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A Comparison of Simple Vapor Cloud Explosion Prediction Methodologies

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ABSTRACT

Advances in research and technology have sprouted several approaches for the prediction of vapor cloud explosion blast loads. The three simple approaches most used in industry are the TNO Multi-Energy Method, Baker-Strehlow Method and the Congestion Assessment Method. The TNT Equivalence Method, although still used to some extent, is not being used as much as in the past since it has been shown to not be representative of vapor cloud explosions. Thus, it will not be reviewed in this paper. The first method, the TNO Multi-Energy Method, was first introduced in 1985 and updated in 1996. The Baker-Strehlow Method was introduced in 1994, updated in 1997 and new blast curves presented in 1998. Lastly, the Congestion Assessment Method was introduced in 1995 and updated in 1999. However, no public comparison has been made of all three approaches since their updates. This paper will compare these three approaches with available test data, case studies, and fictional processes.

A Comparison of Simple Vapor Cloud Explosion Prediction Methods

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1. Abstract

Advances in research and technology have produced improvements in the predictions of vapor cloud explosion effects. The simple approaches most widely used in industry are Baker-Strehlow Method (BSM), Congestion Assessment Method (CAM) and Multi-Energy Method (MEM). These methods have undergone mild to significant changes over the past few years. BSM was introduced in 1994, updated in 1997 and new blast curves presented in 1999. CAM was introduced in 1995 and updated in 1999 (CAM2). Lastly, MEM was first introduced in 1985 and updated in 1996 and 1998 (called MEM2 in this paper). However, no public comparison has been made of all three approaches since their published changes. This paper will compare predictions using these three approaches with data from 58 experiments, an industry event and a fictional process. These provided comparisons to a variety of explosions that ranged from a relatively low severity up to a very high severity. These three simple VCE methods are by their very nature screening tools and are accepted to have more inaccuracy than the most advanced method, computational fluid dynamics. Insufficient information was available from the experimental data to provide many comparisons with the predicted blast wave durations and impulses. Thus, no conclusions were reached regarding durations or impulses. However, the BSM overall tended to predict much greater durations than either the CAM2 or MEM2 while the CAM2 and MEM2 tended to predict similar durations. The comparisons made in this paper indicate the CAM2 provides the smallest errors in pressure predictions with respect to experimental data. However, CAM2 is the most complex method to use and has a level of uncertainty that the predictions could be artificially low for some comparisons due to assumptions made in the comparisons. The MEM2 method has the next smallest pressure prediction error with respect to experimental data (but still acceptable), has a high degree of confidence in the predictions due to the lack of assumptions made in the comparisons and is easier to use than CAM2. The BSM method predicted pressure error was much greater than for CAM2 or MEM2 with respect to experimental data. The error for BSM is much larger than which should be acceptable, even for a screening tool. The BSM predictions have a high degree of confidence due to the lack of assumptions made in the comparisons and it is the easiest of the three methods to apply.

2. Background

Vapor cloud explosions (VCEs) are complex events with numerous variables that make accurate predictions difficult. The most accurate means of VCE prediction involves a computational fluid dynamics (CFD) simulation. However, CFD simulations are very time consuming and require highly experienced users to obtain reliable results. With most petrochemical sites requiring in the range of 10 to 30 VCE scenario evaluations, the cost of CFD simulations is typically beyond the budgets of the onshore petrochemical industry for explosion hazards screening studies. Thus, industry relies upon simple methods of VCE prediction. These simple VCE prediction methods have changed significantly over the last several years as experiments have been published that allow for a better understanding of VCEs. Comparisons in this paper show two of the simple VCE prediction methods have been improved, but at the expense of increasing their complexity.

3. Vapor Cloud Explosion Prediction Methods

There are several methods to chose from for making vapor cloud explosion predictions. The first of which, and the oldest method, is the TNT equivalency method. The preponderance of information about VCEs indicate deflagrations are most likely since a VCE detonation in industry has only been reported in one situation. The TNT equivalency method can easily be shown as a poor representation of a deflagration. For example, a TNT equivalency can be found to provide agreement with either the measured pressure or duration of a deflagration at a specific distance, but not for both. In addition, TNT blasts decay at a different rate than do most deflagrations. Thus, TNT equivalency was not considered for inclusion in this comparison. There are several other public and proprietary methods available for VCE deflagration predictions. The methods considered for inclusion in this comparison had to meet the following criteria:

1) The method had to be easily accessible to anyone (use of the proprietary methods usually require the user to buy-in to the project funding or pay a consultant with access to the method).
2) A large user group must currently use the method.
3) Validations of the methods must be published.

Thus, the methods chosen in this comparison were public, currently in popular use and validated. This left three methods to be used in the comparison, Baker-Strehlow Method[1] (BSM), Congestion Assessment Method[2] (updated version called CAM2) and Multi-Energy Method[3] (using the GAMES program, or MEM2). A brief history of their evolution is as follows:

- Baker-Strehlow Method (BSM) was introduced in 1994. Increased guidance[4] was published in 1997 and new blast curves[5] were presented in 1999.
- Congestion Assessment Method (CAM) was introduced in 1995 and updated[6] in 1999, resulting in CAM2. Errors in the updated paper were corrected in a paper[7] presented in 2001.
- Multi-Energy Method (MEM) was introduced in 1985 and updated[8] in 1995 with the GAME program and another update[9] in1998 with GAMES program. These updates made significant changes to the MEM method such that this paper refers to the method as MEM2 when applying these updated methods.

The following method descriptions are not meant to be a comprehensive guide, just a brief summary of the major points in each method.

3.1. Baker-Strehlow Method

The BSM is a blast curve based method. The pressure and impulse blast charts are divided into 10 flame speed curves ranging from Mach 0.037 to Mach 5.2. The user categorizes fuel reactivity, congestion and confinement to obtain a predicted flame speed. Flame speeds in between the given curves can be interpolated. This information is determined using the following criteria:

- Fuel reactivity: low, average or high based on the laminar burning velocity (LBV) of the fuel. Medium reactivity fuels are defined to have LBVs between 40 and 75 cm/s. Low reactivity fuels are below 40 cm/s while high reactivity fuels are above 75 cm/s.
- Congestion: low, medium or high according to the area blockage ratio (ABR). Low congestion is defined as below 10% ABR, medium congestion is from 10% ABR to 40% ABR and high congestion is 40% ABR or greater.
- Confinement: 1D, 2D, 2½D or 3D. The confinement category actually refers to flame expansion. No confining plane to flame expansion is considered 3D confinement. A single plane (such as a roof) is considered 2D confinement. A pipe, culvert or area with a roof and two vertical walls would be 1D confinement. The update in 1996 also defined 2½ D confinement as an area with limited 2D confinement such as a roof and/or partial walls which might be expected to fail quickly and provide venting, or an area without total 2D confinement such as an elevated fin fan cooler.

