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THE EXPLOSIVE DISSEMINATION OF LIQUIDS OF LOW VOLATILITY (U)

(Status Report)

by

Donald E. Buck

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Chemical Warfare Laboratories Special Publication 1-7
THE EXPLOSIVE DISSEMINATION OF LIQUIDS OF LOW VOLATILITY (U)
(Status Report)

Subproject No.: 4-04-15-029-02
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for W. H. SUMMERSON, Ph.D.
Director of Research

(C)

DIGEST

The present emphasis, by the Chemical Corps, on toxic agents of low volatility points up the need for the development of more efficient techniques in dissemination. If these agents are to be used as inhalants and/or as body impaction contaminants, more efficient means of producing and controlling droplet-size distribution of aerosols is required.

The most direct approach in munition design is the use of explosives as the disseminating force. This report outlines the status of the chamber program for investigating the effect of various munition design parameters on the explosive dissemination efficiency. Major emphasis has been placed on the study of the effect on aerosol mass median diameter of agent-to-burster ratio and wall thickness for miniature steel devices. Tentative empirical equations, based on chamber results, for predicting aerosol mass median diameter as a function of agent-to-burster ratio and wall thickness are presented. The relative dissemination efficiencies as affected by type of explosive and other variables are tabulated. Since many of these results are as yet unexplained, no conclusions are offered. Areas of investigation which should be beneficial to future munition design problems are pointed out.

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THE EXPLOSIVE DISSEMINATION OF LIQUIDS OF LOW VOLATILITY (U)
(Status Report)

I. (C) INTRODUCTION.

(U) Toxic liquid agents are disseminated from munitions in one of the following states: (1) vapor, (2) aerosol, (3) gross splash, or (4) decomposed agent.

(C) The present emphasis on agents of low volatility has directed the munitions research effort toward the enhancement of aerosol effectiveness and the minimization of gross splash and decomposition of agent. Theoretically, there is ample energy available in relatively small explosive charges to convert the liquid fill of a munition into fine aerosol droplets. Thus, it becomes necessary to understand the mechanisms affecting the formation of aerosols to efficiently utilize the available explosive energy.

(U) This report, reflecting the "state of the art" of explosive dissemination, is mainly concerned with data from the chamber test program at the U. S. Army Chemical Warfare Laboratories. The program is designed to investigate the effects of the following parameters: (1) explosive quantity (agent/burster ratio), (2) casing wall thickness and material, (3) type of explosive, (4) burster wall thickness and material, (5) physical properties of liquid fill, (6) effect of size (scaling), (7) cylinder length/diameter ratio, and (8) shape of casing or burster.

(U) The casing materials were selected to determine the effects of elasticity and ranged from a cast metal (Zamack) to rubber, glass, and lucite.

II. (U) HISTORICAL.

Research on the explosive dissemination of liquids has been limited to military research programs at Army Chemical Center, Fort Detrick, and Porton, England. The Army Chemical Center program has included an extensive contractual effort, by the Stanford Research Institute, which until recently was directed at increasing the efficiency of dissemination of volatile liquids. The Fort Detrick (BW) program has included a contractual effort by the George Washington University and has been directed at increasing the efficiency of producing droplets under 5 microns in diameter. This approach has resulted in emphasis on small plastic devices with a special casing design which produces liquid jetting.

The total of these efforts has left a gap in the knowledge of the mechanisms of droplet formation during the explosion process. This may hold the key to the design of munitions which are required to produce aerosols of liquids of low volatility.

III. (C) INVESTIGATIONAL PROCEDURES.

(U) Inherent in a chamber test program is the problem of the effect of the test environment on the results. The measurement of the efficiency of explosive devices in producing aerosols in a test chamber may be in error because of such factors as chamber wall impaction, agglomeration, sonic coagulation, reflected shock waves, heating, etc. Some of these environmental factors may have greater impact on certain types of devices than on others so that a comparison of their relative chamber efficiencies may result in error. The current program seeks to establish trends in the chamber which may be correlated with values obtained in the field. The chamber program discussed in this report is concerned with increasing the efficiency of explosive devices in producing and controlling the size distribution of aerosols.

(U) No experimental techniques are available for direct measurement of the initial (time zero) particle-size distribution of an explosively produced aerosol cloud. However, two indirect techniques[1] have been employed: (1) deposition of droplets on slides followed by microscopic measurement and counting; (2) measurement of the quantity of liquid airborne as a function of time and subsequent calculation of the particle-size distribution from cloud decay theory. It is theoretically possible with this latter technique to determine the cloud characteristics at time zero.

(U) "Flashing" is detected by monitoring the oscilloscope trace resulting from the reaction of a photoelectric pickup to the light produced in the chamber. The duration and intensity of this light give relative indications of the extent of cloud burning which is confirmed by chemical measurement of fill decomposition (figure 1, appendix).

(U) Because of the laborious techniques necessary to determine particle-size distribution of the aerosols produced, test data on the effect of the above variables will be presented in terms of the percentage of

1. (U) It has been found that the range of particle sizes is too broad to permit measurement by a single conventional mechanical device such as the cascade impactor.

fill remaining airborne after 10 minutes of "settling." These values represent the relative ability of the various test devices to produce small aerosol droplets.

(C) Cylindrical test devices with central bursters were used in the experim nts. A 4-inch bomb length was chosen as standard because of the limitation on the quantity of explosive permitted in the test chamber. The devices were filled with bis(2-ethylhexyl) hydrogen phosphite (bis).

IV. (C) RESULTS.

A. (C) Explosive Quantity and Casing Wall Thickness and Material.

(U) The assumption was made at the initiation of the chamber test program that the aerosol produced by an explosive device is the result of shear and drag forces exerted on the liquid fill as it is expelled through the environmental air.

(C) This process should result in aerosols of smaller droplets as the liquid ejection velocity is increased; this would be the case with thin casings and high relative amounts of explosive (low agent/burster ratio). Figure 2 (appendix) shows the results obtained by varying the casing wall thickness of steel devices at a constant agent/burster ratio of 1.8. When these tests were expanded to include other agent/burster ratios, a family of curves resulted which may be represented by the empirical equation:

$$R_{10} = 24\left(\frac{A}{B}\right)^{-1.16} e^{-11.7T} + 31.5T\left(\frac{A}{B}\right)^{-.58}$$

where

R_{10} = percentage of bomb fill airborne after 10 minutes

A/B = ratio of fill weight to explosive weight

T = casing wall thickness

The predictions of this equation are presented in figure 3 (appendix) for steel bombs, bis filled, for varying A/B and T values.

(U) The correlation between test results and the curve predicted by this equation can be seen in figures 4 through 10 (appendix) where the solid lines are the predicted values and the points are experimentally measured values. These data support the original assumption regarding A/B ratio, but the thick walls did not reduce the recovery as anticipated.

(U) Measurement of the expansion velocity of these devices has closely corroborated Gurney's formula[2] which states that the velocity varies inversely as the mass being moved by the explosive. The shape of the thick-walled-casing cloud-decay curves, when compared with that of the thin-walled-casing cloud-decay curves (figure 11, appendix), indicates that different mechanisms, or different applications of a basic droplet formation mechanism, are taking place.

(C) The difference in curve slopes, at the short time periods, for the thin- and thick-walled devices seems to indicate: (1) Thin walls produce a spectrum of droplet sizes, with the larger sizes falling out rapidly; and (2) thick walls produce a result that suggests the fill is either splashed out or broken into small droplets with very little production of intermediate particle sizes.

(C) One explanation may be that with the thin-walled units the explosive energy is utilized in propelling the liquid fill at high velocities, producing the droplet spectrum. As the energy necessary to break the casing increases, the liquid fill velocity decreases to the point where no droplet breakup occurs; but, at the same time, the fragments from thick-walled casings are larger (figure 12, appendix) and may be entraining liquid fill behind them and causing a portion of the fill to move outward at high velocity while being subjected to high-speed vortices.

(C) Another hypothesis to explain improved recovery from thick-walled devices is that the relative timing and sequence of events may be the significant factors. Measurements by the Stanford Research Institute show that the casing fails at elongations comparable to static loading failures. Also, the rate of expansion is inversely related to the mass being moved rather than the strength of the material. Thus, the time of breakup of the casing, the decay rate of the liquid pressure due to the shock wave,[3] plus the outward velocity of the surrounding air after

---

2. (U) R. W. Gurney, Ballistic Research Laboratories Report 405, The Initial Velocities of Fragments From Bombs, Shell, and Grenades, 14 September 1943.

3. (U) See Section V, C, Shock-Wave Behavior.

the passage of the shock wave may all combine in affecting the relative velocity at which the liquid fill is expelled into the air.

(U) Additional evidence may be found in photographs taken by the George Washington University Research Laboratory at Fort Detrick which show the liquid fill leading the primary shock wave at mass ratios up to 3 or 4. At higher mass ratios, the shock leads the liquid fill. This change point is approximately the same as found in the Baratol and Composition C-3 phenomena with light and heavy devices described under section B, below.

(C) There is evidence that this so-called "thick-walled" phenomenon is in reality an "end effect." In the low-mass bombs such as the .004-inch-thick-wall steel and the rubber devices, the homogeneity of the casing wall was observed to be of paramount importance. As casing wall thicknesses are increased, beyond the 1/8-inch thickness of the end plates, it can be seen by photographic techniques that increasing amounts of fill are ejected axially. If this explains the increased efficiency of thick-walled devices, then this axially disseminated cloud must be of smaller particulate sizes than the radial cloud and presumably is ejected at higher speeds. These velocity measurements are being made at this time.

(C) Various materials were investigated to determine the effect of ductile versus brittle outer casing. Ultra-high-speed photographs (figure 13, appendix) had shown that jets of liquid were forming at the cracks in the casing. It was felt that brittle casings which formed cracks early would produce higher velocity jets and therefore smaller droplet aerosols. However, the results indicate marginal superiority over the ductile materials. Zamack (cast white metal) and copper devices, of equal size, gave the following recoveries:

	A/B	R_{10} %
Copper	1.5	18.5, 7*, 15.5**
Zamack	1.5	15, 17.5

* Soft soldered.
** Welded.

(C) The soldered seam of the copper bomb often failed prematurely (figure 13, appendix) and resulted in low returns. The importance of casing homogeneity for consistent results has been noted often. Unfortunately, materials were not available for fabrication of glass and lucite devices of the same size. The A/B ratio of 1.75 for the lucite devices and 2.15 for the glass may be sufficient to account for their differences in performance.

	A/B	R_{10} %
Glass	2.15	9.0
Lucite	1.75	16.0

(C) Casing ductility was further explored by testing rubber devices. Two characteristics of the rubber devices immediately stand out: (1) the great improvement in producing aerosols of small droplets and (2) the long time period and great casing expansion that takes place before release of the liquid fill (figure 14, appendix). It seems logical to associate these two as cause and effect. As the rubber casing expands, the liquid fill is distributed in a thinner and thinner layer and upon rupture a thin sheet of liquid is released. This should result in improved liquid breakup. Again, the explanation may be that the delay in release of the liquid has resulted in a slowing down of the surrounding air which had been accelerated outward by the passage of the explosive shock wave. If this air has had time to slow down, the differential in the velocities of the liquid and air will be greater and will result in improved breakup.

(C) A series of aluminum devices showed higher recovery values than those theoretically predicted for the equivalent steel devices. Figures 15, 16, and 17 (appendix) show the test results from these aluminum devices plotted against the theoretical recovery curves for steel devices with the same casing wall thickness. It has been noted that, when steel devices "flash," the recovery of active bis is higher even though there has been partial burning of the aerosol cloud. However, there is an increasing amount of evidence that flashing of aluminum devices is a result of delayed burning of explosive gases as well as aerosol ignition (see section V, B).

B. (C) Explosive Type.

It was postulated that the more powerful, "faster," explosives would give better droplet breakup. As shown in table 1 the recoveries are inversely related to explosive power except in the cases of the .004-inch-thick-wall steel and the rubber devices which are strongly affected in a direct relationship to explosive power.

