An Update to the Baker-Strehlow-Tang Vapor Cloud Explosion Prediction Methodology Flame Speed Table

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Abstract

The Baker-Strehlow-Tang vapor cloud explosion (VCE) blast load prediction methodology utilizes flame speed as a measure of explosion severity. In previous publications, guidance has been presented for selecting flame speeds as a function of congestion, confinement, and fuel reactivity. These recommended values were based on empirical data available from the literature. Over the last five years, a series of medium-scale VCE tests have been conducted through a joint industry program to better understand vapor cloud explosions and to allow a more accurate definition of the flame speed applicable to a given combination of congestion, confinement, and fuel reactivity. These tests have demonstrated that the previously published flame speeds are not conservative for all configurations for the case of no confinement (3-D flame expansion). This paper provides an overview of the tests along with an update to the flame speed table where the previously published guidance was not conservative.

Introduction

Vapor cloud explosion (VCE) prediction methodologies can be organized into three broad categories: simplified (point source), phenomenological, and numerical. Because each method has its own set of advantages and disadvantages, they are commonly used to address significantly different types of problems. Simplified models are used for many on-shore plant analyses. These models are not the best choice for blast load prediction within or very close to the explosion source because they do not account for the fine details of equipment layout. However, the areas of interest for most on-shore facilities (e.g., occupied buildings) are usually at a significant enough distance from the explosion sources that this shortcoming is not an issue. The simplified models permit analysts to perform assessments more quickly than numerical or phenomenological models, while still providing reasonably accurate results at the areas of interest, consequently offering a significant cost advantage over the more time-consuming approaches.

Background

The three most widely used simplified VCE blast load prediction models are the TNT equivalent method, the TNO multi-energy method[1], and the Baker-Strehlow-Tang (BST) method[2, 3, 4]. All three methods use non-dimensionalized blast curves to predict the blast load for a given source energy and standoff distance. The methodologies differ only in the number and type of curves used. The TNT equivalent model has one pressure and one impulse curve and inherently assumes that all VCEs are detonations that behave like a condensed-phase high explosive. This assumption represents a gross simplification, and this method is no longer widely used. The TNO multi-energy method provides ten numerically derived curves for both pressure and duration. These curves span a range of severities from mild deflagrations to detonations, with the curves evenly spaced based on their maximum pressures. The applied impulse can be estimated from the pressure and duration data provided by the curves. The Baker-Strehlow-Tang method uses a continuum of numerically determined pressure and impulse curves that are based on the Mach number of the VCE flame front relative to a stationary point of reference. Duration can be calculated from pressure and impulse.

Since all three of these simplified methods are based on looking up values from numerically derived non-dimensional blast curves that provide pressure, impulse, and duration, the main difference between the methods is the means of selecting which curve to use. In the TNT methodology, there is only one curve and, therefore, only one option. The TNO methodology can be applied by using severity number 7 unless there is a good reason to use a different value[5], or by using one of several methodologies (GAME, company internal methodologies, etc.) that assign severity based on unit size (number of floors) or congestion level. The BST method provides guidance on selecting a flame speed based on broad categories of congestion (obstacle density), confinement (degrees of freedom of expansion), and fuel reactivity (based on laminar burning velocity).

The accuracy of any of these methods is limited by the ability to select an appropriate curve for a particular plant geometry. The original BST flame speed table was produced based on published experimental data. At the time of publication, much of the published experimental data was determined using small-scale apparatus. It was recognized that some of these small-scale tests might not be ideal for application to a full-scale plant; however, the data were used because no alternative was available. The Explosion Research Cooperative (a joint industry program) initiated an extended series of experiments to refine the functional relationship between flame speed and the degree of congestion and confinement along with the flammable gas mixture reactivity. These tests have been performed over a wide range of congestion levels (low, medium and high) and degrees of confinement (three-dimensional flame expansion, two-dimensional flame expansion with varying aspect ratios, and mixed two- and three-dimensional expansion). Tests have been conducted with near-stoichiometric methane-air, propane-air, and ethylene-air mixtures, which represent low, medium, and high reactivity mixtures, respectively. A limited number of tests have also been performed with other fuels as well as with lean or rich mixtures. The participating companies of the Explosion Research Cooperative agreed to release this update to the flame speed table in order to ensure that the data available in the published literature is conservative.

The Baker-Strehlow-Tang Methodology

The complete Baker-Strehlow-Tang method was first published at the 28th Loss Prevention Symposium in 1994[2] shortly after the development of a correlation for determining maximum flame speed in a VCE. Since that time, the Baker-Strehlow method has been used extensively in VCE hazard assessments in refineries and chemical plants. The goal of the original study in which the methodology was developed was to achieve an objective methodology to provide consistent prediction of VCE blast effects.

The VCE blast curves developed by Strehlow were chosen for the original Baker-Strehlow methodology because blast curves are selected based on flame speed, which affords the opportunity to use empirical data in the selection. Tang and Baker subsequently developed a new set of VCE blast curves, which were adopted in 1999[4] and the methodology was renamed Baker-Strehlow-Tang. The Baker-Strehlow-Tang blast curves are presented in Appendix A.

Determination of the energy term is based on the size of the flammable cloud within confined and congested portions of a plant. Multiple blast sources can emanate from a single release. Fuel reactivity, confinement and obstacle density influence the reaction rate as mentioned above.