A published matrix of these categories provides the user with a flame speed. Explosion energy is calculated using the amount of fuel within the congested region and, if it is not an elevated explosion, is multiplied by a factor of two to account for ground reflection. Explosion energies reported in this paper have already had the factor of two applied to them. The flame speed determines which curve to select. The explosion energy and standoff distance are applied to the blast curves to obtain a predicted pressure and impulse. Duration is derived from these assuming a right triangular blast wave shape. The distance from the point of interest is measured from the center of the congested region.

3.2. Congestion Area Assessment Method

The CAM2 method is also blast curve based. Peak pressure is calculated from one of two equations, one for 2D and one for 3D flame expansion. CAM2 defines 2D as a case where a hemispherical flame front reaches the confining plane before it reaches a vent plane at the edge of congestion. This corresponds to a height to half width aspect ratio of less than one. Aspect ratios greater than or equal to one would be 3D confinement. The CAM2 peak pressure calculations are made using the following inputs:

- Dimensions: Length, width and height, x, y, and z, respectively, of congested region.
- Number of obstacles in each direction: Number of obstacle layers the flame front passes in the x, y and z directions.
- ABR in each direction: Area blockage ratios in the direction of the flame front in the x, y and z directions using the most congested regions in each direction.
- Complexity factor: A variable ranging from 1 to 4 to describe complexity of congestion. A complexity of 1 would be idealized, repetitive congestion. A complexity of 4 would be a typical process layout.
- Fuel factor and expansion ratio: Two variables provided for several fuels to account for reactivity and amount of expansion upon ignition.

Additional calculations are used to decay the blast with distance, determine duration and rise time to peak pressure. The calculation is reported to account for scaling, directionality, energy efficiency, effect of sharp-edged obstacles, an expanding vapor cloud into other congested areas and burning outside the congestion that contributes to the blast wave. Impulse is calculated from the predicted pressure and duration. Blast wave shape is also predicted. Distances to points of interest are measured from the edge of the congestion to the point of interest.

3.3. Multi-Energy Method

The MEM is like the BSM and CAM2 in that it is also a blast curve based method. The blast curves are pressure and duration curves and are divided into 10 severity levels from 1 to 10. Little guidance was provided in the original method description on how to select a severity level. The GAME program provided a change in the method in that a peak pressure is calculated from one of two equations, one for 2D and one for 3D flame expansion, similar to CAM2, and a severity level is solved for corresponding to the calculated pressure. 2D and 3D confinement are also defined the same as in the CAM2. The GAMES program provided guidance on how to choose proper values for the variables in the calculations. The MEM2 calculations are made using the following inputs:

- Volume blockage ratio (VBR): Congested volume divided by total volume.
- Length of flame travel (Lp): A hemispherical radius is calculated from the congested volume filled with the flammable vapor.
- Laminar burning velocity (LBV): Maximum burning velocity of a slightly richer than stoichiometric fuel/air mixture in a quiescent volume without congestion or other turbulence inducing factors.
- Average congestion diameter: Hydraulic diameter has been found to provide best results for most process layouts. Hydraulic diameter is defined as 4 times the ratio between the summed volumes and the summed surface areas of an object distribution. The actual average diameter is used for repetitive obstacles with the same diameter.

The peak internal explosion pressure is then calculated using the above variables. The explosion energy is calculated without the use of the ground reflection factor described for the BSM. A reduced energy term is allowed from the full explosion energy based on the predicted peak pressure as outlined below:

- Less than 0.5 bar peak pressure: 20% energy efficiency
- Less than 1 bar peak pressure: 50% energy efficiency

The severity level is then solved for and used for subsequent blast loads calculations. Impulse is calculated from the predicted pressure and duration. Blast wave shape is also predicted. The distance to the point of interest is taken as the distance from the point of interest to the edge of congestion plus Lp.

4. Comparison Case Descriptions

In selecting experimental data to use in this comparison, criteria were set to ensure the goals of this comparison were met. These criteria were as follows:

- Tests had to be public domain with sufficient information that the prediction methods could be used with confidence,
- Tests should replicate process conditions to the greatest extent possible, and
- Tests had to report pressures outside the explosion.

Three test programs were found that met these criteria. More tests may be available that would have met the criteria, but the data used was sufficient to permit adequate evaluation of the pressure prediction accuracy of the three methods.

Comparisons of the three prediction methods were made for 58 experiments, one industry event case study and one fictional case study. All pressures reported are free field and thus no reflections have been accounted for. However, before the comparison cases are described, the differences between experiments and actual events should be discussed and a fundamental question considered regarding selection of the proper prediction method.

Many factors affect the violence of a vapor cloud explosion. Three of these factors are the fuel-air ratio, the ignition location and whether or not a jet is source of the fuel leak. Flammable vapor mixtures that are at or slightly above stoichiometric tend to produce more severe explosions that those closer to the lean or rich limits. Ignition locations near the center of congested areas can result in the greatest travel distances for flame fronts before encountering a vent plane and can often, but not always, tend to create more severe explosions overall. Similarly, explosions involving jet releases that produce substantial turbulence tend to result in more severe explosions than similar events involving quiescent mixtures.

Tests are often conducted in a format to reduce the number of unknowns and to allow evaluation of the effects of changing one parameter at a time. An example would be a test program to evaluate changes in obstacle density. Here, a controlled fuel-air mixture is used for each test, the ignition location is probably in the center and the obstacle density is varied. Most often, test programs use a quiescent, homogeneous fuel-air mix as close to stoichiometric conditions as can be achieved in the field. This is primarily because reproducing a jet release in an experiment would introduce a variable that would require many more tests to quantify than available funds normally allow. Thus, much of the test data collected and published is for quiescent, homogeneous fuel-air mixtures close to stoichiometric conditions.