Table 1

Effect of Different Explosives Upon Recovery

Wall characteristics		R_{10}		
Material	Thickness	Baratol (5900 m/sec)	Composition C-3 (7000 m/sec)	Tetrytol (7300 m/sec)
	in.		%	
Steel	.004	6.9, 5.0	21.5, 22.0	-
Rubber (dipped)		4.5	30.5	27.0
Steel (type A)	.065	8.7, 9.1	4.0, 4.4	3.5, 4.3
Steel (type B)	.065	8.5	3.3	2.8
Steel	.158	13.0	6.4	3.5
Steel	.250	-	3.8, 4.8	3.1
Steel	.625	32.5	14.2	-
Aluminum	.065	6.1	1.4	-
Aluminum	.125	6.3	1.4	-
Aluminum	.250	7.2	5.5	-

C. (C) Burster Wall Thickness and Material.

(U) The investigation of the effect of the central burster on dissemination efficiency is in the initial stage. The first series combined three burster wall thicknesses with thin- and thick-walled casings. The values in column A of table 2 show a slight increase in recovery as the burster wall thickness increases. In the last case, where the total metal has become relatively massive, the increase in recovery is quite marked. In order to determine if this increase in recovery was due to "end effect," similar bombs were tested with heavy end plates. The results shown in columns C and D, table 2, indicate lower values with the increased mass of the end plates. However, the welded end plates are consistently better than silver soldered end plates. There is not enough known about "end effect" to explain these results.

(C) **Table 2**

Effect of Burster Wall Thickness Upon Recovery

A/B	Casing wall thickness	Burster wall thickness	R_{10}			
			A	B	C	D
			1/8-inch Silver-soldered end plates	1/8-inch Welded end plates	1/2-inch Silver-soldered end plates	1/2-inch Welded end plates
	in.	in.	%			
2.2	.065	.125	3.0	3.3		
3.6	.065	.250	3.5	2.3		
2.4	.065	.344	3.6			
3.4	.450	.065	4.9		4.0	5.3
3.2	.450	.125	5.0		3.4	4.0
2.5	.450	.344	17.8, 14.4		3.1	3.7

(U) Preliminary studies of burster material are inconclusive although the burster seems to be of less importance than the casing in affecting aerosol characteristics. The wide difference in agent recovery between items 1 and 2 of table 3 is probably due to fragments from the steel burster puncturing the rubber casing prematurely.

(C) **Table 3**

Effect of Burster Material on Recovery

(Combinations of Rubber and Steel)

Casing		Burster		
Material	Thickness	Material	Thickness	R_{10}
	in.		in.	%
Rubber	.065	Rubber	.065	20.2
Rubber	.065	Steel	.065	8.5
Steel	.158	Rubber	.065	6.0
Steel	.158	Steel	.065	5.2

(U) The results recorded in table 4 are difficult to asses because of "flashing." There is some doubt as to whether all cases are true flashing (light produced by burning of the aerosol cloud), or a false flashing resulting from light from delayed burning of explosive gases. Where decomposition was measured, the low values of decomposition seem to support the latter explanation.

(C)

Table 4

Effect of Burster Material on Recovery

(Combinations of Steel and Aluminum)

No.	Casing		Burster		R_{10}	A/B	Flash	Decomposition
	Material	Thickness	Material	Thickness				
		in.		in.	%			%
1	Steel	.065	Aluminum	.065	38.9	.3	Yes*	11.5
2	Aluminum	.065	Steel	.065	53.2	.3	Yes	6.8
3	Steel	.065	Steel	.065	34.0	.3	No	-
4	Aluminum	.065	Aluminum	.065	15.5**	.3	Yes	-
5	Steel	.125	Aluminum	.065	44.6	.3	Yes	3.4
6	Aluminum	.125	Steel	.065	76.8	.3	Yes	0.0
7	Steel	.125	Steel	.065	14.2	.5	No	-
8	Aluminum	.125	Aluminum	.065	44.2	.3	Yes	-
9	Steel	.250	Aluminum	.065	37.7	.3	Yes	-
10	Aluminum	.250	Steel	.065	46.0	.3	Yes	-
11	Steel	.250	Steel	.065	18.2	.5	No	-
12	Aluminum	.250	Aluminum	.065	60.6	.3	Yes	-

* See figure 1, appendix.

** This result appears low (figure 13). The relative performance of nos. 4, 8, and 12, above, can be seen in figures 15, 16, and 17; their relative "flashing" is shown in figure 18. (See appendix for figures 15 through 18).

D. (U) Physical Properties of Liquid Fill.

Chamber studies of this variable have not yet been initiated.

E. (C) Size Scaling.

(U) In order to make chamber data more useful in the design of munitions, it is necessary to be able to scale chamber results up to the desired munition size. Identical munitions, except for size, will expand at the same initial velocity but will produce aerosol clouds in proportion to their size. This means that the larger units, producing larger clouds, must decelerate at a lower rate and thus will produce larger droplets.

(U) The results listed under tables 5 and 6 show the trend expected, but absolute ratios of return versus bomb size are questionable since the large units were approaching a size where chamber wall losses are expected and the small units approach the region of marginal chemical analysis accuracy.

(C) Table 5

Effect of Scaling (1:2:3) on Recovery

Size scaling	Casing				A/B	R_{10}
	Diameter	Length	Material	Wall thickness		
	in.	in.		in.		%
1	1	2	Steel	.032	2.1	18.0
2	2	4	Steel	.065	1.8	8.5
3	3	6	Steel	.093	2.4	5.0*

* Flashed - 65% decomposition.

(C) Table 6

Effect of Scaling (1:2:4) on Recovery

Size scaling	Casing				A/B	R_{10}
	Diameter	Length	Material	Wall thickness		
	in.	in.		in.		%
1	9/16	3	Steel	.032	2.5	22.2
2	1-1/8	6	Steel	.065	2.5	5.0
4	2-1/4	12	Steel	.125	2.9	2.1

F. (C) Cylinder Length/Diameter Ratio.

The contribution of the ends to the dissemination of cylindrical devices has not been determined. Tests with thick-walled devices reported in sections A and C, above, indicate the possibility of significant effect. Early British work[4] attributes the increased end efficiency to less dense aerosol cloud at the ends and therefore less agglomeration. As the units approach infinite length, the efficiency should represent the cylinder cross section with negligible end effect (figure 19, appendix).

It is interesting to note the shape of the curves in figure 20 (appendix). There is a definite trend from the short to the long units. However, if we attribute the high recoveries for the short units at early time periods to increased end effect, we found the opposite to be the case with the thick-walled devices (figure 11, appendix). The thick-walled devices, which may have higher recoveries because of increased end effect, produce the flat curves with lower recovery values at the short time intervals.

G. (U) Shape of Casing or Burster.

Chamber studies of this variable have not yet been initiated.

4. (U) James and Banfield, Porton Technical Paper 157, The Dispersion of Toxic Agents, Part 2. The Formation of Aerosols by the High Explosive Dispersion of Liquids.

H. (C) Miscellaneous.

Test devices having a foam plastic liner on the inside of the casing were tested on the theory that negative or rarefaction shock waves would be reflected from the liquid-plastic interface. It was hoped that this rarefaction wave would cause cavitation in the liquid and improved aerosolization. Other units, with linings of the same thickness around the central burster, were tested to emphasize the importance of the location of the plastic.

Device	A/B	R_{10} %
Steel casing (wall thickness - .158 inch)	2.3	6.5
Steel casing with plastic lining	1.8	16.0
Steel casing with burster covering	2.2	5.0

V. (C) DISCUSSION.

A. (U) General.

Many of the recovery values listed above, although a measure of dissemination efficiency, appear contrary to the accepted theories of aerosol production. The aerosol droplets are supposedly produced by the shear or drag forces on the liquid as it moves through the environmental air. The faster the droplets move through the air, the smaller the stable droplet size produced. Since the chamber recovery tests are reproducible (figure 21, appendix), they are either valid, indicating additional or modified mechanisms of aerosol formation, or they are the result of some selective chamber environmental phenomena.

B. (C) Flashing.

One important facet of the explosive dissemination study is the cause and control of "flashing" or burning of the aerosol cloud. Early work with steel devices had shown that quenching of the explosive column, by surrounding it with liquid fill, was beneficial.

The first 10 tests with aluminum test devices revealed a much increased tendency to "flash" and no apparent control by explosive quenching. A "go, no-go" relationship was found with aluminum devices (figure 22, appendix). However, when chemical analyses revealed relatively low amounts of decomposition products and when a water-filled aluminum unit "flashed," the technique of flash detection by recording visible light became suspect. As yet, the source of this visible light, with aluminum devices, has not been determined. One hypothesis is that flashing is burning of incompletely burned gases from the explosive. This would explain the flashing of a water-filled unit. Also, it must follow that the properties of dissemination from aluminum devices are sufficiently different, from the multitude of combinations of other materials tested, to provide the mixing with air, or other environment favorable to ignition and burning of these explosive gases.

C. (C) Shock-Wave Behavior.

One aspect of the explosive liquid phenomena, being investigated under contract by the Poulter Laboratories of the Stanford Research Institute, is the effect of the casing material and wall thickness on the pressure rarefaction process at the liquid-casing interface.[5] Figures 23 and 24 (appendix), taken from the contractor's report, show the flow in the u-p plane resulting from a 25,000 atmosphere (25 kilobars (kb)) incident shock in water, with iron and aluminum casings. The interface pressure is reduced to 5 kb in 14 rarefactions with iron and 6 rarefactions with aluminum. The time to reduce the interface pressure is given by the following relationship:

$$t = \frac{2ND}{C}$$

where

N = number of rarefactions to reach desired pressure

D = thickness of casing wall

C = speed of sound in the casing material (dependent upon the "state" of the material)

The upper and lower limits of time for the rarefaction process to reduce the interface pressure from 25 kb to 5 kb indicate that the casing material is much more significant than the incident shock strength.

5. (U) Stanford Research Institute. Contract DA-18-108-CML-5510, Progress Report 14, Explosive Dissemination of Liquid Agents, 1 December 1956.

(C) Table 7

Incident Shock

Interface materials	Shock pressure	t/D
	kb	μsec/cm
Water - iron	25	101 - 104
Water - aluminum	25	35 - 39
Water - iron	50	115 - 121
Water - aluminum	50	39 - 46

D. (U) Particle-Size Measurement.

The theoretical calculation of particle-size distribution from the aerosol decay curves has been unsuccessful thus far. It is doubtful if true "stirred" or "tranquil" settling conditions can be achieved in the chamber; also, there is no way of knowing what proportion of the original bomb fill contributes to the aerosol decay from time zero and what part is gross splash and does not affect later aerosol recoveries. Decay curves are plotted with recovery as a percentage of original fill, when theoretically it should be percentage of original aerosol cloud.

Particle-size measurements showing the relationship of mass median diameter versus percentage of agent recovery at 10 minutes are shown in figure 25 (appendix). The spread of the results with rubber bombs and with the unit that "flashed" suggests that different particle-size distributions are present to give higher recovery values for the same mass median diameter value.

VI. (C) CONCLUSIONS.

No conclusions are attempted at this stage of the investigation. Continued chamber investigations are required into the mechanisms which apparently make: (1) thick-walled devices more efficient than thin-walled devices, (2) Baratol more efficient than Composition C-3 or Tetrytol as an explosive, and (3) lined devices more efficient than unlined devices. The information obtained, with corroborating field tests, should provide guidelines to munition design which will enhance munition efficiency significantly.

