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SAFE SEPARATION OF ALUMINUM TOTE BINS CONTAINING COMPOSITION A-7

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LARGE CALIBER
WEAPON SYSTEMS LABORATORY
DOVER, NEW JERSEY

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

In the Composition B production line at Holston Army Ammunition Plant, stainless steel tote bins are used to convey Composition A-7. ARRADCOM found, through a series of test firings, conducted at the Sierra Army Depot, that 39.6-m was not a safe separation distance for stainless steel tote bins contained in a steel framed tunnel structure lined with Fiberglas. → over

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20. ABSTRACT (Continued)

A series of full scale tests was conducted to

To determine the minimum safe separation distance between tote bins, Southwest Research Institute (SwRI), under contract to ARRADCOM, carried out a series of full scale tests and determined:

It was determined that: (1)

The source of detonation and propagation to an acceptor bin is caused by the primary tote bin fragments and not the secondary conveyor fragments, and

(2) Kevlar shielding can be eliminated if a brittle material such as 7075-T6 aluminum alloy is used for the tote bins.

Since the tunnel housing the conveyor line focuses the blast and fragments if a detonation occurs, the tunnel should be of the lightest construction possible. A steel frame, transite-covered tunnel was shown to be adequate for weather protection and nondetrimental to the focusing of lightweight aluminum fragments. A 39.6-m separation between tote bins on the conveyor line is adequate when the tote bins are constructed of 7075-T6 aluminum alloy.

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I. INTRODUCTION

The tests described in this report were performed as part of an overall safety engineering program entitled "Safety Engineering in Support of Ammunition Plants" conducted under the guidance of the Manufacturing Technology Directorate, ARRADCOM, Dover, New Jersey. These tests were a follow-on to a previous test program conducted by ARRADCOM at the Sierra Army Depot, Herlong, California, to determine the safe separation distance between tote bins containing 76.2 kg of Composition A-7 enclosed in a tunnel structure simulating existing tunnel or ramp structures connecting operations buildings in a production plant (ref. 1).

Original designs and equipment called for the transporting of the A-7 explosives in stainless steel tote bins covered by plastic lids along a steel roller conveyor system. The results of the program conducted at the Sierra Army Depot indicated that there is no safe spacing between tote bins at a distance of less than 39.6 m in a steel-framed Fiberglas* tunnel structure. Spacing greater than 39.6 m is unacceptable by the production facilities because of the production requirements and equipment constraints. The tests at Sierra also indicated that a spacing of 39.6 m may be tolerable if the tote bins were protected by some sort of a fragment-stopping shield or energy absorbing material to the exteriors of the tote bins themselves. Because of cost, schedule and ease of implementation, the application of a Kevlar**composite shield to the exterior of the bin was considered to offer the most promise. However, it was realized that the use of Kevlar shields may only be a quick fix to a problem, and that a greater understanding of the mechanisms of detonation and/or propagation to an acceptor must be forthcoming.

To test these and other suggestions, SwRI was engaged to carry out a series of full-scale tests to determine:

- What is the effectiveness of the Kevlar shielding?
- Can a safe separation distance of 39.6 m or less be obtained in a steel tunnel configuration with shielded tote bins?

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* Registered trademark of Rohm and Haas Co.
** Registered trademark of E. I. Du Pont de Nemours & Co., Inc.

- Is the source of detonation and/or propagation to a shielded acceptor bin due to primary (tote bin) or secondary (conveyor) fragments, or both?

- What effect does the tunnel construction and tunnel configuration have on detonation and/or propagation to an acceptor?

To determine the answers to these questions and to prove that a totally safe solution had been found, SwRI fired a total of forty-seven (47) full-scale shots broken down as follows:

- Exploratory Test Series No. 1 - twenty-five (25) tests to determine the effectiveness of the Kevlar in stopping the fragments which cause detonation and propagation to the acceptor tote bin, and to determine the blast and fragment focusing effects due to the presence of the adjacent tunnel walls.

- Exploratory Test Series No. 2 - seven (7) tests to determine the effects of enlarging the conveyor tunnel, the effects of increasing the spacing between the donor and acceptors and the effects of changing from a steel tote bin to a brittle and more easily fragmented tote bin material.

- Confirmatory Test Series - fifteen (15) tests to verify the results of the two exploratory test series and to prove that a satisfactory safe solution had been found to the problem of establishing "minimum safe separation distances".

The results of the first series of 25 exploratory shots were published in September 1977 and are noted as Reference 2.
For purposes of summarizing the total investigation, a recap will be made of the test series noted above, and the subsequent tests noted as Exploratory Tests Series 2 and Confirmatory Test Series will be described in detail in Section II of this report. The conclusions and recommendations based upon the test series are made in Section III.

An Appendix describes the analysis used to evaluate the effects of tunnel confinement.

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(2) A. B. Wenzel and R. M. Rindner, "The Effects of Shielded Tote Bins on the Safe Separation of 168 Pounds of Composition A-7 Explosive," Contractor Report ARLCD-CR-77012, ARRADCOM, Dover, N.J. Sept. 1977.

II. EXPERIMENTAL PROGRAM

Exploratory Test Series No. 1

Experimental Tests

The experimental test layout illustrated in Figure 1 shows one donor charge in the center, with two acceptor charges on either side set at distances D_1 and D_2 from the donor. For the majority of the tests, each donor and acceptor was placed inside a tunnel structure fabricated of steel frames, wooden frames, and steel and wooden frames, covered with a liner material made of Masonite* or Fiberglas† to simulate the tunnel or ramp. Each donor and acceptor consisted of 76.2 kg of A-7 explosive contained in a stainless steel tote bin. The tote bins used were of the same geometry and size as the containers to be used in the conveyance system at the Holston Army Ammunition Plant. Figure 2 illustrates the design of these tote bins. The bins were fabricated of 0.183 cm thick welded 304 stainless steel sheet. The hinged lids were made of plexiglass (0.64 cm in thickness.).

The Composition A-7 explosive used in these tests was manufactured at Holston AAP. Each tote bin was placed on a 1.52 m steel roller section, simulating part of the conveyor system, and was elevated 1.52 m above the floor using a 60.9 cm diameter Sonotube‡ as a pedestal. For most of the tests, the tote bins were protected by a sheet of 0.953 cm thick Kevlar shielding to reduce the tote bin's vulnerability against primary (tote bin) and secondary (conveyor) fragment impact. In one test only, 1.91 cm thick Kevlar was used.

Some tests were made in the open air and others were made in either a wood or steel framed tunnel structure. The steel framed tunnels were fabricated from 3.81 cm by 3.81 cm by 0.318 cm angle iron. Each tunnel section measured 1.83 m width, 2.44 m height and 2.44 m long.

The wooden frame tunnel structures were constructed of 5.08 cm by 10.2 cm lumber to which the sheeting of Fiberglas was attached by nailing every 15 cm. The tunnel sections measured 1.83 m width, 2.44m height and 2.44 m length. A view of a half section of one of these tunnels is shown in Figure 3.

Initiation of the donor tote bin was accomplished by inserting a detonator equivalent to a No. 8 blasting cap into 112 g of

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* Masonite - Registered T. M. of Masonite Corp.

† Fiberglas - Registered T. M. of Rohm and Haas Co.

‡ Sonotube - Registered T. M. of Sonoco Products Co.