Test Description

The congested region for these tests was constructed of modular cubic sections. The length, width, and height of each cube are 6 feet (1.8 meters). The congestion is provided by a regular array of vertical circular tubes (2" schedule 40 pipe). A 4x4 array of tubes per cube was used for low congestion, a 7x7 array represented medium congestion, and 11 rows of alternating 4 and 7 tubes were used for high congestion (see Figure 1). The corresponding pitch-to-diameter, area blockage, and volume blockage ratios are provided in Table 1. The corner tubes of the congestion cubicle were used as substitutes for four of the tubes in each congestion pattern.

Table 1: Congestion Levels Utilized in Tests

Congestion Level	Pitch to Diameter Ratio	Area Blockage Ratio (%)	Volume Blockage Ratio (%)
Low	7.6	13	1.5
Medium	4.3	23	4.3
High	3.1	23	5.7

Sixteen such cubes were arranged in a 2x8 pattern for these tests to provide an elongated length-to-width aspect ratio that is representative of many on-shore facilities. An illustration and photograph of the test rig in this configuration are shown in Figure 2 and Figure 3, respectively. The test rig was configured without any confinement (i.e., no wall or roof sections) for all of the tests reported in this paper.

A near-stoichiometric fuel-air mixture was employed in these tests. Methane was used as the low reactivity fuel, propane as the medium reactivity fuel, and ethylene as the high reactivity fuel. The fuel gas was dispersed through the test rig using a distributed set of venturi mixing devices and its concentration was monitored using an online gas analyzer. A thin (0.001 inch) plastic tent was placed around the rig to facilitate development of the flammable gas mixture. The mixture completely filled the congested region, but did not extend beyond it. Weights holding down the bottom of the plastic tent were removed just before ignition to minimize the impact of the tent on flame propagation. The flammable gas mixture was ignited using a low-energy source in the center of the rig at ground level.

An array of pressure transducers was placed inside and outside the rig at distances of up to 300 feet along both the long and short axis centerlines and diagonally from one corner. Figure 4 shows a typical pressure transducer distribution. High-speed video cameras were positioned outside the rig to provide flame front position recordings. An array of ionization probes was placed along the long axis centerline to track the position of the flame front for selected tests.

Test Results

The pressure-time histories for each pressure transducer were analyzed to determine the peak side-on pressure and impulse at each location. The results were plotted against predicted pressure and impulse versus distance for a variety of flame speeds. The flame speed was iterated until the best match with the data was obtained (see Figure 5 for an example of such a fit). Since pressure and impulse predictions outside congestion are the primary objective of the Baker-Strehlow-Tang methodology, greater emphasis was placed on the best match of prediction to test data outside congestion.

A secondary check of the flame speed was performed next. The flame speed yielding the best fit was compared to the flame front location over time as measured by the ionization probes and/or high-speed video. The best fit for subsonic flame speeds (deflagrations) essentially represented the average flame front speed in the rig (see Figure 6). This result shows that the flame speed that is the best fit for prediction of pressure and impulse is also a good fit to the measured flame speeds.

The most likely reason that these flame speeds are higher than the ones originally used for the flame speed table is due to the scale of the experiments. The original experiments were less than 6 feet (1.8 meters) in their longest dimension for many cases and thus, did not have sufficient length for flame acceleration. The current set of experiments was conducted with a rig size approaching that of actual process equipment, so that these results are more applicable to typical industrial plants. Furthermore, the flame speed data given in the following section have been scaled up to account for the maximum size of a typical industrial plant in order to provide additional margin.

During the course of the testing, a detonation-to-deflagration transition (DDT) was observed during a medium congestion, unconfined ethylene test. The DDT caused extensive damage to the test rig and associated systems. After repairs were made, the test was repeated to confirm the result. The details of this portion of the testing and the justification for concluding that the cloud underwent a DDT are discussed in Thomas et al (2003)[6].

Test Results

A new flame speed table (see Table 2) was produced based on the test program discussed in the preceding sections. It is recommended that this flame speed table be used for all BST blast load predictions since it corresponds to a scale representative of typical chemical processing plants.

Table 2: Revised Baker-Strehlow-Tang Methodology Flame Speed Table

Confinement	**Reactivity**	**Congestion**		
		Low	**Medium**	**High**
2-D	**High**	0.59	DDT	DDT
	Medium	**0.47**	0.66	**1.6**
	Low	0.079	0.47	0.66
2.5-D	**High**	**0.47**	**DDT**	**DDT**
	Medium	**0.29**	**0.55**	**1.0**
	Low	0.053	**0.35**	**0.50**
3-D	**High**	**0.36**	**DDT**	**DDT**
	Medium	**0.11**	**0.44**	**0.50**
	Low	0.026	**0.23**	**0.34**

Notes: (1) Bold values have been updated based on the current set of experiments.
(2) 2.5-D values are the simple average between 2-D and 3-D values.

It is important to note that this new flame speed table includes the 2.5-D category that was put forward by Baker et al (1997) to be used in cases where the confinement is made of either a frangible panel or by a nearly solid confining plane (e.g., pipe rack where the pipes are almost touching). As described, the 2.5-D values are obtained by taking a simple average between the 2-D and 3-D confinement values for the same congestion and fuel reactivity. The 1-D entries have been deleted since the maximum flame speed achieved in true one-dimensional expansion conditions (i.e., a pipe) is a function of the length-to-diameter ratio of the pipe in addition to pipe geometry (elbows, tees, etc.), fuel reactivity and congestion level. Many fuels are able to undergo a DDT in a 1-D geometry if the combination of length-to-diameter ratio and obstacle density are sufficiently high. As a result, the use of a single number to represent all length-to-diameter ratios is overly simplified and a more detailed analysis is recommended for all such cases.