APPENDIX

DRAWINGS, GRAPHS, AND PHOTOGRAPHS

Figure 1, Flashing Characteristics

Figure 2, Effect of Casing Wall Thickness on Airborne Recovery

Figure 3, Predicted Recovery of Steel Bombs

Figure 4, Airborne Recovery at Ten Minutes

Figure 5, Airborne Recovery at Ten Minutes

Figure 6, Airborne Recovery at Ten Minutes

Figure 7, Airborne Recovery at Ten Minutes

Figure 8, Airborne Recovery at Ten Minutes

Figure 9, Airborne Recovery at Ten Minutes

Figure 10, Airborne Recovery at Ten Minutes

Figure 11, Effect of Casing Thickness on Aerosol Decay

Figure 12, Fragments From Various Thickness Steel Casings

Figure 13, Jetting Characteristics

Figure 14, Rubber Devices

Figure 15, Airborne Recovery at Ten Minutes

Figure 16, Airborne Recovery at Ten Minutes

Figure 17, Airborne Recovery at Ten Minutes

Figure 18, Effect of Wall Thickness on Flashing of Aluminum Bombs

Figure 19, Effect of Length/Diameter on Aerosol Recovery at Ten Minutes

Figure 20, Effect of Length/Diameter on Aerosol Decay

Figure 21. Reproducibility of Test Technique

Figure 22. Flash Characteristics of Aluminum Bombs

Figure 23. Shock Decay Characteristics

Figure 24. Shock Decay Characteristics

Figure 25. Relationship Between Aerosol M. M. D. and Chamber Recovery

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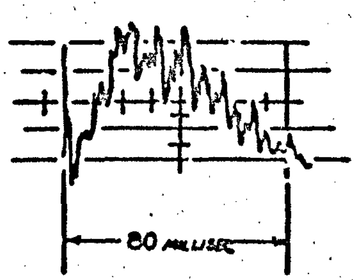
FIGURE 1

Flashing Characteristics



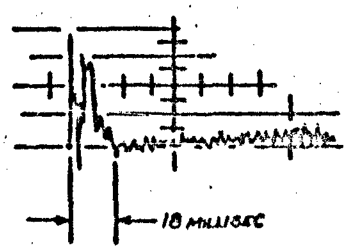
.097" x 3" Steel Casing with a
.095" x 1¾" Steel Burster

Bis fill = 405.0 grams

Agent/Burster = 2.4/1

Recovery at 10 minutes = 5.1%

Fill Decomposed = 65.3%



.065" x 2⅛" Steel Casing with a
.065" x 1⅝" Aluminum Burster

Bis Fill = 65.0 grams

Agent/Burster = .3/1

Recovery at 10 minutes = 38.9%

Fill Decomposed = 11.5%

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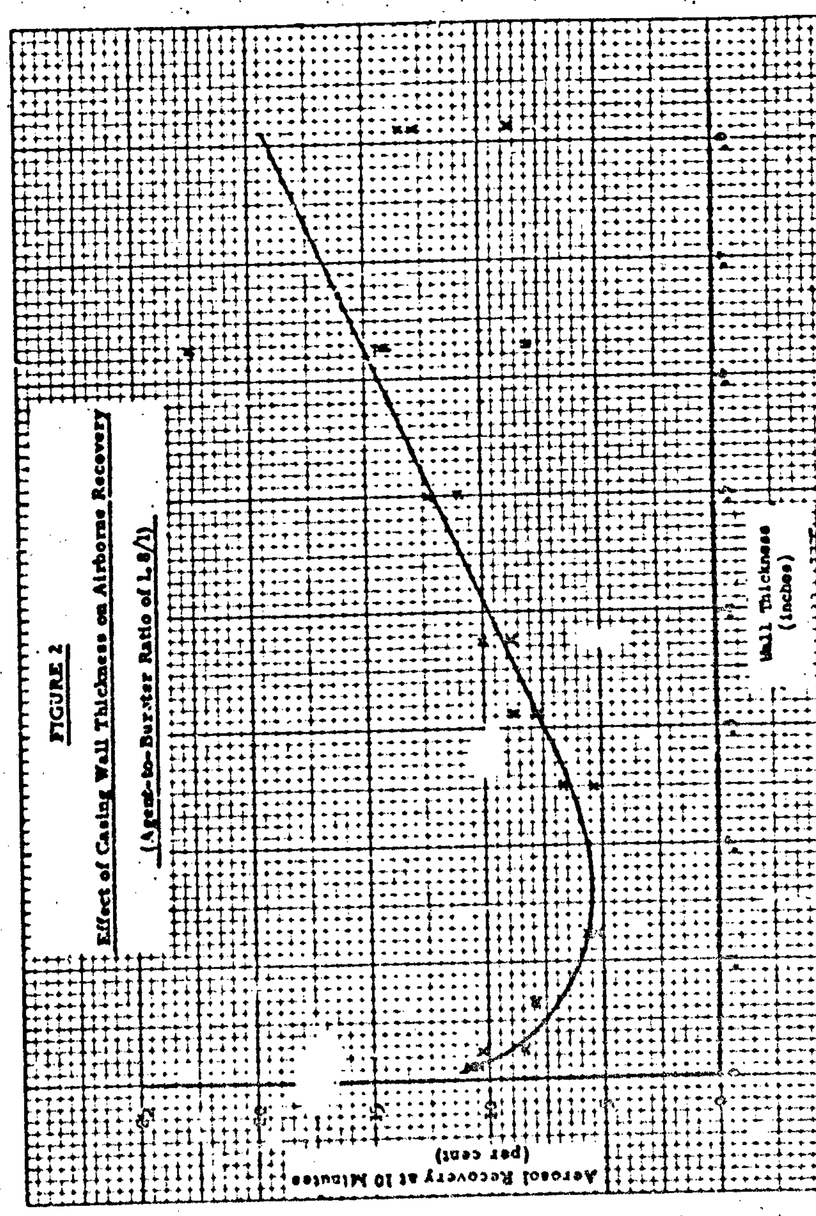

FIGURE 2

Effect of Casing Wall Thickness on Airborne Recovery

(Agent-to-Burster Ratio of 1.8/1)

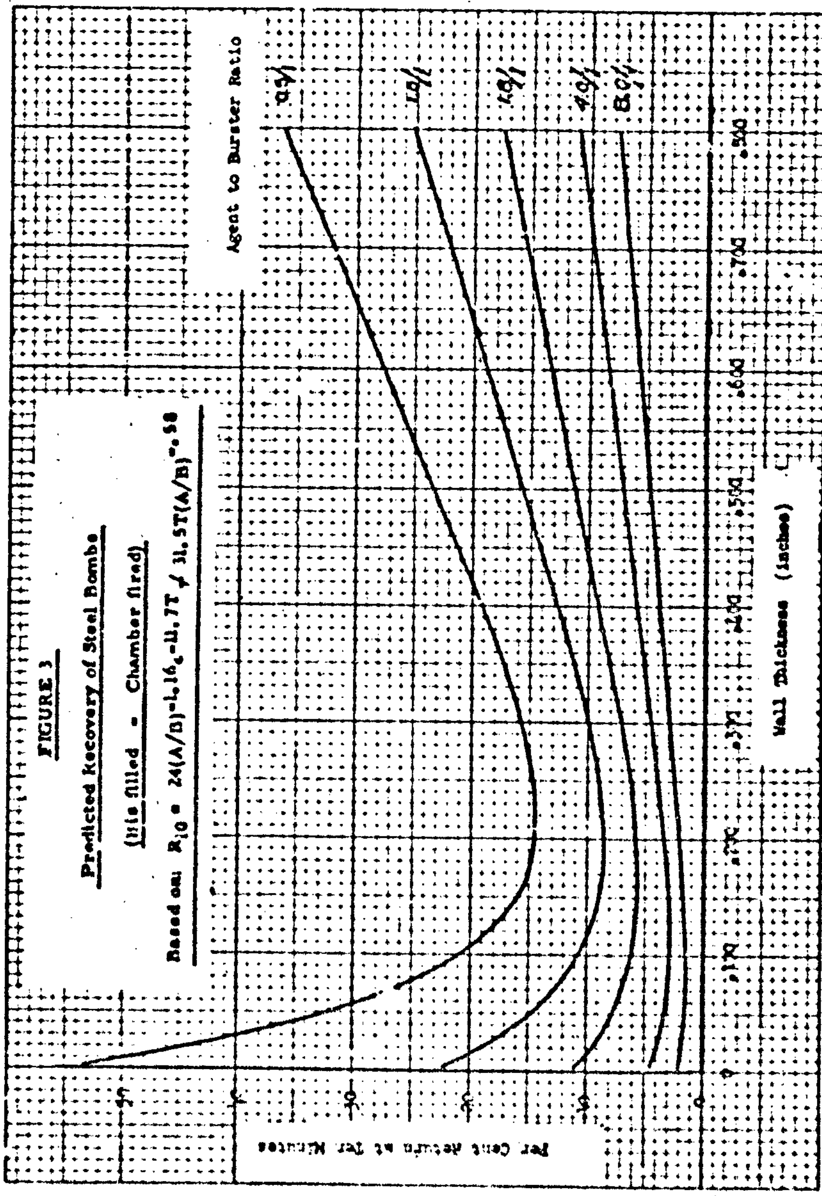

FIGURE 3

Predicted Recovery of Steel Bombs

(Hte filled - Chamber fired)

Based on: $R_{10} = 24(A/B)-1.16_c-11.7T + 11.5T(A/B)^{-.58}$

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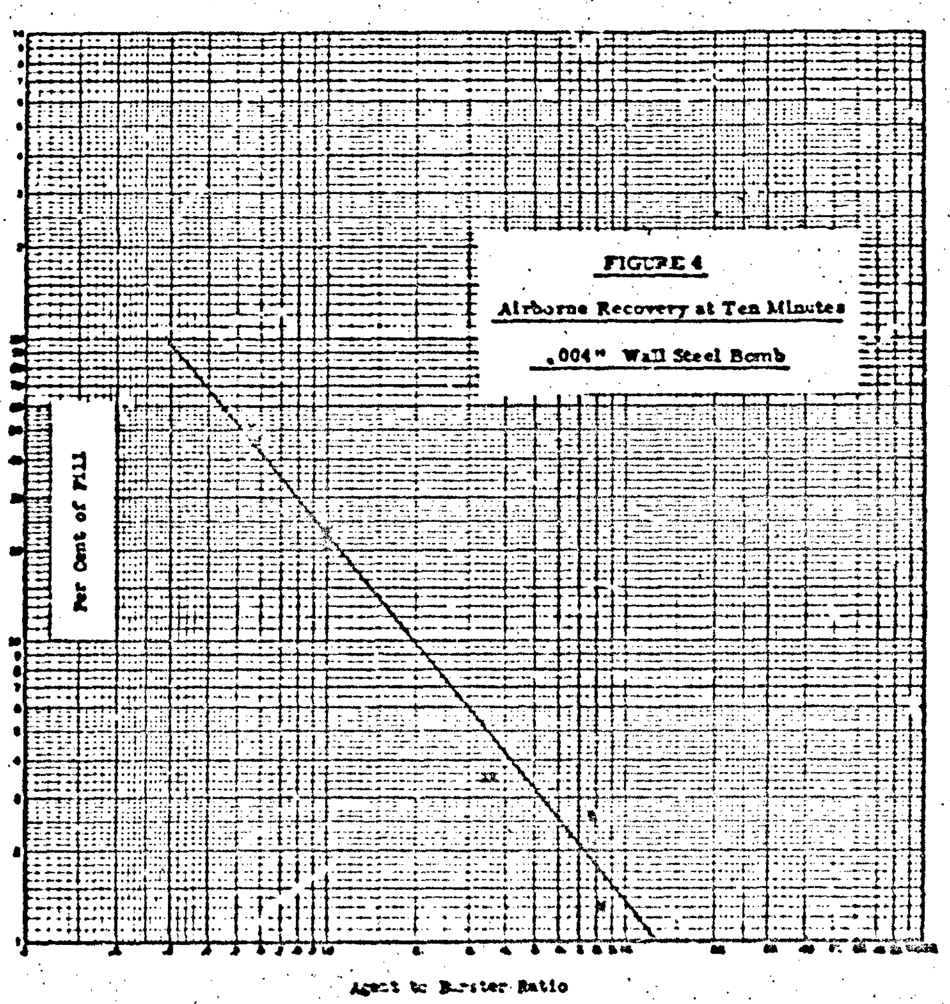

