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Detonation of a Flammable Cloud Following a Propane Pipeline Break

The December 9, 1970, Explosion in Port Hudson, Mo.

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The December 9, 1970, Explosion in Port Hudson, Mo.

by

D. S. Burgess[1] and M. G. Zabetakis[2]

ABSTRACT

This report summarizes the incidents that preceded the December 9, 1970, propane-air explosion in Port Hudson, Mo., and then attempts to establish the nature of the explosion from the ensuing events. Special emphasis is given to possible ignition sources, the distribution of flammable vapors, and the analysis of blast damage. Both near- and far-field damage indicated that this explosion may be attributed to the detonation of propane in air with an energy release equivalent to that from about 50 tons of detonating TNT.

INTRODUCTION

The Bureau of Mines was invited by the National Transportation Safety Board (NTSB) to investigate a propane-air explosion that occurred in Port Hudson, Mo., on December 9, 1970. This explosion, in the vicinity of a pipeline break, was unique in the investigators' experience in that it involved the detonation of a large unconfined cloud of flammable mixture. It is also of current interest in that it represents a "worst-possible" sort of case history for assessment of the hazards of fuel transportation.

The facts of the incident have been completely reported in a Pipeline Accident Report issued by NTSB.[3] For the account which follows, we have drawn heavily upon the NTSB report and on many communications with NTSB officials and with most of the witnesses at the public hearing. This present report goes somewhat beyond the Bureau's contribution to the public hearing to include treatments of data that have evolved in the intervening months; the report is submitted with NTSB concurrence.

ACKNOWLEDGMENT

We are particularly grateful to Barry M. Sweedler of NTSB who arranged for one of us to visit the accident scene on December 21, 1970, and who has

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[1] Research supervisor, Fire and Explosion Prevention.

[2] Research supervisor, Methane Control and Ventilation.

[3] National Transportation Safety Board. Testimony in Investigation of Products Pipeline Accident in Franklin County, Missouri, on December 9, 1970. Report No. NTSB-PAR-72-1, Docket No. SS-P-7, June 12, 1972, 43 pp.

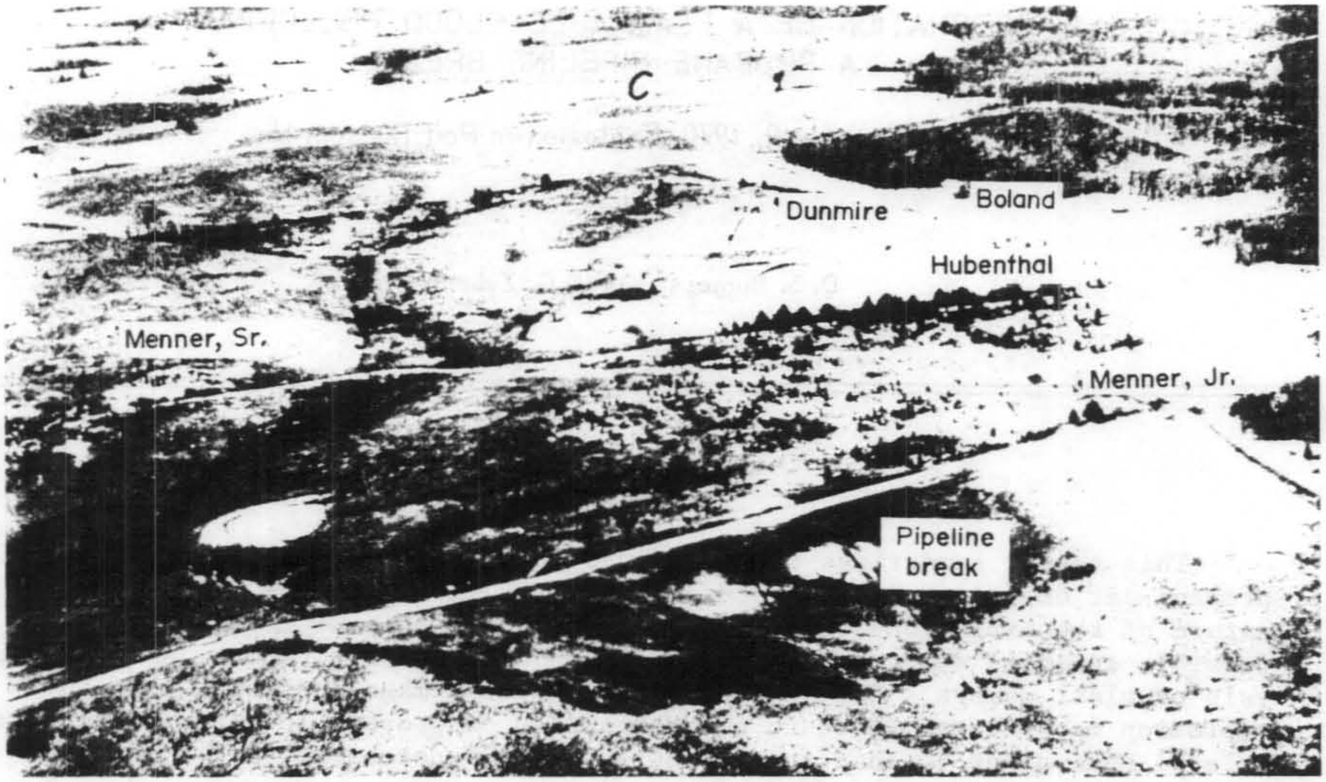

FIGURE 1. - View of Port Hudson aftermath looking west.

been most helpful in establishing our communications with other investigators of the accident. Figures 4-10 were reproduced from NTSB Docket No. SS-P-7.

DESCRIPTION OF ACCIDENT

According to records of the pipeline company, an abnormality occurred at a pumping station at Villa Ridge, Mo., 15 miles downstream of Port Hudson, at 10:07 p.m. on December 9. Pumps were automatically shut down over a 3-minute interval and pressures redistributed within the pipeline. At 10:20 p.m., there was a sudden increase of throughput at the next upstream station (Rosebud, Mo.), indicating a substantial break in the line; the pipeline pressure at the time and place of rupture was thought to be about 942 psig, and about 750 barrels of liquid propane are thought to have escaped during the first 24 minutes.[4]

Several witnesses became aware of the noise of the escaping propane jet at about 10:25 p.m. A plume of white spray (presumably droplets of propane and of condensed atmospheric moisture) was observed to be rising 50 to 80 feet above ground level. The crater dug by the escaping liquid, said to be about 4 feet deep and 10 feet in diameter (subsequently enlarged by repair crews), is shown in the right foreground of figure 1.

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[4] Work cited in footnote 3.

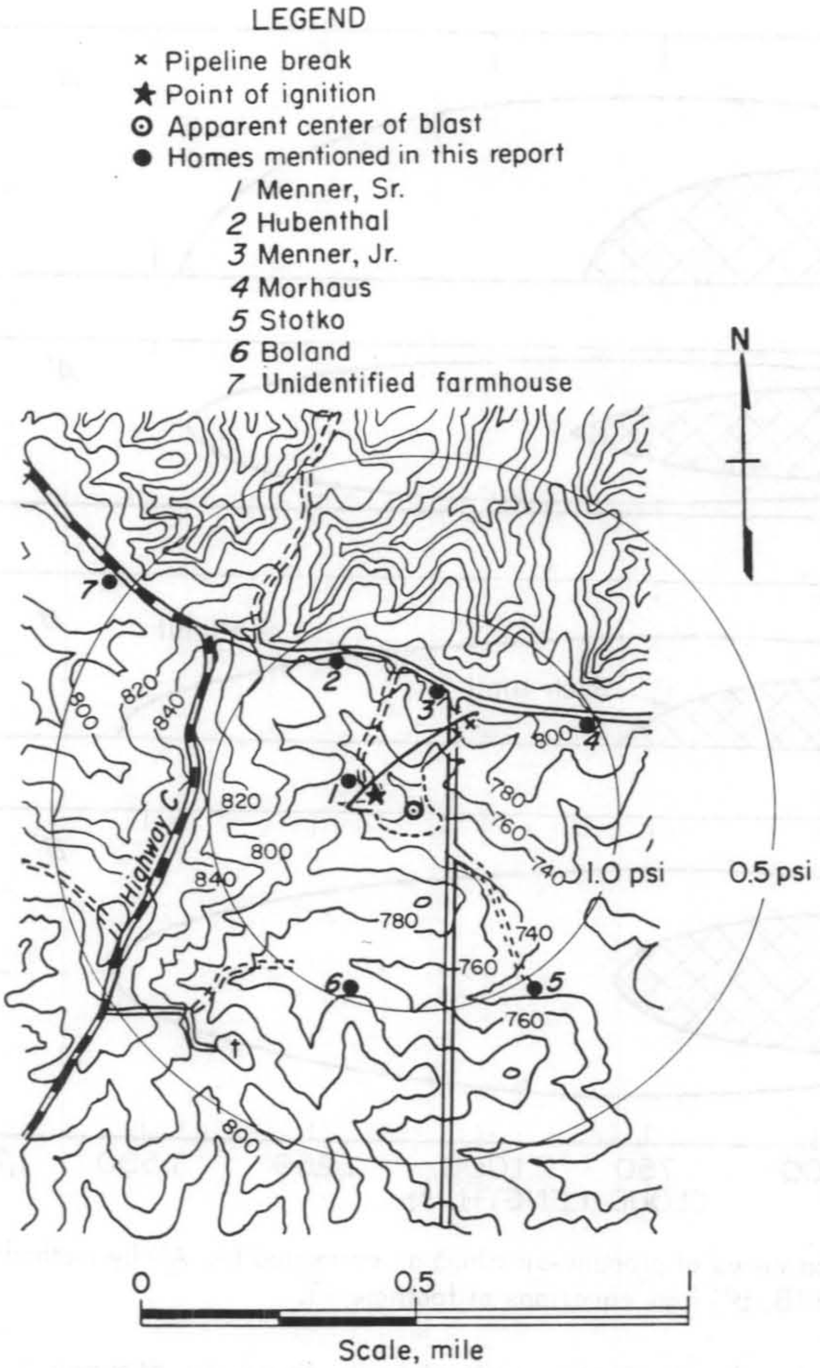

FIGURE 2. - Map of accident area showing postulated location of detonable cloud and locations of damaged homes.

