Hazards Produced by Explosions Inside Earth-Covered Igloos

by

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ABSTRACT

The airblast and fragmentation produced by explosions inside earth-covered explosive storage structures (igloos or bunkers) have been reexamined and reanalyzed. The data were examined with the following questions in mind: (1) How do they compare with current Department of Defense Explosive Safety Standards? (2) Can the data be scaled to produce general, empirically-derived, prediction equations? Both goals were met. The data from very small-scale model tests to very large scale events collapse to a single set of prediction lines. These prediction equations are presented. It was discovered that there is a major deficiency in the data relating to the debris/fragmentation produced by explosions inside such structures.

INTRODUCTION

At the request of the Department of Defense Explosives Safety Board (DDESB), the Naval Surface Warfare Center (NAVSWC) has conducted a review of the available airblast and fragmentation/debris information that was been produced by explosions within earth-covered, explosives-storage magazines. The goals of this effort are to recommend possible changes to the applicable standards (if needed) and to provide the best available prediction tools for both fragmentation/debris and airblast. The effort began during the 1990 fiscal year with the collection and collation of the data. During fiscal year 1991, the data were compared with existing Department of Defense (DOD) explosives safety standards and the results published as reference 1. It should be pointed out that all the information developed to date has been based on full-scale testing. During the current fiscal year (1992), the results of several model studies have been included in this data base. The model studies were conducted in the United States, the United Kingdom, and France. This paper, then, updates Reference 1.

According to DOD-6065.9-STD[2], standard earth-covered magazines are approved for all quantities of explosives up to 500,000 pounds (227,273 kg) net explosive weight (NEW). The standard defines five basic types of standard magazines: (1) reinforced concrete, arch-type magazines, (2) Navy-type magazines, (3) box-type A magazines, (4) earth-covered, corrugated steel, arch-type, and (5) earth-covered, circular composite arch. During the past 40 plus years of testing, most or all of these types have been tested at one time or another. For the remainder of this report, the author will use the generic term "earth-covered igloo" when referring to all of these above-ground, earth-covered storage magazines.

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The United States Air Force has conducted many tests in structures which they have termed Modular or Hayman Igloos. These are also earth-covered but of a much simpler design. These Air Force structures have not been established as a standard type of magazine, therefore, they are only approved for storage up to 250,000 pounds.

The earliest documented testing of earth-covered igloos occurred shortly after World War II. These tests were conducted at the Naval Proving Ground, Arco, Idaho. During the 1960s, tests were conducted at the Naval Ordnance Test Station (NOTS) (now, Naval Air Weapons Center, China Lake, CA). These tests examined earth-covered, steel arch type magazine construction. Beginning in 1971, the DDESB began a series of tests call ESKIMO (ESKIMO is an acronym for Explosive Safety Knowledge IMprovement Operation). The Air Force testing of their Hayman and Modular Igloos was conducted during the period 1986 to 1988. These events are discussed in more detail in Reference 1.

While this full-scale testing was on-going, a series of model tests was also being conducted. Two small-scale test series (1/50-scale and 1/30-scale) were conducted by Kingery, et. al., in 1976[3] and 1982[4]. The United Kingdom conducted two series of 1/10-scale model tests in 1971[5] and 1976[5]. The French have recently (1991) completed a series of 1/3-scale model tests[6]. These events were not considered in the compilations presented in Reference 1.

These, then, form the basis from which a data base of airblast and fragmentation has been prepared. Many of events considered for this program and presented in Reference 1 were not suitable for inclusion in the data base. The reasons for the omissions are discussed in detail in Reference 1.

Table 1 gives some details for each of the events in the data base. The information includes charge weight and type and the charge-to-volume ratio. Further details can be obtained from Reference 1, 3, 4, 5, and 6. Many tests were not conducted under standard conditions. Because of this, all the data have been scaled to sea level conditions before inclusion in the data base. Other analyses have shown that the charge-to-volume ratio is not a controlling variable for ratios greater than 0.7. For this reason each of the events shown that had tests at multiple charge-to volume ratios have been plotted as the same event.

FRAGMENTATION/DEBRIS

The DDESB defines a hazardous fragment density as "...a density of hazardous fragments exceeding one per 600 sq. ft. (56.7 m^2)." A hazardous fragment is defined as "one having an impact energy of 58 ft-lb (79 Joules) or greater." Recent interpretations by the Secretariat of the DDESB have taken the 600 ft^2 to be measured trajectory-normal as opposed to ground surface pickup. Procedures for the standardization of the analyses of debris have also been produced[7]. These standardized procedures have been used to reexamine the available debris data.

Only three events collected debris information that might be considered useful-ESKIMO I, ESKIMO VI, and HASTINGS IGLOO. Of these three, the ESKIMO I event collected detailed fragmentation/debris data over a full 360° azimuth. ESKIMO VI presented only descriptive information, so no quantitative determinations can be drawn from it.

ESKIMO I

These data were presented in graphs in terms of debris densities as a function of range for various debris weights ($\geq$0.125 pound, $\geq$0.28 pound, and $\geq$1.0 pound). The data were converted to pseudo-trajectory normal densities as described in Reference 7 and analyzed according to the recommended procedures. Figures 1 through 3 present the results. Remember that the hazardous fragment range is the range at which the pseudo-trajectory normal density reaches a value of 1. Thus, out the front of the igloo on this test the hazardous fragment range was 3857 feet; off the side it was 2743 feet; off the rear it was 2376 feet. These correspond to scaled ranges of 66.0, 46.9, and 40.6 ft/lb$^{1/3}$, respectively.

HASTINGS IGLOO

Significant debris data were collected on four of the HASTINGS IGLOO tests--the 60-, 80-, 100-, and 150-pound tests. Fragment density distributions at distances less than 175 feet (53 meters) were not used due to the masking effect of a blast shield in front of the structure.

It is necessary to describe the test structures before the results are presented. The site was part of an abandoned Navy Ammunition Depot that was constructed during World War II. All the structures exhibited structural failures in the form of hairline cracks in the sidewalls, arch crest, backwall, and headwall. Erosion of the earth cover was observed in many cases due to a lack of maintenance. The magazine headwalls faced an earth-backed concrete blast shield. The distance between the vertical headwalls and the blast shields varied between 12 feet at the base and 15 feet at the top.

The debris results are summarized in Figures 4 through 7. On each test, debris was collected in three separate zones: 0° to 5°, 5° to 10°, and 10° to 45°. The hazardous fragment range (i.e., the range at which the hazardous fragment density becomes 1) extended to significant scaled distances out the front. The unscaled ranges are shown on each graph. These ranges correspond to scaled distances of 104.7, 122.3, 91.3, and 126.3 ft/lb$^{1/3}$. These scaled ranges are much greater that those measured on ESKIMO I. They may be affected by the poor condition of the structures existing at the time of the test. More importantly, however, the loading densities (charge weights/internal volume of structure) used on these tests were quite low; thus, the roof and sides of the structure did not fail, causing the debris to channel out the front like a shotgun. Even though the scaled debris ranges were quite large, the actual range is less than 700 feet for the 150 pound event.