CONFIDENTIAL

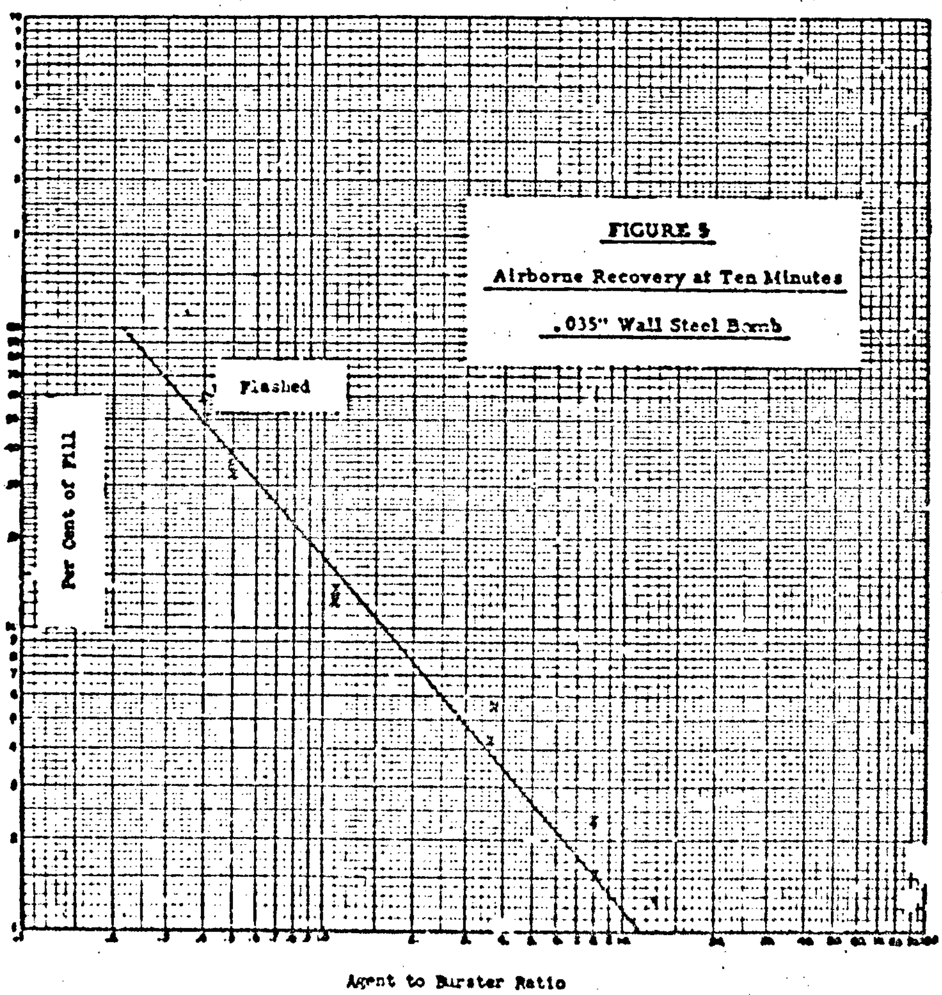
FIGURE 5
Airborne Recovery at Ten Minutes
.035" Wall Steel Bomb
Flashed
Per Cent of Fill
Agent to Burster Ratio

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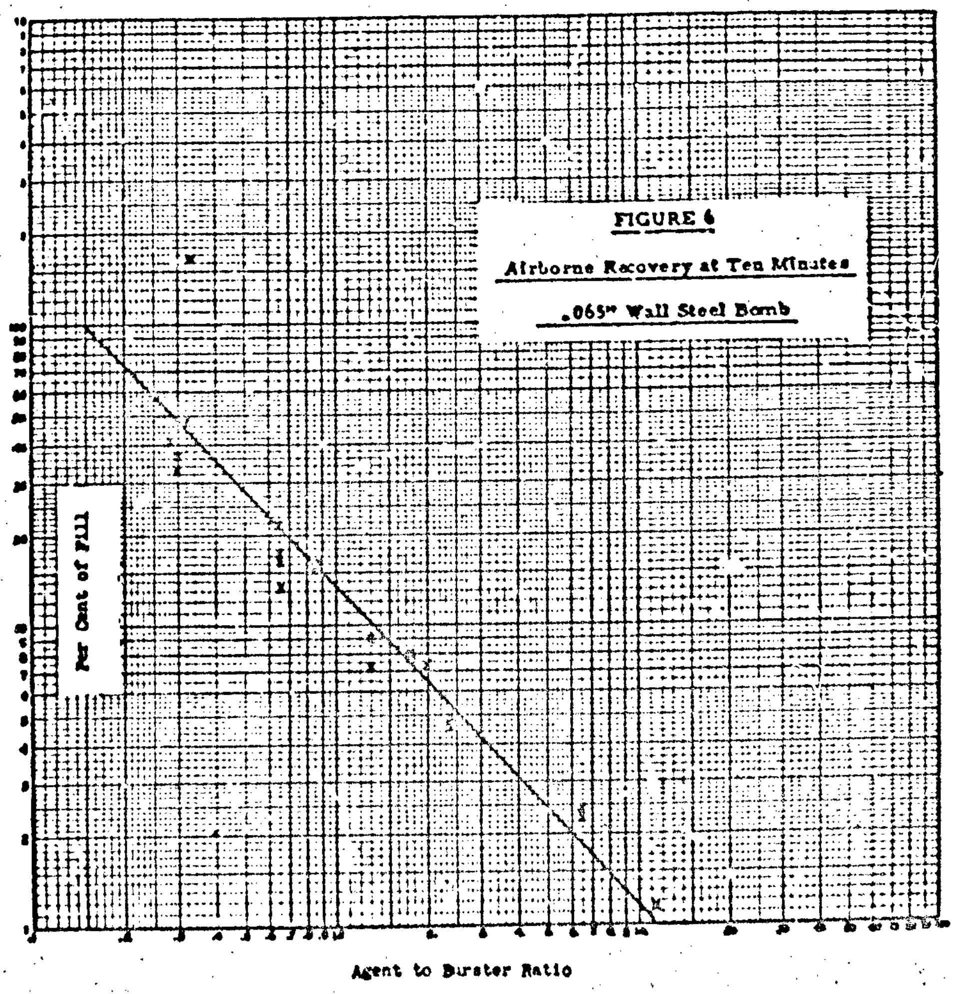

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Appendix

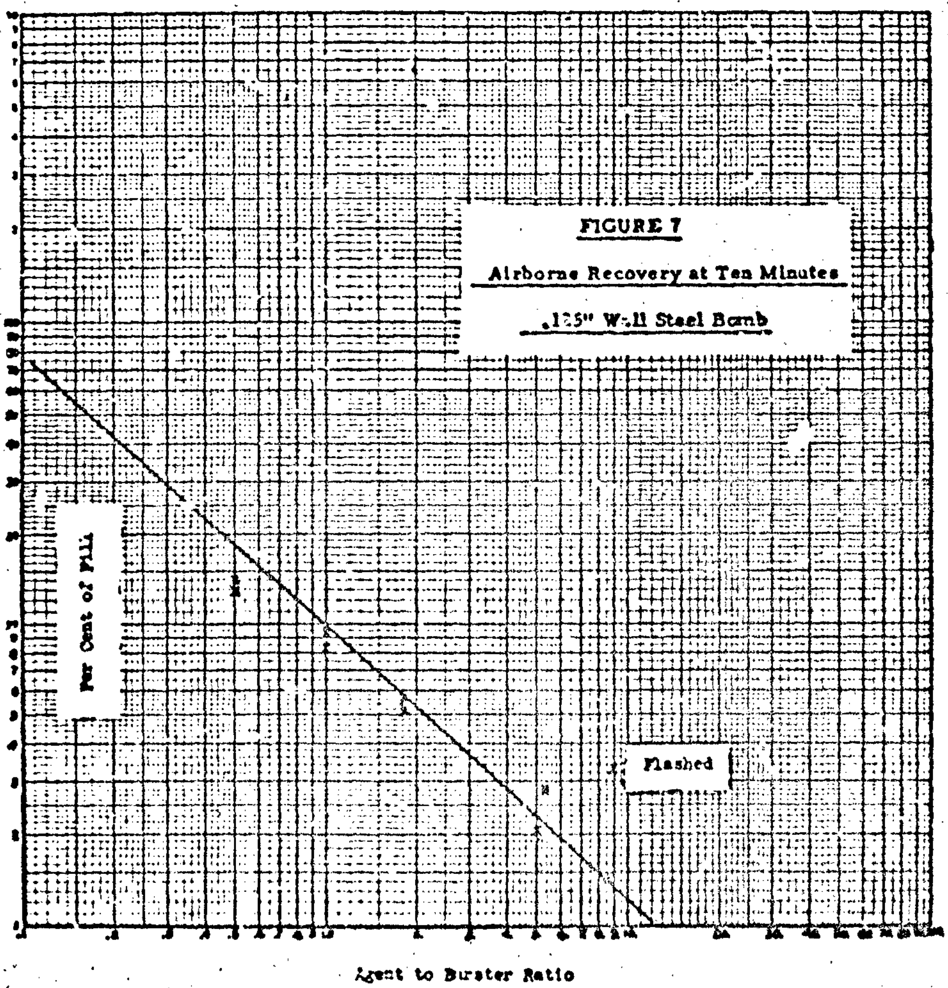


FIGURE 7
Airborne Recovery at Ten Minutes
.125" Wall Steel Bomb
Per Cent of Fill
Flashed
Agent to Burster Ratio

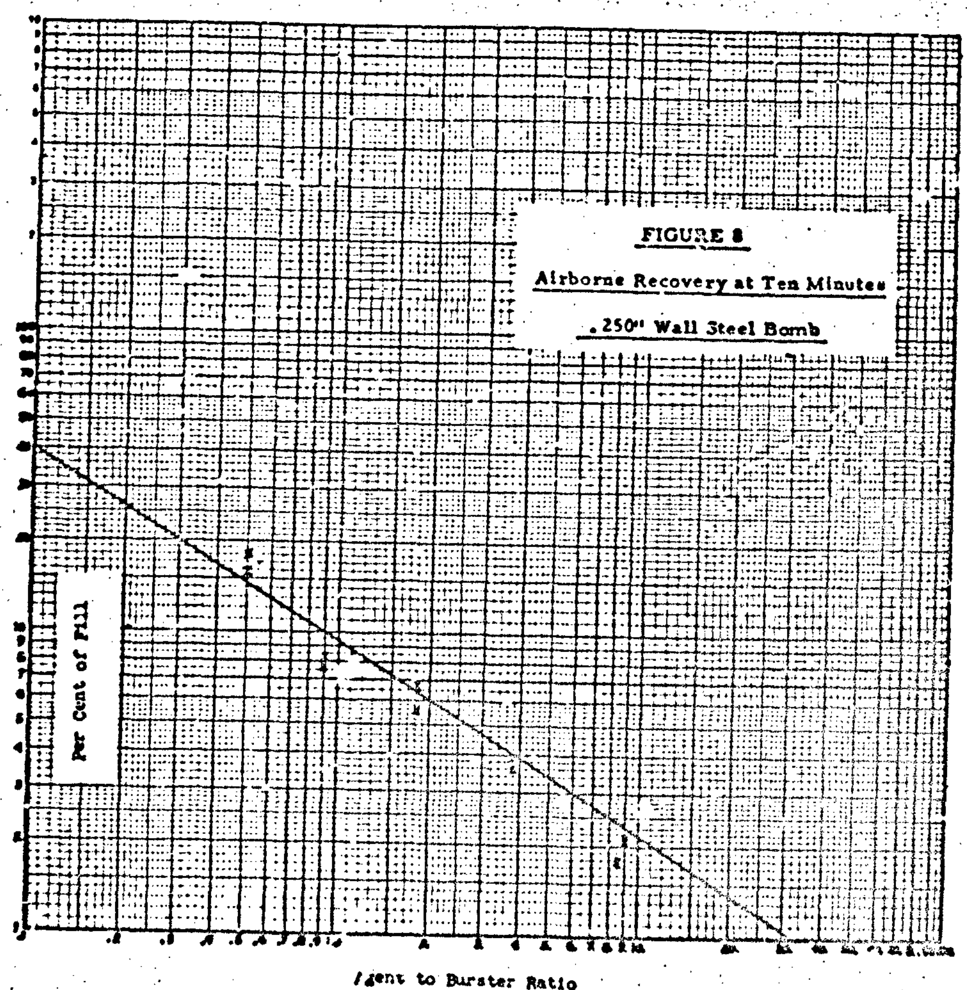


FIGURE 8
Airborne Recovery at Ten Minutes
.250" Wall Steel Bomb
Per Cent of Fill
Agent to Burster Ratio

