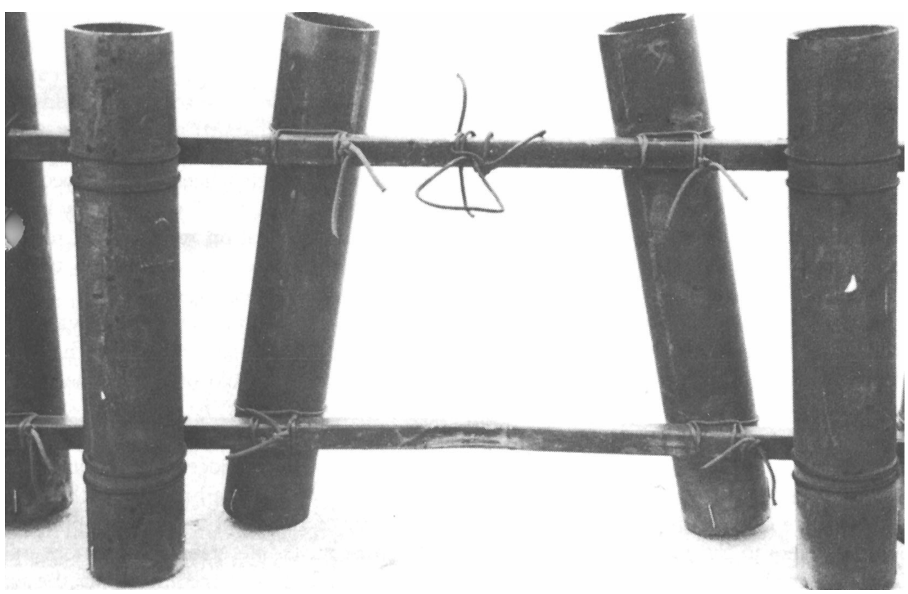

Photo 3. Typical damage to a "fence-type" finale rack produced by exploding a 3-inch (76-mm) salute in a mortar.

steel tubing ($13) and approximately 100 feet of parachute cord ($5) totals less than $20 (US). The skills required to assemble them are slightly more specialized, in that it requires welding as opposed to basic carpentry, but the assembly time is probably less. Also, they are very easy to set up on a display site, since they connect to one another (end to end with adjacent racks at 90°) using common 2-inch diameter × ½-inch wide (50 × 13 mm) automobile hose clamps (Photo 4), or they can be used singly by driving a steel bar into the ground, through the vertical member.

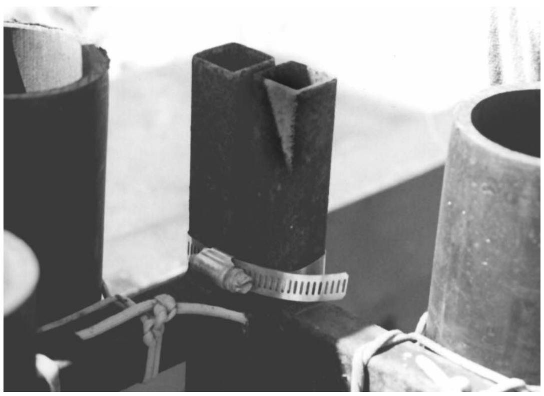

Photo 4. Two sections of "fence-type" finale racks joined using hose clamps. (Note that the second, lower, hose clamp is not shown.)

The primary operational difference between these racks and standard wooden racks is that they are not easily angled for wind direction. Also since they have no bottom, they depend on the ground to support the mortar plugs. As a result, the tension in the attachment lines should allow for adjusting each mortar's height to accommodate irregular surface features. This was not considered a serious drawback for this company, since the display equipment is mounted on trailers, and they can be angled if necessary. When a display is large enough to warrant placing the racks on the ground, the policy is to set them at the maximum distance from the audience that the site will allow, usually the NFPA's fallout distance for the largest shell in the show. If the wind conditions are so severe that a dud 3-inch (76-mm) shell fired vertically from greater than 210 feet (the NFPA required fallout radius for 3-inch [76-mm] shells) might be carried into the audience, then the conditions already exceed the permissible safety margins and the show would be canceled. This renders the question of angled finale mortar racks moot for our situation.