AIRBLAST

DOD 6055.9-STD and NATO guidelines define several acceptable exposures which might be applied to aboveground magazines. These are:

1. Permissible exposure to airblast overpressure-barricading required: $9W^{1/3}$ (11.7 psi)
2. Unbarricaded aboveground magazine distance: $11W^{1/3}$ (8.0 psi)
3. Unbarricaded intraline distance: $18W^{1/3}$ (3.5 psi)
4. NATO Workshop distance: $20.2W^{1/3}$ (2.95 psi)
5. Public Traffic Route Distance-W < 100,000 pounds: $24W^{1/3}$ (2.3 psi)
6. Public Traffic Route Distance-W>250,000 pounds: $30W^{1/3}$ (1.7 psi)
7. NATO Public Traffic Route: $37.5W^{1/3}$(1.28 psi)
8. Inhabited Building Distance-W < 100,000 pounds: $40W^{1/3}$(1.2 psi)
9. Inhabited Building Distance-W>250,000 pounds: $50W^{1/3}$ (0.9 psi)
10. NATO Inhabited Building Distance: $58.7W^{1/3}$(0.725 psi or 50 mbar)
11. NATO Twice Inhabited Building Distance: $115W^{1/3}$ (0.29 psi or 20 mbar)

These guidelines will form the basis of comparison against which the composite data generated in this study will be compared.

Airblast information has been collected on all of the events listed in Table 1. These data have been Hopkinson-scaled to sea-level conditions and a charge weight of 1 pound. The TNT equivalence of the various types of explosives used on these tests has not been taken into account; rather, the net explosive weight (NEW) of the event has been used. Figures 8, 9, and 10 present the peak pressure out the front, side, and rear of the structure. Figures 11, 12, and 13 present the positive impulse for these same three directions. Also shown on each Figure is a least-squares curve fit to the data.

Because of the least squares fitting process, approximately 50% of the data will be above the fitted curve and 50% will be below. When the scatter in the data is small or when general estimates are required, the fact that 50% of the data can be above the fitted curve is not worrisome. However, when making estimates for safety purposes, the fact that 50% of the data could be above the fitted curve is extremely worrisome. This can be addressed in one of several ways--each of which would produce a more safety-conservative estimate. A traditional method has been to increase the NEW by a safety factor--usually taken to be 20%. A second method has been to increase the predicted pressures by a safety factor--again taken to be 20%. A third method which has been discussed is to take the upper bound of the 90% confidence interval for the predicted pressure.

Each method has its advantages and disadvantages. The third is the most rigorous from a statistical standpoint; however, making these types of estimates for non-linear curve fits is a time consuming and difficult process. The second is probably the easiest to understand, and the first is rooted in tradition. Unfortunately, the idea of increasing predicted ranges for safety predictions often meets considerable resistance. This problem is still to be resolved. The first two methods are compared in Table 2. As can be seen, the second method (that of increasing the predicted values by a factor of 1.2) is extremely conservative. The first method, that of increasing the charge weight by a factor of 1.2, is a reasonable compromise.

The equations given in Figures 8, 9, and 10 have been used to make predictions for the acceptable exposures given above. These results are presented in Table 3. Also given in this Table are the currently accepted (Standard) values. It is evident that off the rear of the structure, the Standard is overly conservative for all exposure levels considered. Off the front and side, the Standard is overly conservative only at the lower exposure levels.

Another effort of this study was the determination of an equivalent weight (relative to the Standard) for each direction. It must be remembered, however, that this equivalence does not take into account any effects produced by the case effects of the munitions or the TNT equivalence of their fills. Figures 14, 15, and 16 present the equivalence for each direction. The average equivalence for the front and side are quite close; that out the rear is significantly lower. Out the front and the side there is a significant dependence of the equivalence on the pressure level--indicating that the pressure-distance curves in these directions are not behaving in the same manner as the standard; i.e., the curves are not parallel with the standard. Out the rear, this is not the case. The equivalence is almost independent of the pressure level--indicating that over this pressure range (0.5-10 psi) the curve is parallel to the standard.

SUMMARY/DISCUSSION

A data base of debris and airblast produced by explosions inside earth-covered, aboveground storage structures has been generated. Based on this data base, prediction equations for the airblast have been generated. These equations were then used to predict values which were compared with the current standard.

Only a limited amount of debris information exists. Before significant refinements in the standards for debris can be developed, additional information must be obtained.

Using the prediction equations developed, the equivalence (relative to the Standard) has been developed. Out the rear, the Standard grossly over-predicts the pressure (the equivalence is only about 0.3). Out the front and side, the equivalence averages approximately 0.7. At the lower pressure ranges, the Standard still over-predicts the pressure--indicating that the Standard should be changed.

Scientists in the United Kingdom have taken a slightly different approach to this problem. Instead of developing prediction equations based on the composite data, as was done here, they have developed curve fits for each separate test (ESKIMO I, NOTS 6, etc). The predictions based on the answers from all of these curve fits are then averaged to produce a single result[5]. A comparison of the two methods has indicated that the results do not differ by more than about 5%.

The Standard is currently tied to airblast data. Before the hazard ranges are changed for earth-covered igloos, the debris hazard range must also be considered. ESKIMO I has produced the only useable debris data. This data indicates that the debris hazard range exceeds the airblast hazard range, implying that any changes to the Standard must include both effects.

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4. Kingery, et. al., "Effect Of Low Loading Density On Blast Propagation From Earth Covered Magazines," Technical Report ARBRL-TR-02453, Dec 1982.

5. Connell, M. and Poynton, J., "Blast Pressure Quantity-Distance Reduction For Double Bay UK RC Box Igloos," UB 822/12/1/3, 11 Jan 1991.

6. Besson, J., private communication, January 1992.

7. Swisdak, M. M., "Procedures For the Analysis of the Debris Produced By Explosion Events," Minutes of the Twenty-Fourth Explosives Safety Seminar, August 1990.