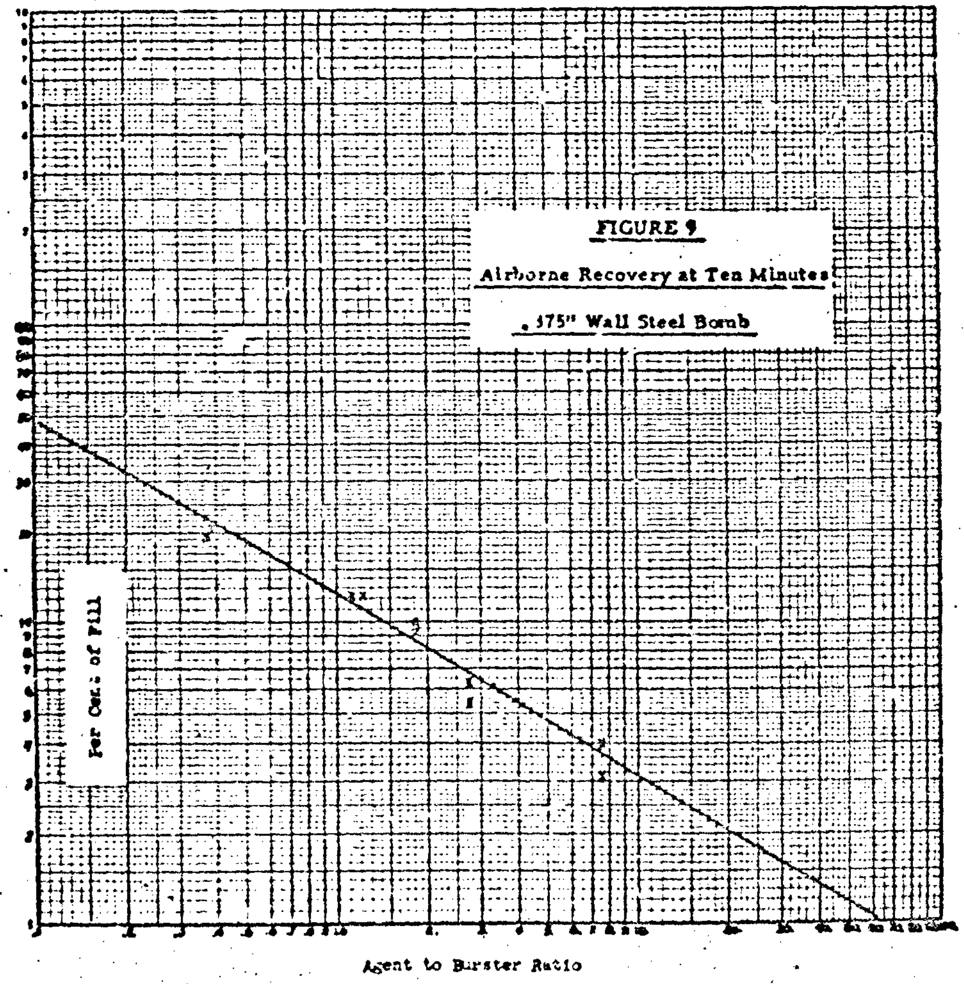


FIGURE 9
Airborne Recovery at Ten Minutes
.375" Wall Steel Bomb
Per Cent of Fill
Agent to Burster Ratio

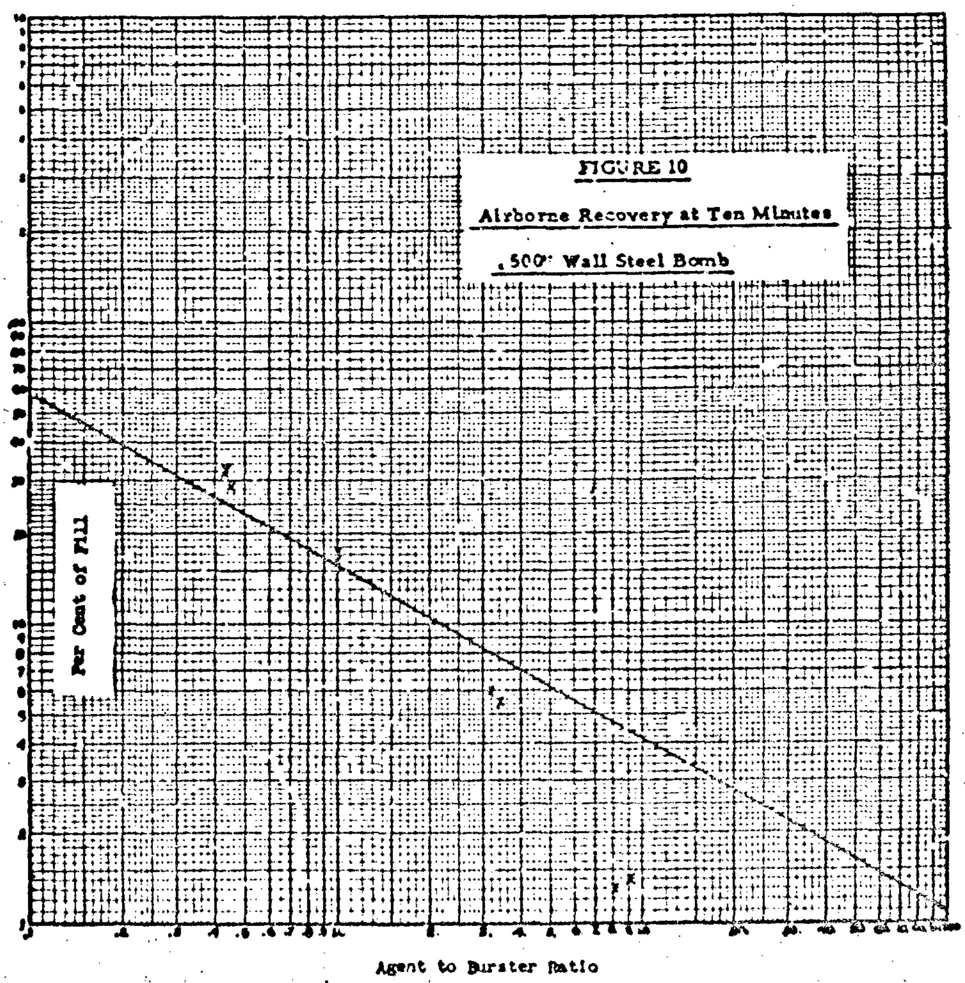


FIGURE 10

Airborne Recovery at Ten Minutes

.500" Wall Steel Bomb

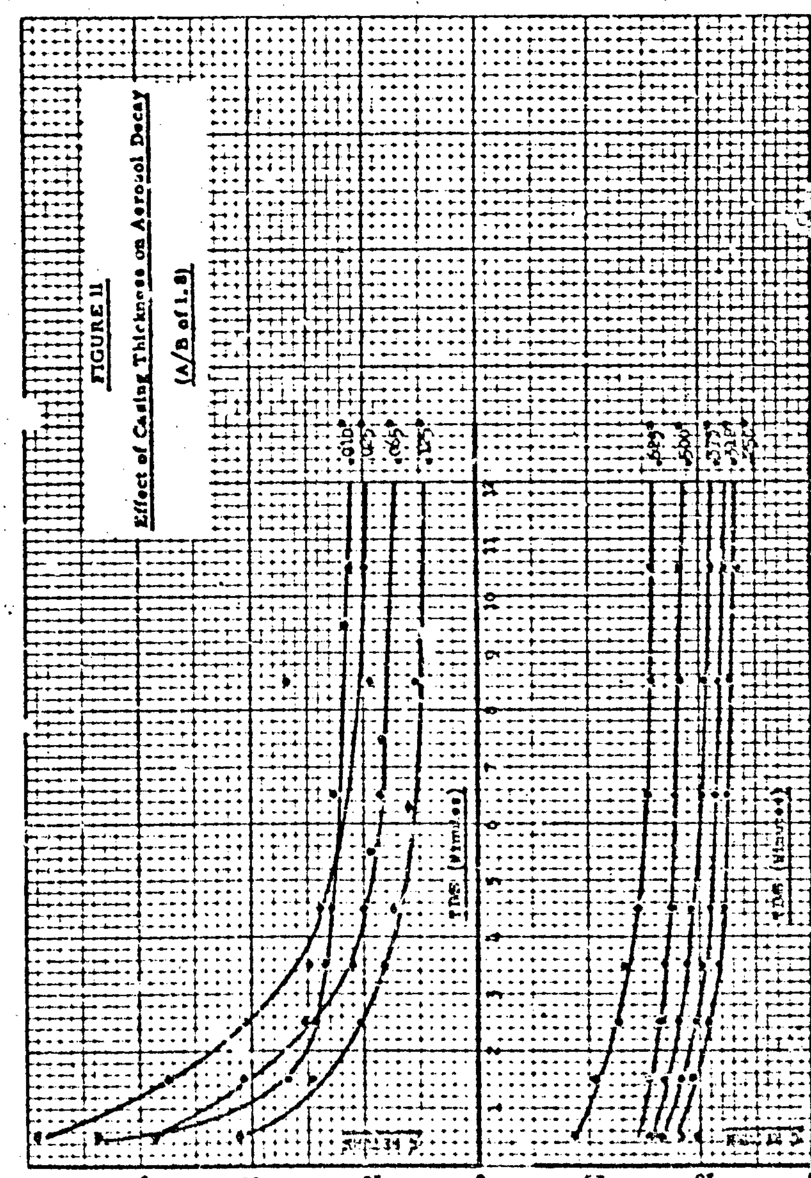


FIGURE 11

Effect of Casing Thickness on Aerosol Decay

(A/B of 1.8)