Finale Rack Test Results

The preliminary testing of these racks was accomplished by repeated explosions of 3-inch (76-mm) cylindrical salutes in the mortars at various locations along the racks. Attempts were made to determine whether an explosion of this magnitude could cause significant damage to the rack itself or to the adjacent mortars. Significant damage was characterized as: a) any physical alteration of the rack that could cause a subsequent aerial shell to be fired in an unsafe direction, b) any repositioning of adjacent mortars such that they would fire at an unsafe angle, c) the removal of an adjacent mortar, or d) any damage to an adjacent mortar that could cause that shell to misfire.

It soon became apparent during this testing that this system was adequate to the task at hand. Under no circumstances could we damage the rack's structural steel beyond a dent on the surface facing the explosion (Photo 3), even when the salute was placed at the top of a mortar adjacent to the intersection of two joined racks. Even under this "worst case" scenario, we did not significantly damage the steel, separate the racks, or damage the upper hose clamp holding the racks together. All subsequent tests confirmed these results, and the fundamental design requirement: *A 3-inch (76 mm) salute does not generate enough blast overpressure to produce sufficient force (over the surface area of this configuration) to cause a loss of structural integrity.* At no time did we observe more than a moderate movement of adjacent mortars and no mortar denting whatsoever. It should be noted that we performed these tests using powerful cylindrical salutes of domestic manufacture, utilizing an antimony sulfide, German dark aluminum and potassium perchlorate flash powder formula. While less than 20 rounds were fired, it was decided that further testing would be superfluous. These racks clearly performed far better than conventional wooden racks under the same conditions. Indeed, since 1987 when these racks were first put into service, over a half dozen incidents of salute explosions in finale racks (using various manufacturers' products) have been experienced. In every case, the racks survived and the remaining shells all fired in safe directions.

High Performance Mortars for "Dense-Pack" or Matrix Rack Display Systems

Another area of concern for many companies is individual mortar performance under adverse circumstances, such as an aerial shell exploding powerfully within a mortar. Extensive testing by Contestabile[5] and Myatt[6] have demonstrated the relative performance of many types of mortar materials under these conditions. However, of particular interest is the performance of mortars proximate to one which has suffered some catastrophic shell failure.

In a "dense-pack" [7] or matrix type[6] mortar support system (Photo 5), the mortars are held in close proximity to one another (1 to 3 inches or 25 to 76 mm) by some support structure that can withstand a shell malfunction of the type mentioned above without significant structural failure. Once a support system is in place that meets these requirements, consideration must be given to the level of damage that could be sustained by adjacent mortars that would be held rigidly in place by this architecture. It is conceivable that such mortars could be damaged so severely that unfired aerial shells contained therein may subsequently explode as well. At the very least, these mortars will sustain sufficient damage that shells fired from them would be expected to malfunction in some way due to severe denting or tearing of the mortar wall.

Photo 5. An example of a "dense-pack" style mortar rack containing "matrix mortars," which are "double-walled" and foamed.

Matrix Mortar Design

Figure 3 shows a cross section of a matrix mortar design. It is essentially a 4-inch ID (10-cm) HDPE mortar placed inside a 6-inch ID (155-mm) HDPE mortar with the lengths of the mortars chosen so that the top of the 4-inch (102-mm) "inner" mortar is even with the top of the 6-inch (155-mm) "outer" mortar. The void space between the two mortars is then filled with a silicone based foam product from Dow Corning (36548 Silicone RTV Foam).