FIGURE 1. ESKIMO I: HAZARDOUS FRAGMENT DENSITY VERSUS RANGE--FRONT

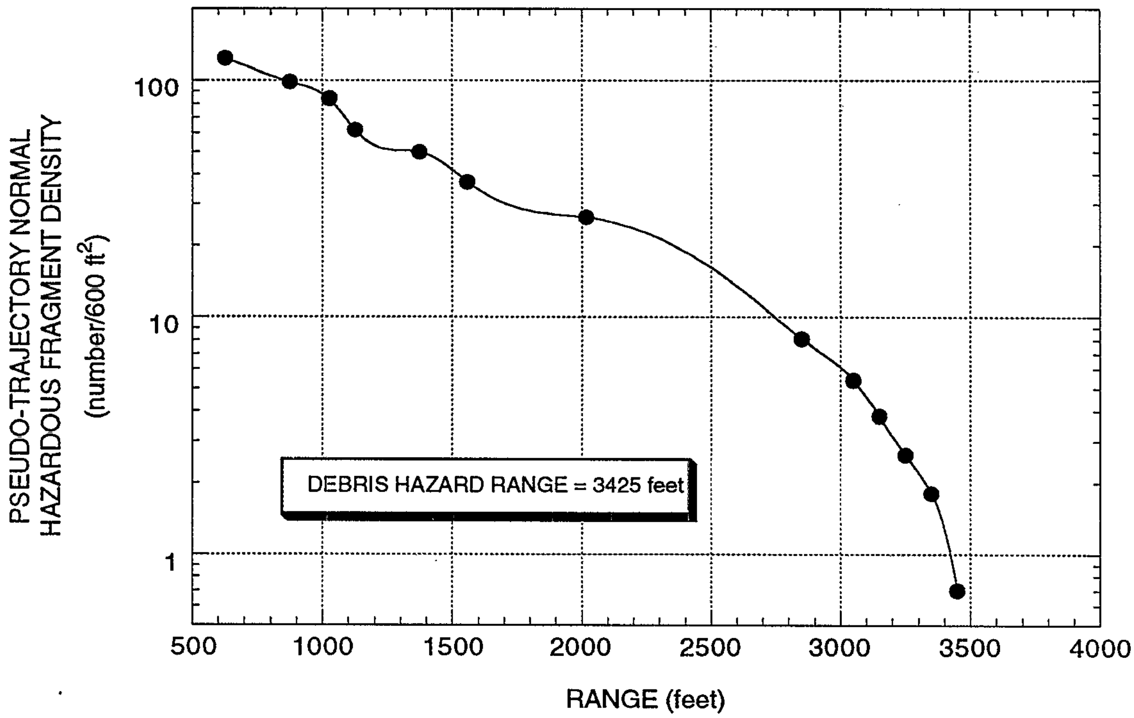

FIGURE 2. ESKIMO I: HAZARDOUS FRAGMENT DENSITY VERSUS RANGE--SIDE

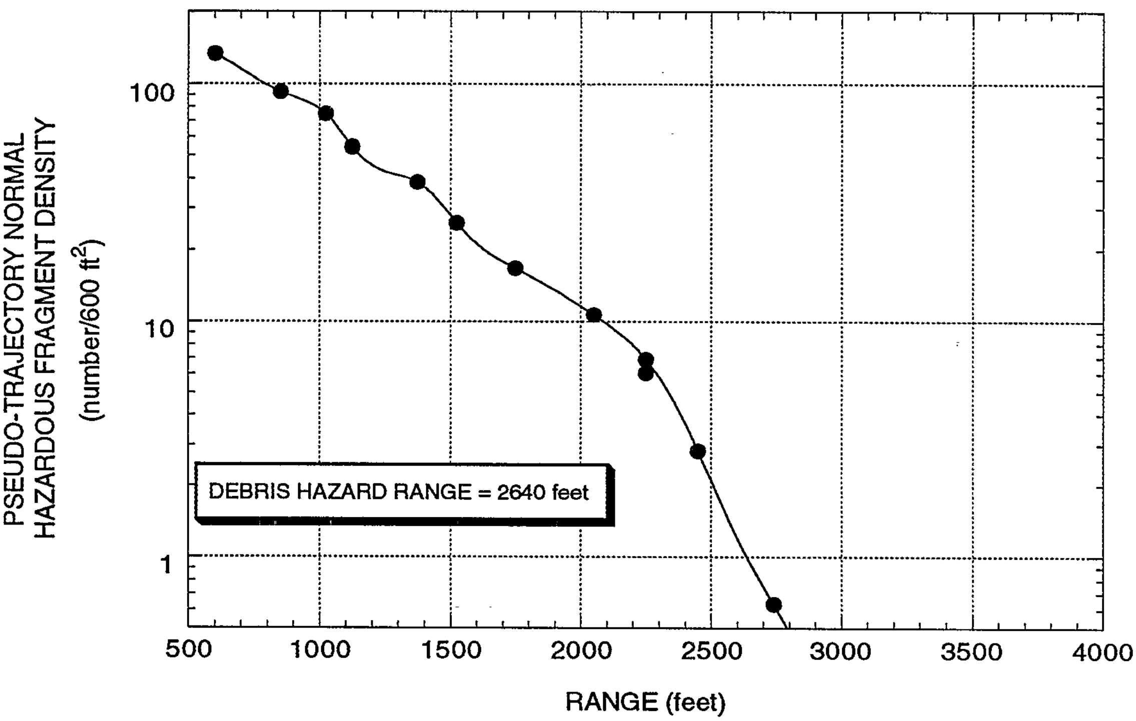

FIGURE 3. ESKIMO I: HAZARDOUS FRAGMENT DENSITY VERSUS RANGE--REAR

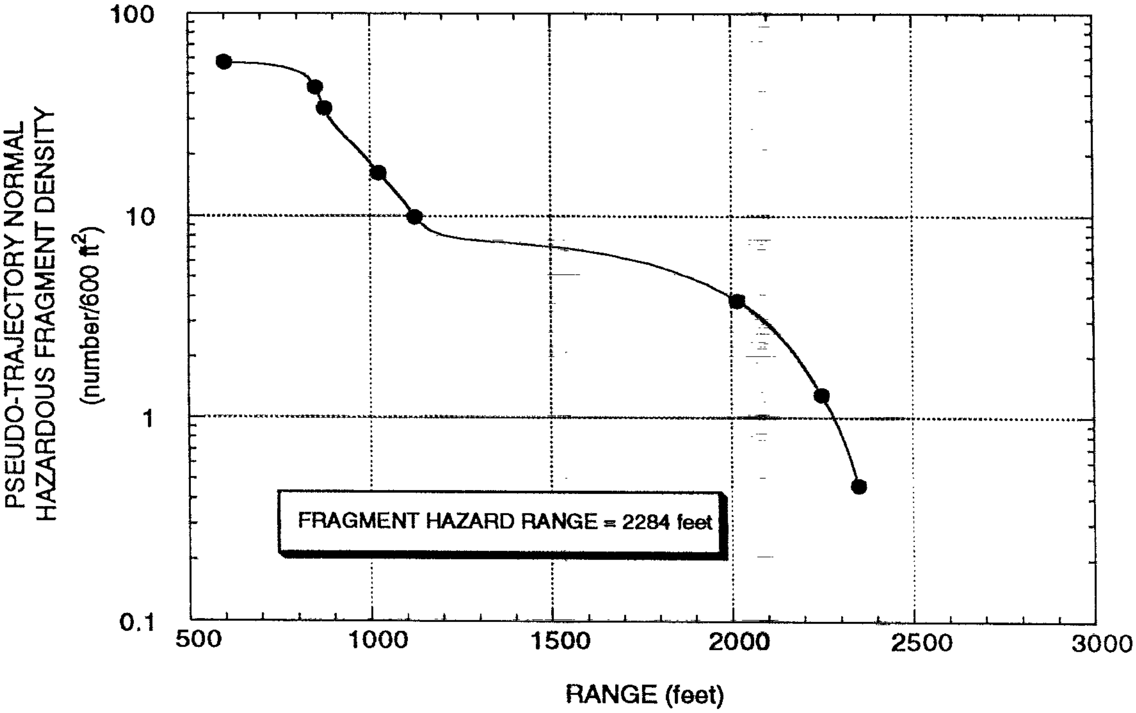

FIGURE 4. HASTINGS IGLOO (60 POUND):HAZARDOUS FRAGMENT DENSITY VERSUS RANGE

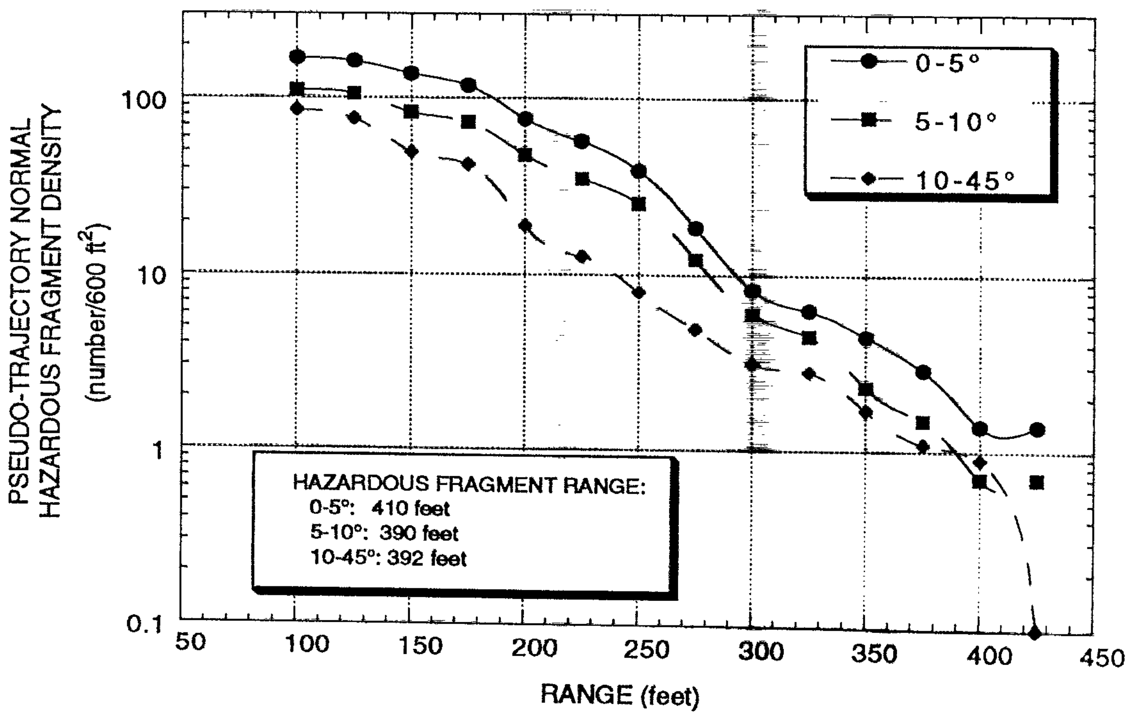

FIGURE 5. HASTINGS IGLOO (80 POUND): HAZARDOUS FRAGMENT DENSITY VERSUS RANGE

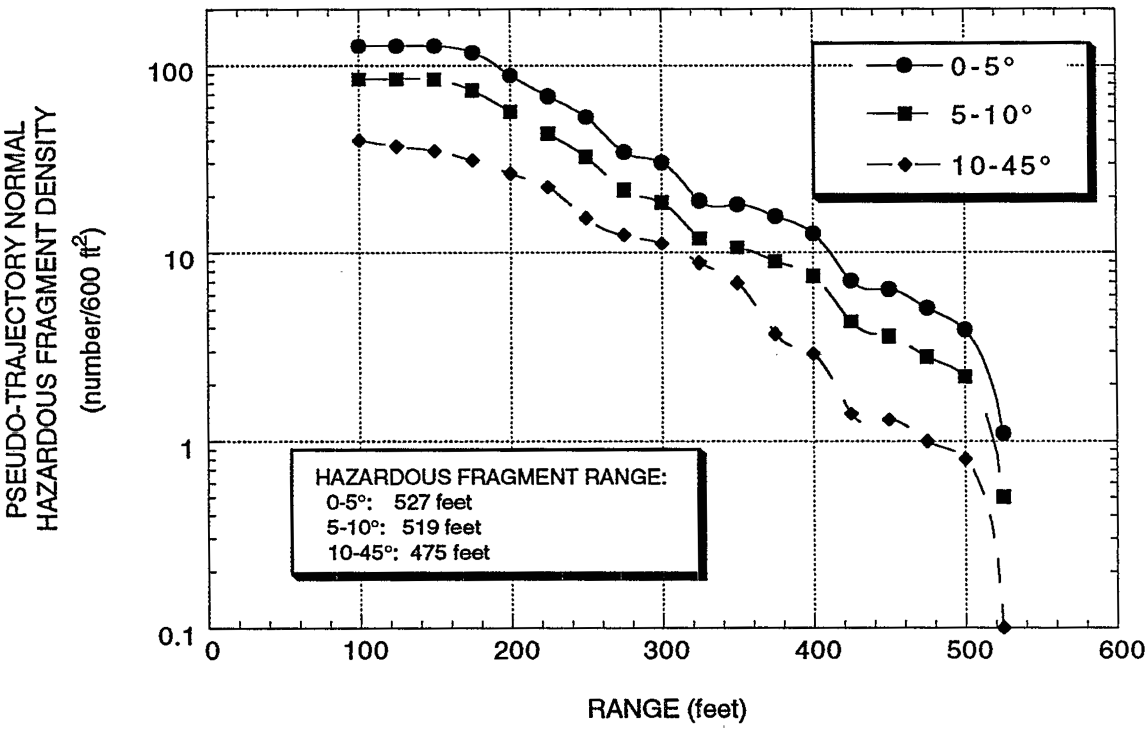

FIGURE 6. HASTINGS IGLOO (100 POUND): HAZARDOUS FRAGMENT DENSITY VERSUS RANGE

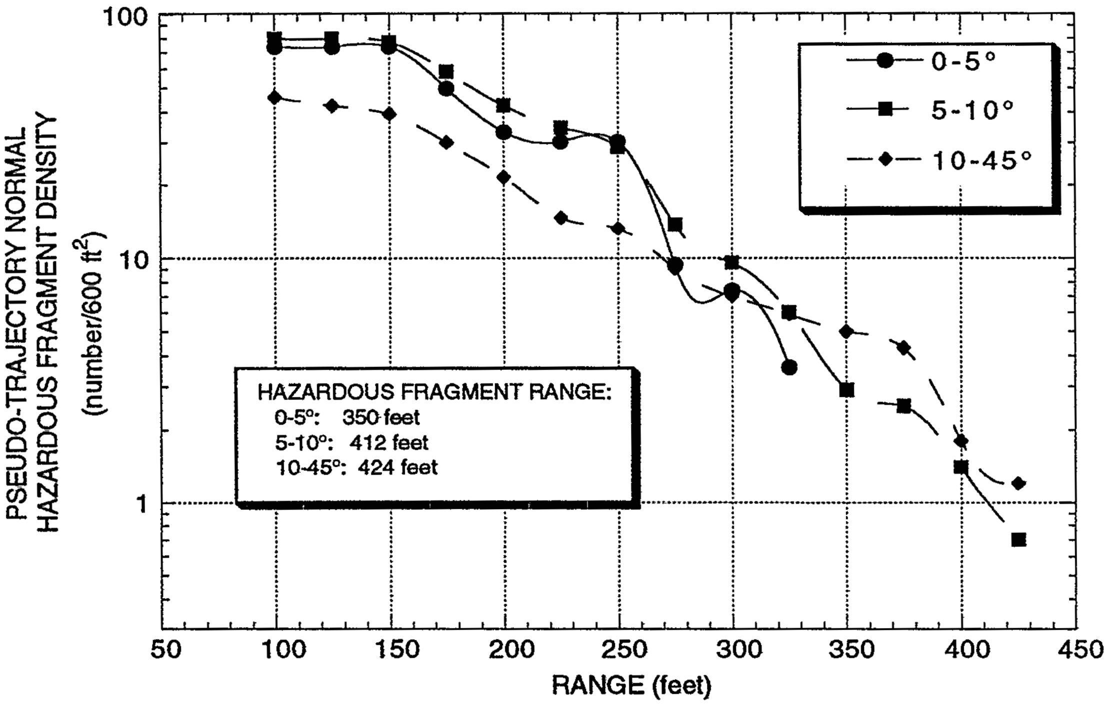

FIGURE 7. HASTINGS IGLOO (150 POUNDS): HAZARDOUS FRAGMENT DENSITY VERSUS RANGE

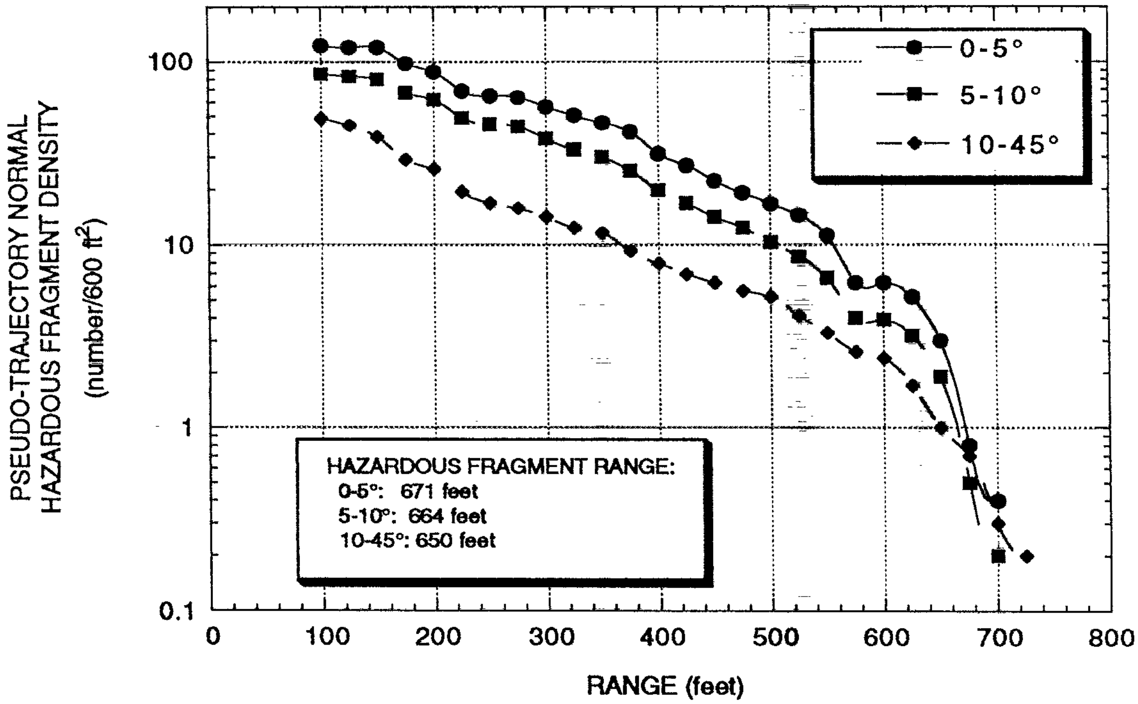