Unlike tests, explosion incidents in industry are uncontrolled events. Often, an incident will involve a failure related to a high-pressure line, resulting in an expanding and mixing jet that strikes obstacles. In many events, such jets are sustained long enough to create steady-state fields that include non-homogeneous but turbulent fuel-air mixtures. Ignition location can be random, unlikely to be centered in the flammable region and more likely to be at the edge of the flammable vapor. Thus, care must be taken when evaluating an explosion event in the industry and using it to compare to a prediction method. This is because it would be expected that changing one variable of the event such as where the leak occurred, wind direction and/or speed or ignition location might have resulted in a more severe explosion.

Hence, experiments do not always duplicate incident conditions and an industry incident may not be reflective of a typical or a worst-case event. Which set of conditions would result in the more severe event can be debated but a high degree of jet-induced turbulence should result in a more severe explosion when compared to a similar quiescent vapor explosion. This issue brings to light a fundamental viewpoint that each user needs to evaluate before choosing the best prediction method for the intended application. Does one select a method to best match test and industry data or should a more conservative method be considered to better characterize worst-case conditions that may not have been adequately represented in the test and industry data?

If the desire is to predict a worst-case explosion, then the prediction method selected should ideally have used worst-case industry explosion data in their validation. These would be explosion events where variables were favoring the worst-case conditions. Additionally, these methods should predominately over predict explosion experiments. However, if one desires to predict an average explosion that does not favor either the worst- or best-case event, but represent a typical explosion, then a method which is neutral to test data and ideally must have a very large database of industry events used in the validation. This latter point is necessary to have confidence in what is defined as a typical explosion and subsequently used in the validation. Since an industry database of events with sufficient information to apply the prediction methods does not exist, the method that tries to simulate an average explosion would do a haphazard job when applied to select industry events. Conversely, the method that tries to predict worst-case events will over predict the majority of results from industry events if it has been validated against known worst-case events. Once the fundamental decision is made as to whether to predict a worst-case or a typical explosion, the comparisons made in this study will help provide users with information that will help determine which method is more appropriate for their applications.

4.1. Experimental Programs

Fifty-eight experiments were evaluated in this comparison from three experimental programs. They were picked to provide the most realistic recreations of VCEs. Some of the experiments reproduced process layouts while some of them idealized the congestion by using regular, repetitive obstacles. Insufficient information was available in the experimental data to provide good comparisons with the predicted blast wave durations and impulses. Where data did exist, it a comparison is provided, but no conclusions regarding durations or impulses can be drawn from the limited amount of information.

The test programs examined differing size, confined geometries, deluge effects, congestion density, fuels and ignition position. Tests with deluge were not considered in this evaluation since none of the methods considered the effects of deluge. Some experiments were conducted with different ignition positions. It has been well documented that center ignition is worst case in most situations except for some long geometries. Experiment ignition position was not considered in the comparisons since it can be difficult to predict an ignition location for an actual accident. Grouping a series of tests together that had different ignition locations was expected to have the effect of increasing the data scatter, but was believed to provide a more realistic depiction of an average explosion. Thus, tests without deluge were grouped in this evaluation only according to size, confinement, congestion density and fuel.

Some of the inputs required for the predictive methods, such as fuel used, geometry, dimensions, VBR and average congestion diameter were provided by the respective test reports. However, three of the inputs, ABR, number of obstacles and average obstacle hydraulic diameter (OHD), had to be calculated from the given information for some of the tests.

The first variable to be calculated, ABR, was needed for the BSM and CAM2 methods. The BSM used the ABR indirectly to determine the congestion category while the CAM2 used the ABR for each direction directly in calculations. ABR was first calculated assuming an idealized congestion arrangement. To determine ABR, the following was performed:

- The given average obstacle diameter was first used with the given VBR to calculate the number of obstacles needed in each direction, assuming a uniform pitch between obstacle rows and uniform ABR in each direction.
- The tests that recreated a process layouts provided equipment plans such that it could be seen if there was preferential venting in the x or y directions. Where preferential venting was indicated, an arbitrary factor of 50% was used to increase the calculated pitch for the plane of preferential venting. Since the x-y equipment plans did not indicate if there was preferential venting in the z direction, it was assumed that no preferential venting was allowed in the z direction.
- The new pitch for the plane of preferential venting was used to solve for the ABRs of the remaining planes such that the given VBR was conserved. These calculated ABRs were then used in the CAM2 evaluations. The largest calculated ABR was used in the BSM evaluations.

For example, in one set of tests, the VBR was given as 8.46%. The calculated uniform ABR was 37% for all directions. Applying the 50% pitch factor in the x direction resulted in ABRs of 43%, 30% and 43% in the x-y, x-z and y-z planes, respectively. These ABRs were then used directly in the CAM2 evaluation while the BSM evaluation took the 43% ABR to indicate high congestion. Without this pitch factor, the BSM would have technically been medium congestion. Although it can be debated as to how much of a pitch factor would best represent preferential venting, it is believed that the 50% factor provided more accurate results than if it had not been applied.

The next variable to be calculated, the number of congestion layers, was needed for the CAM2 method. In the case of the tests simulating process layouts, the case study and the fictional process unit, a plot plan of equipment was provided from which the number of congestion layers in the x and y directions was obtained. Since side views of equipment layout were not provided in the reports, the number of obstacle layers in the z direction was scaled from the average of the x and y direction obstacle densities. The idealized congestion test report provided the number of obstacles directly for each direction.

The last variable to be calculated, the OHD, was needed for the MEM2 method for application where the obstacles were not of identical diameter. All tests provided average obstacle diameters in their respective reports. It was found that the average OHDs for the examples provided in the GAMES report were multiples of between about 2.1 and 2.3 times the average obstacle diameter. Thus, a factor of 2.2 was applied to the average obstacle diameter to obtain the OHD. For both the industry case study and the fictional case study, the average diameter of the tests that replicated process layouts was used as the average obstacle diameter and the factor of 2.2 applied to obtain the OHD.