Acknowledgements

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Recommendations for Future Work

While the tests discussed in this paper have increased the understanding of VCE phenomena and contributed greatly to enhancing the BST blast load predictive methodology, it is recognized that there are many relevant questions these tests do not address. The Explosion Research Cooperative continues to support VCE testing research. The Cooperative invites companies with an interest in VCE blast loads to join with them and participate in these efforts.

Figures

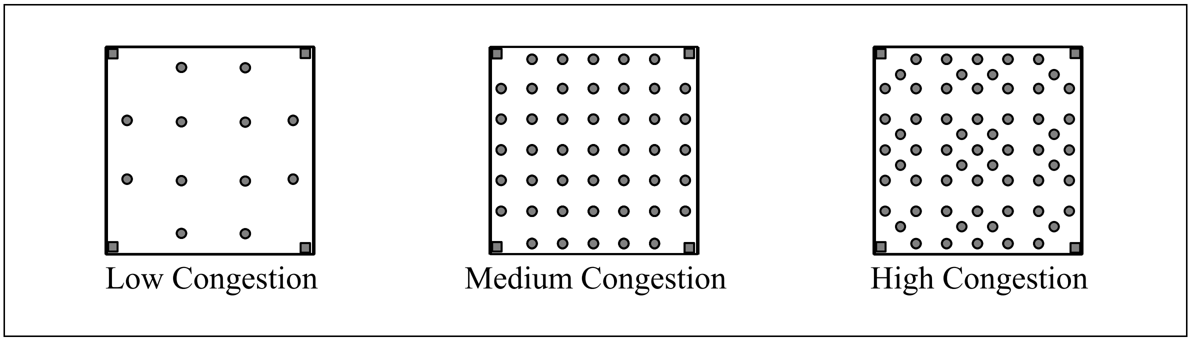