By 10:44 p.m., four families had evacuated their homes and were assembled in their automobiles at the intersection of highway C near the top center of figure 1. (See also the contour map of fig. 2.) From this high ground they observed a white cloud settling into the valley around the complex of buildings owned by A. Menner, Sr., which buildings were about 1,000 feet southwest (downwind) of the propane spray and perhaps 20 to 30 feet lower in elevation. Two estimates of the dimensions of the detonable cloud are shown in figure 3; by either estimate, the Menner, Sr., buildings could have been well within the zone of detonable mixture.

At about 10:44 p.m., the valley reportedly "lit up." All witnesses agreed that there was no observable period of flame propagation but a sudden flash as in heat lightning. There was an almost immediate pressure pulse, and one of the witnesses, who was walking between automobiles, was knocked down. She was about a half mile from the center of the propane-air cloud. A State trooper who was cruising about 15 miles from the accident site reported that his patrol car swerved. A seismograph at St. Louis University, about 60 miles to the east, recorded a 2.2×10^{-3} millimeter (vertical) ground displacement and an air wave of undeterminable magnitude; these records fix the time of explosion as 16 seconds after 10:44 p.m.[5]

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[5] We are indebted to O. W. Nuttli, Professor of Geophysics, St. Louis University, for this information.

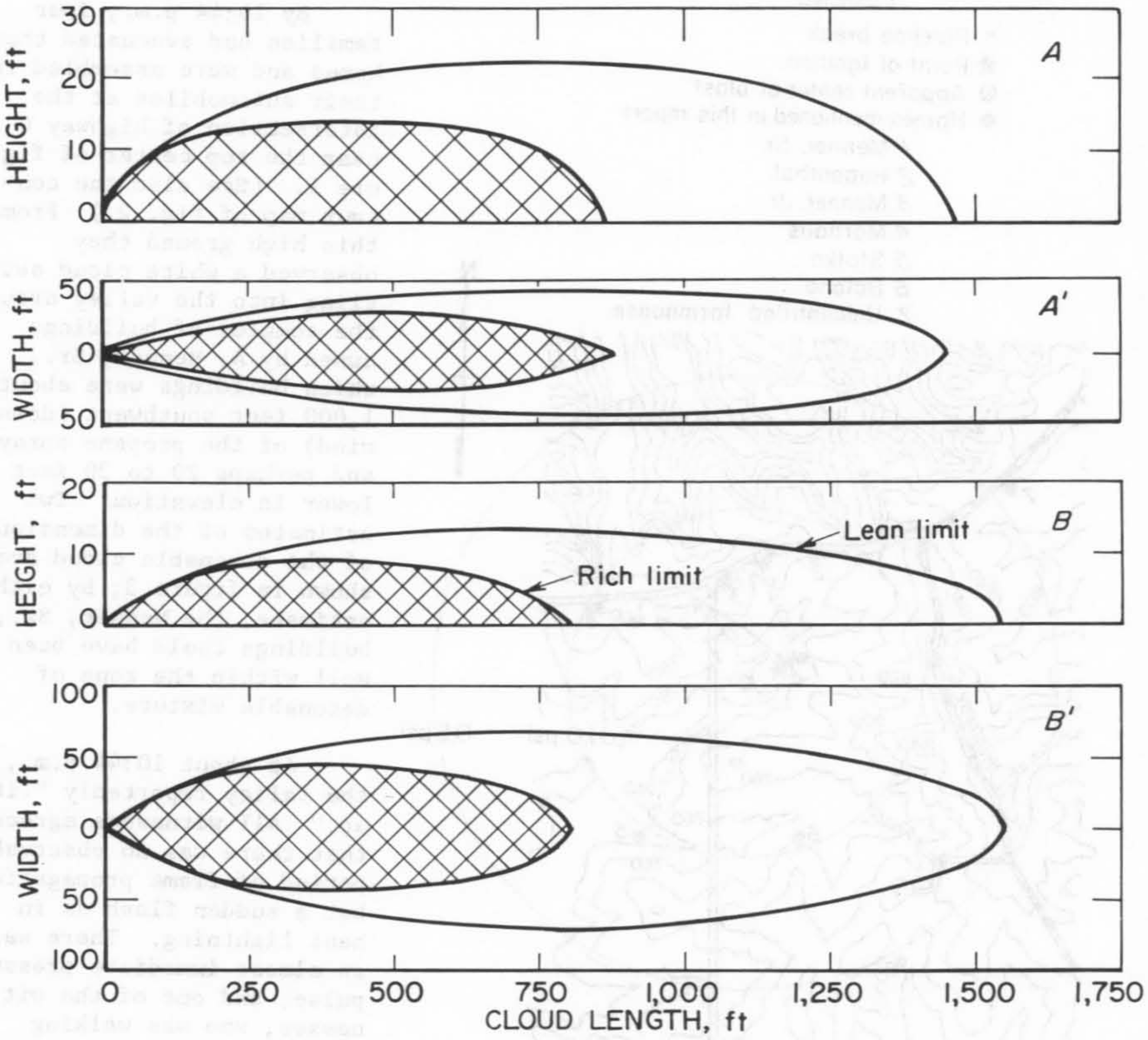

FIGURE 3. - Side views and top views of propane-air cloud as estimated (A, A') by methods of footnote 8, and (B, B') from equations of footnote 13.

Building damage in the neighborhood of the explosion is shown in figures 4 to 9. Judging from such damage and the abruptness of the illumination of the valley, we think the witnesses had the unusual experience of observing a gas detonation.

In the seconds following detonation, a firestorm[6] was observed to "roll" in a generally east to west direction; that is, up the sloping terrain toward highway C. All witnesses immediately drove off to the northwest; on arriving

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[6] That is, a diffusion flame with very high winds which consumed the remainder of the propane.

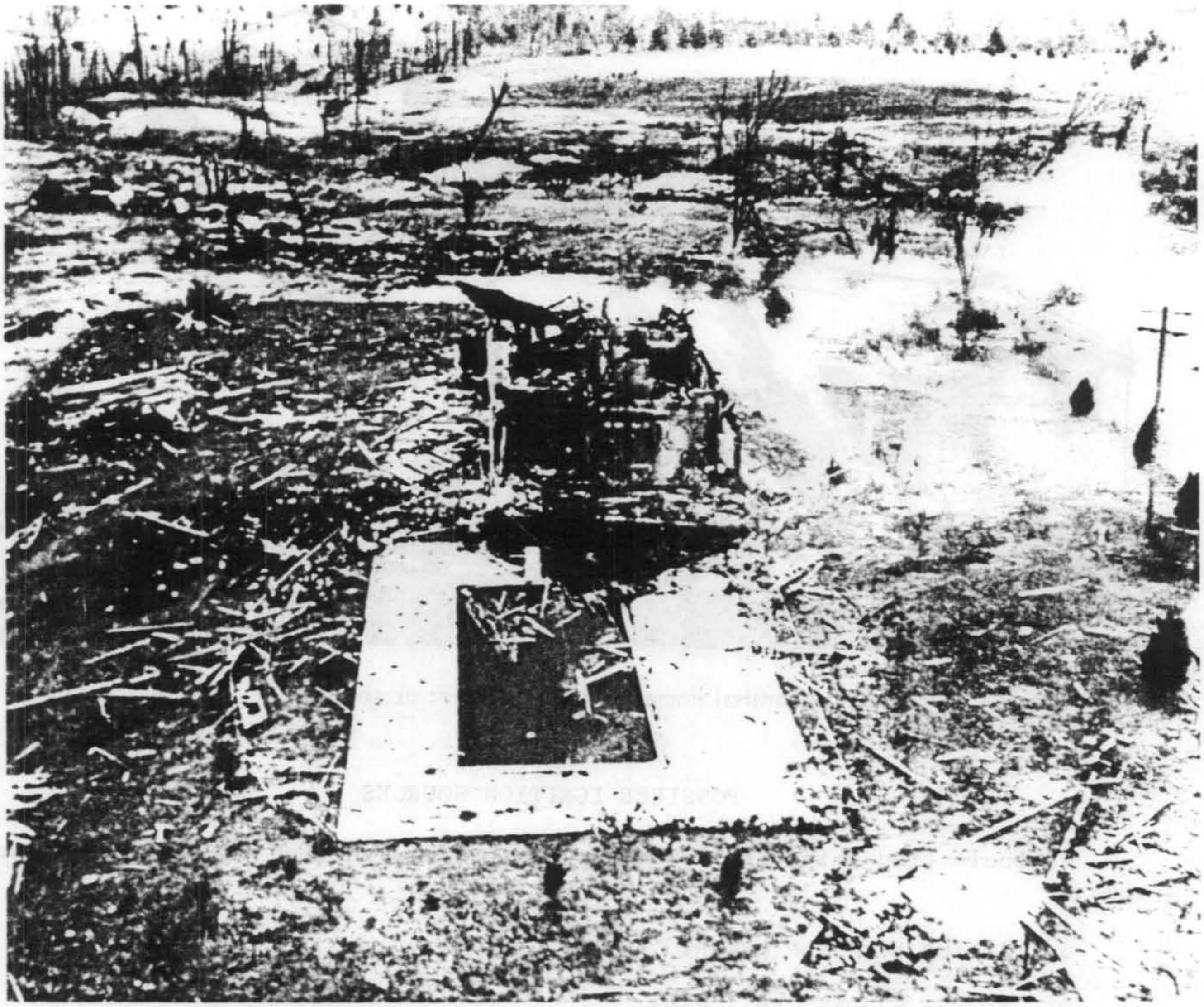

FIGURE 4. - Damage to Menner, Sr., complex near western extremity of flammable cloud.

at the farmhouse labeled 7 in figure 2, about three-quarters of a mile from the accident site, they observed the fallout of debris from the Menner, Sr., outbuildings. The witnesses' accounts are not informative as to how long the flame persisted in the valley or as to how high the thermal column extended. A red glow in the sky was reported at Kansas City, 200 miles to the west. The glow was probably from the continued burning of propane at the pipeline break; the total loss of propane was 4,538 barrels.