4.1.1. Test Program: Blast and Fire Engineering for Topside Structures - Phase 2 (BFETS2)

The Steel Construction Institute conducted this test program[10] and included 27 VCE experiments. Seventeen of the tests in this program could not be used because they were beyond the limits of allowed geometries and evaluated effects of deluge. However, ten of the tests were within the bounds of the BSM but outside the bounds of the CAM2 and MEM2. These tests were comprised of a congested volume with a roof and two vertical walls along the long sides as depicted in Figure 1. This was typical 1D confinement according to the BSM criteria. The CAM2 and MEM2 do not provide for 1D confinement evaluations so 2D calculations were used for these methods. Since these tests were not within the bounds of the CAM2 and MEM2 methods, only the BSM results were included in the final comparison. The CAM2 and MEM2 evaluations were found to be of benefit to qualitatively determine if 1D applications existed where the 2D CAM2 and MEM2 calculations could predict the measured blast loads. All of the BFETS2 tests were conducted with methane.

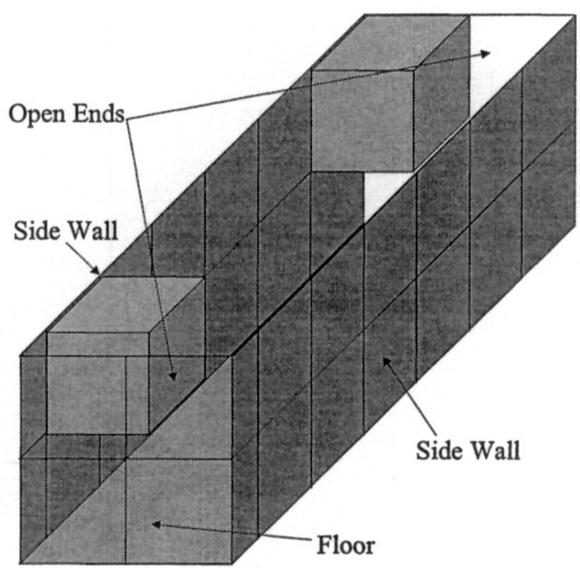

Figure 1 – Illustration of BFETS2 1D Geometry (roof left out for clarity)

Two obstacle densities were evaluated. They were described as low and high equipment density in the BFETS2 report. The VBR for the low and high densities was given to be 7.28% and 9.58%, respectively. This resulted in calculated uniform ABRs of 34% and 39%, respectively. Using the BSM definitions, both of these would be considered medium congestion. However, when the figures in the report for the low equipment density were examined, it was apparent that a majority of the congestion obstacles were large diameter with a lot of void space. Thus, the BSM congestion was taken to be low for the reported low equipment density (7.28% VBR). The figures in the report clearly indicate the congestion for the high equipment density was greater than that for the low equipment density. An ABR of 39% is very close to the lower limit for BSM high congestion (40%) such that one might be inclined to take it as high congestion. However, like for the low equipment density, the figures indicate more void space than that which would be expected for BSM high congestion. Thus, the BSM congestion was taken to be medium for the high equipment density configuration. The comparison results show that these modified congestion assessments helped reduce the BSM prediction errors when compared with results if higher degrees of congestion had been used.

The information provided in Table 1 show parameters provided by the BFETS2 report and the information derived from the report for use in the three methods.

Table 1 – Information Used for BFETS2 Experiment Predictions

BFETS2	Universal Inputs							BSM Inputs					Misc Notes
Description	Length (ft)*	Width (ft)*	Height (ft)*	Fuel*	Average Diameter (ft)*	VBR*	Uniform ABR	Confinement	Congestion	Fuel Reactivity	Flame Speed (Mf)	Energy (in-lb)	No. of tests at Ignition Location
1-6	84.0	26.2	26.2	Methane	0.80	7.28%	34%	1D	Medium	Low	1.029	9.0E+10	4=End,2=Center
7,12,15,16	84.0	26.2	26.2	Methane	0.46	9.58%	39%	1D	High	Low	2.265	9.0E+10	1=End, 3=Center

BFETS2	CAM2 Inputs								MEM2 Inputs				Misc Notes
Description	Confinement	xy ABR	xz ABR	yz ABR	No. of x obstacles	No. of y obstacles	No. of z obstacles	Complexity Factor	Confinement	Pmax (psi)	Energy (in-lb)	Severity Level	Preferential Venting
1-6	2D	34%	34%	34%	14.0	5.0	4.7	4	2D	6.14	9.0E+09	5.799	None
7,12,15,16	2D	39%	39%	39%	14.0	5.0	4.7	4	2D	26.65	4.5E+10	7.793	None

* Indicates information provided in the BFETS2 report. Other information derived from the given information or the text of the report.

4.1.2. Test Program: Explosions in Full Scale Offshore Module Geometries (BFETS3a)

British Gas conducted this test program[11] as a continuation of the previous test program BFETS2. Forty-five experiments were performed in this test program but like in the BFETS2 program, only 21 were used in this comparison because some tests were beyond the limits of allowed geometries and evaluated effects of deluge. All of the BFETS3a tests included in this comparison were conducted with methane. Most of the tests included in this comparison from the BFETS3a test program are unique because they have only partial roof confinement that would be considered 2½D confinement by the BSM criteria. Depictions of the geometries included in this comparison are provided in Figure 2. Since the height to half width aspect ratio for both geometries was equal to one, the CAM2 and MEM2 methods considered these geometries as 3D confinement.