Figure 1: Congestion Patterns Used

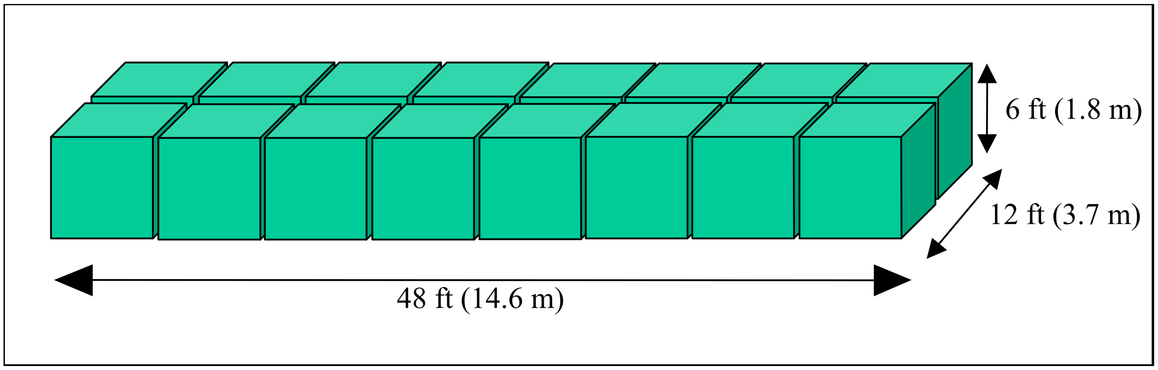

Figure 2: Illustration of test cube arrangement

Figure 3: Photograph of test rig

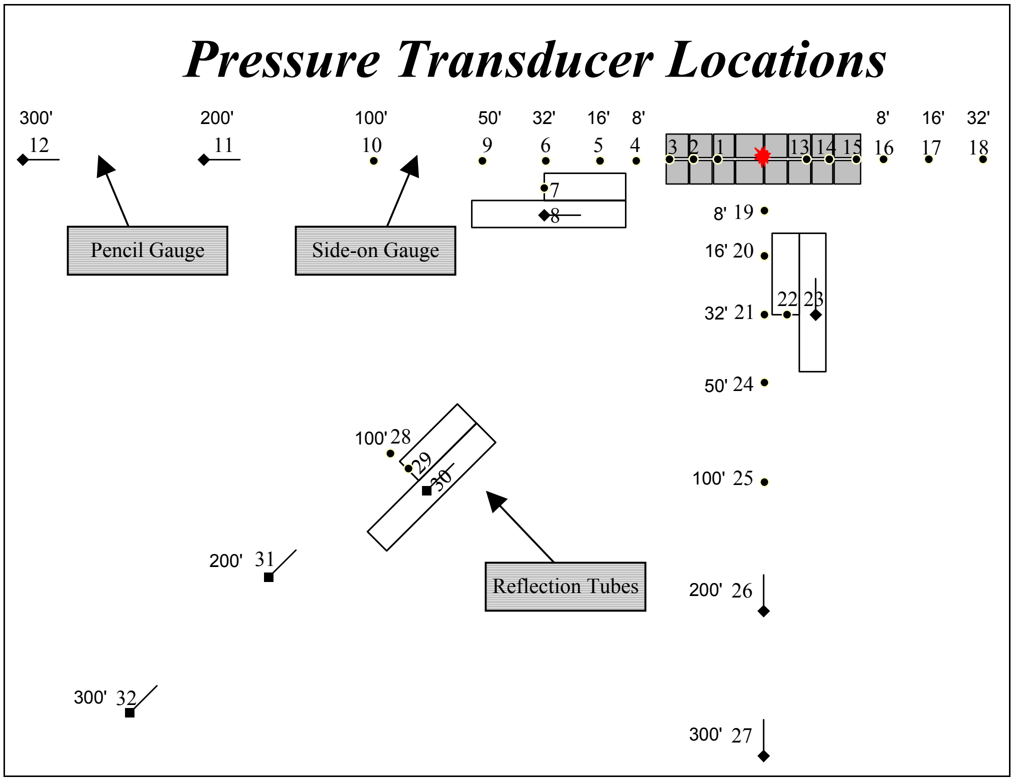

Figure 4: Pressure Transducer Locations

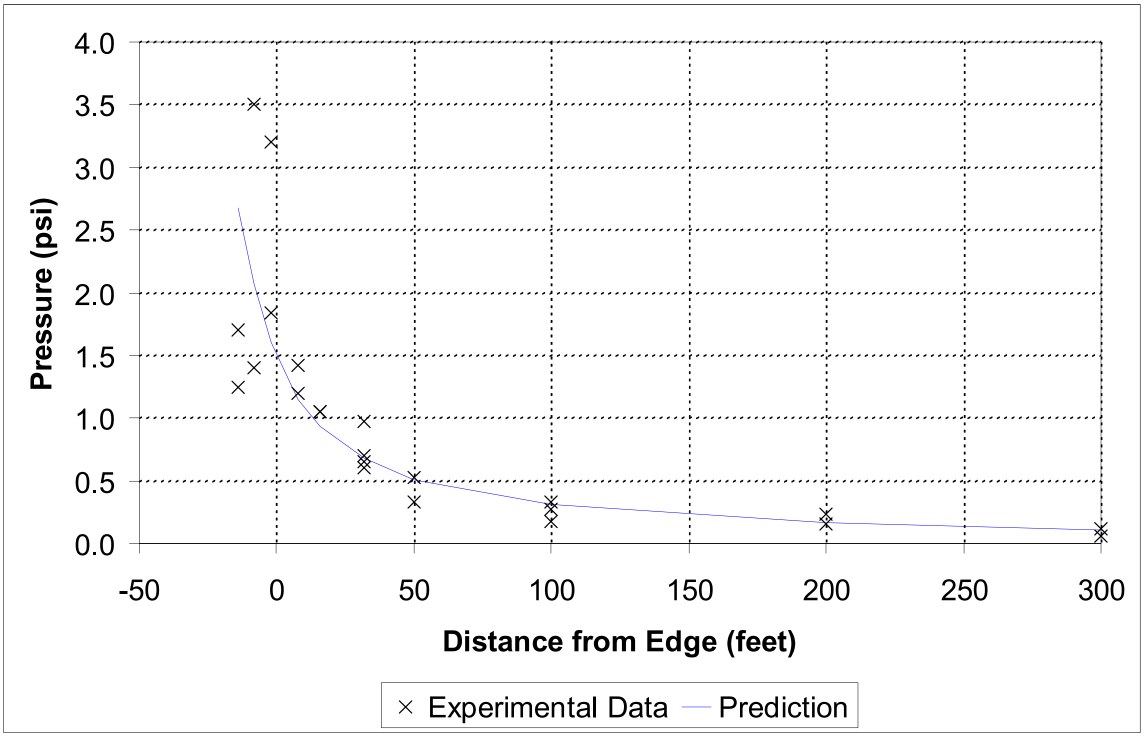

Figure 5: Sample fit of Flame Speed to 3-D High Congestion Propane Pressure Data

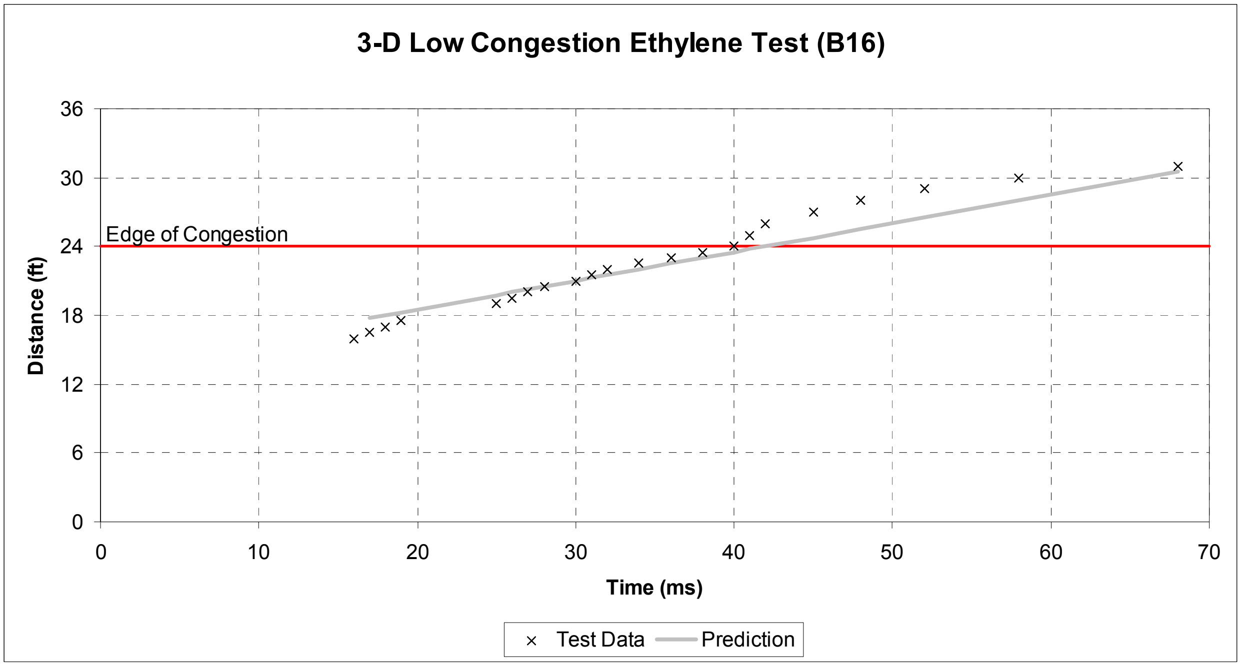

Figure 6: Comparison between predicted and actual flame front location for a deflagration

References

1) TNO Yellow Book, 3rd ed., Apeldoorn, TNO, The Netherlands, 1997.