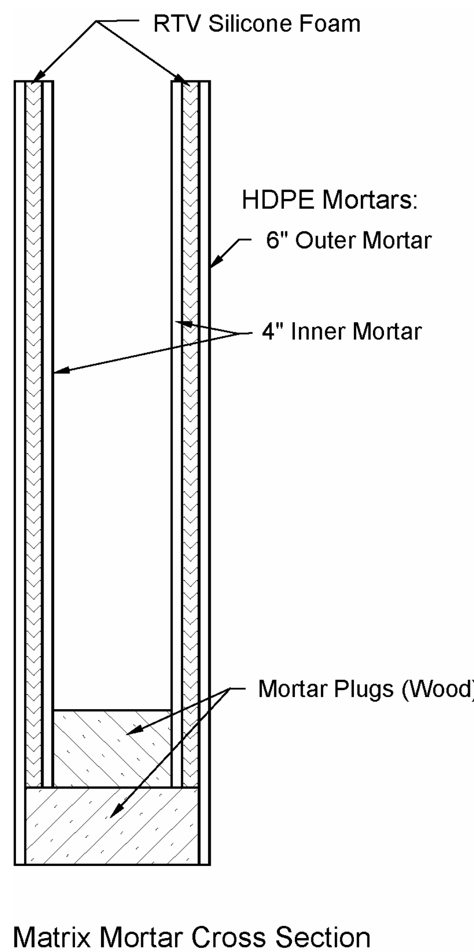

Figure 3. Cross section of matrix mortar showing void space filled with RTV silicone foam.

This shock absorbing foam product is the key to the design. It is described in Dow promotional literature as a black, elastomeric foam with a density of approximately 20 pounds per cubic foot when cured. It is applied by first mixing the contents of a two component kit and pouring the mixture into the void; it should be noted that foam added after an initial application will adhere to the first foam, forming a continuous solid. The mixture cures to a "no flow" state in 1–2 minutes, and its volume expands 2 to 2.5 times. The material cures to form a highly elastic solid that is extremely fire resistant (its primary industrial use is to fill voids around electrical conduit to form a fire stop), also it remains stable in direct UV exposure. In our experience, it has undergone no noticeable degradation due to contact with lift charge combustion products. (It is available in 7-ounce, 2-pound, 16-pound, and 80-pound two-part kits from distributors around the country. Contact Bob Schroeder of Dow Corning at (517) 496-8330 for the location of a distributor in your area.)

Matrix Mortar Explosion Test Results

For the purposes of testing the dense-pack mortar design, a maximum survivable explosion standard was established as a 4-inch (102-mm) cylindrical salute. At the time, this was the largest salute Night Musick would allow in the "body" of a display (since then NFPA regulations have restricted salutes to 3-inch [76-mm]), and it was assumed that this level of explosion pressure would at least equal that of the most destructive 6-inch (155-mm) star shell to be used in this system.

Photo 6 shows the test matrix used during the destructive testing of the mortars. It is a 3 × 3 matrix constructed of welded 1-inch (25-mm), 14 gauge, square tubular steel stock. The two supporting horizontal frames (upper and lower) are held in place at the corners by four vertical 1-inch (25-mm) angle iron supports. Each mortar position in this configuration is 7-inches (180-mm) square (internal) for the 6-inch (155-mm) mortars tested. This frame can restrict the mortars to be no further than 2 inches (50 mm) apart. It should be noted that this configuration was used only for testing the mortars; our production matrix racks have 48 positions and are inherently stronger due to the extensive number of welded interconnections occurring in a matrix this large. While this configuration survived the test explosions intact, it is not recommended that such a small matrix be used for actual displays.

Photo 6. A 9-position (3×3) test mortar support system used in testing matrix mortars. (Note that at the time, the method for filling and the type of foam was being investigated.