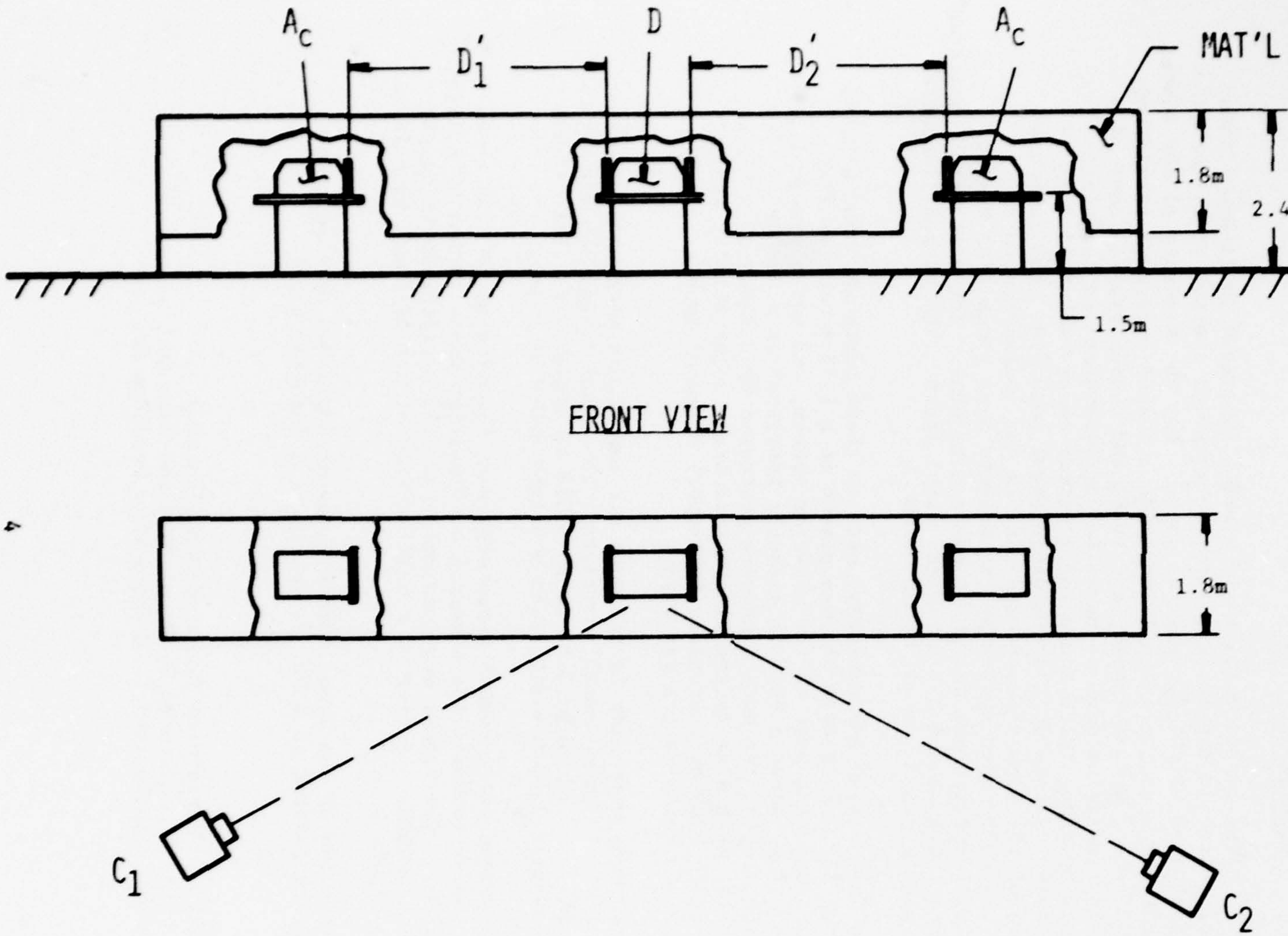
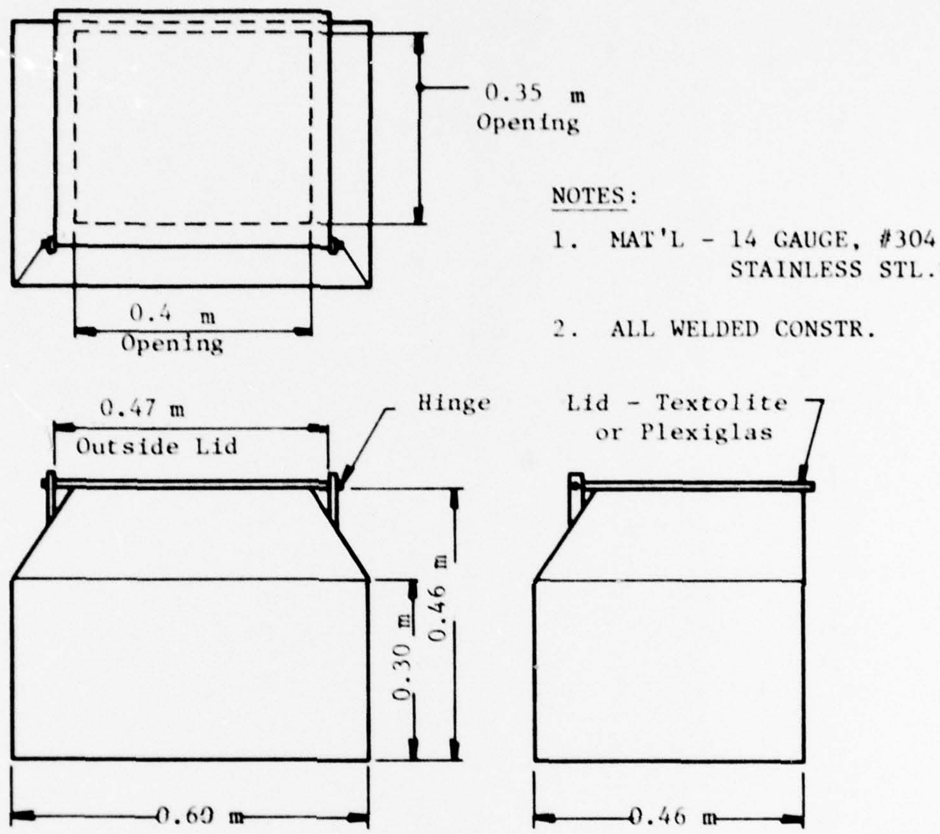


FIGURE 1. EXPERIMENTAL TEST LAYOUT



* See Text for Material Variations

FIGURE 2. TOTE BIN GEOMETRY

FIGURE 3. VIEW OF 39.6m SECTION OF THE WOOD-FIBERGLAS TUNNEL

Composition C-4 explosive, and placing it into the Composition A-7 explosive in the tote bin. Each test was instrumented with two high-speed framing cameras located in positions C_1 and C_2, as shown in Figure 1, and one real time, slow speed camera located in position C_1. The cameras were located approximately 106.7 m from the donor and at an angle of 30° from the tunnel axis.

This level of camera coverage provided documentation of the information shown in the next section of this report. The high-speed camera settings ranged between 4,000 and 5,000 frames per second and the settings for the real time camera were 60 frames per second. Calculation of fragment velocity was made from the high-speed camera coverage when detonation of the acceptors occurred.

Results of the Test Program

The results of Exploratory Test Series No. 1 are summarized in Table 1. The table identifies the test program by test number, the material of the tunnel, the distance D_1 from donor to acceptor C_1, the distance D_2 from donor to acceptor C_2, the number of impacts that the Kevlar shielding on acceptors AC_1 and AC_2 received, whether a detonation or burn was experienced by acceptors AC_1 and AC_2, the thickness of the Kevlar shield used, and the number of penetrations experienced through the shield. The detailed test results of this exploratory test series are given in Reference 1; however, a brief recap of the results follows:

(1) Comparing the results given in Reference 1, where tests in open air were conducted without shields with the results of this program, the Kevlar shield was effective in reducing the separation distance. However, applying 0.953 cm thick Kevlar in the steel framed tunnel case was not effective in preventing a fire at 39.6 m.

(2) As mentioned above, a safe separation distance greater than 39.6 m is required in a steel framed tunnel configuration.

(3) The primary source of propagation of the acceptors is due to fragments emanating from the donor bin.

(4) At 39.6 m separation between donor and acceptor, no propagations or detonations occurred in the wooden tunnel configuration tested by ARRADCOM and SwRI. However, it was observed that the rigidity and stiffness of the tunnel have an effect on the safe separation distance. Therefore, if a wooden frame tunnel had the same rigidity as those in the production plant, we suspect, based on the results of the steel framed tests and the analysis reported in the appendix, that separation distances greater than 39.6 m would be required.

TABLE 1

RESULTS OF EXPLORATORY TEST SERIES No. 1

Shot No.	Tunnel Material	D_1	D_2	No. of Impacts on AC_1	No. of Impacts on AC_1	Detonation AC_1	Detonation AC_2	Thickness of Kevlar® (CM)	No. of Penetrations Through Kevlar®
1	S + M	80	48	--	--	DET	DET	0.95	-
2	Air	80	48	45	--	No	DET	0.95	-
3	Air	48	40	40	40	No	No	0.95	1
4	Air	90	60	10	15	No	No	0.95	1
5	S + M	120	100	20	26	No	No	0.95	1
6	S + M	120	100	27	--	No	DET	0.95	2
7	S + M	110	120	--	30	DET	No	0.95	2
8	S + F	110	120	34	25	No	No	1.9	2
9	S + F	120	110	30	26	Celotex®	Celotex®	---	-
10	S + F	120	110	40	15	Celotex®	Celotex®	---	-
11	S + F	130	130	5	9	No	No	0.95	1
12	S + F	130	130	--	8	Burn	No	0.95	2
13	S + F W + F	130	130	--	2	Burn	No	0.95	2
14	S + F W + F	130	130	15	3	No	No	0.95	-
15	W + F	130	130	17	7	No	No	0.95	-
16	W + F	130	130	18	6	No	No	0.95	1
17	W + F	130	130	3	1	No	No	0.95	-
18	W + F	130	130	9	4	No	No	0.95	-
19	W + F	130	130	1	3	No	No	0.95	-
20	W + F	130	130	5	8	No	No	0.95	-
21	W + F	130	130	8	12	No	No	0.95	-
22	W + F	130	130	8	5	No	No	0.95	-
23	W + F	130	130	6	13	No	No	0.95	-
24	W + F	130	130	4	3	No	No	0.95	-
25	W + F	130	130	5	--	No	--	0.95	-

NOTES:

S + M = steel-Masonite®

S + F = steel-Fiberglas®

W + F - wood-Fiberglas®

Distances measured edge-to-edge of bins

(5) The experimental results indicated that the tunnel has an effect on the safe separation distance. The analysis, to be summarized below, demonstrated that blast focusing can affect the trajectory of the fragments, and also it is possible to increase the fragment flight velocity when reflective surfaces are present in the vicinity of the donor.

Analysis of Tunnel Confinement

The results of the 25 exploratory tests showed that at a distance of 39.6 m, no propagation or burning of the acceptors was experienced using the wooden framed tunnel structure. However, comparing the effects of open air with the steel-framed and the wooden-framed tests, it is evident that the rigidity and stiffness of the tunnel have an effect on the safe separation distance. Care must be taken in interpreting the results of these tests because the rigidity and stiffness of the tunnels tested here are not typical of those present in actual production plants. Therefore, had a wooden-framed tunnel with the rigidity of those present in a production plant been tested, separation distances greater than 39.6 m would be required.

On this subject, the reader is encouraged to refer to the appendix of this report for an analytical approach to the effects of the tunnel confinement. This analysis should eventually be applied to a "real-life" tunnel design, but for this report, the analysis clearly shows that a fragment can be focused into a "hit" trajectory. Depending on the number and energy of these focused fragments, the statistical probability of detonation propagation is enhanced by the tunnel confinement.