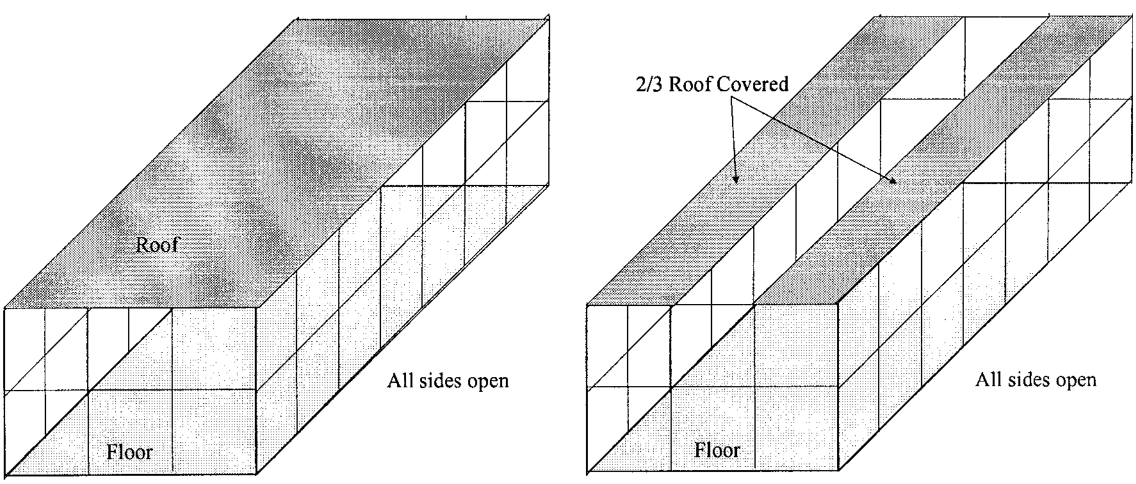

Figure 2 – BFETS3a Test 2D and 2½D Geometries (2D on the left)

The BFETS3a report described five different equipment layout plans for each configuration. The reported VBRs ranged from 8.27% to 9.67% for the tests included in this comparison. This resulted in a calculated uniform ABR from 37% to 40%. Although this indicates some of the tests should be considered medium congestion according to the BSM, all tests were taken as high congestion to err on the conservative side. The equipment layout plans clearly indicated equipment placement that would help venting out the long sides of the apparatus. Thus, the

CAM2 ABRs in the x, y and z directions were modified as previously described such that the ABR along the long side was reduced while the ABR for the y and z directions were increased to conserve the VBR.

The information provided in Table 2 show parameters provided by the BFETS3a report and the information derived from the report for use in the three methods.

Table 2 – Information Used for BFETS3a Experiment Predictions

BFETS3a	Universal Inputs							BSM Inputs					Misc Notes
Description	Length (ft)*	Width (ft)*	Height (ft)*	Fuel*	Average Diameter (ft)*	VBR*	Uniform ABR	Confinement	Congestion	Fuel Reactivity	Flame Speed (Mf)	Energy (in-lb)	No. of tests at Ignition Location**
1-4	91.9	39.4	26.2	Methane	0.44	8.46%	37%	2D	High	Low	0.662	1.5E+11	$1=I_1, 1=I_2, 1=I_3, 1=I_4$
16-17,19,22	91.9	39.4	26.2	Methane	0.44	8.46%	37%	2.5D	High	Low	0.405	1.5E+11	$1=I_2, 2=I_3, 1=I_4$
24-26,29,32	91.9	39.4	26.2	Methane	0.43	9.62%	40%	2.5D	High	Low	0.405	1.5E+11	$5=I_2$
37,38	91.9	39.4	26.2	Methane	0.42	9.67%	40%	2.5D	High	Low	0.405	1.5E+11	$2=I_2$
39-44	91.9	39.4	26.2	Methane	0.42	8.27%	37%	2.5D	High	Low	0.405	1.5E+11	$6=I_3$

BFETS3a	CAM2 Inputs								MEM2 Inputs				Misc Notes
Description	Confinement	xy ABR	xz ABR	yz ABR	No. of x obstacles	No. of y obstacles	No. of z obstacles	Complexity Factor	Confinement	Pmax (psi)	Energy (in-lb)	Severity Level	Preferential Venting
1-4	3D	43%	30%	43%	15.0	7.0	4.5	4	3D	13.87	3.7E+10	6.908	Width
16-17,19,22	3D	43%	30%	43%	15.0	7.0	4.5	4	3D	13.87	3.7E+10	6.908	Width
24-26,29,32	3D	45%	31%	45%	15.0	7.0	4.5	4	3D	20.69	7.4E+10	7.452	Width
37,38	3D	45%	32%	45%	15.0	7.0	4.5	4	3D	22.36	7.4E+10	7.557	Width
39-44	3D	42%	29%	42%	15.0	7.0	4.5	4	3D	14.54	3.7E+10	6.976	Width

* Indicates information provided in the BFETS3a report. Other information derived from the given information or the text of the report.

** I_1 – Center on grade, I_2 – Center at half height, I_3 – End at quarter height, I_4 – Third length of long edge on side at grade

4.1.3. Test Program: Extended Modeling and Extended Research into Gas Explosions (EMERGE)

The EMERGE tests[12] were conducted by TNO, BG, and CMR to explore the effects of size, fuel reactivity and induced turbulence. Thirty-six tests were small scale, fifteen tests were medium scale and four tests were large scale. Twenty-seven of these tests were used in this comparison. The comparisons were not limited to size to evaluate if any of the methods could be applied to small scale explosions. However, since the small and medium scale tests were not realistic for most industry applications, they were evaluated for information regarding scale application and only the large scale tests were included in the final comparisons. All tests were unconfined with idealized congestion arrangement as illustrated in Figure 3.

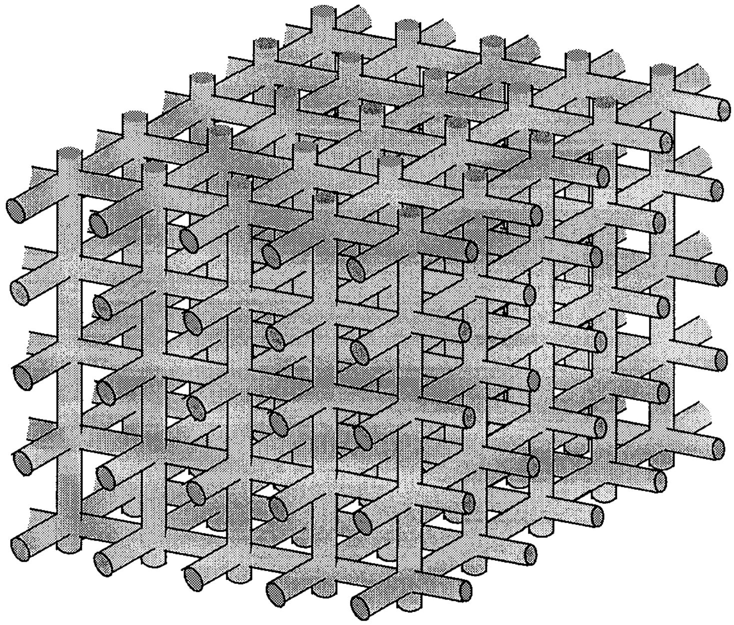

Figure 3 – Typical Geometry and Congestion Arrangement of EMERGE Tests

All of the tests had a VBR of 10%. Since the congestion diameter and pitch was constant, the ABR was easily calculated to be 40% in all directions. This resulted in a BSM congestion category of high congestion. Without any confining planes, all methods considered these tests as 3D confinement.