2) Baker, Q. A., M.J. Tang, E.A. Scheier and G.J. Silva (1994) "Vapor Cloud Explosion Analysis," 28th Annual Loss Prevention Symposium.

3) Baker, Q. A., C.M. Doolittle, G.A. Fitzgerald and M.J. Tang (1997) "Recent Developments in the Baker-Strehlow VCE Analysis Methodology," 31st Annual Loss Prevention Symposium.

4) Tang, M.J., Baker, Q.A., "A New Set of Blast Curves from Vapor Cloud Explosions," 33rd Loss Prevention Symposium, American Institute of Chemical Engineers, Paper 29e, March 14-18, 1999.

5) Crowl, D. A., Understanding Explosions, Center for Process Safety of the American Institute of Chemical Engineers, New York, 2003

6) R.A. Strehlow, R.T. Luckritz, A.A. Adamczyk and S.A. Shimp, "The Blast Wave Generated By Spherical Flames", *COMBUSTION AND FLAME*, 35: 297-310, 1979

7) Thomas, J.K., A.J. Pierorazio, M. Goodrich, M. Kolbe, Q.A. Baker and D.E. Ketchum (2003), "Deflagration to Detonation Transition in Unconfined Vapor Cloud Explosions," Center for Chemical Process Safety (CCPS) 18th Annual International Conference & Workshop, Scottsdale, AZ, 23-25 September 2003.

8) Tang, M.J and Baker, Q.A., "Predicting Blast Effects From Fast Flames", 32nd Loss Prevention Symposium, AIChE March 1998

9) Tang, M.J., Cao, C.Y., and Baker, Q.A., "Blast Effects From Vapor Cloud Explosions", International Loss Prevention Symposium, Bergen, Norway, June 1996

Appendix A. Baker-Strehlow-Tang Blast Curves

The Baker-Strehlow-Tang blast curves are constructed as scaled blast wave properties versus scaled distance and are presented as families of curves with the flame Mach number as the parameter. The flame Mach number is the apparent flame speed divided by the ambient sound velocity. The blast properties and the distance are in non-dimensional coordinates, as shown in figures on the following pages.

According to Sach's scaling, following non-dimensional parameters are used in Baker-Strehlow-Tang blast curves.

$$\overline{P^+} = \frac{p_{\max}{}^{+} - p_0}{p_0} \qquad \overline{P^-} = \frac{\left|p_{\max}{}^{-} - p_0\right|}{p_0}$$

$$\overline{I^+} = \frac{i^+ a_0}{E_t^{1/3} p_0^{2/3}} \qquad \overline{I^-} = \frac{i^- a_0}{E_t^{1/3} p_0^{2/3}}$$

$$\overline{t^+} = \frac{t^+ a_0}{\left(E_t / p_0\right)^{1/3}} \qquad \overline{t^-} = \frac{t^- a_0}{\left(E_t / p_0\right)^{1/3}}$$

$$\overline{t_a} = \frac{t_a a_0}{\left(E_t / p_0\right)^{1/3}} \qquad \overline{U} = \frac{u_{\max}}{a_0}$$

$$\overline{R} = \frac{R}{\left(E_t / p_0\right)^{1/3}}$$

where p_0 is atmospheric pressure;
a_0 is the sound velocity at ambient conditions;
p_{max}^{+} is the maximum of positive peak absolute pressure;
p_{max}^{-} is the maximum of negative peak absolute pressure;
R is stand-off distance;
E_t is the total energy release from the explosion source;
i^+ is positive specific impulse;
i^- is negative specific impulse;
t^+ is time duration of positive phase;
t^- is time duration of negative phase;
t_a is the arrival time of wave front;
u_{max} is the maximum of flow velocity.