To review the analysis, reference is made to two phenomena which were observed:

- All of the fragments which struck the acceptor were of stainless steel--therefore, they emanated from the donor tote bin and not from the conveyor rollers, tunnel support frames, or wall material.

- The minimum distances at which propagation occurred were far greater for the confined tests (i.e., with tunnels) than for the unconfined tests (i.e., open air--no tunnel).

It was apparent then that the tunnel did have a significant contributory effect on the propagation, not by contributing to the fragmentation, but rather by focusing the shock wave and/or focusing more fragments into striking the acceptor tote bin.

To examine the feasibility of this focusing concept, an analysis was carried out to calculate: (1) the peak pressure and impulse of a shock wave after being reflected off the walls of the tunnel; and (2) the interaction of these reflected waves with a fragment in terms of increasing the fragment velocity and in the possibility of redirecting (focusing) a fragment such that a "near miss" fragment would become a "hit" on the acceptor tote bin.

These calculations are shown in detail in the appendix. A variety of sample fragments which had been recovered in the Celotex tests was weighed, and the presented area and drag coefficient were determined. Four random mass fragments (0.014 to 1.17 grams) were then used as typical cases, and each of these fragments was found to be seriously affected by the reflected shock. Two of the four sample fragments, which had been on a "near miss" trajectory traveling down the tunnel, would have been focused by the shock and redirected into a "hit" trajectory.

The consequences of this focusing effect are now obvious. The confinement offered by the tunnel is significant and must be considered when determining any minimum safe separation distance. The calculations shown in the appendix merely verify the principle of the focusing effect, but also it is important in the future to consider the real magnitude of the confinement (i.e., steel versus wood framing and the wall material, thickness, mounting rigidity, etc.). Although the analysis performed to date did not consider this effect, the experiments have indicated that the steel-framed tunnel offered more confinement than the wood-framed tunnel. In retrospect, an examination of the wood-framed and steel-framed tunnels used in the experiments showed that, although the wall material was identical, it was simply nailed to the wood frames, while it was riveted to the steel frames. Thus, the rigidity of the reflecting wall surfaces was quite different. Also, the wood offered faster venting, hence falling apart quicker than the steel frames.

Exploratory Test Series No. 2

Experimental Tests

Based upon the conclusions of the first exploratory test firing series, the second series of exploratory tests was designed to evaluate the following recommendations:

- A simple change could be instituted without affecting production schedules or costs. This change was to convey double tote bins (i.e., two tote bins side by side) and increase their separation distance to 79.2 m.

- To minimize blast focusing effects, tests were conducted wherein the tunnel dimension was increased to allow distance to attenuate the blast waves before they reflect from the tunnel walls. The recommended new dimension was 3.66 m x 3.66 m high.

- To minimize the primary fragment hazard, the tote bin material must be changed to any material which is compatible with the explosive, meets the safety criteria, has good wear resistant properties and is brittle. A good selection which meets all of these constraints is the aluminum alloy 7075-T6.

Based on these recommendations, exploratory test series No. 2 was conducted in the same manner as the earlier tests using the same method of donor initiation and the same high-speed and real time camera coverage.

Results of the Test Program

The results of Exploratory Test Series No. 2, (noted as tests 26 through 32) are summarized in Table 2. Here it can be seen that the 79.2 m separation distance between the double tote bins was adequate to prevent propagation from the donor to the acceptor bin. These two tests, Nos. 26 and 27, demonstrated that 79.6 m separation was adequate to prevent detonation and/or propagation; however, the magnitude of the blast wave and the noise levels created by the detonation of 152.4 kg of A-7 explosive were unacceptable from an environmental point of view.

The single test, No. 30, using a 3.66 m x 3.66m wide tunnel cross-section, resulted in no propagation of the detonation to the acceptor tote bin; however, it was observed that a total of 12 fragments were impacted on the acceptor tote bin and 15 fragments impacted on the surrounding witness Celotex material. This number of fragments from the stainless steel tote bin was judged to be above a tolerable limit and, on a statistical basis, propagation to the acceptor tote bins could and would eventually occur.

The tests conducted using 7075-T6 tote bins, tests 28, 29, 31 and 32, were very successful in preventing propagation when the minimum safe separation of 39.6 m was maintained. At a distance less than 39.6 m it was apparent that propagation could occur and, in one case (shot No. 32), the propagation of a fire did occur.

As a result of a careful review of all 32 exploratory shots, and in conference with the ARRADCOM personnel, a series of 15 confirmatory tests was planned to demonstrate that the combined effects of the aluminum tote bins, the rigid tunnel construction, and a

TABLE 2
RESULTS OF EXPLORATORY TEST SERIES NO. 2

Test No.	Tote Bins	Tunnel	D_1	D_2	Total Hits AC_1 & AC_2 Tote Bin/Celotex	Detonation AC_1	Detonation AC_2
26	SS with Kevlar	S + F Double Bins	79.3m	-	0/5	NO	-
27	SS	S + F Double Bins	79.3m	-	0/2	NO	-
28	7075-T6	S + F	39.6m	39.6m	0/6	NO	NO
29	7075-T6	S + F	39.6m	39.6m	0/10	NO	NO
30	SS	S + F/12' Section	39.6m	39.6m	12/15	NO	NO
31	7075-T6	S + F	33.5m	33.5m	1/80	NO	Celo-tex
32	7075-T6	S + F	24.4m	33.5m	N.A.	NO	Fire

39.6 m separation would be adequate to insure that no propagation of the detonation from donor tote bin to acceptor tote bin would occur. The results of these confirmatory test shots follow.

Confirmatory Test Series

Experimental Tests

The simulated conveyor line for all 15 confirmatory tests was housed in a tunnel that was built in accordance with the design sketches approved by the Holston AAP. Photographic views of the tunnel and its construction details can be seen in Figures 4 thru 9. The tunnel had overall dimensions of 2.44 m wide x 2.44 m high x 86.9 m long, and was constructed in three sections. The midsection of the tunnel was a rigid structure designed to contain and focus the blast waves from the donor tote bin towards the acceptor tote bin. This section was 24.4 m long, 12.2 m on each side of the donor tote bin. At each end of this tunnel midsection a lighter construction was used extending the tunnel out each direction, and the two acceptor tote bins were placed near the end of this tunnel extension.

For the rigid midsection of the tunnel (Figure 5), a frame was built of 7.6 cm x 7.6 cm x 0.476 cm angle iron which was reinforced by a similar angle iron cross-member between the frame. The side walls of the frame building were of transite sheeting in 1.22 m by 2.44 m by 0.635 cm thick sections, and each section was bolted to the steel frame using 0.953 cm bolts. On the roof of the rigid midsection, galvanized steel roofing was used in 0.61 m by 2.44 m by 20 gauge sections. To make this tunnel midsection even more rigid, 7.6 cm angle iron anchors were driven 0.61 m into the ground at 2.44 m intervals on both sides of the tunnel sections (Figure 6). The frame building was bolted to these anchors using 1.27 cm bolts. For the 31.1 m extensions on either side of the midsection of the tunnel, 3.81 cm by 3.81 cm by 0.318 cm angle iron frames were used and these were covered with Fiberglas sheeting 0.61 m by 2.44 m by 0.09 cm thick. The Fiberglas was used on both the walls and the roof, and these two end sections were not anchored to the ground.

The donor tote bins and the two acceptor tote bins were fabricated using 0.318 cm thick 7075-T6 aluminum identical to those used in the exploratory tests previously (see Figure 2). These tote bins were placed on a pedestal 1.52 m above ground level and were not shielded from one another in any manner (Figures 7-9). Celotex witness sheets were placed around the two acceptor tote bins in order to trap any fragments which might be propagated down the tunnel. Each of the tote bins was loaded with 76.2 kg of Composition A-7 and the center, or donor tote bin, was detonated using a 0.453 kg C-4 primer charge ignited by an engineer's special blasting cap.