Figure 10 shows typical wind damage in the aftermath of the firestorm. Most of the broken tree limbs and uprooted small trees were left pointing in the direction of the Menner, Sr., outbuilding in which we speculate that ignition occurred. Thus, it appeared as though the winds rushed in from northeast and southeast toward this focal point and then were carried aloft by buoyant forces; there was no evidence of wind from westward of the scene.

FIGURE 5. - Damage to Hubenthal home, about 1,500 feet north-northwest of presumed center of blast.

POSSIBLE IGNITION SOURCES

We could find only three potential points of ignition within the accident area:

1. At the pipeline break.

2. At the Menner, Sr., home.

3. Within a warehouse among the Menner, Sr., outbuildings.

We tend to discount the first two in favor of the third.

At the pipeline break, the propane could have been ignited by static electrification, by shocks from the high-pressure jet of propane, or by frictional heating of particles such as rust dislodged from within the pipe. However, after 24 minutes of propane flow, the crater surrounding the broken pipe must have been filled with nearly pure propane so that local ignition sources within this volume could hardly have been effective. Conceivably, a discharge of static electricity could have occurred aloft in the plume of propane droplets; however, ignition of this plume could hardly have gone unobserved by the many witnesses, and it is difficult to imagine how such an ignition could have led to immediate "lighting up" of the whole valley.

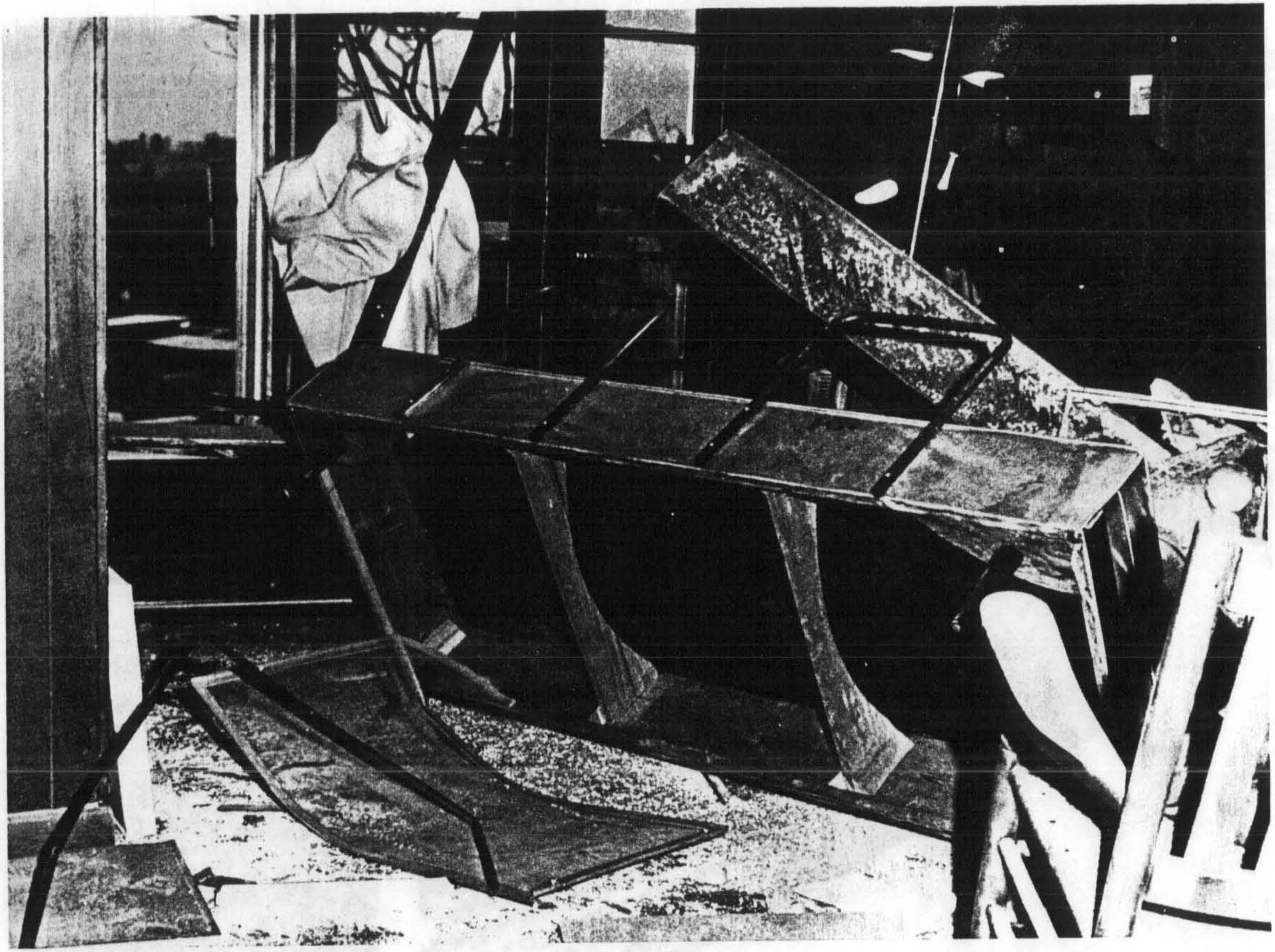

FIGURE 6. - Interior view of Menner, Jr., home, about 1,400 feet north of center of blast.

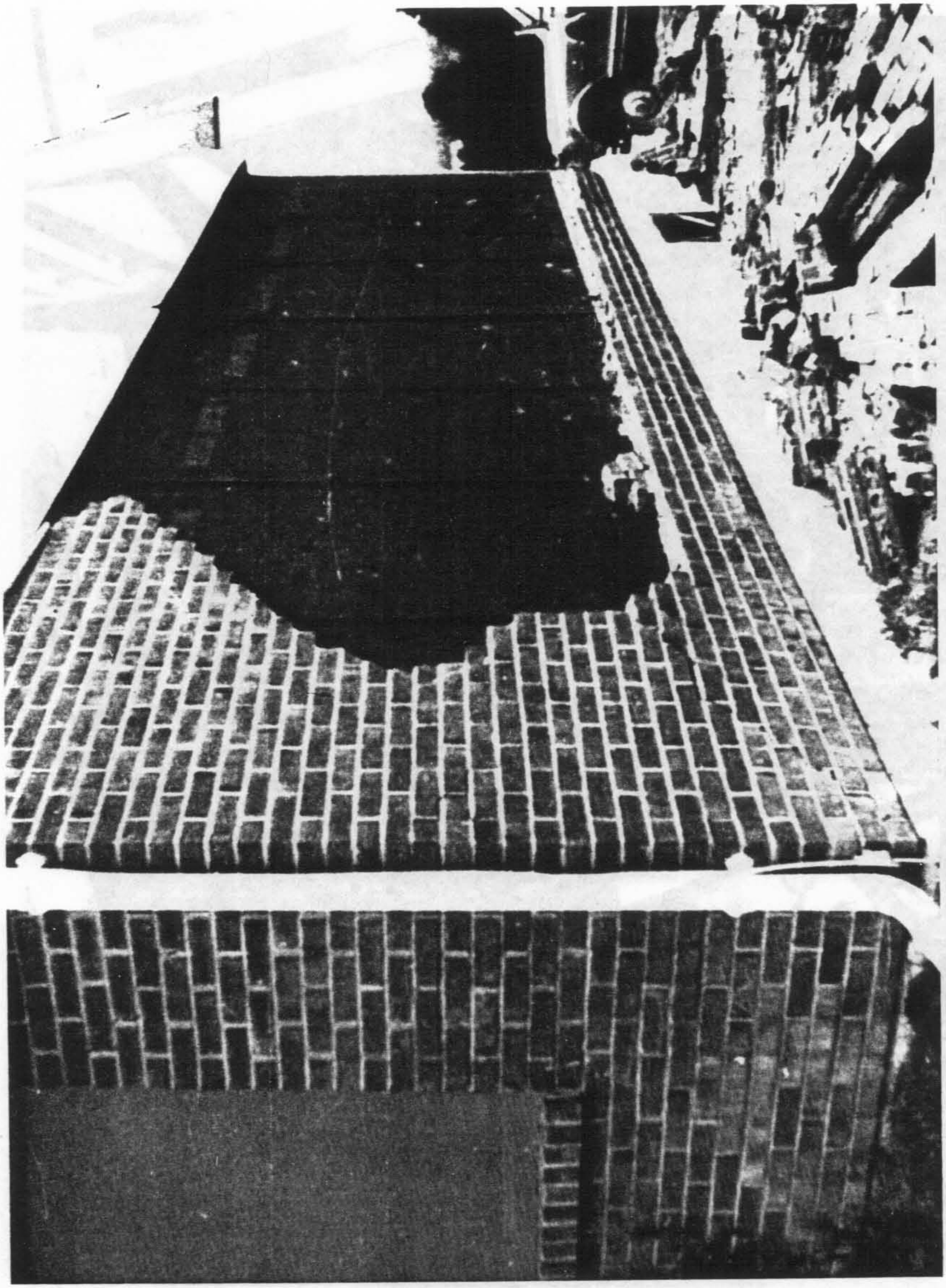

FIGURE 7. - Damage to Morhaus home, about 1,700 feet northeast of center of blast.