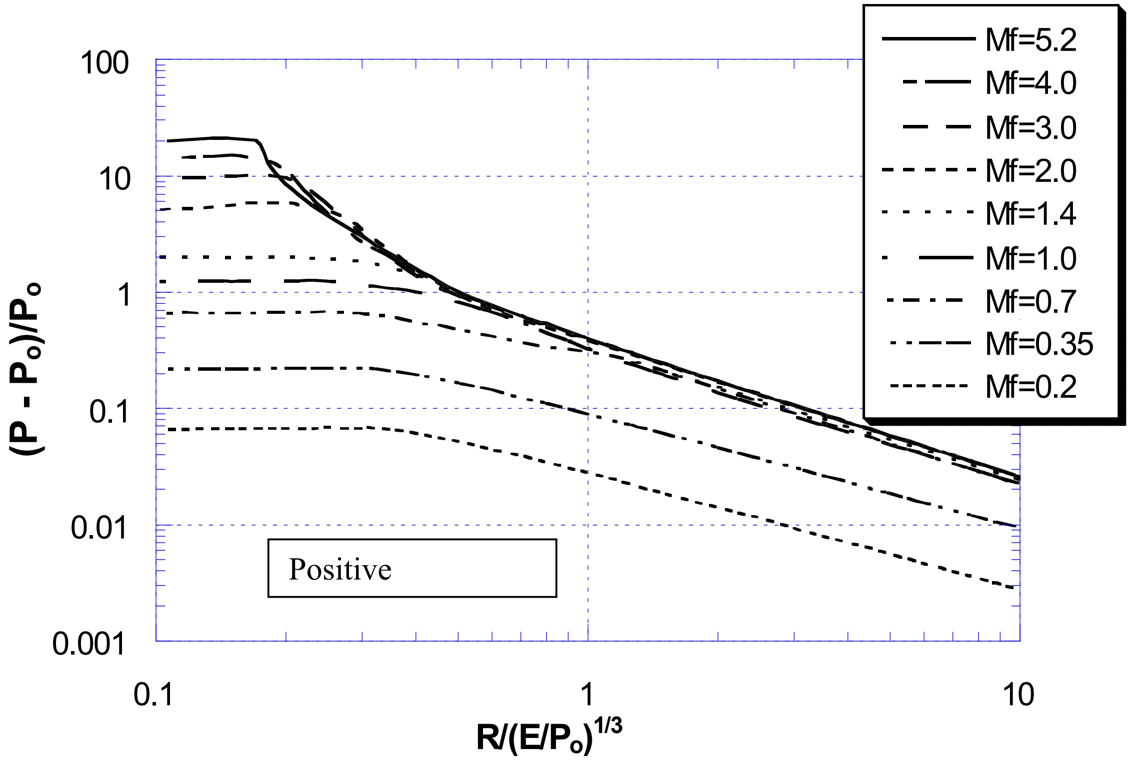

Figure A1 Positive Overpressure vs Distance for Various Flame Speeds

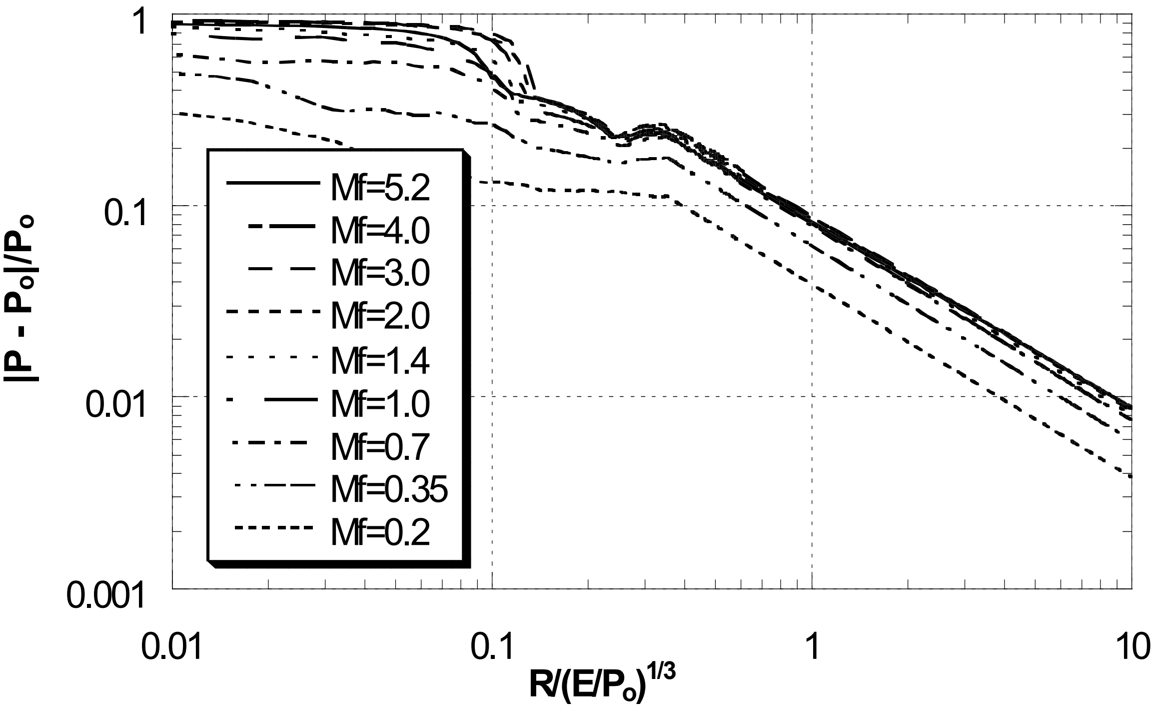

Figure A2 Negative Overpressure vs Distance for Various Flame Speeds

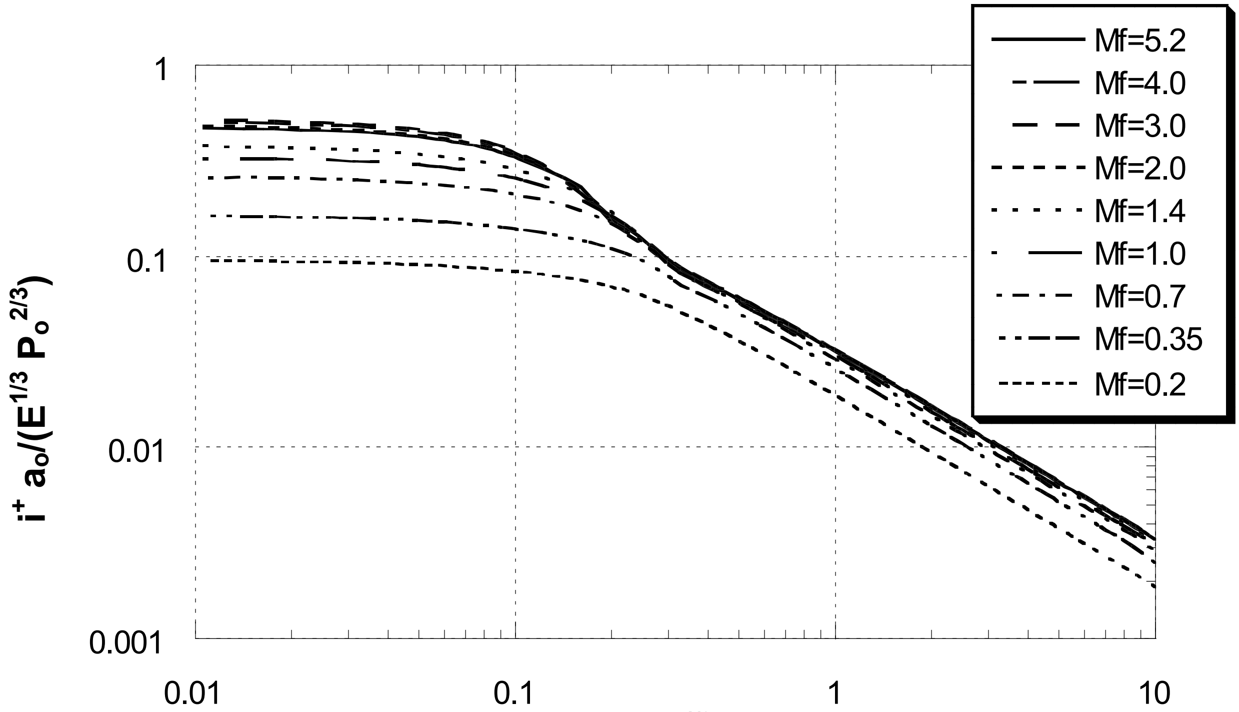