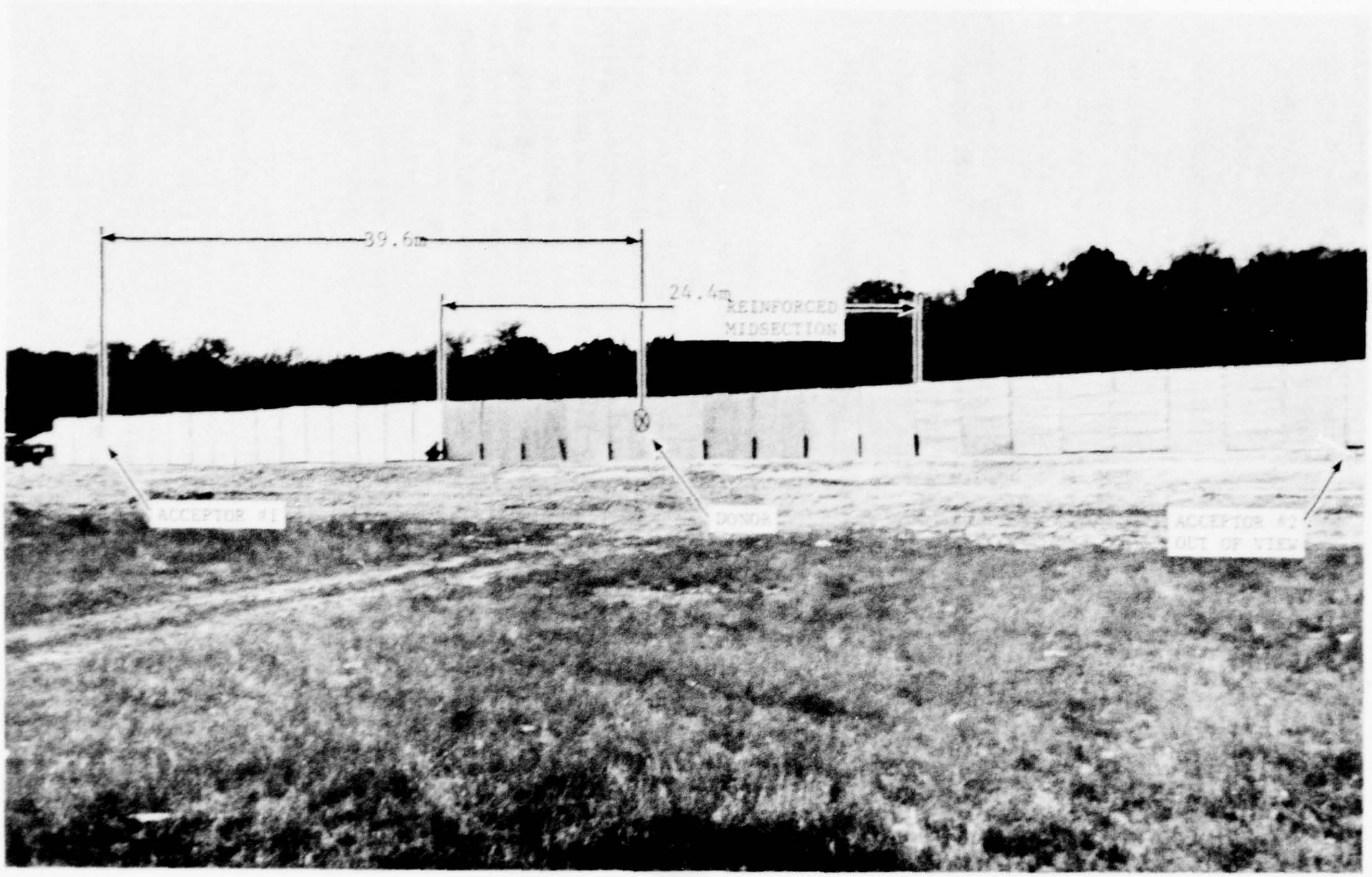


FIGURE 4. TUNNEL ENCLOSURE FOR A-7 CONVEYOR LINE

FIGURE 5. VIEW OF TUNNEL SHOWING CONSTRUCTION FEATURES

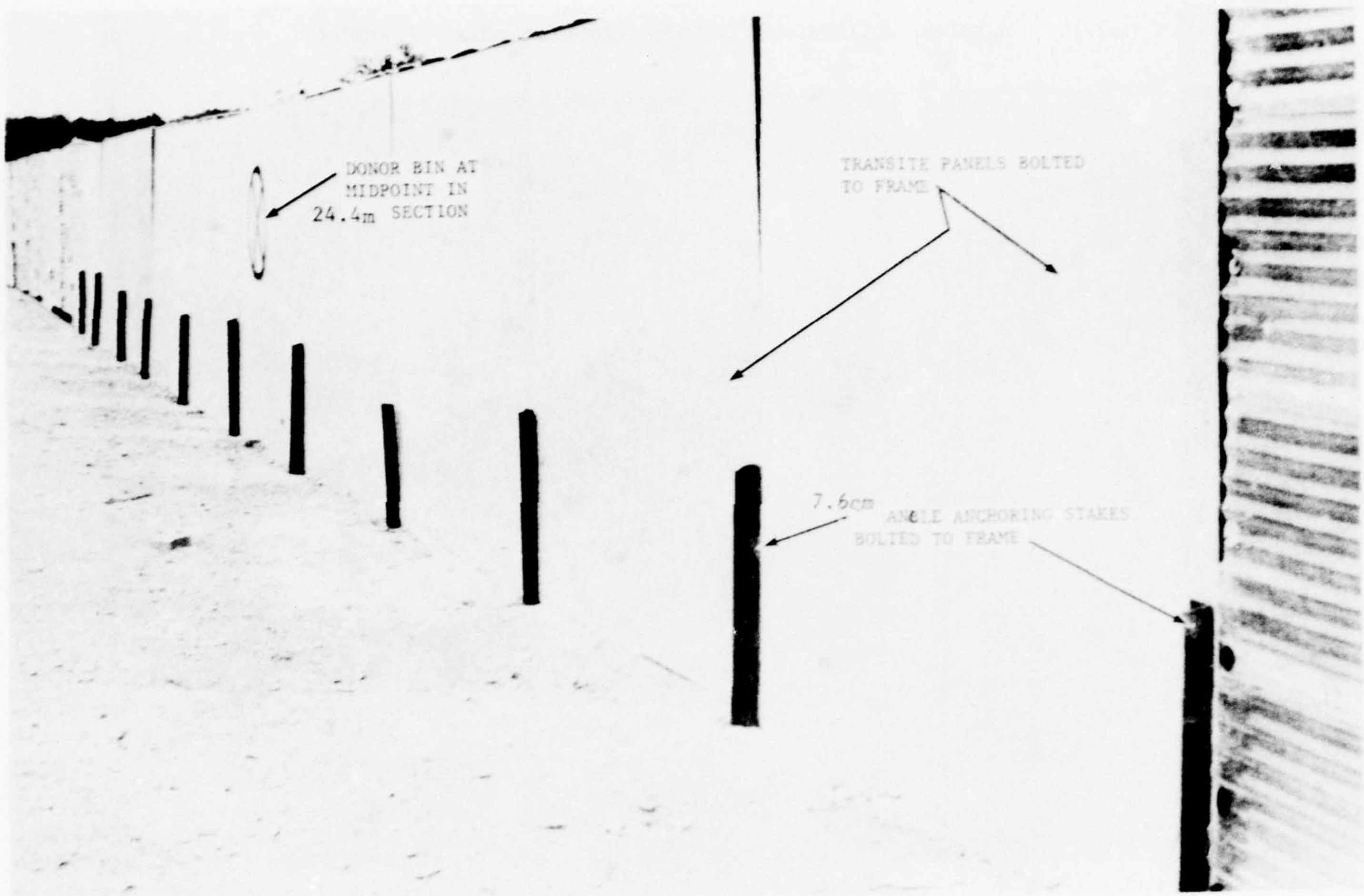


FIGURE 6. CLOSE-UP VIEW OF TUNNEL SHOWING REINFORCED MIDSECTION

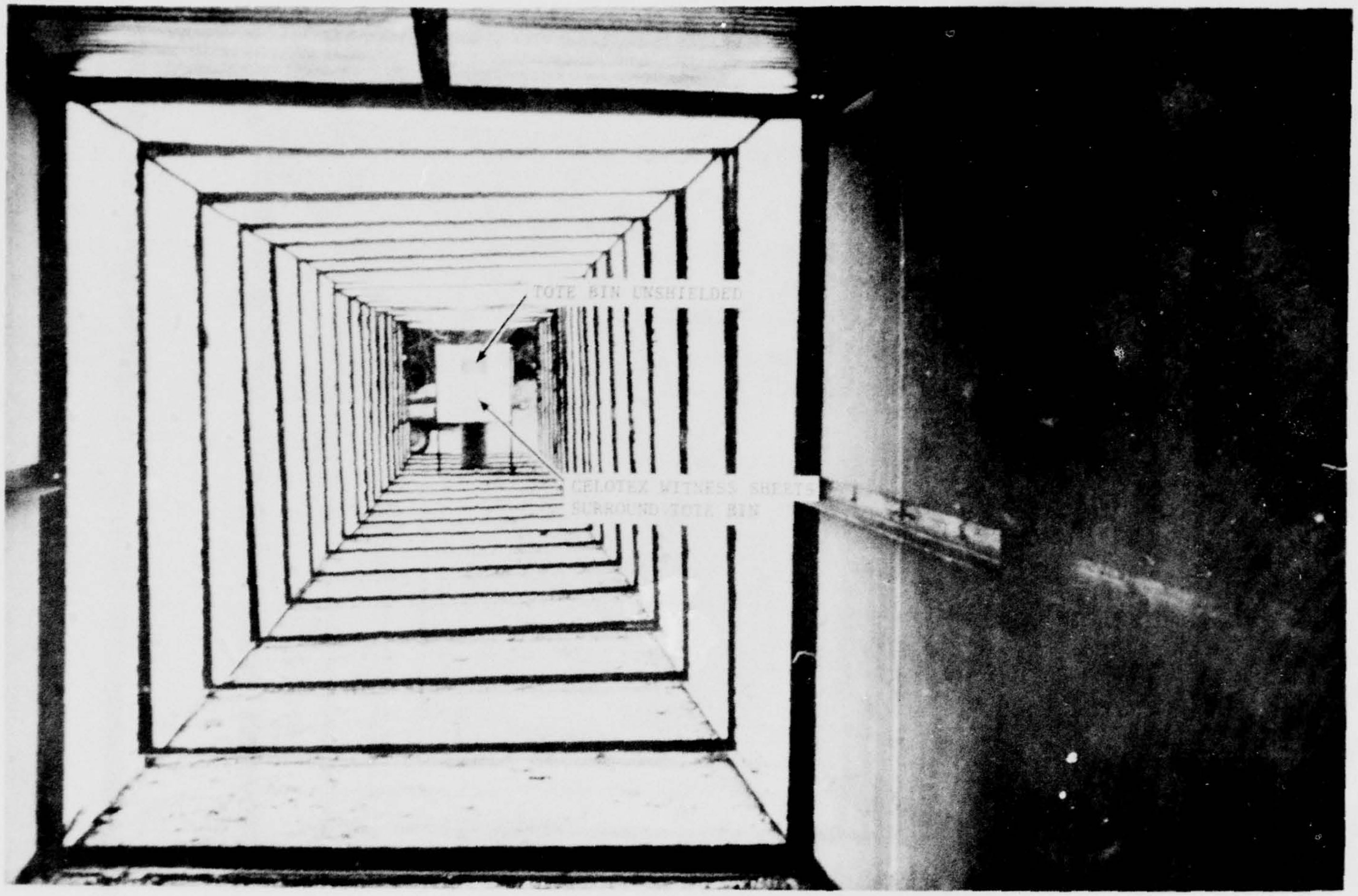


FIGURE 7. INSIDE VIEW OF TUNNEL LOOKING FROM DONOR TO ACCEPTOR TOTE BIN

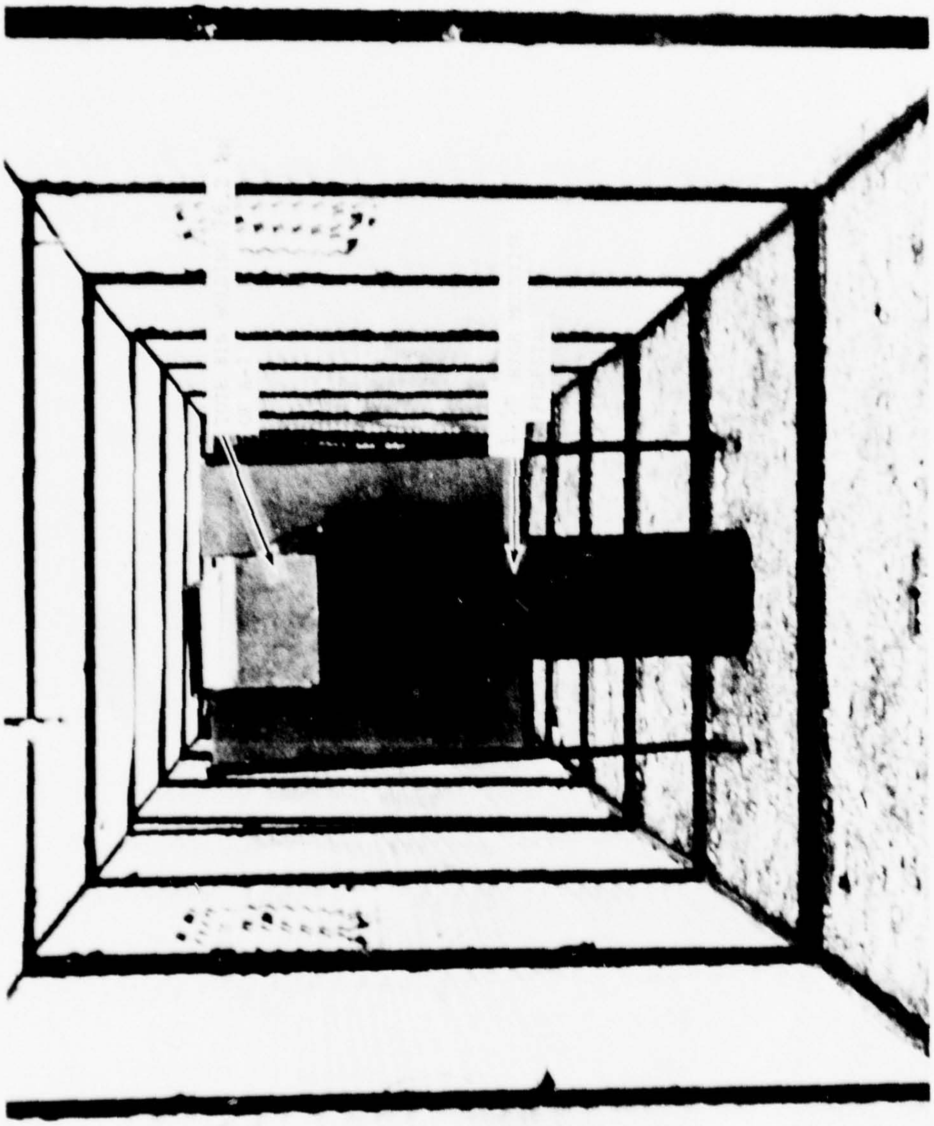


FIGURE 8. REAR VIEW OF ACCEPTOR TOTE BIN AND CELOTEX WITNESS PANELS

FIGURE 9. DONOR TOTE BIN SHOWN RESTING ON CONVEYOR ROLLERS

For the initial series of confirmatory tests, a high speed camera (4,000 frames per second) was used to photograph each test firing. After several of the confirmatory tests had been fired and it was realized that indeed there would be no propagation, the confidence factor rose to a point where economic considerations took over, and for the remaining series of confirmatory tests, only a real time camera was used to record each test firing.

Results of Test Program

A summary of the 15 shot confirmatory test series is given in Table 3. Note that detonation of the donor tote bin did not propagate to either of the acceptor tote bins on any of the 15 confirmatory shots. Photographs of typical damage to the tunnel as a result of donor detonation are shown in Figures 10 thru 12. As noted above, the donor tote bin was placed at the midpoint of the 24.4 m section of rigid tunnel construction. This rigid midsection of the tunnel was totally destroyed on all shots. The transite sheeting was fragmented into pieces measuring not more than 0.09 m^2 and the galvanized steel roofing was blown off in fragments ranging in size from small pieces to whole sheets. The anchor stakes which had been used to anchor the tunnel to the ground were either bent over at approximately a 45° angle or were sheared off completely. The 7.62 cm angle iron frames of the rigid portion of the tunnel were broken off at the weld point and the individual pieces of the tunnel were found in an area measuring approximately 30.5m in radius from the ground zero point. However, pieces of the anchor stakes, parts of the roller conveyor, and random sized pieces of transite were found as far as 182.9 m away from ground zero.