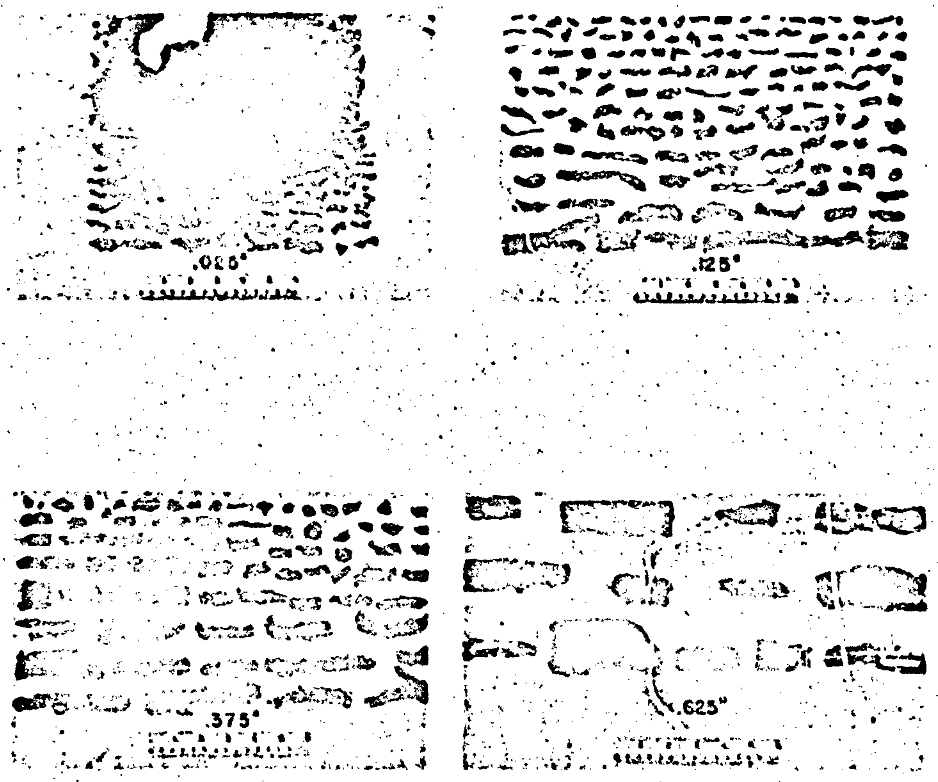
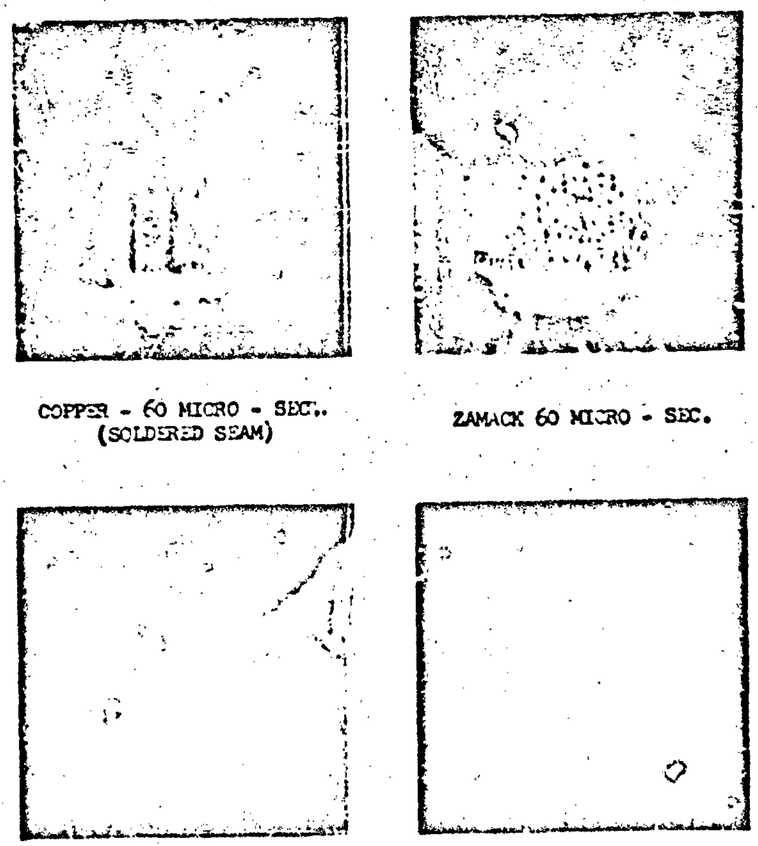


FIGURE 12

Fragments from Various Thickness Steel Casings



COPPER - 60 MICRO - SEC.
(SOLDERED SEAM)

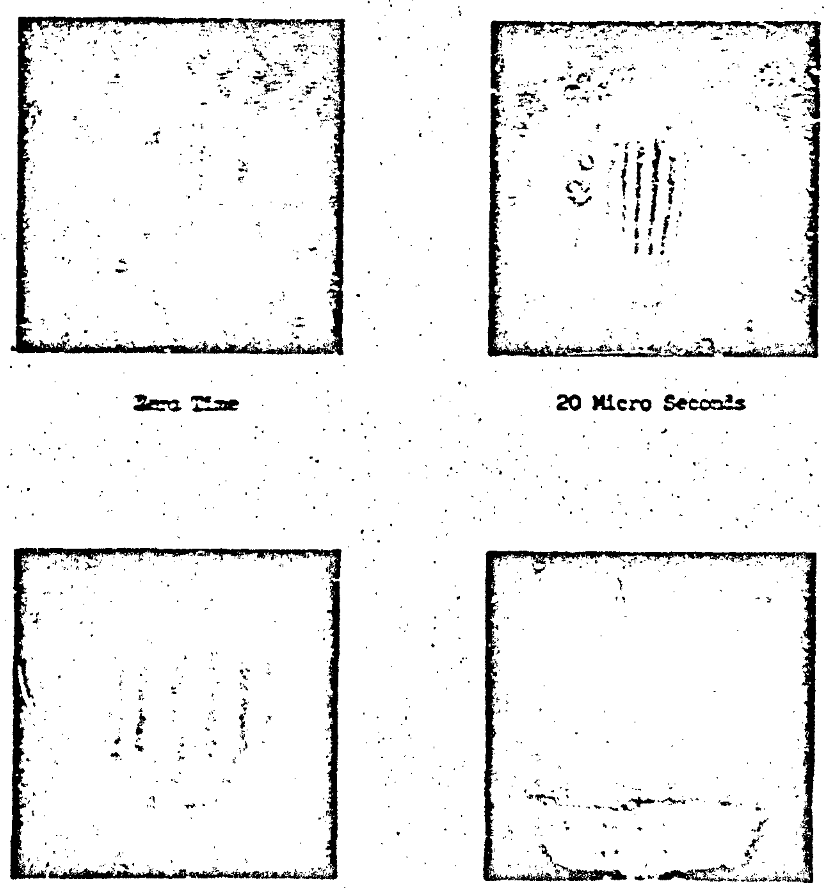
ZAMACK 60 MICRO - SEC.

STEEL - RUBBER COVERED
60 MICRO - SEC.

STEEL - RUBBER COVERED
80 - MICRO SEC.

FIGURE 13

JETTING CHARACTERISTICS



Zero Time

20 Micro Seconds

60 Micro Seconds

100 Micro Seconds

FIGURE 14

Rubber Devices

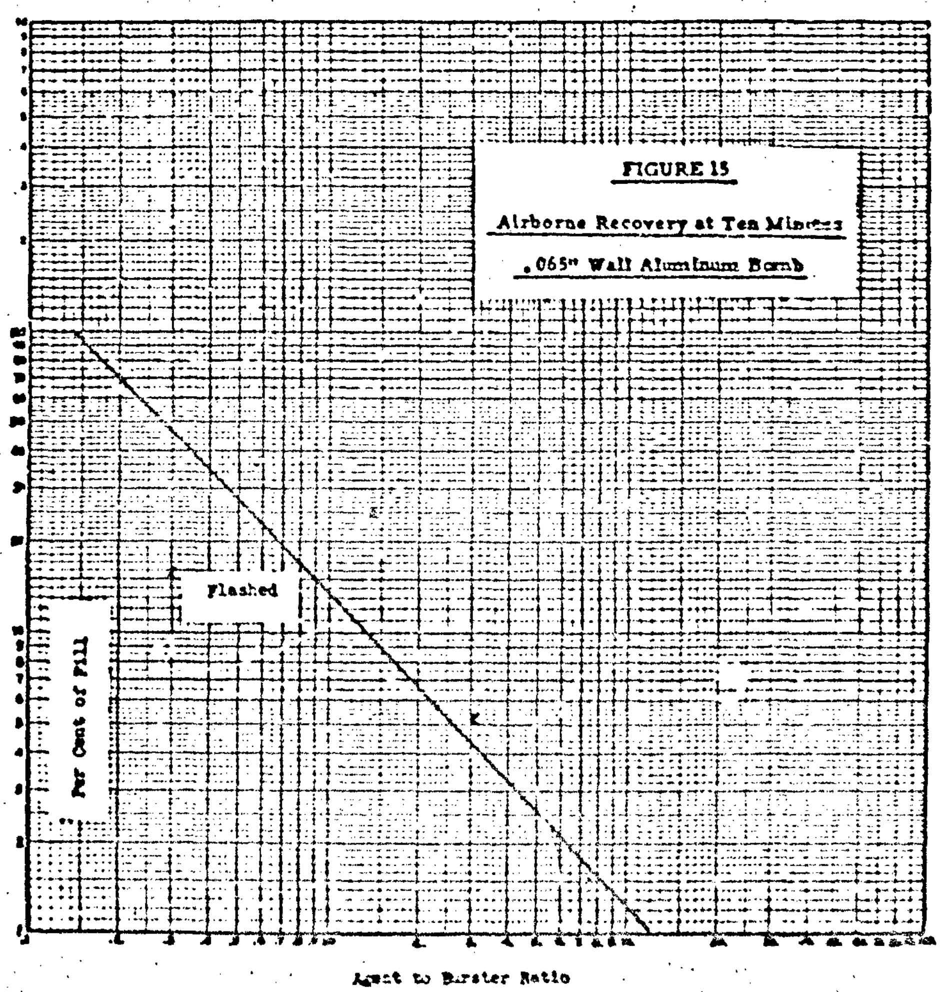


FIGURE 15

Airborne Recovery at Ten Minutes

.065" Wall Aluminum Bomb

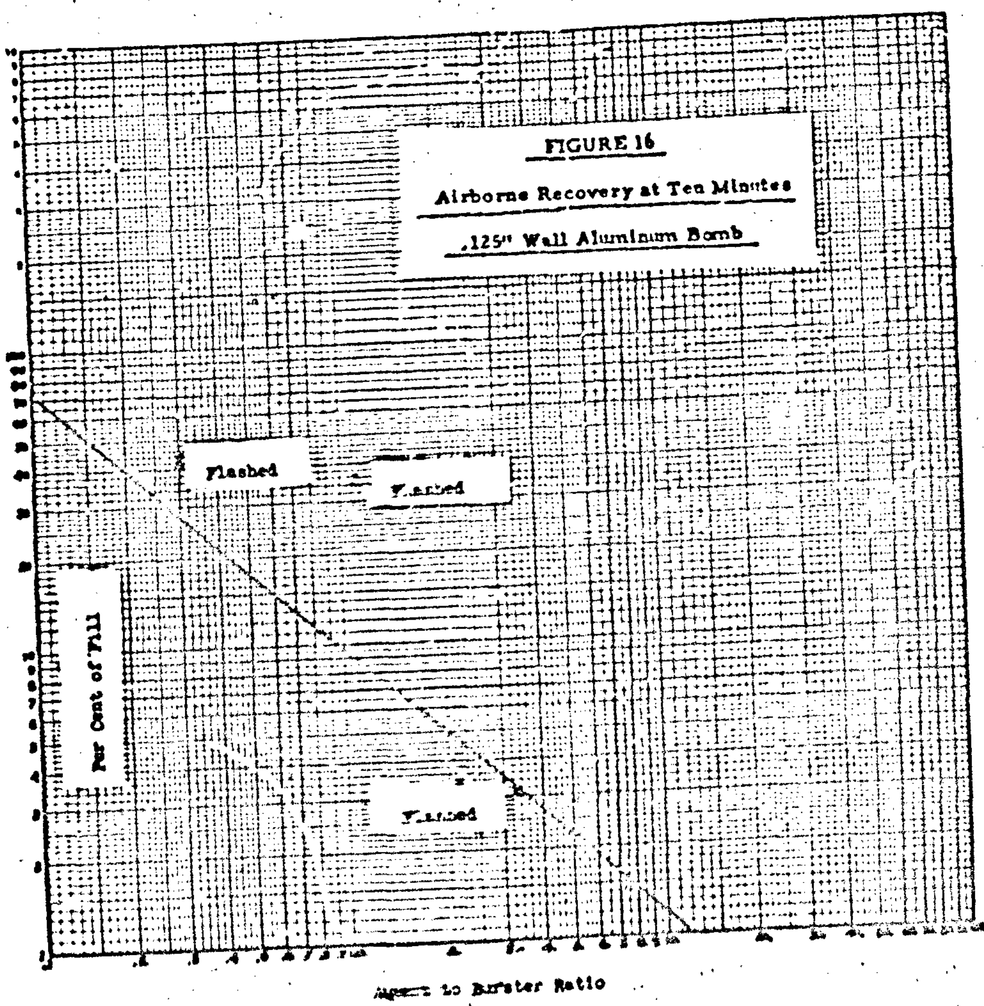


FIGURE 16
Airborne Recovery at Ten Minutes
.125" Wall Aluminum Bomb
Flashed
Flashed
Flashed
Per Cent of Fill
Agent to Burster Ratio