Figure A3 Positive Impulse vs Distance for Various Flame Speeds

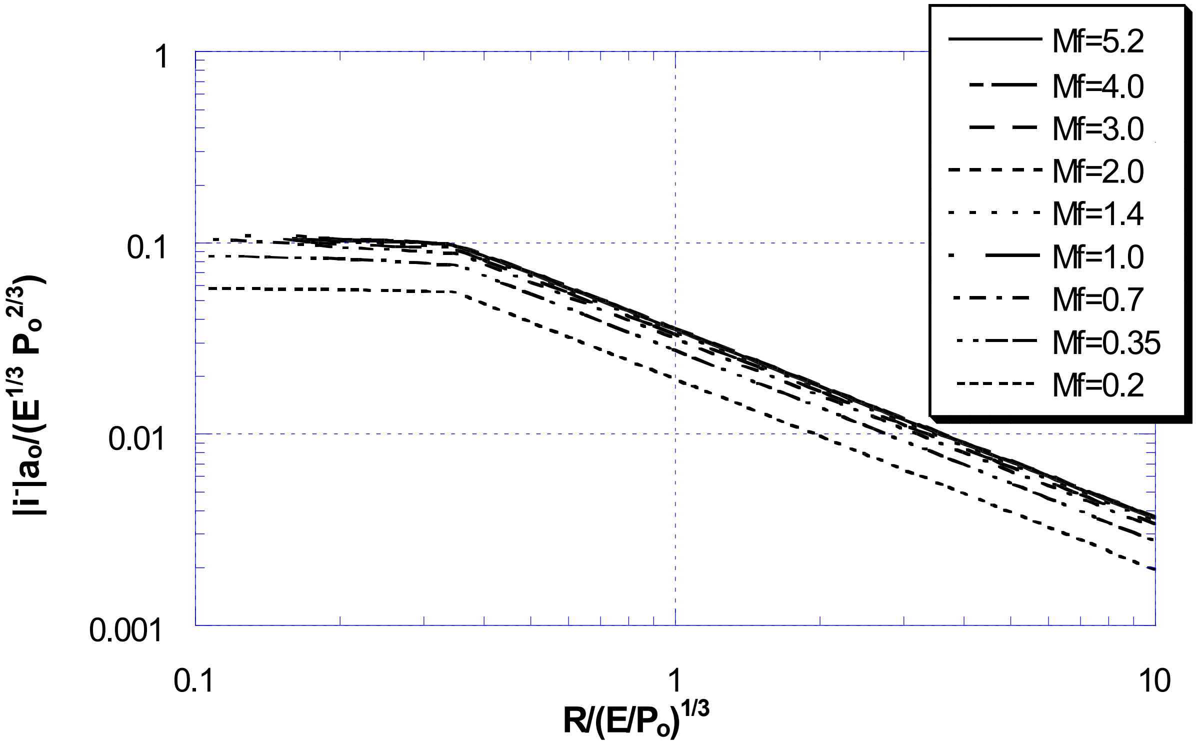

Figure A4 Negative Impulse vs Distance for Various Flame Speeds

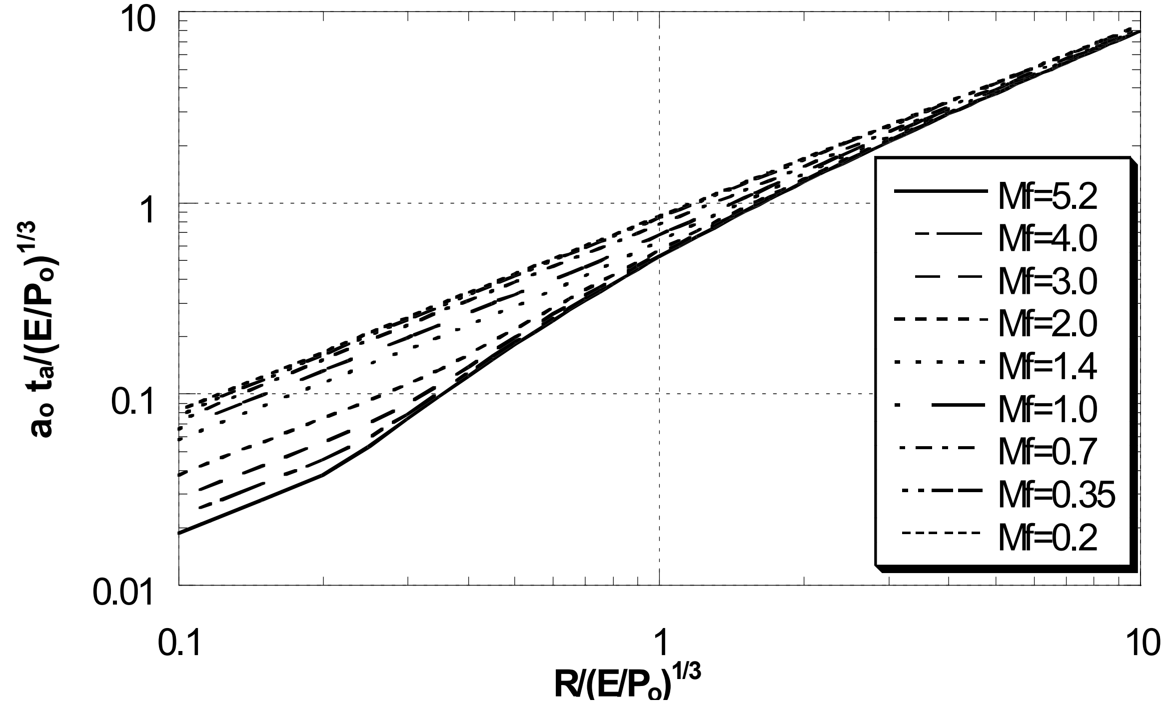

Figure A5 Arrival Time vs Distance for Various Flame Speeds

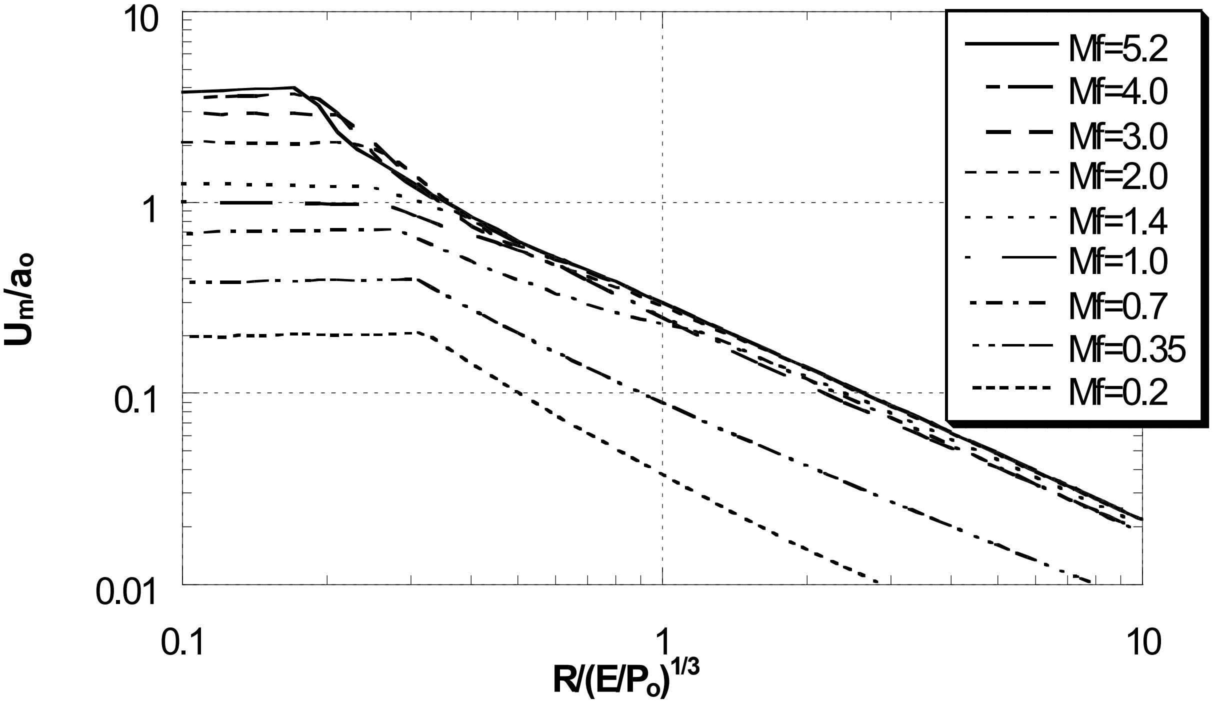

Figure A6 Maximum Particle Velocity vs Distance for Various Flame Speeds

Reference:

Tang, M.J., Baker, Q.A., “A New Set of Blast Curves from Vapor Cloud Explosions,” 33rd Loss Prevention Symposium, American Institute of Chemical Engineers, Paper 29e, March 14-18, 1999.