The lightweight tunnel extensions on each side of the rigid midsection of the tunnel were also severely damaged. On the average, the first three lightweight angle iron frames (7.32m) on each side of the donor were completely destroyed, the next three frames were stripped of the Fiberglas covering, and the remaining 11 sections were undamaged and reusable in future tests.

It has been noted that in none of the 15 confirmatory shots did the detonation of the donor tote bins propagate to either of the two acceptors. The blast overpressures from the detonation did cause severe damage to the center section of the tunnel; however, the fragments generated from the breakup of the brittle aluminum tote bin did not propagate down the tunnel and strike the acceptor tote bin. Obviously these tote bin fragments must have been small in size and sufficiently light in weight that only a few of them even reached the Celotex. Note in the last column of Table 3 that in only one case (shot 42) did a single fragment strike (scratch) an acceptor. Also, there were relatively few hits on the Celotex and all of these were small fragments which were stopped in the first 1.27 cm sheet of Celotex.

TABLE 3

RESULTS OF CONFIRMATORY TESTS

TEST NO.	TOTE BINS	TUNNEL*	D_1	D_2	DETONATION AC_1	DETONATION AC_2	TOTAL HITS ON AC_1 & AC_2 TOTE BIN/CELOTEX
33	7075-T6	S + T & F	39.6m	39.6m	NO	NO	0/4
34	7075-T6	S + T & F	39.6m	39.6m	NO	NO	0/6
35	7075-T6	S + T & F	39.6m	39.6m	NO	NO	0/6
36	7075-T6	S + T & F	39.6m	39.6m	NO	NO	0/5
37	7075-T6	S + T & F	39.6m	39.6m	NO	NO	0/3
38	7075-T6	S + T & F (Heavy Weld)	39.6m	39.6m	NO	NO	0/1
39	7075-T6	S + T & F	39.6m	39.6m	NO	NO	0/3
40	7075-T6	S + T & F	39.6m	39.6m	NO	NO	0/1
41	7075-T6	S + T & F	39.6m	39.6m	NO	NO	0/7
42	7075-T6	S + T & F	39.6m	39.6m	NO	NO	1/9
43	7075-T6	S + T & F	39.6m	39.6m	NO	NO	0/4
44	7075-T6	S + T & F	39.6m	39.6m	NO	NO	0/2
45	7075-T6	S + T & F	39.6m	39.6m	NO	NO	0/2
46	7075-T6	S + T & F	39.6m	39.6m	NO	NO	0/15
47	7075-T6	S + T & F	39.6m	39.6m	NO	NO	0/8

* S - Steel Frame
T - Transite Covered Midsection
F - Fiberglas Covered Extension Sections

FIGURE 10. AFTER SHOT VIEW (MIDSECTION OF TUNNEL DESTROYED. NO PROPAGATION TO ACCEPTOR TOTE BINS.)

FIGURE 11. CLOSE-UP VIEW OF DESTROYED MIDSECTION. (NOTE ACCEPTOR TOTE BIN STILL STANDING.)

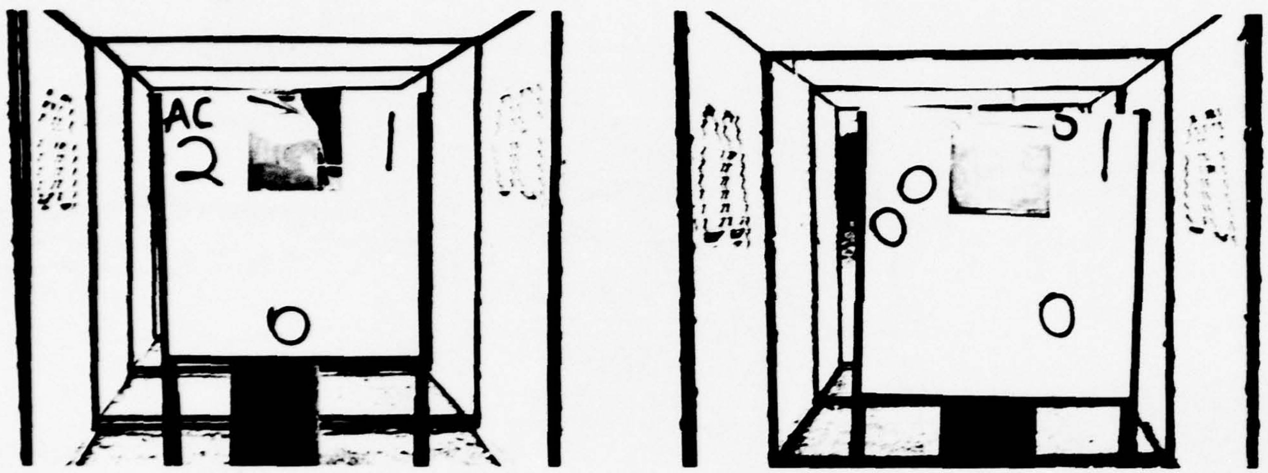


FIGURE 12. MINOR FRAGMENT HITS ON CELOTEX. (NO HITS ON EITHER TOTE BIN.)