The information provided in Table 3 show parameters provided by the EMERGE report and the information derived from the report for use in the three methods.

Table 3 – Information Used for EMERGE Experiment Predictions

EMERGE	Universal Inputs							BSM Inputs					Misc Notes
Description	Length (ft)*	Width (ft)*	Height (ft)*	Fuel*	Average Diameter (ft)*	VBR*	Uniform ABR	Confinement	Congestion	Fuel Reactivity	Flame Speed (Mf)	Energy (in-lb)	Ignition Locations
28-34	6.6	6.6	3.3	Methane	0.06	10.0%	40%	3D	High	Low	0.147	2.2E+08	Center at grade
40-42,50,52	6.6	6.6	3.3	Propane	0.06	10.0%	40%	3D	High	Average	0.206	2.4E+08	Center at grade
A1,4	13.1	13.1	6.6	Methane	0.14	10.0%	40%	3D	High	Low	0.147	1.8E+09	Center at grade
A2-3	13.1	13.1	6.6	Propane	0.14	10.0%	40%	3D	High	Average	0.206	1.9E+09	Center at grade
F1,3,6-7	13.1	13.1	6.6	Methane	0.14	4.80%	28%	3D	Medium	Low	0.1	1.8E+09	Center at grade
F2,4-5	13.1	13.1	6.6	Propane	0.14	4.80%	28%	3D	Medium	Average	0.1	1.9E+09	Center at grade
L1-2	26.2	26.2	13.1	Methane	0.27	10.0%	40%	3D	High	Low	0.147	1.4E+10	Center at grade
L3-4	26.2	26.2	13.1	Propane	0.27	10.0%	40%	3D	High	Average	0.206	1.5E+10	Center at grade

EMERGE	CAM2 Inputs								MEM2 Inputs				Misc Notes
Description	Confinement	xy ABR	xz ABR	yz ABR	No. of x obstacles*	No. of y obstacles*	No. of z obstacles*	Complexity Factor	Confinement	Pmax (psi)	Energy (in-lb)	Severity Level	No. of Tests with Initial Turbulence**
28-34	3D	40%	40%	40%	20.0	20.0	10.0	1	3D	15.36	1.1E+08	7.051	2=none,1=low,3=high
40-42,50,52	3D	40%	40%	40%	20.0	20.0	10.0	1	3D	22.70	1.2E+08	7.577	4=none,1=low,1=high
A1,4	3D	40%	40%	40%	20.0	20.0	10.0	1	3D	19.58	8.8E+08	7.378	1=low,1=high
A2-3	3D	40%	40%	40%	20.0	20.0	10.0	1	3D	28.93	9.5E+08	7.904	1=low,1=high
F1,3,6-7	3D	28%	28%	28%	20.0	20.0	10.0	1	3D	2.60	1.8E+08	4.815	2=none,1=low,1=high
F2,4-5	3D	28%	28%	28%	20.0	20.0	10.0	1	3D	3.84	1.9E+08	5.285	1=none,1=low,1=high
L1-2	3D	40%	40%	40%	20.0	20.0	10.0	1	3D	35.07	7.1E+09	8.139	1=low,1=high
L3-4	3D	40%	40%	40%	20.0	20.0	10.0	1	3D	51.81	7.6E+09	8.586	1=low,1=high

* Indicates information provided in the EMERGE report. Other information derived from the given information or the text of the report.
**EMERGE report concluded that the initial turbulence induced was insufficient to affect results.

4.2. Industry Incidents

An industry incident with sufficient public information to do a comprehensive comparison of the three prediction methods was not found. However, an incident was found that had enough public information such that the three methods were applied with some limited assumptions for comparison in the far field. A sensitivity analysis of these assumptions showed any errors introduced by these assumptions were very small. In addition, with a limited amount of damage data available, only a limited number of conclusions can be drawn.

4.2.1. Industry Case Study: Shell Deer Park Ethylene Explosion

In 1997, the Shell Chemical Company plant in Deer Park, Texas experienced a large explosion in the Olefins Plant Number III. A joint EPA and OSHA investigation was performed and reported[13] in 1998. Part of the investigation involved an effort to perform VCE modeling. Information such as congested volume, fuel composition, relative degree of congestion, presence of confining planes and distances to observed window damage was provided in the report. The VCE prediction methods used in the report were TNT equivalency method and the original MEM. The report concluded that a 20% TNT equivalency or MEM severity level of 6-10 would have produced the observed damage. Most reported VCEs correspond best to TNT equivalencies of 10% or less. Thus, this case study is believed to fall near to the worst-case event for this location.

Since information needed to apply the BSM is relatively simple, sufficient information was provided in the report to apply the BSM without making any assumptions. Thus, a high degree of confidence is placed in the BSM predictions that a more detailed inspection would not significantly change the predictions. In addition, the explosion was so severe that it is most likely that any changes made to the predictions after a detailed inspection would not affect far field predictions.

To apply the BSM, the area was taken to be high congestion with 2.5D confinement. The EPA/OSHA report text described the unit as highly congested and photographs in the report support this congestion assessment. The area had an elevated fin fan cooler high above grade such that the BSM definition of 2.5D confinement was applicable. The fuel was reported to be mostly ethylene with about 19% hydrogen content. Thus, the fuel reactivity was taken to be high. Together with the reported volume of the congested region, all inputs needed to apply the BSM were provided without making any assumptions.