FIGURE 8. - Damage to Stotko farm, about 2,000 feet southeast of center of blast.

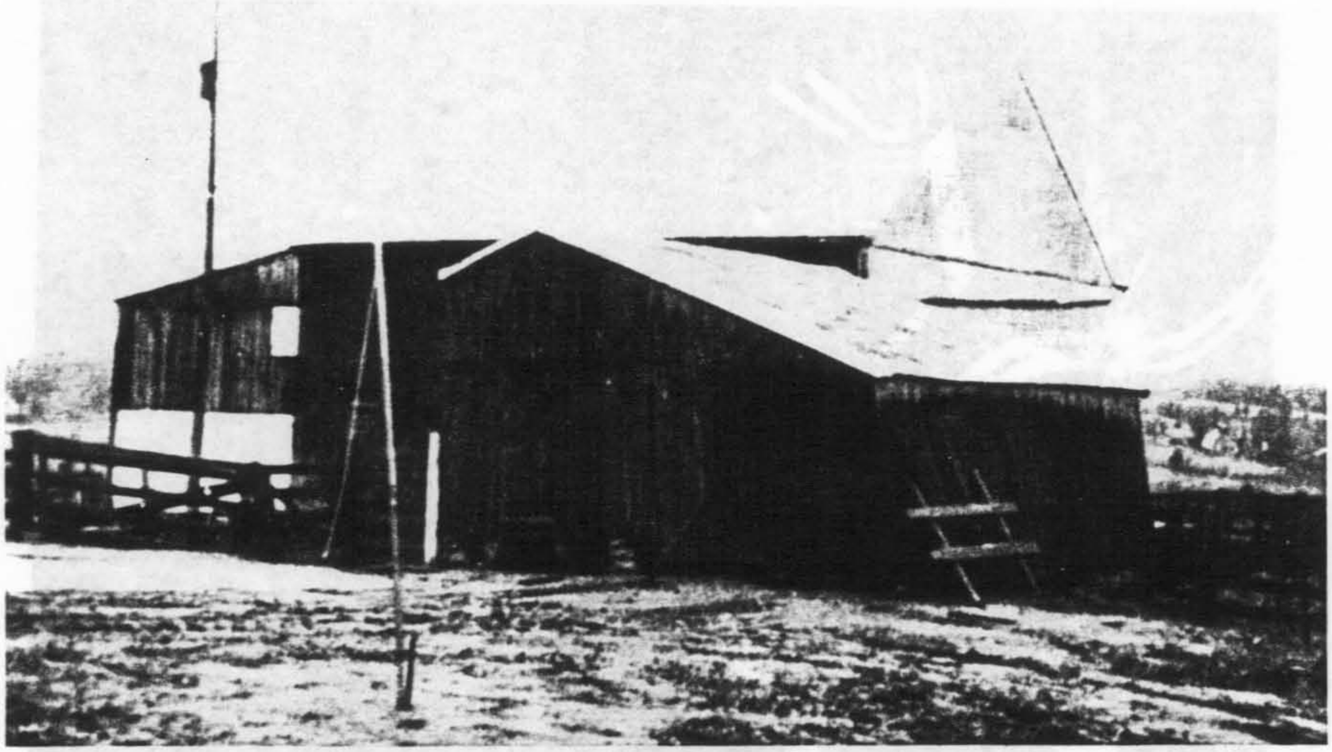

FIGURE 9. - Damage to Boland farm building, about 2,000 feet south of center of blast.

The Menner, Sr., home was on slightly higher ground than were the outbuildings and appeared, from several pieces of evidence, to be slightly outside the flammable zone of propane-air. Note, in particular, that the lawn and the small evergreens around the house (fig. 4) are almost unscorched. Moreover, the house had been closed for an extended period, and it is questionable whether sufficient propane could have leaked in within the 24 minutes of propane flow for the interior atmosphere to have become explosive.

About 150 feet southeast of the house (toward upper left in fig. 4), there had been a 54- by 32-foot concrete block warehouse. The ground floor of this building, partitioned into four rooms, contained six deep freeze units in operation at the time of the accident. Diffusion into this building could have been relatively rapid via sliding garage doors facing the driveway on the left of figure 4. We speculate that ignition could have occurred at the controls of a refrigerator motor; as flame filled the warehouse, considerable turbulence would be expected at doorways, and detonation may well have developed within the building. In any case, as the pressure of the constant volume explosion was relieved at the doors and windows, shocks could have developed of sufficient strength to initiate the ambient propane-air cloud directly into detonation.

FIGURE 10. - Aftermath of detonation and firestorm, near presumed point of ignition.

FLAMMABLE VAPOR DISTRIBUTION

Table 1 lists pertinent meteorological conditions at the time and place of the accident as estimated by the National Weather Service.[7] The low wind

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[7] H. W. Waldheuser, supervising forecaster at Lambert Field, St. Louis, was a witness at the public hearing of the National Transportation Safety Board (footnote 3). He and Mr. W. Parker have provided helpful advice for this analysis.

speed at the surface, the thin overcast, and the temperature inversion at 2,000 feet are suggestive of stability category F in the nomenclature of the "Workbook of Atmospheric Dispersion Estimates."[8] From figures 3-2 and 3-3 of this reference, one obtains a measure of the dispersion of propane in the lateral direction, σ_y, and in the vertical direction, σ_z, at any downwind distance, x. The first three columns of table 2 list these distances.

TABLE 1. - Estimated meteorological conditions, Port Hudson, Mo., December 9, 1970[1]

Elevation, ft	Temperature, ° C	Sound speed, ft/sec	Wind speed, ft/sec	Wind direction, degrees
0	1.0	1,089.5	8.4	60
500	3.0	1,093.5	13.5	70
1,000	7.0	1,101.3	16.9	90
2,000	11.0	1,109.2	16.9	90
3,000	9.0	1,105.3	16.9	193
5,000	6.0	1,099.4	20.3	228

[1] National Weather Service. Information from NTSB Pipeline Accident Report; see text footnote 3.

TABLE 2. - Dimensions of detonable plume downwind of 900 ft^3/sec propane source, stability category F, wind speed 8 ft/sec

Downwind distance, x, ft	Plume dispersion (standard deviations), ft		Centerline concentration, pct	Horizontal distance from plume axis, ft		Vertical distance from plume axis, ft	
	Horizontal σ_y	Vertical σ_z		To rich limit y_r	To lean limit y_ℓ	To rich limit z_r	To lean limit z_ℓ
300	13	7.9	35	23	29	14.2	17.9
500	20	10.5	17	26	38	13.9	20.0
700	26	14	10	21	42	12.0	22.4
870	-	-	7.0	0	-	0.0	-
1,000	36	18	5.6	-	43	-	21.4
1,400	50	24	3.0	-	17	-	8.2
1,470	-	-	2.8	-	0	-	0.0

The centerline (directly downwind) concentration of propane is given by

$$\chi_{CL} = \frac{Q}{\pi \sigma_y \sigma_z \bar{U}}, \qquad (1)$$

where Q is flow rate of propane and $\bar{U}$ is average wind velocity. In this case, Q is 900 ft^3 (STP) of propane per second, assuming a constant leakage rate, and $\bar{U}$ is 8 ft/sec. These centerline (maximum) concentrations range from 35 percent propane at 300 feet to 2.8 percent propane, the lean detonable limit,[9] at 1,470 feet from the source (column 4 of table 2).

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[8] Turner, D. Bruce. Workbook of Atmospheric Dispersion Estimates. Public Health Service Pub. No. 999-AP-26, 1969, 84 pp.

[9] Benedick, W. B., J. D. Kennedy, and B. Morosin. Detonation Limits of Unconfined Hydrocarbon-Air Mixtures. Combustion and Flame, v. 15, 1970, pp. 83-84.

The contour lines for rich (7.0 percent) and lean (2.8 percent) limits of detonability were obtained as follows: At any distance from the source, the off-center line concentration is

$$\chi = \chi_{CL} \exp\left\{-1/2\left[\left(\frac{y}{\sigma_y}\right)^2 + \left(\frac{z}{\sigma_z}\right)^2\right]\right\}. \tag{2}$$

Thus, at x = 300 feet and at ground level where z = 0, the y-coordinate of the rich limit y_r is given by

$$7.0 = 35 \exp\left(-1/2\left[\frac{y_r}{13}\right]^2\right), \tag{3}$$

from which y_r = 23 feet; similarly, the distance from the centerline of the plume to the lean limit y_ℓ is 29 feet, and so forth. Figure 3 (A, A') shows the plume outline in top view and side view, the hatched area being too rich to detonate and all mixtures outside the outer contour being too lean to detonate.

The total volume of the detonable zone is estimated to be 1,100,000 cubic feet. Assuming the average mixture strength to be 4.9 percent propane, the volume of propane in the detonable zone is 54,000 ft^3 or about 4.2 percent of the total leakage at the time of ignition.[10] Approximately the same volume of propane is contained within the overrich (hatched) zone of figure 3 (A, A'); therefore, the greatest part of the propane has been dispersed beyond the 2.8 percent contour as a nondetonable mixture.

The weight of 1,100,000 cubic feet of 4.9 percent propane-air at somewhat less than ambient temperature is about 100,000 pounds. The enthalpy release on detonation is about 260 kilocalories per pound,[11] and the comparable value for detonating TNT is 500 kilocalories per pound; therefore, the TNT equivalent of the detonable gas zone in figure 3A is approximately 50,000 pounds.