Hence, they were totally incapable of causing propagation to the acceptors.

On the basis of the test results of the 15 confirmatory tests (30 data points), it has been demonstrated that the selection of brittle aluminum for use in tote bin construction is the solution to preventing the generation of large fragments and their consequent impact damage should they strike an acceptor tote bin. The separation distance of 39.6m appears to be adequate and the blast focusing effect caused by the rigid tunnel construction appears to have negligible effect on the small and lightweight aluminum fragments.

III. CONCLUSIONS

SwRI conducted a series of three test programs in which a total of 47 full scale shots were fired. From these tests the following conclusions were made:

1. Exploratory Test Series No. 1 demonstrated that a safe separation distance for steel tote bins was greater than 39.6 m when confined in a steel framed tunnel configuration. In open air and in a flimsy wood framed tunnel, 39.6 m separation would be adequate; however, in the ammunition plant, this is not a realistic environment. It was also found that the primary source of propagation of the detonation from donor to acceptor was due to fragments emanating from the donor tote bin. Also, the analytical program demonstrated that these fragments can be focused down the rigid tunnel causing additional impacts on the acceptor tote bins.

2. Exploratory Test Series No. 2 demonstrated that if the tote bin conveyor lines were housed in a larger tunnel (3.66 m by 3.66 m rather than 2.44 m by 2.44 m), the detrimental focusing effect could be reduced; however the number of fragment hits from the stainless steel tote bin was still judged to be above a tolerable limit and that propagation would eventually occur. To maintain production rate, double tote bins were placed at a separation of 79.2 m which did prevent propagation; however, the tests proved that the magnitude of the blast waves and the noise levels created by the detonation of 152.4 kg of A-7 explosive was unacceptable from an environmental point of view. This test series also demonstrated that by changing the tote bin material to 7075-T6 aluminum alloy, the resultant fragments were lower in density and lighter in mass and hence, less lethal should they impact on the acceptor tote bin.

3. The Confirmatory Test Series of 15 shots (30 data points) demonstrated that the selection of brittle aluminum for use in tote bin construction is the solution to preventing the generation of large fragments and their consequent impact damage should they strike an acceptor tote bin. The separation distance of 39.6 m was adequate and the blast focusing effect caused by the rigid tunnel construction appeared to have a negligible effect on the small and lightweight aluminum fragments.

IV. RECOMMENDATIONS

1. A brittle material such as 7075-T6 aluminum alloy should be used for the construction of the tote bins. Should a detonation occur, this material will fragment into less dense and smaller fragments; and, should impacts on the acceptor occur, these fragments will be incapable of causing a propagation.

2. The tunnel configuration housing the conveyor line between the buildings at the ammunition plants does focus the blast and fragments should a detonation occur. Therefore, the tunnel should be of the lightest construction possible. A steel frame, transite-covered tunnel was shown to be both adequate for weather protection and non-detrimental to the focusing of lightweight aluminum fragments.

3. A 39.6 m separation between tote bins on the conveyor line is an adequate safe separation distance when the tote bins are constructed of 7075-T6 aluminum alloy.

REFERENCES

1. W. Seals, R. S. Kukuvka, H. Sarrett, and R. M. Rindner, "Safe Separation Tests of Composition A-7 Explosive in 168-Pound Tote Bins," Technical Memorandum 2189, Picatinny Arsenal, Dover, NJ, October 1975.

2. A. B. Wenzel and R. M. Rindner, "The Effects of Shielded Tote Bins on the Safe Separation of 168 Pounds of Composition A-7 Explosives," Contractor Report ARLCD-CR-77012, ARRADCOM, Dover, NJ, September 1977.

APPENDIX

Feasibility of altering trajectory of fragment through interaction with reflected blast waves

Several simplifying assumptions were made in examining the interaction of blast waves with fragments. The main assumptions were:

(1) The angle of incidence equals the angle of reflectance for shock waves.

(2) Incident pressure and impulse are determined by total wave path as if no reflections are present (i.e., no loss of energy in reflection).

(3) The fragment interacts with shock waves from two opposite walls, and the net effect of interaction with reflected shock waves from other walls is zero.

(4) The two shock waves interact with the fragment at the same time.

For this particular problem, we assume that the acceptor is 130 ft* from the donor and has a presented edge length of 1.25 ft* as shown in Figure A-1. If there are no tunnels present and fragments travel in a straight path, all fragments within the divergence angle δ_0 should strike the acceptor. Thus, if e is the target edge length in feet, and d is distance of the acceptor from the donor in feet, then

$$\delta_0 = 2 \tan^{-1} \left(\frac{e/2}{d} \right) = 0.55° \qquad \text{(A-1)}$$

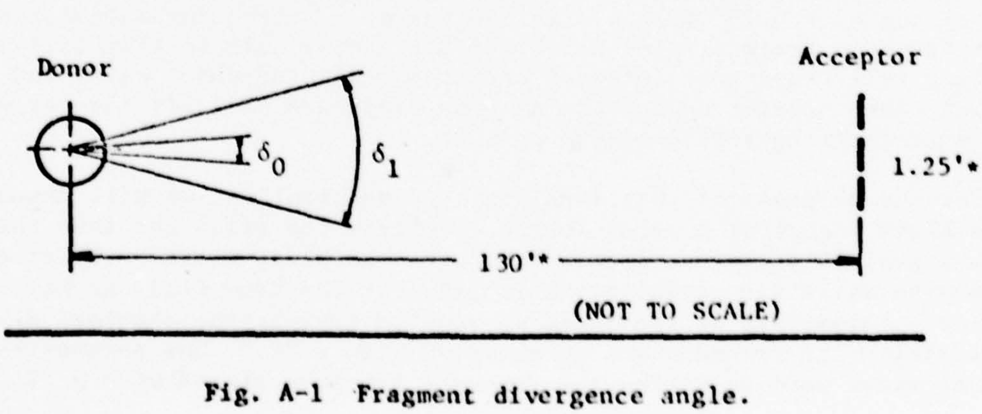


Fig. A-1 Fragment divergence angle.

*130 = 40m and 1.25 = 0.38m

The ratio of the target area to the total area which will be affected by fragmentation at a distance of 130 ft* is

$$\frac{e^2}{4\pi e^2} = \frac{(1.4)^2}{4\pi(130)^2} = 7.36 \times 10^{-6} \qquad \text{(A-2)}$$

If one assumes that the presence of the tunnel walls causes twice as many fragments to strike the acceptor, then the effective area ratio becomes 1.47 x 10^{-5}, and the effective target edge length e becomes