FIGURE 8. PEAK PRESSURE--FRONT

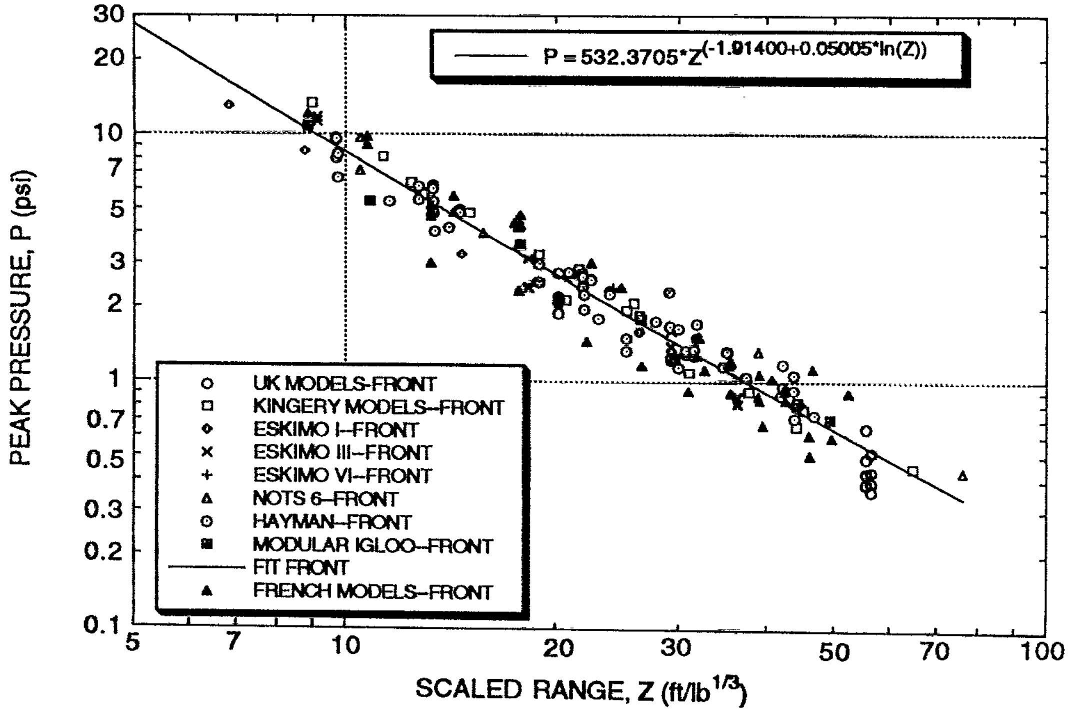

FIGURE 9. PEAK PRESSURE--SIDE

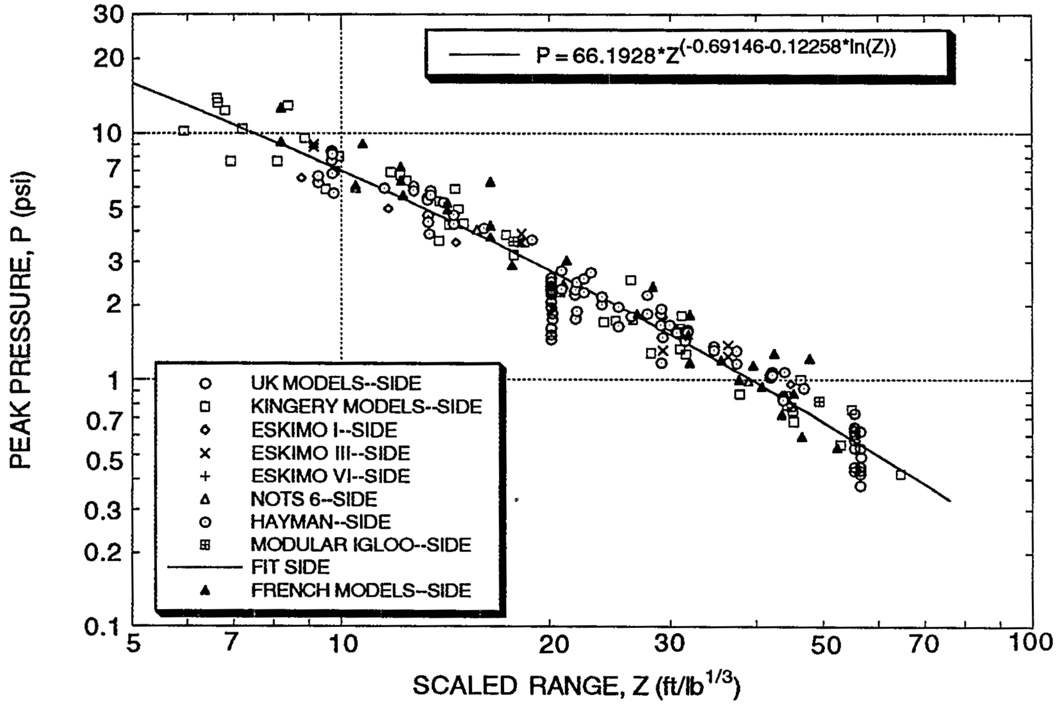

FIGURE 10. PEAK PRESSURE--REAR

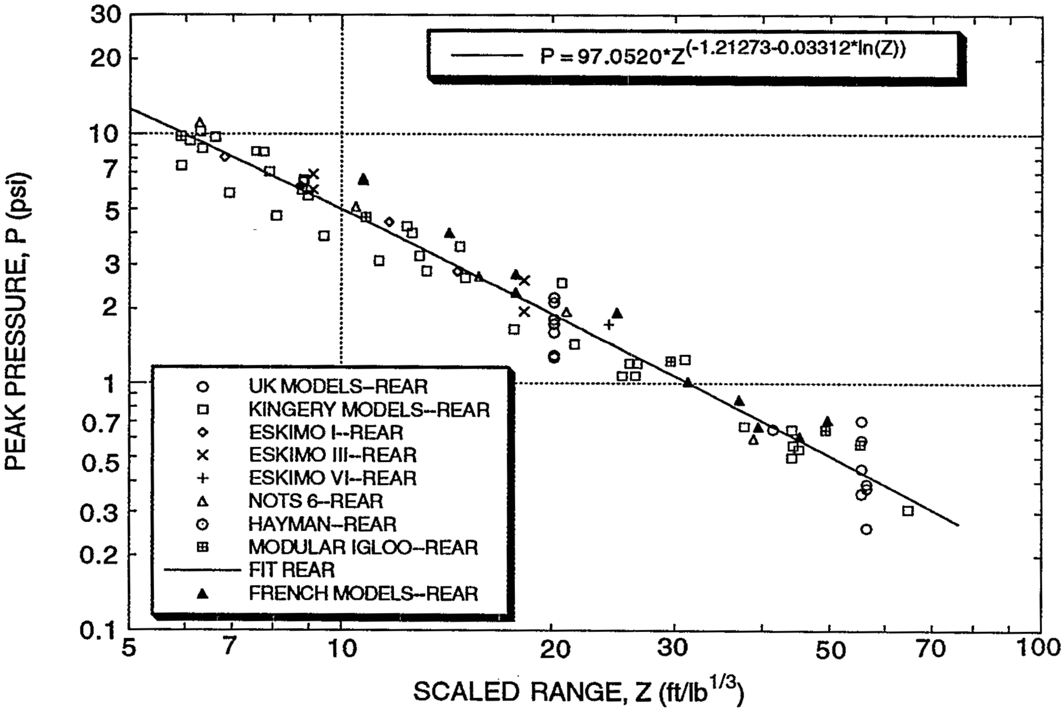

FIGURE 11. SCALED POSITIVE IMPULSE--FRONT

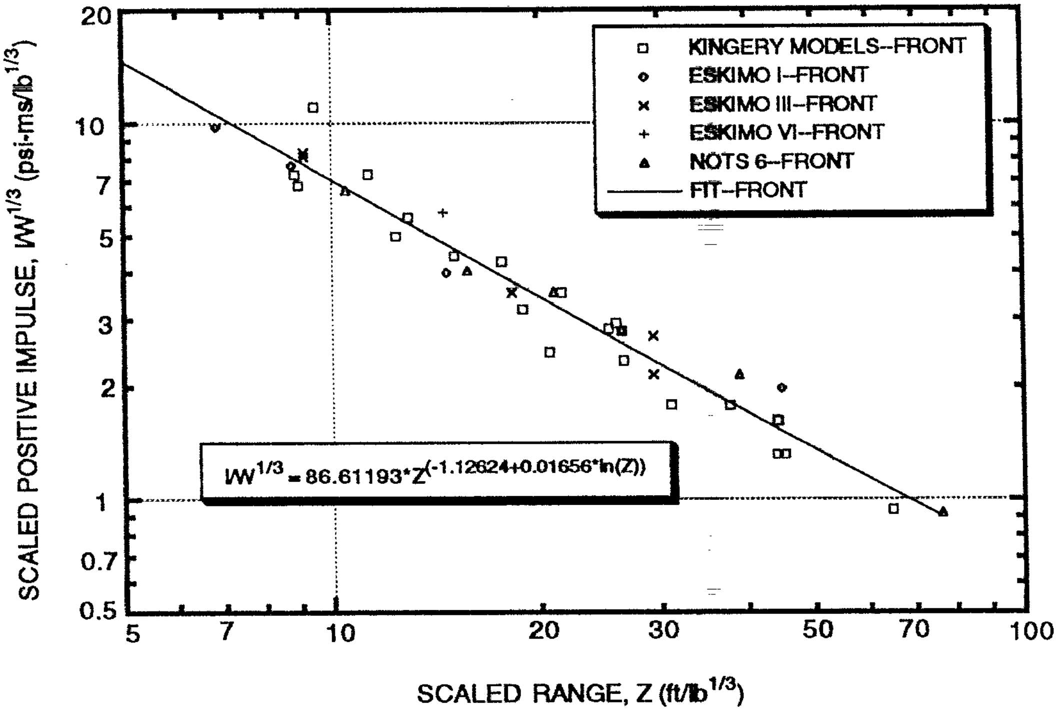

FIGURE 12. SCALED POSITIVE IMPULSE--SIDE

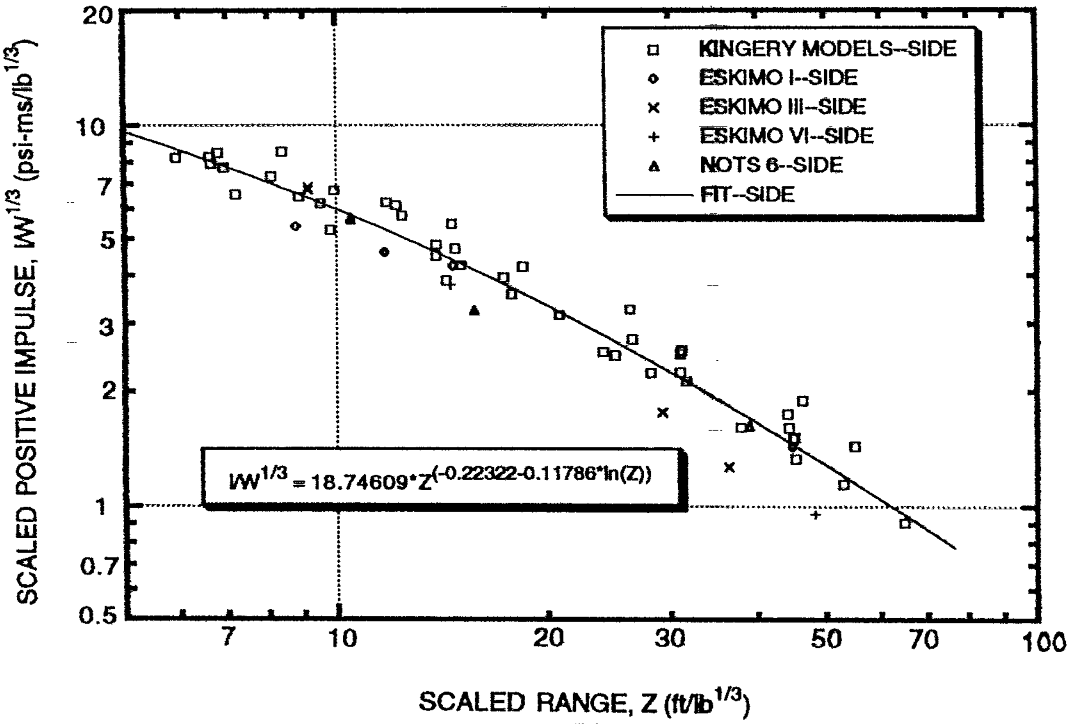

FIGURE 13. SCALED POSITIVE IMPULSE--REAR

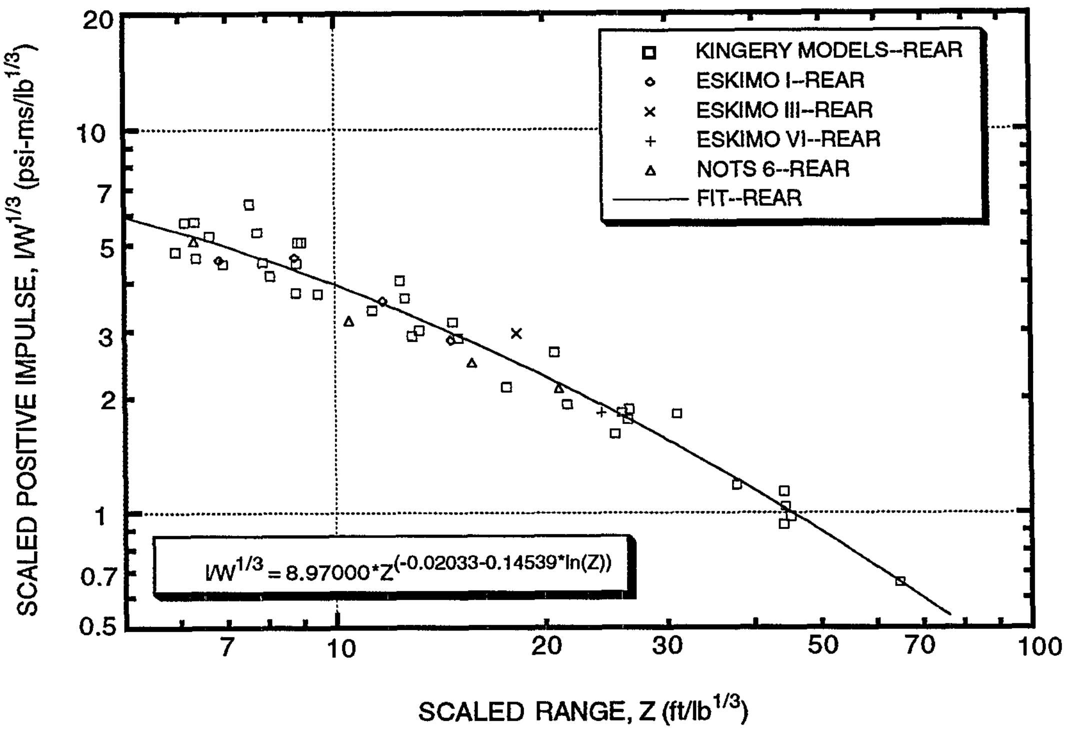

FIGURE 14. IGLOO EQUIVALENCE--FRONT

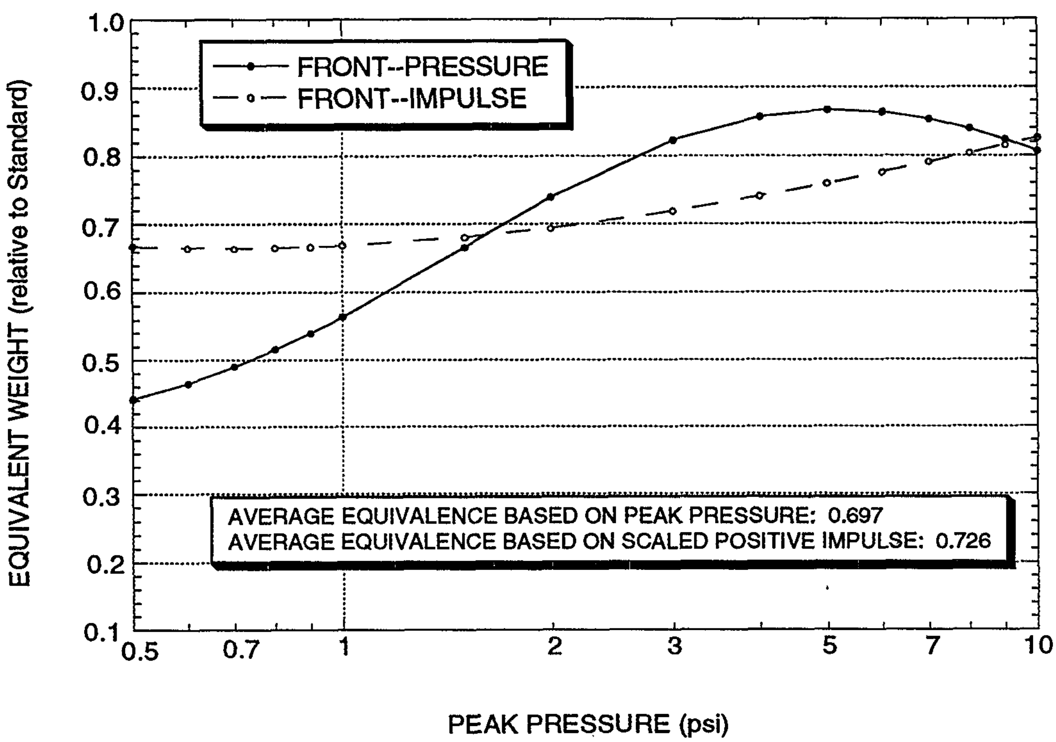

FIGURE 15. IGLOO EQUIVALENCE--SIDE

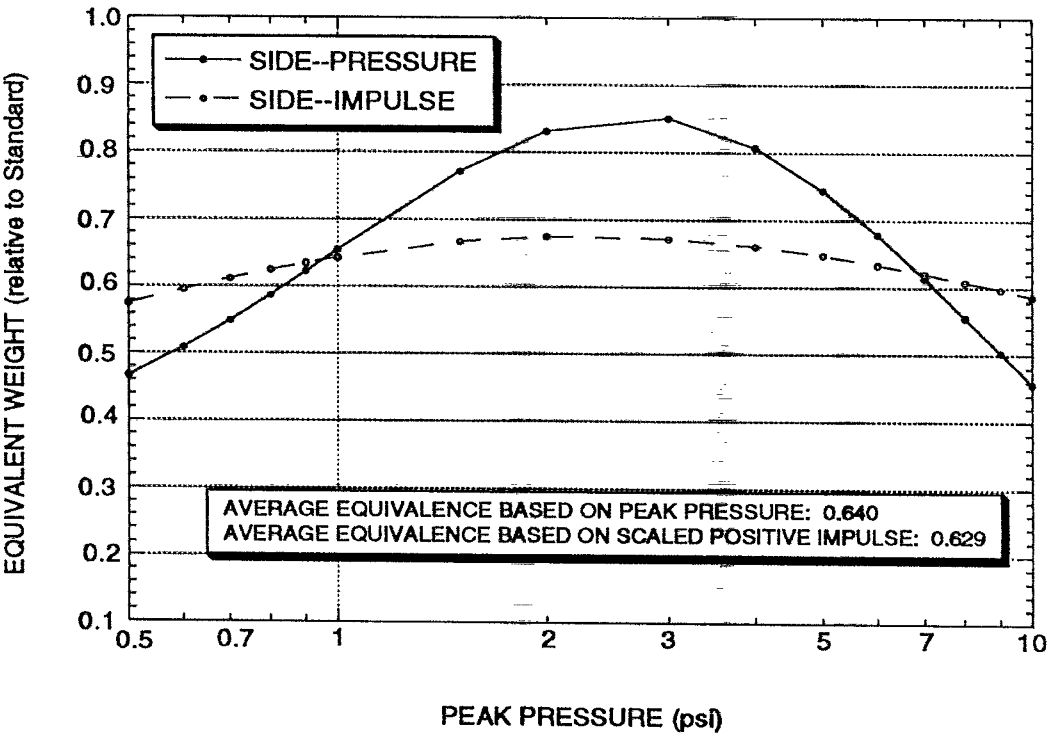

FIGURE 16. IGLOO IMPULSE--REAR

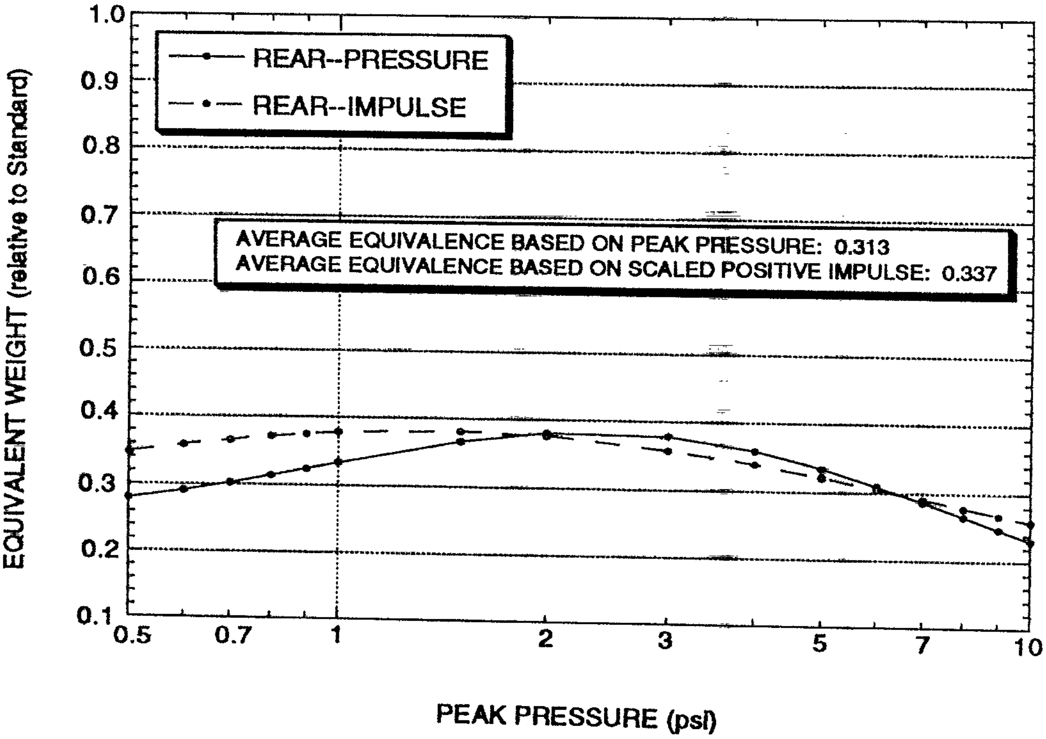

TABLE 1. PHYSICAL CHARACTERISTICS OF EVENTS IN DATA BASE

EVENT	NET EXPLOSIVE WEIGHT (pounds)	EXPLOSIVE	LOADING DENSITY (pounds/cubic foot)	SCALE