No account was taken in the above calculations of the heavier-than-air density of propane mixtures. The assumption of atmospheric stability category F does imply a "lid" on vertical dispersion; in table 2, values of σ_z are about half the values of σ_y. However, in recent experimental studies of the dispersion of cold natural gas vapors and of chlorine, the Bureau has found σ_z to be given more nearly by 0.2 σ_y.[12] Accordingly, the flammable zone was recalculated using the plume dimensions of Singer and Smith[13] as summarized in table 3. (Note that for the stable atmospheric condition, gustiness

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[10] The enthalpy of detonation is quite insensitive to mixture ratio in the range of 4 to 5 percent propane.

[11] See footnote 10.

[12] Burgess, D. S., J. N. Murphy, and M. G. Zabetakis. Hazards Associated With the Spillage of Liquefied Natural Gas on Water. BuMines RI 7448, 1970, 27 pp.

Murphy, J. N., M. E. Harris, and D. S. Burgess. Hazards in the Marine Transportation of Liquid Chlorine. Final report to U.S. Coast Guard on MIPR. No. Z-70099-9-93754, 1970, 37 pp.

[13] Singer, I., and M. Smith. Relation of Gustiness to Other Meteorological Parameters. J. Meteor., v. 10, 1953, pp. 121-126.

classification D in the Singer and Smith nomenclature, σ_z is given exactly by $0.2\ \sigma_y$.) The resultant contours of 7.0 (upper limit) and 2.8 (lower limit) percent propane are given in figure 3 (B, B'). The length of flammable cloud is extended from 1,470 to 1,550 feet and the area is increased from 2.4 to 3.8 acres; however, because the maximum cloud depth is decreased from 22 to 14 feet, the volume of detonable mixture increases only from 1.1 to 1.5×10^6 ft^3 (table 4). Since Turner[14] only claims to predict concentrations within a factor of two, these differences are not surprising; in fact, it is reassuring that predicted volumes of detonable mixture are so insensitive to extremely different assumptions as to layering.

TABLE 3. - Representative atmospheric conditions[1]

Gustiness classification	Frequency of occurrence	Wind speed,[2] ft/sec		Plume dimensions, ft	
		Mean	σ	σ_y	σ_z
A--extremely unstable....	1	5.9	3.6	-	-
B_2--unstable............	3	12.4	5.9	$0.45x^{0.91}$	$0.46x^{0.91}$
B_1--unstable............	42	22.8	10.0	$0.42x^{0.86}$	$0.39x^{0.86}$
C--neutral...............	14	35.0	10.0	$0.42x^{0.78}$	$0.29x^{0.78}$
D--stable[3]..............	40	(4)	(4)	$0.44x^{0.71}$	$0.088x^{0.71}$

[1] Taken from Singer and Smith (text footnote 13) and other publications of the Brookhaven National Laboratory.

[2] Measured at 325-ft elevation; lower values may pertain to ground level dispersions.

[3] Primarily a nocturnal phenomenon.

[4] Depends on height of inversion; taken as 8 ft/sec in present calculation.

TABLE 4. - Detonable cloud dimensions as affected by fuel flow and atmospheric parameters

Q, ft^3/sec	Stability category	Wind speed, ft/sec	Cloud length, ft	Cloud area, ft^2	Cloud volume, ft^3
900	F (footnote 8)	8.0	1,470	104×10^3	1.1×10^6
900	D (footnote 13)	8.0	1,550	165×10^3	1.5×10^6
900	C (footnote 13)	35.0	150	3.3×10^3	$.026 \times 10^6$
900	B_1 (footnote 13)	22.8	100	3.0×10^3	$.031 \times 10^6$
90	D (footnote 13)	8.0	300	9.7×10^3	$.024 \times 10^6$

Since these simplified analyses imply a steady state of fuel flow into a fairly steady wind, the volume of the detonable zone should approach constancy after about a 10-minute interval. Thus, if the ignition of the gas cloud had been delayed for a matter of hours, there would have been no greater accumulation of detonable mixture. One finds this a bit difficult to believe, and several factors are discussed below which have further bearing on the size and shape of the propane-air plume.

First, the terrain is not flat but slopes at an average inclination of about 2 percent in the downwind direction and somewhat more steeply crosswind.

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[14] Work cited in footnote 8.

Thus, one would expect a heavy layer of propane-air to drain toward the deepest part of the valley somewhat as shown in figure 2. (The solid curve of the postulated cloud seeks to preserve the distribution of figure 3, and the dotted outline reflects drainage into a deep pocket where the mixture would be somewhat protected from the wind.) The reality of the dotted portion of the cloud outline is supported by the statements of witnesses that the cloud "filled" the valley, by the post-accident observations of wind damage and of scorching, and by the distribution of blast damage; as drawn, it contributes to a total cloud area of about 10 acres.

Also, some mention should be made of the source of propane vapors at the pipeline break. Since propane issued into the ambient atmosphere as a liquid at about 1° C, about one-fourth of it must have quickly flash-vaporized, cooling the remainder to its boiling point, which is -42° C. According to witnesses, this cold liquid was dispersed as a plume about 50 to 80 feet high. The crucial point here is that the cold droplets of propane must then have derived their heat of vaporization from the ambient air rather than from the ground. It takes the heat capacity of about 9 pounds of air at 1° C to volatize 1 pound of propane at -42° C; the resultant mixture, which is 10 weight-percent or 7 volume-percent propane at -42° C, is about 20 percent more dense than the surrounding atmosphere. At some intermediate wind speed, one could visualize a very tenacious ground layer, which was only slightly above the rich limit of detonability; as this cold mixture warmed and mixed with ambient air, a much higher proportion than 4.2 percent of the initial propane could be within the detonable concentration range.

Thus, figure 3 represents a rather unlikely condition of minimum hazard. Each of several factors that are specific to the accident scene would have tended to increase the volume of detonable mixture at the time of ignition.

BLAST DAMAGE ANALYSIS

There are two sets of data from which to infer the weight of detonating TNT that might have caused damage equivalent to that of the subject propane-air explosion.

1. Structural damage to homes within the immediate neighborhood where the overpressures should have been about 1 psi or more;

2. Damage in the extremely far field, primarily in the form of window breakage, where overpressures would have been a few pounds per square foot.

As will be discussed later, neither of these sources of information is entirely satisfactory, but taken together they contribute to a credible representation of the blast.

Damage Within a Half Mile of the Explosion

Figures 4 through 9 show the aftermath of the explosion in the form of damage to six structures around the detonable cloud. Each of these six locations was assigned a damage category by reference to table 5, which was abstracted from a study of several hundred chemical explosions.[15] Each category of damage occurs at an average value of scaled distance, λ, which is related to the actual distance, d, in feet and to the weight of explosive, W, in equivalent pounds of TNT:

$$\lambda = d/W^{1/3}. \tag{4}$$

Having assigned values of λ to each of the six damaged buildings and assuming that the same value of W should apply in each case, one proceeds by trial and error to find an apparent center of the blast from which to measure consistent values of d. One reasonable placement of the center is located on figure 2, near the deepest part of the presumed cloud of propane-air. Using this initiation point of the blast, we find that five of the six structures suffered damage as though from 50 to 75 tons of TNT (see table 6); however, one structure, the Stotko home, position 6 of figure 2, was so heavily damaged that no reasonable location of the center of blast could bring its TNT equivalency to a value consistent with those of the other five buildings; we presume that topography may have focused the pressure pulse on this home or that a vapor trail may have extended in its direction.

TABLE 5. - Statistical survey of building damage in accidental explosions

Category	Damage description	Scaled distance (λ)
A	Demolished, not standing.................	7.4
B	Damage severe; standing but substantially destroyed, some walls gone.	16.6
C	Moderate damage; walls bulged, roof cracked or bulged, studs and rafters broken.	25.0
D	Slight damage; doors, sashes, or frames removed; plaster or wallboard broken; shingles or siding off.	28.1
E	Minor damage to glass or miscellaneous small items (similar to that resulting from high wind).	42.7

Source: Armed Services Explosives Safety Board Work Group Report (text footnote 15).

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[16] Filler, W. S., J. M. Rossi, and H. R. J. Walsh. Barricade Effectiveness Evaluated From Records of Accidental Explosions. Armed Services Explosives Safety Board Work Group Report, AD 487554L, July 1966, 56 pp.

TABLE 6. - TNT equivalency of propane-air detonation as judged from damage to neighboring properties

Property	Direction	Damage category	Scaled distance, λ	Distance, ft	TNT equivalent, lb
Menner, Sr...	W	B	16.6	750	97,000
Hubenthal....	NNW	D	28.1	1,500	150,000
Menner, Jr...	N	D	28.1	1,400	125,000
Morhaus......	NE	D-E	[1]35	1,700	110,000
Stotko.......	SE	C	25.0	2,000	500,000
Boland.......	S	D-E	[1]35	1,800	130,000

[1] Interpolated from table 5.

An obvious shortcoming of this procedure is that the dimensions of the propane-air cloud are comparable to the distances to the damaged structures. Also, we have no good reason to suppose that the blast from a pancake-shaped detonable cloud should have an apparent point of origin. Finally, one might expect that damage would be heaviest in the near field, along the direction of propagation of the detonation. But despite these limitations, it is still useful to say that housing in the neighborhood was damaged as though by the blast from 50 to 75 tons of TNT centrally located.

Minor Damage in the Far Field

The extent of window damage following an explosion has been used for many years as a measure of explosive energy release. The older texts[16] suggest a critical pressure of 0.5 to 1.0 psi for glass breakage from which one would infer that such damage should have been restricted to a small area around the present explosion (fig. 2). However, as window areas have increased in modern construction, the critical pressure for breakage has decreased; for present purposes we accept a critical value of 0.05 psi as determined in a recent survey.[17]

We have no count of windows broken, but we do have a count of damage claims against the pipeline company and assume that most instances of damage in the extremely far field must have been window damage.