$$\frac{e_1^2}{4\pi(130)^2} = 1.47 \times 10^{-5} \qquad \text{(A-3)}$$

$$e_1 = \left[(4\pi)(130)^2(1.47 \times 10^{-5})\right]^{1/2}$$

$$e_1 = 1.77 \text{ ft*}$$

The new divergence angle δ_1 is

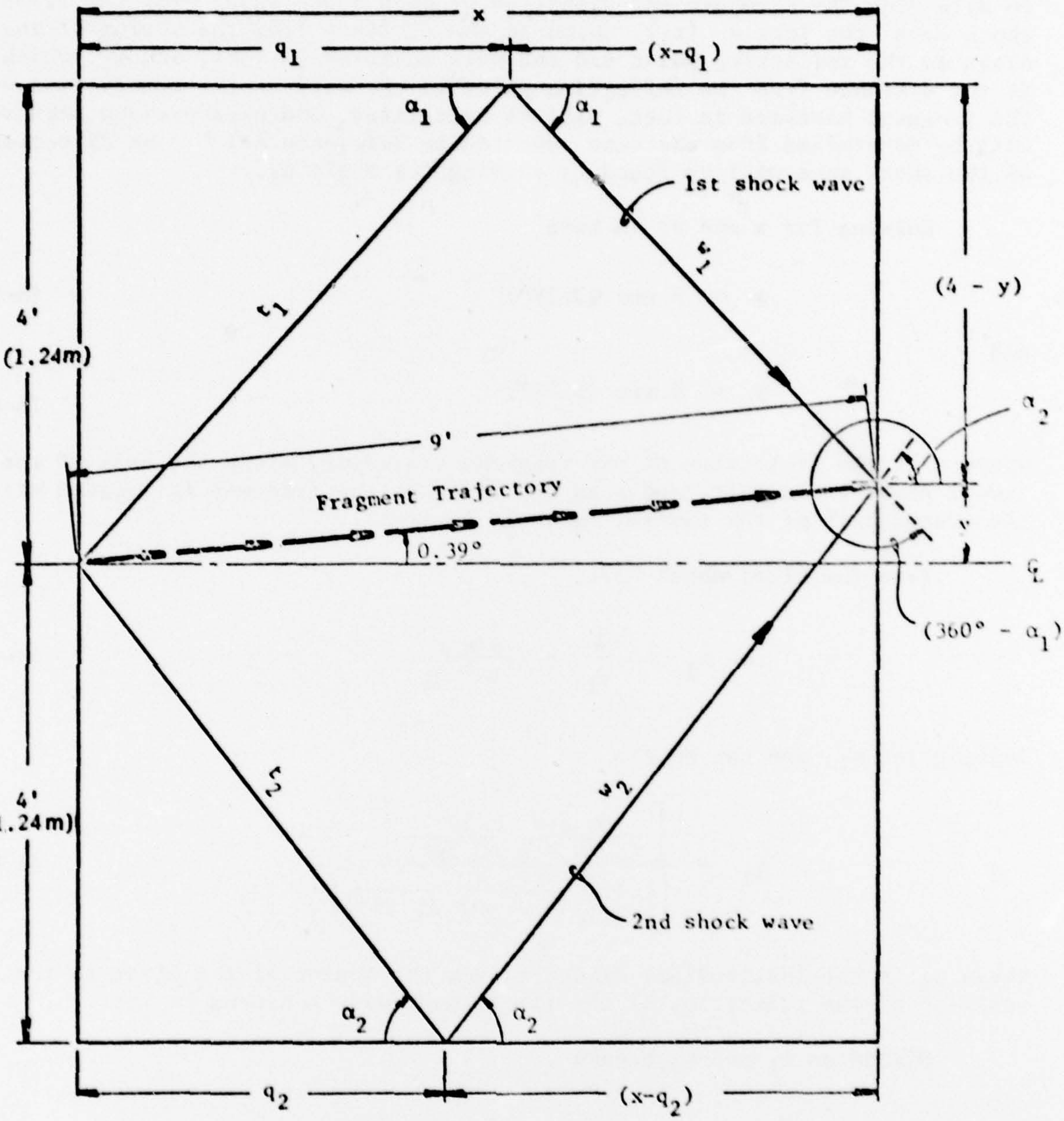
$$\delta_1 = 2 \tan^{-1} \left(\frac{e_1/2}{d}\right)$$

$$\delta_1 = 2 \tan^{-1} \left(\frac{1.77/2}{130}\right) = 0.78° \qquad \text{(A-4)}$$

This means that if the fragment distribution from the donor is radially symmetric and fragments are identical, and if the presence of the walls causes twice as many fragments to strike the acceptor, then all fragments within the divergence angle of 0.78° must strike the target. Subsequent calculations assume a fragment trajectory of 0.39° off the center axis so that if fragments along this trajectory interact with the reflected shock waves and strike the target, then greater than twice as many fragments will hit the target than if no reflecting surfaces were present.

For the purposes of this feasibility demonstration, we will assume that the blast occurs at a point source 4 ft* from the walls and that the fragment travels 9 ft* before interaction with two blast waves reflecting from opposite walls and striking the fragment at the same time, as shown in Figure A-2. Parameters of the shock wave which travels the shortest distance before striking the fragment are subscripted with a "1." The parameters of the second shock wave to strike the fragment are subscripted with a "2."

*130 ft = 40m, 4 ft = 1.29m, 9 ft = 2.75m



(NOT TO SCALE)

Fig. A-2 Interaction of fragment with two shock waves reflected from opposite walls.

To determine the effect of the shock waves on the fragment, it is necessary to determine the strength and direction of each shock wave. For the first shock wave, the length (t_1), which is the distance from the source of the blast to the reflecting point and the wall measured in feet, and w_1, which is the distance from the reflecting point in the wall to the interaction with the fragment measured in feet, will be calculated, and pressure and impulse will be determined from the data reported in Reference A-1.* The direction of the shock wave will be found by solving for angle α_1.

Solving for x and y, we have

$$x = 9 \cos (0.39°) \qquad \text{(A-5)}$$

and

$$y = 9 \sin (0.39°) \qquad \text{(A-6)}$$

where x is the projection of the fragment trajectory along the axis of the tunnel measured in feet, and y is the distance the fragment is located off the center axis of the tunnel, measured in feet.

From the first shock wave,

$$\tan \alpha_1 = \frac{4}{q_1} = \frac{4 - y}{x - q_1} \qquad \text{(A-7)}$$

Solving for q_1, one can obtain

$$q_1 = \frac{\left[\dfrac{36 \cos (0.39°)}{4 - 9 \sin (0.39°)}\right]}{\left[1 + \left[\dfrac{4}{4 - 9 \sin (0.39°)}\right]\right]} \qquad \text{(A-8)}$$

where q_1 is the longitudinal distance from the source of the blast to the position of the reflection of the first shock wave measured in feet.

Distances t_1 and w_1 become

$$t_1 = \sqrt{4^2 + q_1^2} = \sqrt{16 + \left\{\frac{\dfrac{36 \cos (0.39°)}{4 - 9 \sin (0.39°)}}{1 + \dfrac{4}{[4 - 9 \sin (0.39°)]}}\right\}^2}$$

$$= 6.0467 \text{ ft} \quad (1.8430 \text{ M}) \qquad \text{(A-9)}$$

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*(A-1) W. E. Baker, Explosions in Air, University of Texas Press, Austin, Texas, May 1973, pp. 150-163.

and

$$w_1 = \sqrt{(x - q_1)^2 + (4 - y)^2}$$

$$= \sqrt{\left\{ 9 \cos (0.39°) - \frac{\left[\frac{36 \cos (0.39°)}{4 - 9 \sin (0.39°)} \right]}{1 + \frac{4}{[4-9 \sin (0.39°)]}} \right\}^2 + [4 - 9 \sin (0.39°)]^2}$$

$$w_1 = 5.9541 \text{ ft} \quad (1.8148 \text{ M}) \qquad \text{(A-10)}$$

Summing t_1 and w_1, one has

$$t_1 + w_1 = 12.0008 \text{ ft} \quad (3.6578 \text{ M})$$

If the donor is 168 lb (76 Kgm) of A-7, with energy of 3.61×10^9 in lb (4.11×10^{12} cm-gm), scaled distance for the first shock R_1 becomes, from Reference A-1,

$$\overline{R}_1 = \frac{R\, p_o^{1/3}}{E^{1/3}} \simeq 0.230 \qquad \text{(A-11)}$$

where p_o is atmospheric pressure of 14.7 psi (1-1.4 Kpa). Using Reference A-1, incident pressure P_{si}, impulse I_{si}, and the nondimensional time constant b_1 are found to be 223 psi (1538 Kpa) , 0123 psi-sec (0.848 kpa/sec and 27.7, respectively

For the second shock,

$$\tan \alpha_2 = \frac{4 + y}{x - q_2} = \frac{4}{q_2} \qquad \text{(A-12)}$$

where

$$q_2 = \frac{\left[\frac{36 \cos (0.39°)}{4 + 9 \sin (0.39°)} \right]}{1 + \frac{4}{[4 + 9 \sin (0.39°)]}} \qquad \text{(A-13)}$$

Distances t_2 and w_2 become:

$$t_2 = \sqrt{4^2 + q_2^2} = \sqrt{16 + \left\{ \frac{\frac{36 \cos (0.39°)}{4 + 9 \sin (0.39°)}}{\left[1 + \frac{4}{4 + 9 \sin (0.39°)}\right]} \right\}^2} = 5.9952 \text{ ft } (1.8273 \text{ m}) \quad \text{(A-14)}$$

and

$$w_2 = \sqrt{(x - q)^2 + (4 + y)^2}$$

$$= \sqrt{\left\{ 9 \cos (0.39°) - \frac{\left[\frac{36 \cos (0.39°)}{4 + 9 \sin (0.39°)}\right]}{\left[1 + \frac{4}{[4 + 9 \sin(0.39°)]}\right]} \right\}^2 + [4 + 9 \sin (0.39°)]^2}$$

$$w_2 = 6.0870 \text{ ft } (1.8553 \text{ m}) \quad \text{(A-15)}$$

Summing t_2 and w_2, one has

$$t_2 + w_2 = 12.0822 \text{ ft } (2.4827 \text{ m})$$

Scaled distance for the second shock $\overline{R}_2$ becomes 0.232, and incident pressure P_{s2}, impulse I_{s2}, and nondimensional time constant b_2 are found to be 216 psi (1487 Kpa), 0.122 psi-sec (0.841 Kpa/sec) and 27.8, respectively, from Reference A-1. The average blast path length is approximately 12 ft (3.65 M), which implies a shock wave arrival time in this instance of 1.4 milliseconds. From this, one can calculate what the average fragment velocity should be in order for that fragment to interact with the converging shock waves at a point 9 ft (2.75 m) from the source. This average velocity is 6220 ft/sec (1892 m/sec).