In order to apply the CAM2 method, some assumptions had to be made. An ABR of 40% was assumed for all directions since the area of the explosion was reported to be highly congested. According to the BSM definitions, this is the minimum value for high congestion. Thus, any errors in this assumption should err on the low side. The experiments in this comparison that replicated process layouts indicate a 40% ABR would correspond to a VBR of about 10%. The dimensions of the congested volume were assumed rectangular with a length to width ratio of 2 and a height of 50 feet such that the volume reported was conserved. This height was approximated from photographs provided in the EPA/OSHA report and was believed to be in the range of typical fin fan cooler elevations found in industry. This length to width ratio is also believed to be typical for the industry and should provide a better prediction than a square assumption. The number of obstacles in each direction was also needed for the CAM2 prediction. Thus, another assumption was made that the obstacle density for the case study was the same as the average of the obstacle densities used in the high congestion experiments that replicated process environments. Another assumption had to be made since hydrogen is not included in the CAM2 list of fuels. Thus, it was assumed that the fuel was 100% ethylene. The average obstacle diameter was taken to be the average of the average diameters reported in the experiments that replicated process layouts. Again, any errors introduced in these assumptions would be expected to err on the low side.

The information provided in Table 2 show parameters used in this comparison.

Table 4 – Information Used for Industry Case Study Predictions

Industry Case Study	Universal Inputs							BSM Inputs				
Description	Length (ft)**	Width (ft)**	Height (ft)**	Fuel*	Average Diameter (ft)+	VBR+	Uniform ABR+	Confinement	Congestion*	Fuel Reactivity	Flame Speed (Mf)	Energy (in-lb)
Shell Olefins Case Study	166.1	83.1	50.0	19% H2/81% Ethylene	0.43	10.0%	40%	2.5D	High	High	1.177	1.2E+12

Industry Case Study	CAM2 Inputs								MEM2 Inputs				Misc Notes	
Description	Confinement	xy ABR+	xz ABR+	yz ABR+	No. of x obstacles+	No. of y obstacles+	No. of z obstacles+	Complexity Factor	Confinement	Pmax (psi)	Energy (in-lb)	Severity Level	Ignition Location	Preferential Venting
Shell Olefins Case Study	3D	40%	40%	40%	27.2	14.9	8.6	4	3D	1023	6.0E+11	10	Unknown	None

* Indicates information provided in the OSHA/EPA report.

** Indicates information derived from pictures in the OSHA/EPA report.

+ Indicates information derived from typical high congestion tests that replicated process plant layouts

4.3. Fictional Processes

A comparison using a fictional process is of limited value because actual data does not exist from which to draw conclusions. A CFD analysis comparison would provide the most confidence in a prediction. However, even a CFD analysis has an error band that could call such a comparison into doubt. Thus, a fictional process was used only to compare the three prediction methods to each other. In doing so, no conclusions can be reached but the results can help reinforce trends observed elsewhere.

4.3.1. Fictional Case Study: Highly-Congested and Unconfined Process Plant

The fictional process chosen was taken from an example given in the original BSM paper. The example in that paper was an unconfined process area with high congestion and a high reactivity fuel mixture of 10% hydrogen and a balance of light hydrocarbons. The BSM update paper presented in 1997 provided a method for determining the reactivity of fuel mixtures. Applying that procedure to this fuel mixture results in an average fuel reactivity category as long as the ethylene component is less than about 63%. Thus, it was assumed that the fuel was average reactivity with the resulting mixture laminar burning velocity being 55 cm/s. Since most other examples in this comparison have been high congestion (about 10% VBR), it was assumed that this fictional process would have a VBR of 6% to provide a wider range of data for comparison. If the average obstacle diameter were the same as the average of the average obstacle diameters reported for the tests that replicated process layouts, then an ABR of 31% results. This would be representative of the BSM medium congestion category. The plot plan presented in the example indicated the equipment layout would produce a lower ABR for the long sides than for the end or top. Thus, the pitch for obstacles along the long sides was modified as was done for the experiments, only affecting the CAM2 predictions. The length to width aspect ratio was scaled from the equipment plan and a height of 10 feet was assumed to be representative of similar process areas in industry. The number of obstacles was calculated as was described for the industry case study, using the average of the obstacle densities for the experiments that replicated process layouts.

The information provided in Table 5 show parameters used in this comparison.

Table 5 – Information Used for Fictional Case Study Predictions

Fictional Case Study	Universal Inputs							BSM Inputs					Misc Notes
Description	Length (ft)**	Width (ft)**	Height (ft)**	Fuel*	Average Diameter (ft)+	VBR+	Uniform ABR+	Confinement	Congestion*	Fuel Reactivity	Flame Speed (Mf)	Energy (in-lb)	Ignition Locations
Typical Process Area	41.6	20.8	10.4	10% H2/90%C3	0.43	5.0%	29%	3D	Medium	Average	0.1	1.9E+10	Unknown

Fictional Case Study	CAM2 Inputs								MEM2 Inputs				Misc Notes
Description	Confinement	xy ABR+	xz ABR+	yz ABR+	No. of x obstacles+	No. of y obstacles+	No. of z obstacles+	Complexity Factor	Confinement	Pmax (psi)	Energy (in-lb)	Severity Level	Preferential Venting
Typical Process Area	3D	29%	29%	29%	6.8	3.7	1.8	4	3D	0.76	1.9E+09	3.04	None

* Indicates information provided in the original BSM report.

** Indicates information derived from the text of the report.

+ Indicates information derived from typical high congestion tests that replicated process plant layouts

5. Comparison Results

An important item to keep in mind is the relative complexity of each method and the probability that a detailed inspection of each experiment/case study would produce similar results. For example, the BSM is the simplest of the three methods and all information to apply the BSM was provided directly such that none of the results would change after a detailed inspection. Because the BSM is a simple method, subjective judgements are typically made as to the degree of congestion. In experiments where the congestion was just below the BSM high congestion definition (<40% ABR), the congestion was taken as high to be sure to provide the highest possible pressures. Thus, the BSM predictions are intentionally biased to provide the highest pressures. The results show the BSM predictions were low for all cases except for a single far field 2D prediction and all 1D geometry predictions. Thus, a more detailed inspection would only serve to reduce the predicted pressures.

The next most complex method is the MEM2. Although it is more complex than the BSM, all required data was provided in the experiment reports. Thus, there is also a high confidence level that the results would not change the MEM2 predictions much after a detailed inspection of the test apparatus.