A count of the damaged properties within distances of 1 to 5 miles from the explosion site is given in table 7 along with the total number of structures found in each area. These data were used to generate the cumulative frequency values given in column 4. A plot of the values in column 4 against the distance, R, from the explosion site is given in figure 11 on log-normal probability paper. From this figure, the median distance for reported damage, R_{50}, is 3.4 miles (18,000 feet) and the standard deviation, S, is 0.30.

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[16] Robinson, C. S. Explosions, Their Anatomy and Destructiveness. McGraw-Hill Book Co., Inc., New York, 1944, 88 pp.

[17] Reed, Jack W. Evaluation of Window Pane Damage Intensity in San Antonio Resulting From Medina Facility Explosion on November 13, 1963. Annals of the New York Academy of Sciences, v. 152, art. 1, 1968, pp. 565-584.

TABLE 7. - Structures with reported damage around the explosion site, Port Hudson, Mo., December 9, 1970

Radius, miles	Structures damaged	Structures, total	Cumulative percent damaged
1	36	37	97.3
2	69	92	75.0
3	97	168	57.7
4	109	284	38.4
5	126	419	30.0

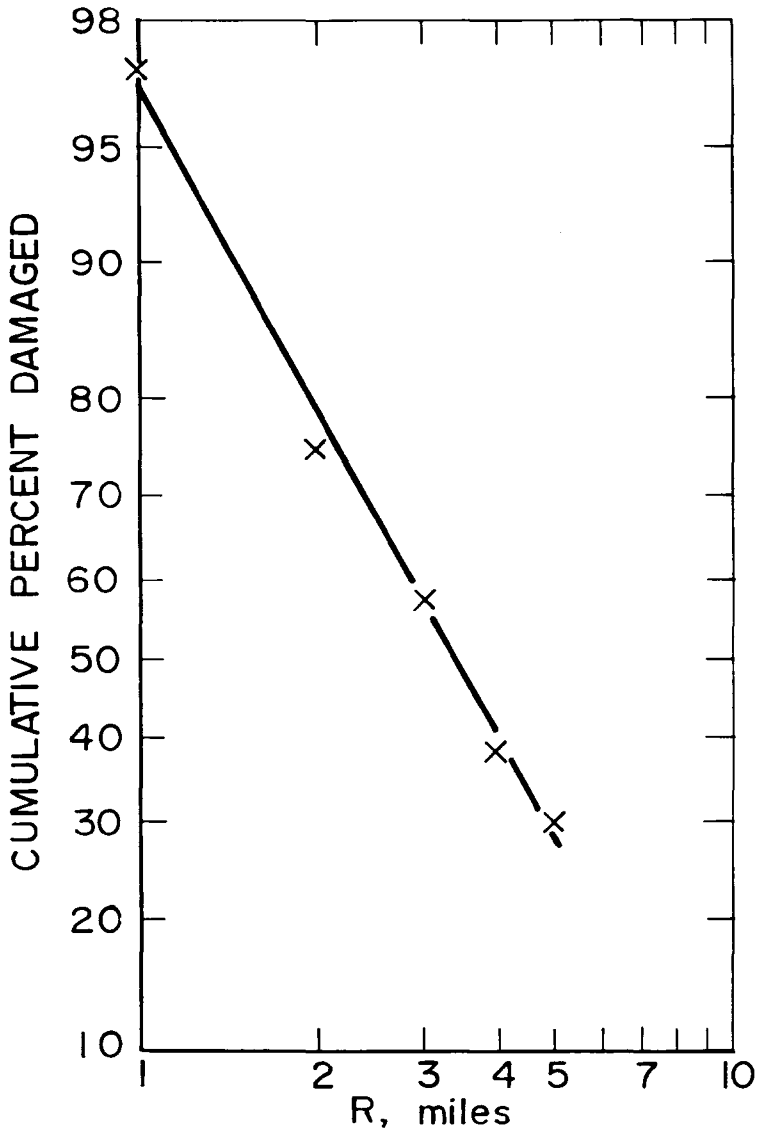

FIGURE 11. - Percentage of structures with window damage within 5 miles of the Menner farm explosion site.

According to the overpressure versus scaled distance chart prepared by Kingery and Pannill[18] for hemispherical charges of TNT, the scaled distance, λ, corresponding to an overpressure of 0.05 psi is 390; thus we have

$$\lambda = 390 = \frac{R}{W^{1/3}} = \frac{18{,}000}{W^{1/3}}, \quad (5)$$

or $W^{1/3} = 46.2$

and $W = 98{,}000$ lb TNT.

This value is to be compared with the 97,000- to 150,000-pound estimates derived from near-field damage and with the minimum of 50,000 to 75,000 pounds inferred from the size of the detonable cloud in figure 3.

Atmospheric Effects

One would expect the probability of damage to decrease

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[18] Kingery, C., and B. Pannill. Peak Overpressure vs Scaled Distance for TNT Surface Burst (Hemispherical Charges). BRL Memorandum Report 1518, Ballistic Research Lab., Aberdeen, Md., 1964, 22 pp.

monotonically to zero with increasing distance from the center of the explosion. While this was true out to about 5 miles, there were areas beyond this distance to the north and northeast where there were clusters of structures that suffered window damage (fig. 12). For example, one such cluster was found toward the northeast about 6 to 8 miles from the explosion site, another in the Washington, Mo., area, approximately 12 miles away, and still another in New Haven, north of the explosion site. Such damage may be attributed to refraction of the pressure wave by the atmosphere and perhaps to reflections from buildings and hills.

Refraction effects can best be illustrated by considering an optical analogy. When a light beam or ray passes from one medium (for example, air) into another (for example, water), its speed changes. At the same time, unless the light beam enters the second medium at right angles, its direction will change in accordance with Snell's law:

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{C_1}{C_2}, \tag{6}$$

where the θ's are the angles between the ray and the normal to the interface, and the C's are the speeds of light in mediums 1 and 2, respectively. The same relationship is applicable to a sonic ray. Accordingly, the behavior of a sound wave in the atmosphere is determined by the factors that influence its speed. Chief among these are the air temperature and wind velocity.[19] In still air, the speed of sound is given by the equation

$$C = 1{,}087.5\sqrt{1 + \frac{T}{273.16}}\ \text{ft/sec}, \tag{7}$$

where T is the temperature in ° C. In moving air, the speed of a sound wave relative to a stationary observer on the earth is

$$V = C + U \cos \theta', \tag{8}$$

where U is the air speed and θ' is the angle between the sound ray and the wind vector.

Thus, a sound ray that is initially parallel to the earth's surface is bent upward (away from the earth) when sound speed decreases with elevation, and is bent downward if the reverse situation exists; a ray will travel in a straight line only if the sound speed does not vary with elevation. In still air, sound speed normally decreases with elevation, and we would expect sound rays to be bent away from the earth's surface; this effect is associated with the adiabatic lapse rate of approximately 1 C°/330 meters. However, temperature inversions and winds are apt to alter the picture completely. For example, the surface winds in the Port Hudson vicinity during the evening of December 9 (table 1) were adequate to reverse the effects of the temperature inversion in the northeast quadrant. The air temperature and corresponding

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[19] Rayleigh, Lord John. The Theory of Sound. Dover Publications, New York, v. 2, 1945, p. 287f.

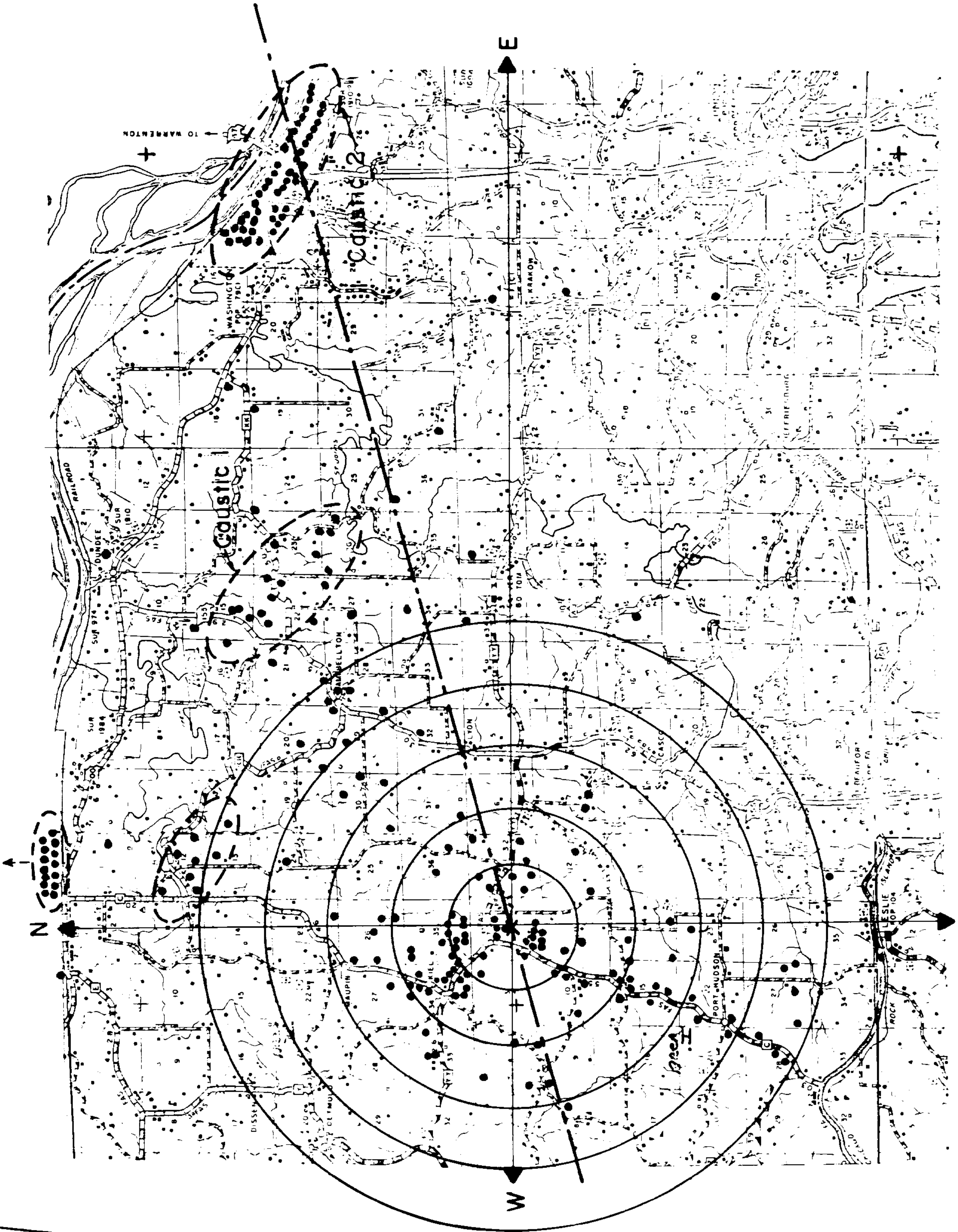

FIGURE 12. - Map of area showing damage claims resulting from explosion.