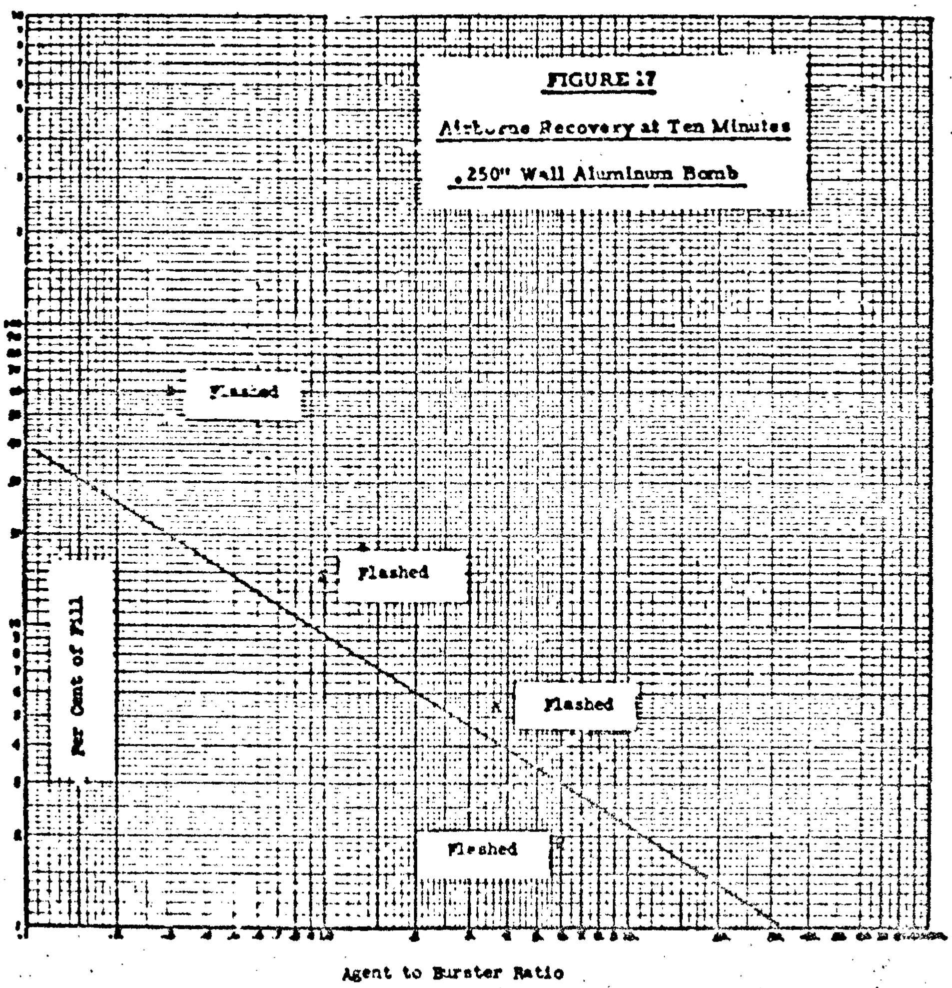
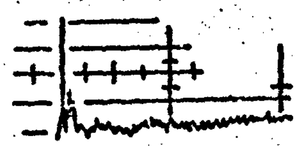


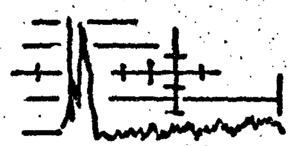
FIGURE 17
Airborne Recovery at Ten Minutes
.250" Wall Aluminum Bomb
Flashed
Flashed
Flashed
Flashed
Per Cent of Fill
Agent to Burster Ratio

FIGURE 18

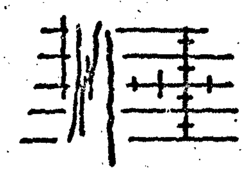
Effect of Wall Thickness on Flashing of Aluminum Bombs



A .065" casing bomb.



A .125" casing bomb.



A .250" casing bomb.

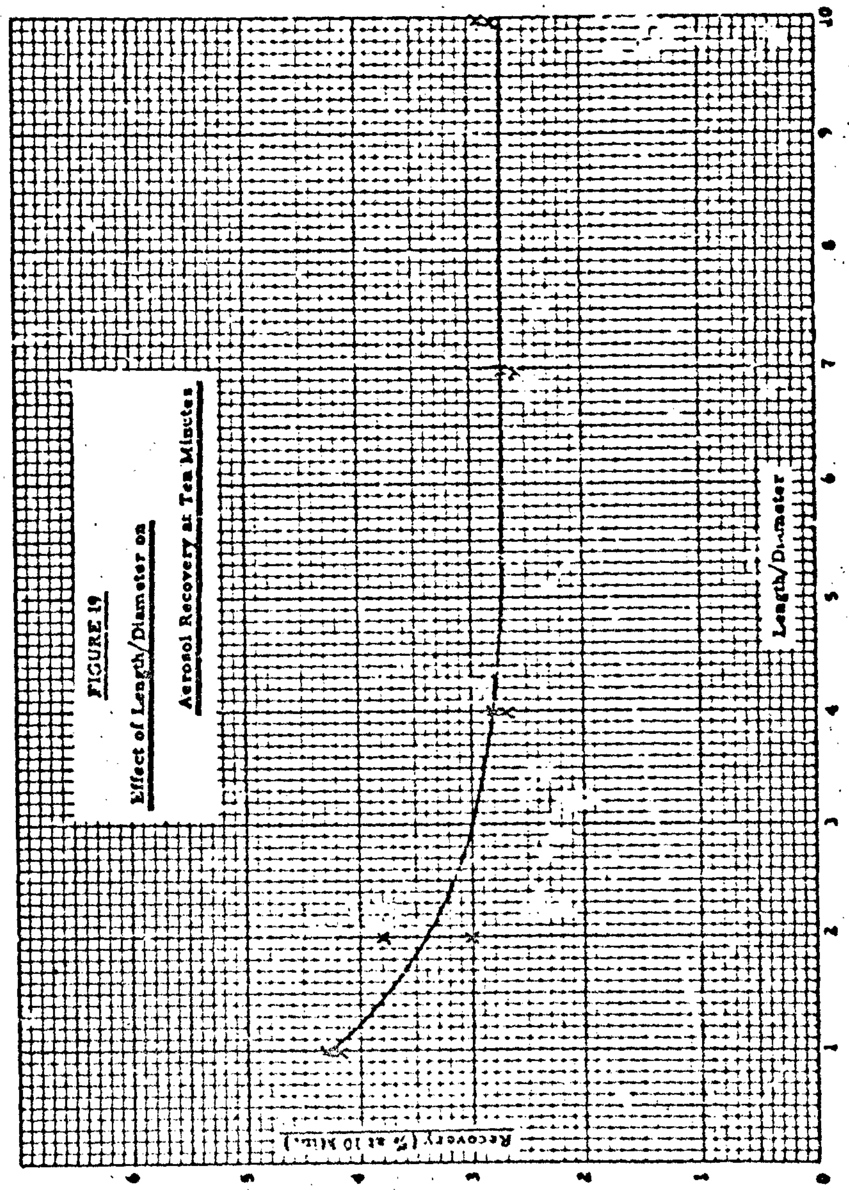


FIGURE 19

Effect of Length/Diameter on Aerosol Recovery at Ten Minutes

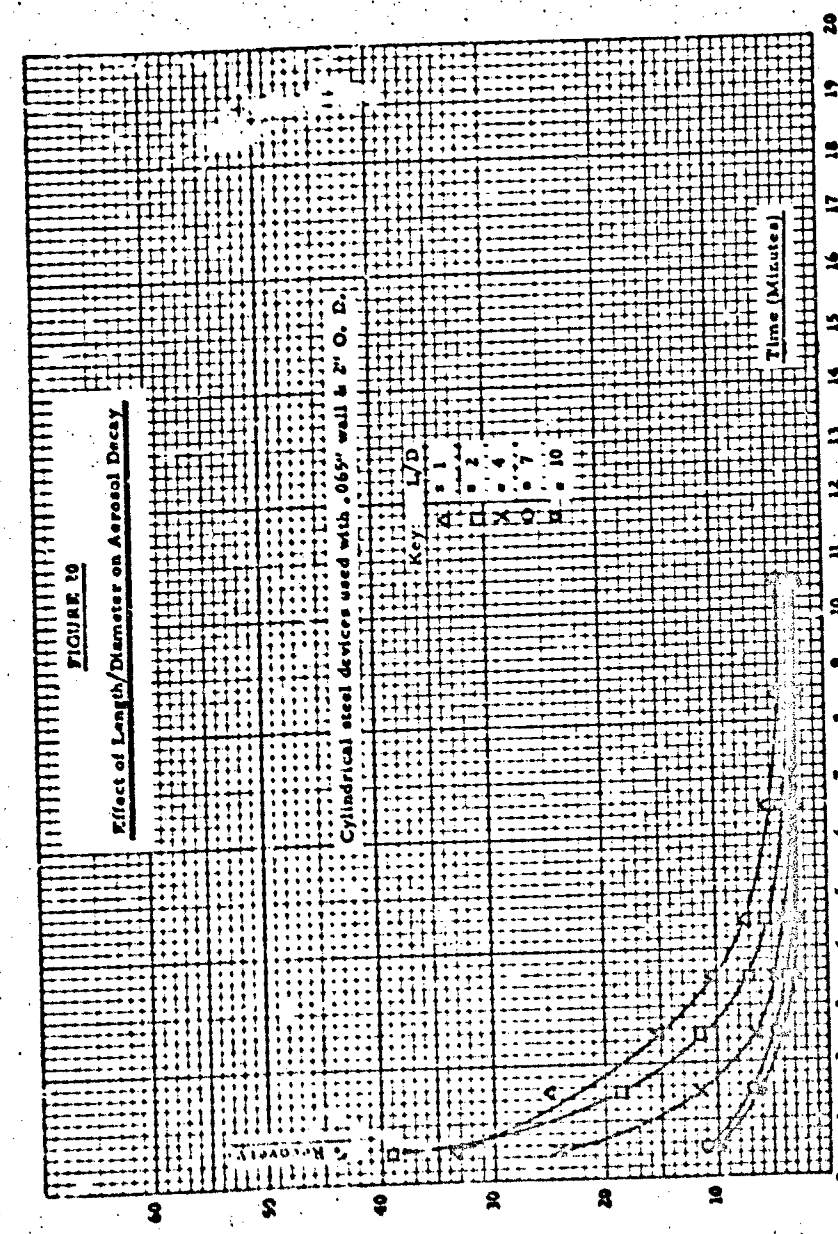


FIGURE 10
Effect of Length/Diameter on Aerosol Decay
Cylindrical steel devices used with .065" wall & 2" O. D.
Key L/D
△ = 1
□ = 2
X = 4
⬠ = 7
⌧ = 10
Time (Minutes)
% Recovery
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
10 20 30 40 50 60