Figure A-3 shows the range of new flight paths the fragment must follow to be on a collision course with the acceptor after it interacts with the two reflected shock waves as demonstrated in Figure 2. The new fragment angular vector direction θ must be such that $\psi < \theta < \gamma$ in order for it to hit the acceptor. Solving for the various distances, shown in Figure A-3,

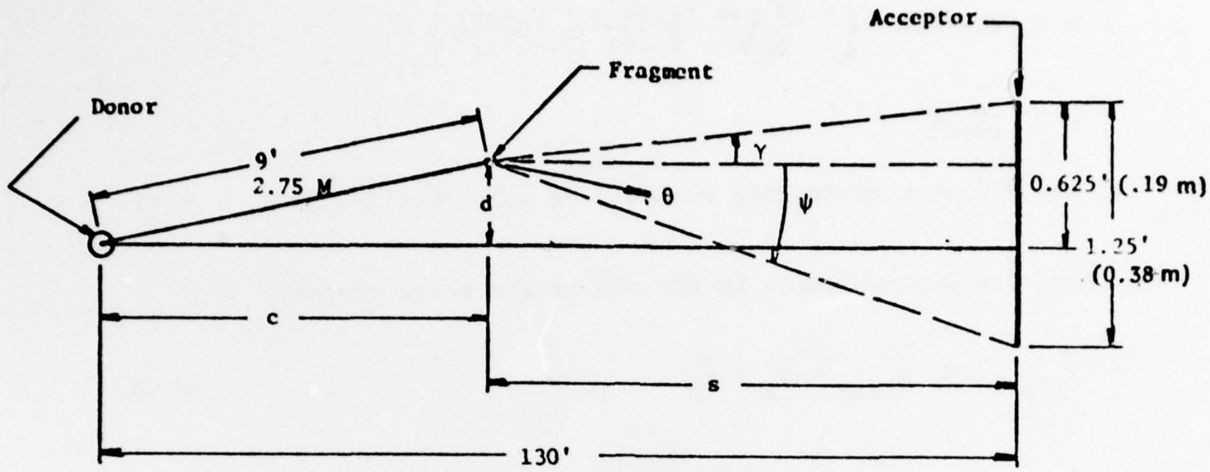

Fig. A-3 New fragment flight path for collision with acceptor.

$$c = 9 \cos (0.39°) \quad \text{(A-16)}$$

$$d = 9 \sin (0.39°) \quad \text{(A-17)}$$

$$s = 130 - C = 130 - 9 \cos (0.39°) \quad \text{(A-18)}$$

Solving for angles γ and ψ, one has

$$\gamma = \text{arc tan} \left(\frac{0.625 - d}{s}\right) \quad \text{(A-19)}$$

or

$$\gamma = \text{arc tan} \left\{\frac{[0.625 - 9 \sin (0.39°)]}{[130 - 9 \cos (0.39°)]}\right\}$$

$$\gamma = \underline{\underline{+ 0.27°}}$$

$$\psi = \text{arc tan} \left[-\left(\frac{d + 0.625}{s}\right)\right] \quad \text{(A-20)}$$

or

$$\psi = \text{arc tan} \left\{ - \frac{[9 \sin (0.39°) + 0.625]}{[130 - 9 \cos (0.39°)]} \right\}$$

$$\psi = \underline{\underline{-0.32°}}$$

That is, the new fragment trajectory θ should be such that $(-0.32°) < \theta < (+0.27°)$.

The final fragment velocity is the sum of the three vectors:

$$\vec{v}_{final} = \vec{v}_{frag} + \vec{v}_1 + \vec{v}_2 \qquad \text{(A-21)}$$

where

$\vec{v}_{frag}$ = velocity of the fragment at time of interaction with the blast waves

$\vec{v}_1$ = velocity of the fragment due to interaction with the first reflected shock wave

$\vec{v}_2$ = velocity of the fragment due to interaction with the second reflected shock wave

The initial velocity of the fragment at the time of interaction with the blast waves is

$$\vec{v}_{frag} = v_x \hat{i} + v_y \hat{j} \qquad \text{(A-22)}$$

$$\vec{v}_{frag} = v \cos (0.39°) \hat{i} + v \sin (0.39°) \hat{j} \qquad \text{(A-23)}$$

$$\vec{v}_{frag} = 6220 \cos (0.39°) \hat{i} + 6220 \sin (0.39°) \hat{j} \qquad \text{(A-24)}$$

The velocity components of the fragment due to interaction with the first reflected shock wave are

$$\vec{v}_1 = v_x \hat{i} + v_y \hat{j} \qquad \text{(A-25)}$$

$$\vec{v}_1 = v_1 \cos (360° - \alpha_1) \hat{i} + v_1 \sin (360° - \alpha_1) \hat{j} \qquad \text{(A-26)}$$

where

$$\alpha_1 = \text{arc tan}\left(\frac{4}{t_1}\right) = \text{arc tan}\left(\frac{4}{6.0467}\right)$$

$$\vec{v}_1 = v_1 \cos\left[360° - \text{arc tan}\left(\frac{4}{6.0467}\right)\right] \hat{i}$$

$$+ v_1 \sin\left[360° - \text{arc tan}\left(\frac{4}{6.0467}\right)\right] \hat{j} \qquad \text{(A-27)}$$

The velocity components of the fragment due to interaction with the second reflected shock wave are:

$$\vec{v}_2 = v_x\hat{i} + v_y\hat{j} \qquad \text{(A-28)}$$

$$\vec{v}_2 = v_2 \cos(\alpha_2)\,\hat{i} + v_2 \sin(\alpha_2)\,\hat{j} \qquad \text{(A-29)}$$

where

$$\alpha_2 = \text{arc tan}\left(\frac{4}{t_2}\right) = \text{arc tan}\left(\frac{4}{5.9952}\right)$$

$$\vec{v}_2 = v_2 \cos\left[\text{arc tan}\left(\frac{4}{5.9952}\right)\right] \hat{i} \qquad \text{(A-30)}$$

$$+ v_2 \sin\left[\text{arc tan}\left(\frac{4}{5.9952}\right)\right] \hat{j}$$

Adding Eqs. (24), (27), and (30), one can obtain

$$\vec{v}_{final} = \left\{6220 \cos(0.39°) + v_1 \cos\left[-\text{arc tan}\left(\frac{4}{6.0467}\right)\right]\right.$$

$$\left. + v_2 \cos\left[\text{arc tan}\left(\frac{4}{5.9952}\right)\right]\right\} \hat{i} + \left\{6220 \sin(0.39°)\right.$$

$$+ v_1 \sin\left[-\text{arc tan}\left(\frac{4}{6.0467}\right)\right]$$

$$\left. + v_2 \sin\left[\text{arc tan}\left(\frac{4}{5.9952}\right)\right]\right\} \hat{j} \qquad \text{(A-31)}$$

The new trajectory angle θ of the fragment is

$$\theta = \text{arc tan} \left\{ \frac{\left[\left(v_{final}\right)_y\right]}{\left[\left(v_{final}\right)_x\right]} \right\} \qquad (A-32)$$

Baker, et al., have developed a computer program to calculate the velocity attained by fragments subjected to blast waves, as reported in Reference A-2.* This program was recently adapted to a Hewlett-Packard 9830 minicomputer, and a copy of the program and sample output appears in Figure A-4. Pertinent parameters of this program are:

M = total mass of fragment (lb)

H = minimum transverse dimension of the mean presented area of fragment (in.)

X = dimension from front of fragment to location of its largest cross-sectional area (in.)

A = mean presented area of fragment (in^2)

C = drag coefficient of fragment

P = peak incident overpressure of blast source at point of interaction (psi)

I = peak incident specific impulse of blast source at point of interaction (psi-sec)

B = nondimensional time constant

V8 = nondimensional final velocity of fragment

V9 = final velocity of fragment (ft/sec)

Pertinent parameters from actual fragments recovered from the steel tunnel test program are shown in Table A-1.

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*(A-2) W. E. Baker, J. J. Kulesz, R. E. Ricker, R. L. Bessey, P. S. Westine, V. B. Parr, and G. A. Oldham, Workbook for Predicting Pressure Wave and Fragment Effects of Exploding Propellant Tanks and Gas Storage Vessels, prepared for National Aeronautics and Space Administration by Southwest Research Institute, NASA CR-134906, 1975, Chapter 4, pp. 38-50.

Table A-1

Parameters from fragments recovered from tests

Fragment No.	Mass M (lb/gm)	Fragment Area A (in^2/cm^2)	Drag Coefficient C	Fragment Transverse Dimension H (in/cm)	Fragment Longitudinal Dimension X (in/cm)
1	7.36×10^{-3} (3.345 gm)	0.56/3.60	1.6	0.66/1.68	0.03/0.08
2	3.96×10^{-2} (18.0 gm)	2.04/13.10	1.6	1.10/2.79	0.20/0.51
3	4.25×10^{-3} (1.92 gm)	0.36/2.32	1.6	0.55/1.40	0.15/0.38
4	4.85×10^{-4} (0.22 gm)	0.05/0.34	1.0	0.10/0.25	0.05/0.13

After exercising the computer program described and given in Figure A-4 for these four fragments, the velocity v_1 of each fragment due to the first shock was calculated. Similarly, the velocity v_2 of each fragment due to the second shock was also calculated.

Summing $\vec{v_1}$ and $\vec{v_2}$ and the initial fragment velocity $\vec{v}$ frag, using Eq. (A-31), one obtains the vertical velocity component v_y and the horizontal veloctty component V_x for the final fragment velicity. Using these values and Eq. (A-32), one can obtain the new fragment trajectory caused by the interaction of the fragment with the blast waves. The results of these calculations are given in Table A-2.

Table A-2
Final fragment parameters

Fragment No.	V_x (ft/sec M/sec)	V_y (ft/sec M/sec)	θ (degrees)	Remarks
1	7629/2320	35.32/10.75	+0.27	Hit
2	7221/2200	36.79/11.20	+0.29	No Hit
3	7778/2370	34.73/10.56	+0.26	Hit
4	7419/2260	37.12/11.29	+0.29	No Hit

Note from the results given in Table A-2 that the horizontal component of the velocity is greater than the initial velocity, indicating velocity enhancement by the focusing of the blast waves due to the tunnel interaction. Also, note that some of the trajectories have been altered from a no hit

$\left(\frac{\delta_1}{2} = 0.39°\right)$ to a hit trajectory of $(-0.32°) < \theta < (+0.27)$. This was the case for Fragments 1 and 3.

This analysis demonstrates that blast focusing can affect the trajectory of the fragments, and it is also possible to increase the flight velocity when reflective surfaces are present. Therefore, this explains why the tunnel confinement had an effect on increasing safe separation distance.

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