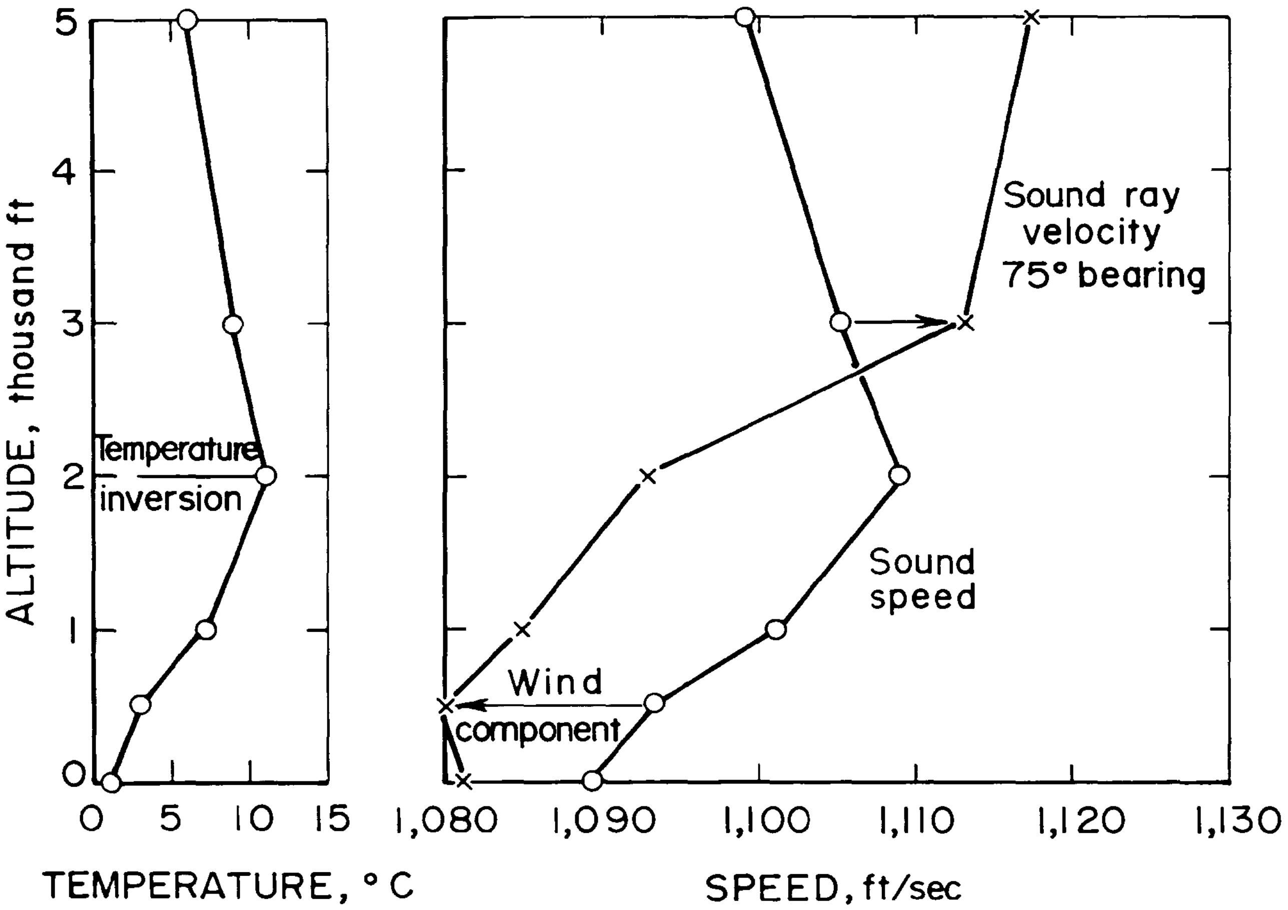

FIGURE 13. - Temperature, sound speed, and sound ray velocity versus altitude (75° bearing).

sound speed are included in figure 13. The resultant velocity of a sound ray (sound speed plus effects of wind) in the east-northeast direction (75° bearing) is also included in this same figure. Note in particular that a horizontal sound ray would be bent upward to an altitude of about 500 feet and then back down toward the earth. An approximate focal point for such a ray may be obtained by noting that the radius of curvature ρ is given by the equation

$$\rho = - \frac{V}{dV/dZ}, \tag{9}$$

where dV/dZ is the (constant) velocity gradient along a normal to the earth's surface.[20] Cox, Plagge, and Reed[21] have developed a series of equations to simplify such computations.

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[20] Cox, Everett F. Sound Propagation in Air. Handbuch der Physik, v. 48, 1957, pp. 455-478.

[21] Cox, Everett F., H. J. Plagge, and J. W. Reed. Meteorology Directs Where Blast Will Strike. Bull. Am. Met. Soc., v. 35, No. 3, March 1954, pp. 95-103.

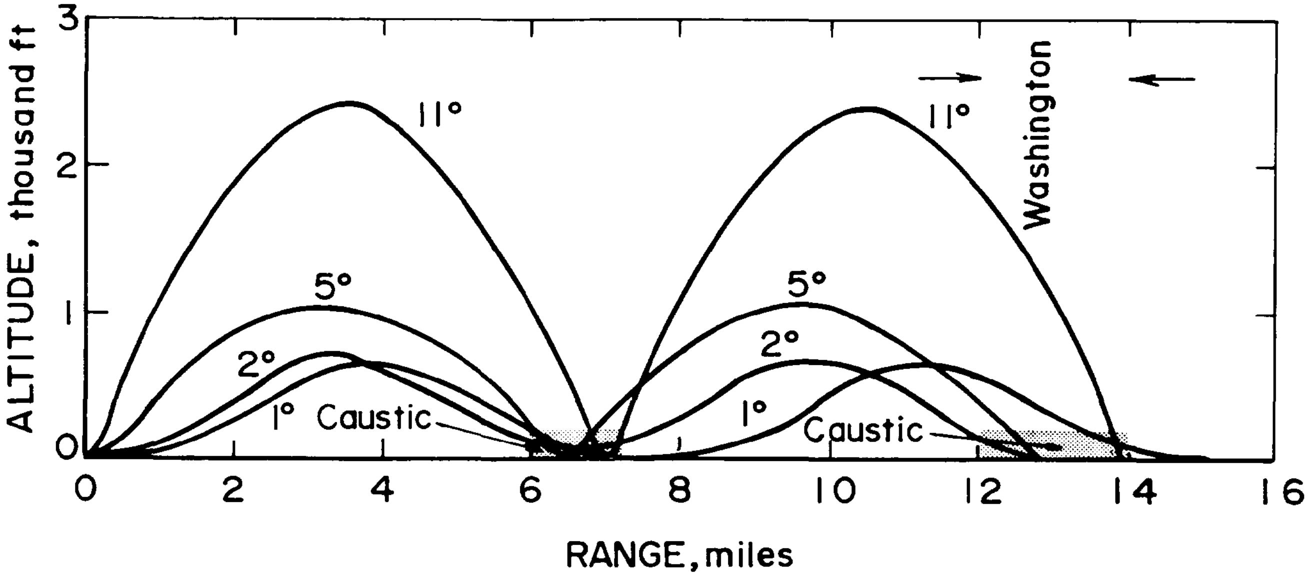

FIGURE 14. - Selected blast ray paths toward Washington, Mo. (75° bearing).

More recently, Thompson has prepared a program that permits the systematic tracing of rays emanating from a pressure disturbance in the atmosphere.[22] A modification of this program from Dr. Jack W. Reed of Sandia Laboratories was used to obtain the paths of rays along a number of bearings. A summary of some of these results for the 75° bearing (toward Washington, Mo.) is presented graphically in figure 14. This figure illustrates the focusing action and therefore blast magnification of the refracted rays to form caustics at about 6 to 7 and also 12 to 14 miles from the explosion site. These correspond to the clusters of window damage evident in the corresponding areas depicted in figure 12. In particular, note that damage occurred at both the first and second caustics in the neighborhood of the 75° bearing. According to Dr. Reed, this is not uncommon. Similar damage zones were found north of the explosion site, but there was very little evidence of such focusing in the other quadrants (fig. 12).