Tests were performed by exploding a series of commercial 4-inch (102-mm) cylindrical salutes in the center mortar of the 9 position test matrix. The shell was placed about halfway up the tube. It was felt that in this position the overpressure experienced at the walls of the adjacent mortars would be maximum, since the pressure wave would not be disturbed by the presence of the steel cross members surrounding the mortar at a lower level. Tests were conducted on: (1) RTV silicone foamed double wall mortars, (2) double wall mortars foamed with expanding insulating foam, (3) double wall mortars without any material between the mortar walls, and (4) standard single wall 6-inch (155-mm) HDPE mortars.

The results of these tests were dramatic. All of the 16 single-wall HDPE mortars suffered serious denting that ranged from 30% to 80% reduction in inside diameter. Two of these mortars had small, 2 to 3 inch (50 to 76 mm) long fissures. The double-wall mortars with no filler material performed only slightly better. This configuration exhibited serious compression damage of the outer mortars and denting of the 4-inch

(102-mm) inner mortars from 20% to 40% of their original diameter. In no case was it possible to separate the inner mortar from the outer mortar after the tests.

The RTV silicone-foamed, double-walled, "matrix mortars" fared much better. In two trials, *no blast damage was immediately visible on any of the 16 mortars.* On closer examination, a slight compression of the outer mortars (<2% of the diameter) on two of the mortars was detected when they were measured for "roundness." There was no measurable change in the diameter of the inner mortar for double-wall foamed mortars. Photo 7 shows representative examples of the blast damage that occurred to each of the three mortar configurations tested.

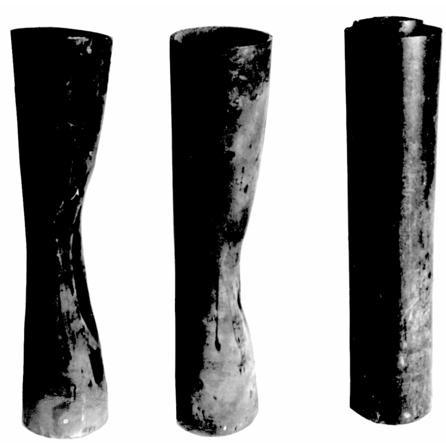

Photo 7. Typical mortar damage in tests of a matrix rack configuration. (Left, single mortar tube; middle, double tube without foam filling void; right, "matrix" mortar with foam-filled void.)

The double-wall mortars that were filled with standard insulating foam from a spray can did perform adequately. No serious denting occurred in these mortars. However, this material was found to be very difficult to work with. It was not made to fill volumes this large; it tends to form voids in the material if too much is used in a single application. It does not bond with previous applications when successive layers are applied, and it takes about 3 applications to complete the fill for the mortar size tested. It must be applied from the bottom up, through holes drilled in the side of the outer mortar. It is also *very* messy and it sticks to everything, especially clothing.

Conclusion

Both designs presented (fence-type racks and matrix mortars) meet their primary operational criterion; they survive. They can absorb the force of a powerful shell explosion within a mortar without suffering catastrophic damage that may threaten the safety of the audience or crew. They give the pyrotechnician the ability to remove an element of risk from the display that previously was beyond his control, namely, the reliability of the aerial shell, at least with respect to mortar explosions. Even manufacturers that use their own shells must assume that periodically a malfunction will occur that will result in an accident of this nature. It is the opinion of the author that to assume otherwise is wishful thinking. Six times in the last eight years, salutes (all of domestic origin) have exploded in the mortars of Night Musick's finale racks, and in every case, the shells that continued to fire, all did so in safe directions. What consequences were avoided because these racks were in place? While a mortar explosion during a display with the matrix mortars is yet to be experienced, it is anticipated that the outcome will be similar to the finale rack explosions; no injuries. Not because of luck, but because this type of accident was anticipated and prepared for.

Acknowledgments

I wish to acknowledge the invaluable contributions of the highly skilled, creative personnel that this company is very fortunate to be associated with. Without the help of these people, Night Musick would simply not exist. And a special thanks to Bob Schroeder and Dow Corning who provided the RTV material we used during testing that proved to be so successful for the application described here.

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