ESKIMO I	200,000	TNT	13.8	1::1
ESKIMO III	350,000	TRITONAL	17.8	1::1
ESKIMO VI	45,000	HBX-3	4.93	1::1
NOTS 6	100,035	COMPOSITION B	6.87	1::2
HAYMAN IGLOO	51,840	TRITONAL	3.24	1::1
HAYMAN IGLOO	59,904	TRITONAL	3.74	1::1
HAYMAN IGLOO	59,904	TRITONAL	3.74	1::1
HAYMAN IGLOO	120,960	TRITONAL	7.56	1::1
HAYMAN IGLOO	90,720	TRITONAL	5.67	1::1
HAYMAN IGLOO	45,360	TRITONAL	2.84	1::1
HAYMAN IGLOO	60,480	TRITONAL	3.78	1::1
HAYMAN IGLOO	60,480	TRITONAL	3.78	1::1
MODULAR IGLOO	450,450	COMPOSITION B	21.1	1::1
KINGERY (1/50)	1.81	PENTOLITE	28.6	1::50
KINGERY (1/50)	1.09	PENTOLITE	17.1	1::50
KINGERY (1/50)	0.36	PENTOLITE	5.71	1::50
KINGERY (1/30)	0.50	PENTOLITE	0.77	1::30
KINGERY (1/30)	0.80	PENTOLITE	1.23	1::30
KINGERY (1/30)	2.40	PENTOLITE	3.70	1::30
KINGERY (1/30)	4	PENTOLITE	6.17	1::30