Ground Waves

If, as a rough average of values given previously, the blast energy was 5×10^{10} calories (50 tons TNT equivalent), then approximately 1.5×10^{8} calories (300 lb TNT equivalent) would have been transmitted into the ground, assuming the normal incidence reflection factor (0.997) for sonic waves is applicable here. While this coupling is very poor, the resultant seismic signal would have had a magnitude of 3.1 on the Gutenberg-Richter scale.[23] Interestingly, signals were received at the Florissant and St. Louis stations of St. Louis University; while these signals were found to be superimposed on those caused by an earthquake in Peru, a vertical ground motion of 2.2×10^{-3}

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[22] Thompson, R. S. Computing Sound Ray Paths in the Presence of Wind. Sandia Lab. Rept. SC-RR-67-53, 1967, 31 pp.

[23] Richter, Charles F. Elementary Seismology. W. H. Freeman and Co., San Francisco, Calif., 1958, p. 366.

millimeters was inferred from the St. Louis records. The predicted value, using an extrapolation of the data of Thoenen and Windes,[24] is about five times greater.

Unfortunately, there is no way of using the seismic data to arrive at an independent energy release figure at present because the characteristics of the soil in this area are not as well known as those in southern California area where Richter made his measurements.

DISCUSSION

Explosive Yield

If the 750 barrels of escaped propane had detonated in a homogeneous, stoichiometric (4 percent) mixture with air, the enthalpy release would have been 666 x 10^9 calories. By definition, the enthalpy of detonation of TNT is 10^9 calories per ton. Therefore, by the concept of TNT equivalency, the present explosion gave 50/666 or 7.5 percent of maximum theoretical yield.

While recognizing the inadequacy of TNT equivalents as applied to gas mixtures, it is still useful to compare this value of 7.5 percent with values derived in the same way from other explosions. For example, in the summary by Brasie and Simpson[25] of three major gas explosions (styrene, butadiene, and vinyl chloride), 22 items of damage were listed with which to estimate a "TNT" yield. Their yields ranged from a minimum of 0.3 percent to a maximum of 4 percent of the theoretical. We think that the unusual 7.5 percent yield in the present accident derived from direct initiation of the flammable cloud to detonation. That is, little or none of the initially flammable gas was consumed in subsonic flame propagation, and all of the blast was delivered in one pulse.

If we now accept that a steady-state cloud such as those shown in figure 3 could be established in 10 minutes,[26] the same explosive yield could have resulted from the loss of about 300 barrels of propane in 10 minutes. This corresponds to a nearly 20-percent yield. It shows, in fact, that there is little merit in relating yield to a total quantity of flammable material. In figure 3, the essential parameters affecting detonable cloud volume are the volume rate of fuel flow and the interrelated variables of wind speed and stability category.

Figure 15 shows how these factors affect the approximate contours of lean limit concentration. In figure 15<u>A</u>, the fuel flow is held constant at 900 ft^3/sec into stable (D), neutral (C), and unstable (B_1) atmospheres using

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[24] Thoenen, J. R., and S. L. Windes. Seismic Effects of Quarry Blasting. BuMines Bull. 442, 1942, 83 pp.

[25] Brasie, W. C., and D. W. Simpson. Guidelines for Estimating Damage From Chemical Explosions. Symp. Loss Prevention in the Process Ind. 63d Nat'l Meeting, AIChE, St. Louis, Mo., Feb. 18-21, 1968, preprint 21A (available from AIChE).

[26] Work cited in footnote 8.

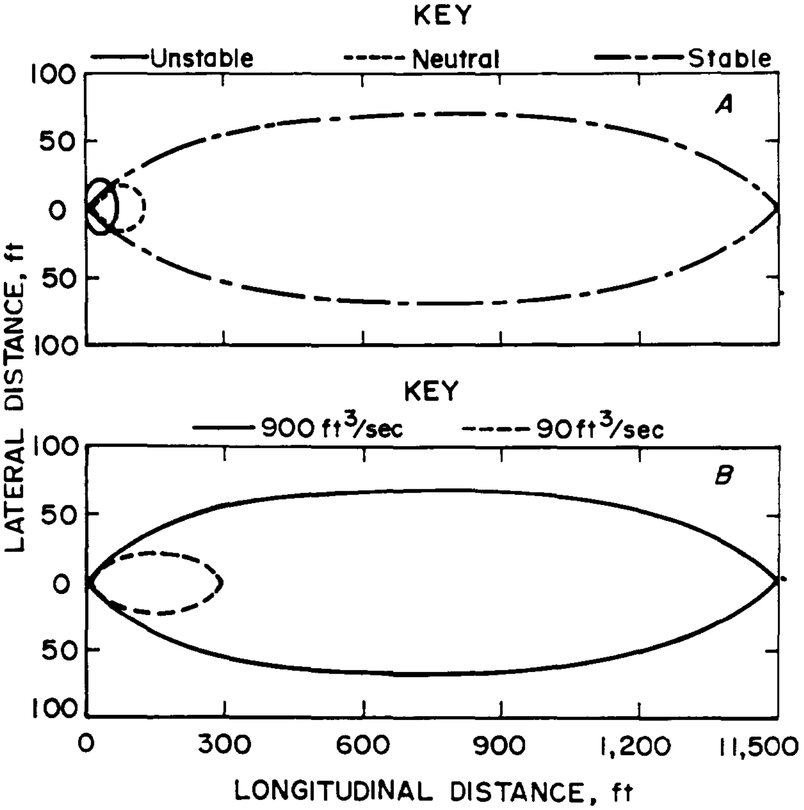

FIGURE 15. - Approximate contours of 2.8 percent propane, as affected by *A*, atmospheric stability, and *B*, fuel flow.

the mean wind speeds given in table 3. In figure 15B, the atmospheric variables are constant while fuel flows are 90 and 900 ft^3/sec. Table 4 summarizes pertinent distances, areas, and volumes, and shows that atmospheric stability can be more important than a tenfold reduction of leak rate.

The Firestorm

The aftermath of the explosion, in which the residual propane was consumed, is no less interesting than the detonation. One would like to know whether such a windstorm could occur in any ignition of a large unconfined cloud or whether the detonation was a necessary precondition. Unfortunately, our investigation produced very little hard evidence on which to argue.

In general, the area of wind damage was also the area that showed scorching in aerial photographs. Note, for example, in figure 1 the many small evergreens at the right center. Similar trees within the blackened area were uprooted and pointing along the axis of the vapor plume. The sharp localization of the windstorm area is even more evident in figure 4. Scattered around the residence on the unscorched lawn are many hundreds of board feet of roofing lumber. This area does not look as though it had been swept by any hurricane-strength wind; however, about 100 feet beyond the residence, the garage that had housed the two automobiles has disappeared. To the left of the photograph (just beyond the parked truck) is a utility pole that has been snapped off at ground level; like most of the debris, it points toward the outbuilding area where we surmize that the detonation was initiated.

Suppose these winds were induced by a thermal column of the products of combustion, one is then at a loss as to why the airflow was induced only within a 135° angle; that is, from southeast to north and not from other compass directions as well. Perhaps as a restatement of the same paradox, why was the thermal column located over the extreme edge of the flammable cloud when most of the residual propane must have been in the deeper part of the valley and closer to the pipeline break, as indicated in figures 2 and 3?

Also, what length of time would it take to consume the propane as compared to the time required to establish an updraft that was capable of inducing 100-mph winds? The two time scales do not seem compatible.

We think it is significant that the wind direction was everywhere directly opposite to the postulated direction of propagation of the detonation. As the detonation swept through the pancake-shaped cloud, it transported mass beyond its extremities leaving behind an overexpanded volume of cooling combustion products; pressures then equalized by airflow from the edges. Since the main direction of detonation was eastward, it was on the eastward edge of the cloud that the suction phase was most pronounced. Admittedly, there have been no independent observations to support this speculation.

Implications Regarding Such Incidents in the Future

In relating the previously stated observations to what might have happened under other circumstances or in another locality, one is tempted to overindulge in speculations. Had Port Hudson, Mo., been a highly populated area, devastation and fatalities would have been expected within the area of the flammable cloud, about 10 acres. Yet this accident also demonstrated an effective, though unrehearsed, evacuation of a neighborhood. Persons occupying homes within the 1.0-psi isobar would have been in grave danger; this area includes about 300 acres. However, a resident did walk out of the house shown in figure 8, and a couple in their automobile were unhurt as they left the home shown in figure 5. Outside the 1.0-psi isobar, many picture windows were blown in, but there were no serious injuries from flying glass.

Probably the most important lesson from this investigation was the coincidence of factors that are apparently required for such an explosion and fire to occur. Thus, the topography and the weather were nearly perfect for forming an extensive zone of detonable mixture. The delayed initiation within a heavy-walled building was a probable contributing factor, and the dispersion of the fuel as a spray was possibly important. The public hearing[27] brought out that this was the 13th comparable loss of propane from this particular pipeline; it was apparently the first occasion on which overpressures or wind velocities were observed.

In discussions of this type the question arises as to the desirability of flaring an escaping flammable as opposed to allowing it to accumulate.[28] The present experience illustrates the advantage of flaring; however, this practice cannot usually be undertaken on an impromptu basis. Therefore, the decision as to whether escaping flammables should be ignited is applicable mainly to fixed installations, like storage tanks, where the factors of topography and population density can be estimated in advance of the credible accident.

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[27] Work cited in footnote 3.

[28] Welker, J. R., H. R. Wesson, and C. M. Sliepcwich. LNG Spills: To Burn or Not To Burn. Pres. at the Distribution Conf., Operating Sec., American Gas Association, Inc., Philadelphia, Pa., May 12-15, 1969 (available from AGA).

CONCLUSIONS

From an investigation of the accident scene and study of records supplied by the National Transportation Safety Board, we conclude the following:

1. The damage in Port Hudson was unmistakably the result of a detonation.

2. This detonation involved a propane-air cloud extending to about 10 acres in area and comprising a volume of at least 1 to 2 million cubic feet.

3. The blast from this explosion was equivalent to that of about 50 tons of detonating TNT.

4. The gas detonation contributed to a subsequent afterburning of the residual overrich propane in a manner best described as a firestorm.

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