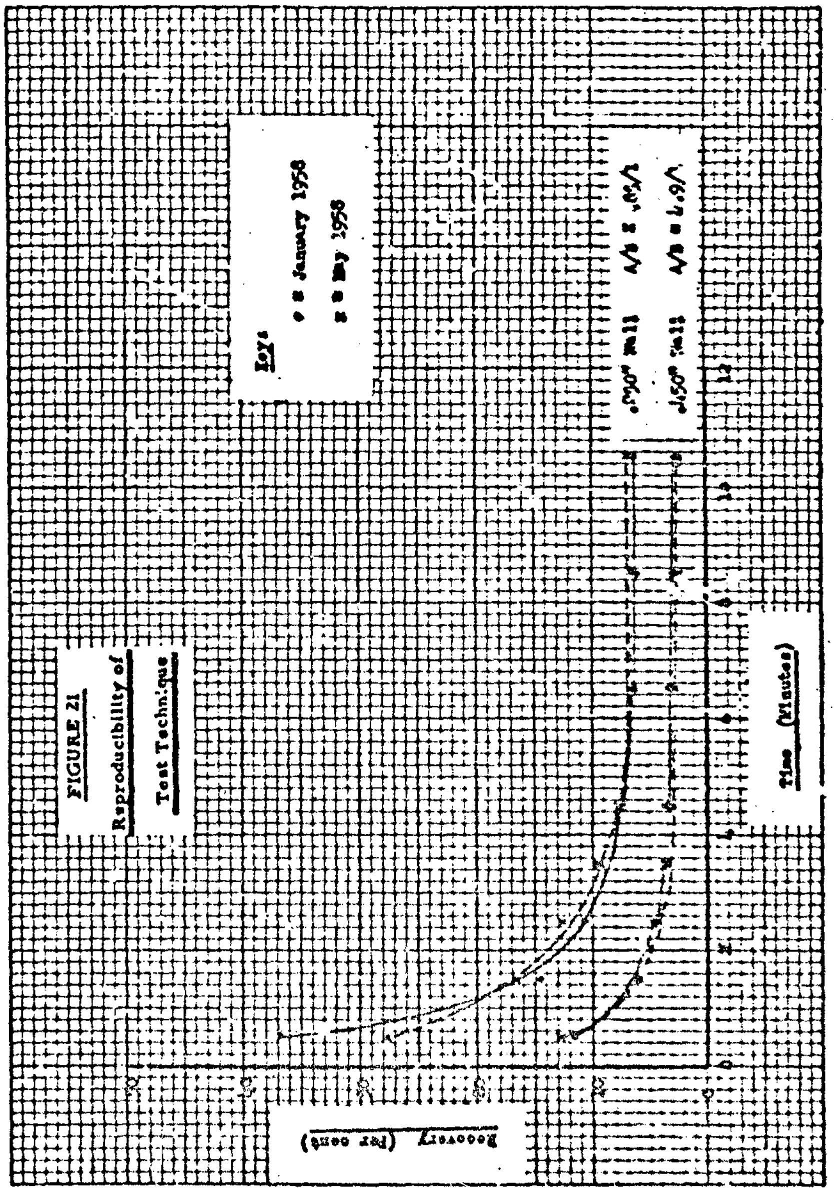


FIGURE 21
Reproducibility of Test Technique

[redacted]

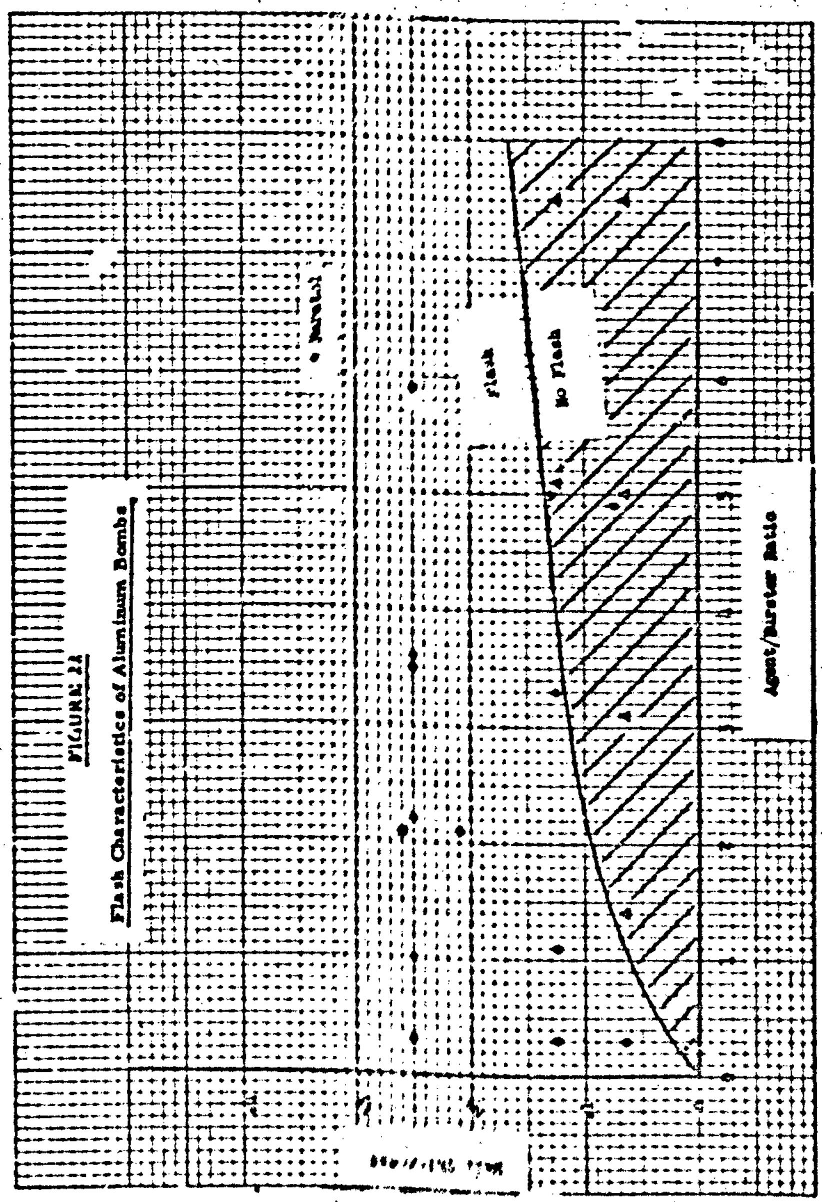


FIGURE 22

Flash Characteristics of Aluminum Bombs

[redacted]

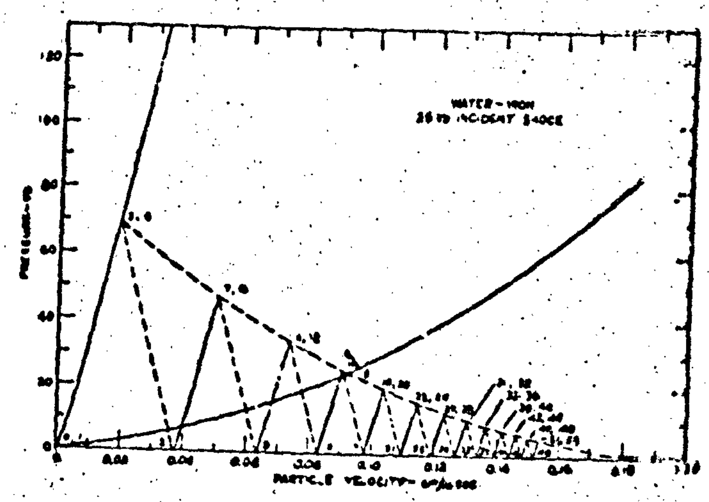


FIGURE 23

SHOCK DECAY CHARACTERISTICS

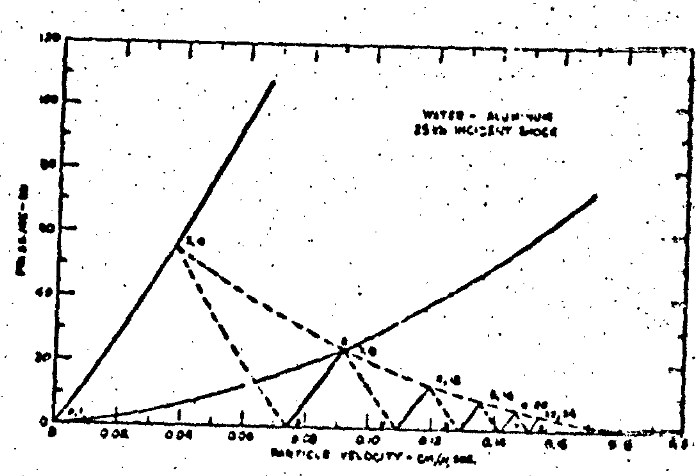


FIGURE 24

SHOCK DECAY CHARACTERISTICS

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[redacted]

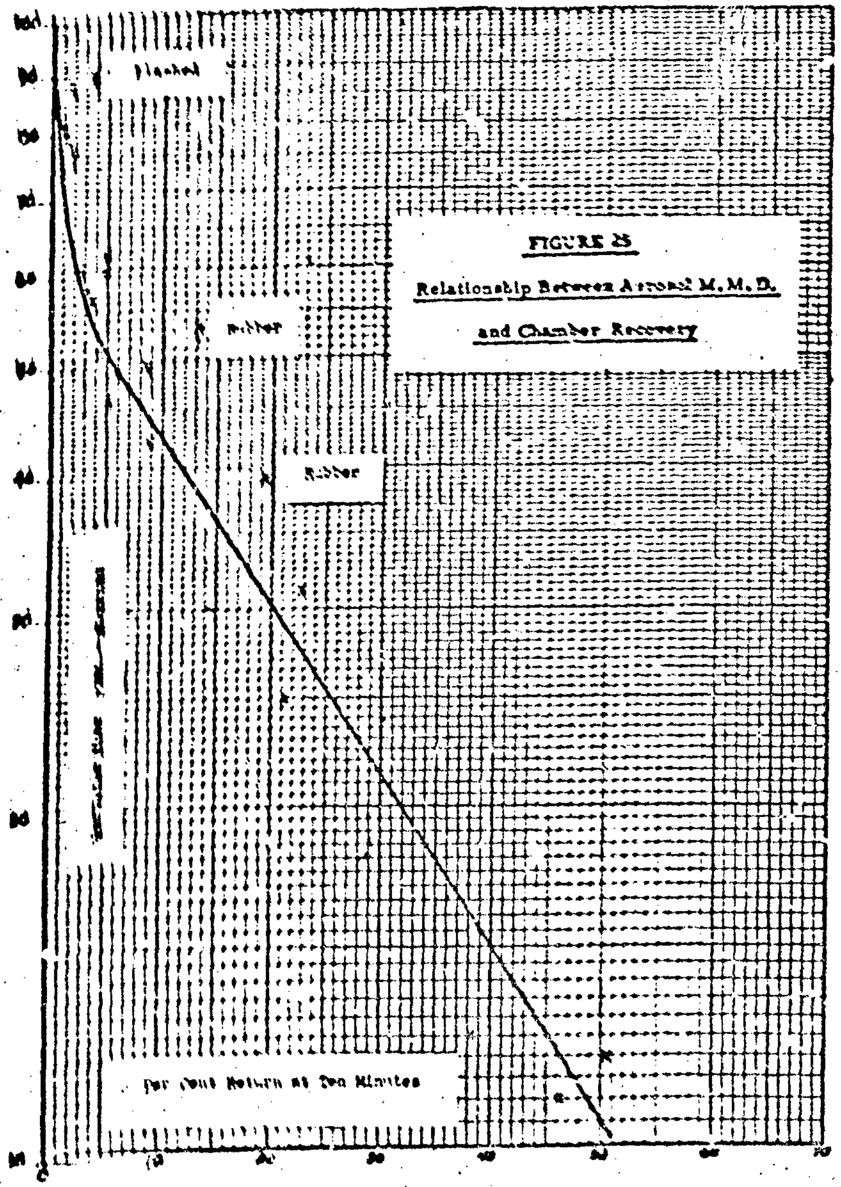

FIGURE 25

Relationship Between Aerosol M.M.D. and Chamber Recovery

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