KINGERY (1/30)	11	PENTOLITE	17.0	1::30
ESTC-1	141	TNT	7.37	1::10
ESTC-2	141	TNT	7.37	1::10
ESTC-2	276	TNT	11.4	1::10
ESTC-2	476	TNT	19.7	1::10
FRENCH	6,393	TNT	4.64	1::3
FRENCH	4,850	TNT	3.52	1::3
HASTINGS IGLOO	60	TNT	0.0035	1::1
HASTINGS IGLOO	80	TNT	0.0047	1::1
HASTINGS IGLOO	100	TNT	0.0059	1::1
HASTINGS IGLOO	150	TNT	0.0087	1::1

TABLE 2. SAFETY FACTOR COMPARISONS

NUMBER OF DATA POINTS–PEAK PRESSURE

FRONT	SIDE	REAR
159	190	83

NUMBER AND PERCENTAGE OF DATA POINTS ABOVE FITTED CURVE

	FRONT	SIDE	REAR
STANDARD LEAST SQUARES	91 57.2%	101 53.2%	40 48.2%
1.2* PREDICTED BY LEAST SQUARES	19 11.9%	26 13.7%	11 13.3%
1.2* CHARGE WEIGHT	53 33.3%	70 36.8%	27 32.5%

NUMBER OF DATA POINTS–SCALED POSITIVE IMPULSE

FRONT	SIDE	REAR
38	58	58

NUMBER AND PERCENTAGE OF DATA POINTS ABOVE FITTED CURVE

	FRONT	SIDE	REAR
STANDARD LEAST SQUARES	19 50.0%	26 44.8%	32 55.2%
1.2* PREDICTED BY LEAST SQUARES	4 10.5%	5 8.6%	14 24.1%
1.2* CHARGE WEIGHT	13 34.2%	19 32.8%	28 48.3%

TABLE 3. COMPARISON OF PREDICTED VALUES WITH CURRENT STANDARD

	PRESSURE										
	11.7	8	3.5	2.95	2.3	1.7	1.28	1.2	0.9	0.725	0.29
STANDARD (Kingery)	9.00	11.00	18.00	20.20	24.00	30.00	37.50	40.00	50.00	58.70	115.00
LEAST SQUARES-FRONT	8.26	10.34	17.04	18.93	22.09	26.70	**31.96**	**33.31**	**40.09**	**46.14**	**85.00**
1.2*NET EXPLOSIVE WEIGHT-FRONT	8.78	10.99	18.11	20.11	23.47	28.37	**33.97**	**35.40**	**42.60**	**49.03**	**90.32**
1.2* LEAST SQUARES-FRONT	9.20	11.53	19.06	21.19	24.76	29.97	**35.92**	**37.45**	**45.13**	**52.00**	**96.27**
LEAST SQUARES-SIDE	6.55	9.02	16.96	19.16	22.79	27.94	**33.63**	**35.05**	**42.03**	**48.01**	**82.14**
1.2*NET EXPLOSIVE WEIGHT-SIDE	6.96	9.58	18.02	20.36	24.22	29.69	**35.74**	**37.25**	**44.66**	**51.02**	**87.29**
1.2* LEAST SQUARES-SIDE	7.66	10.43	19.32	21.77	25.79	31.50	37.78	39.35	**47.03**	**53.61**	**90.97**
LEAST SQUARES-REAR	**5.30**	**7.06**	**12.94**	**14.64**	**17.50**	**21.69**	**26.47**	**27.69**	**33.82**	**39.25**	**73.01**
1.2*NET EXPLOSIVE WEIGHT-REAR	**5.64**	**7.50**	**13.76**	**15.56**	**18.60**	**23.04**	**28.13**	**29.43**	**35.94**	**41.71**	**77.59**
1.2* LEAST SQUARES-REAR	**6.09**	**8.08**	**14.76**	**16.69**	**19.92**	**24.65**	**30.06**	**31.44**	**38.35**	**44.47**	**82.44**

NOTES:

(1) All distances shown are in ft/lb^1/3

(2) Numbers in BOLD represent pressures attenuated by earth-covered structures relative to values for aboveground structures at the same indicated scaled distances