The most complex method is the CAM2. Several inputs such as ABR and numbers of obstacles in each direction had to be derived from given information and equipment plans. Small changes in these parameters would not change the CAM2 results significantly. Thus, it is not believed that a more detailed inspection would change the CAM2 predictions based on ABR or numbers of obstacles. However, the CAM2 method was not applied in this comparison to account for any sharp-edged obstacles due to the lack of information regarding the presence of sharp-edged obstacles. If sharp-edged obstacles were present, then CAM2 would predict more turbulence and the resulting pressures would increase. Unfortunately, it is not known if or how much the CAM2 pressures would increase following a more detailed inspection of the experimental apparatus. Thus, there is less confidence that a detailed inspection of the test apparatus would not change the CAM2 predictions.

Since the BSM only provided acceptable results for the 1D confinement, medium congestion experiments and for the case study which was high congestion and high reactivity fuel, it is believed that the BSM method is best applied only for situations that are likely to produce high peak pressures. Further work is needed before it can be said conclusively, but these situations may include 2D or 2½D confinement, high congestion situations with high reactivity fuel. Comparisons in this study indicate other situations should always apply either the CAM2 or MEM2 methods.

Whether to use the CAM2 or MEM2 method may depend on if the goal is to predict an average explosion or a worst-case explosion as was previously discussed. If one wanted to predict the results from an average explosion, then the MEM2 method would be the best choice because it gave good correlations and there was a high degree of confidence in the predicted results. If sharp-edged obstacles were present in the experiments (other than EMERGE tests), then the CAM2 predictions would have increased for those tests and would probably be the best choice to predict a worst-case explosion. However, this is not conclusive since it is unknown if and how much obstacle blockage was present due to sharp edges in the experiments.

No conclusions could be reached regarding the predicted durations since there was only limited measurements reported for duration. Overall, the BSM tended to predict durations much greater than the CAM2 and MEM2 durations while the CAM2 and MEM2 predicted durations were similar.

5.1. Explosion Experiment Comparisons

Overall, the results of the experimental result comparisons to the methods indicate the BSM can greatly under predict measured pressures, CAM2 tends to over predict measured pressures slightly while MEM2 tends to under predict measured pressures somewhat. These conclusions are illustrated in Figure 4 and Figure 5. Figure 4 is a plot of all measured averaged pressures versus predicted pressures while Figure 5 is only a plot of the measured averaged pressures less than 10 psi versus the predicted pressures. Since a majority of predicted pressures on buildings at on shore industrial sites are less than 10 psi, Figure 5 should provide a better indication of how the prediction methods would compare in practice. The term averaged measured pressures and durations refer to how pressures and durations were reported for multiple tests in the same comparison. Here, the measured pressures and durations at the same distances were averaged together for the average pressure and duration at that distance.

The plots do not include the EMERGE small and medium scale experiments since those are not believed to be representative of industry applications. Also, the CAM2 and MEM2 1D predictions (BFETS2 experiments) are not included since these methods do not have 1D confinement calculations. However, since the BSM does allow for 1D confinement, those results are included.

The average BSM error was calculated to be –75% for all large-scale experiments plotted, excluding the 1D tests. The BSM calculated errors do not include the 1D BSM predictions because 1D confinement is rare in the on shore industry and the desire is to produce comparisons representative of the on shore industry. The average CAM2 error was calculated to be +20% for the large-scale experiments. The average MEM2 error was calculated to be –23% for the large-scale experiments. Neither CAM2 nor MEM2 errors included the 1D predictions since they are not validated for that application.

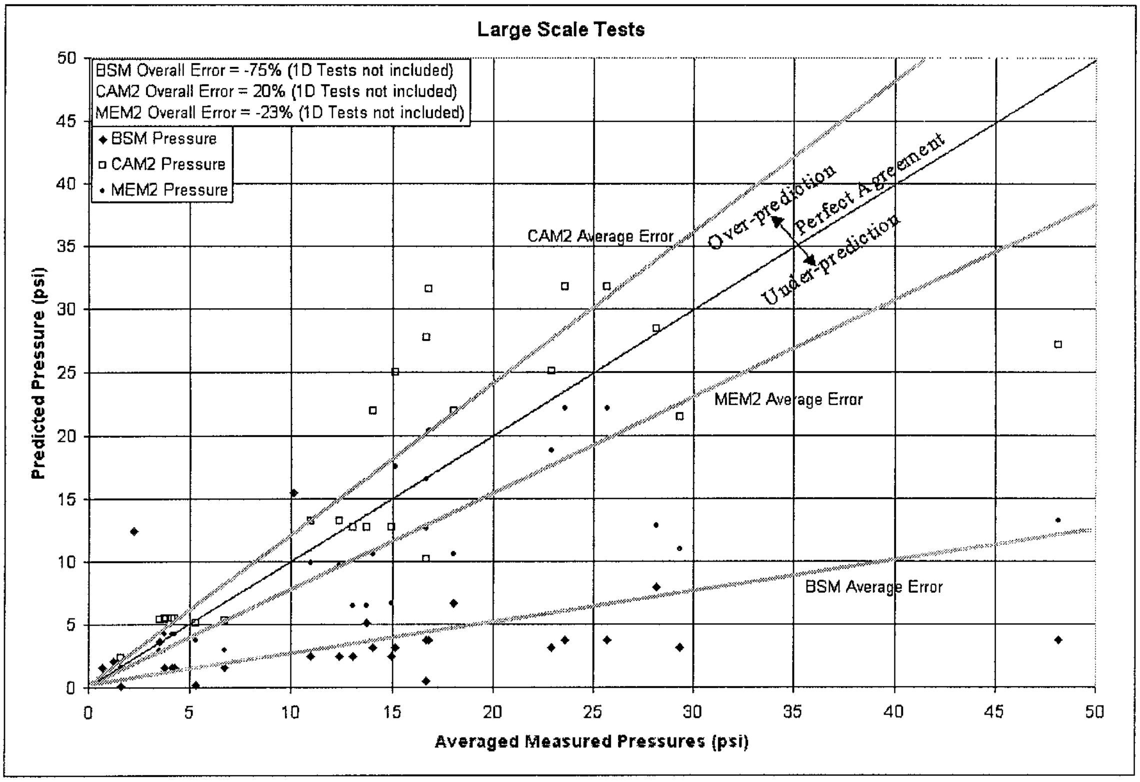

Figure 4 – Plot of All Large-scale Averaged Measured Pressures versus Predicted Pressures

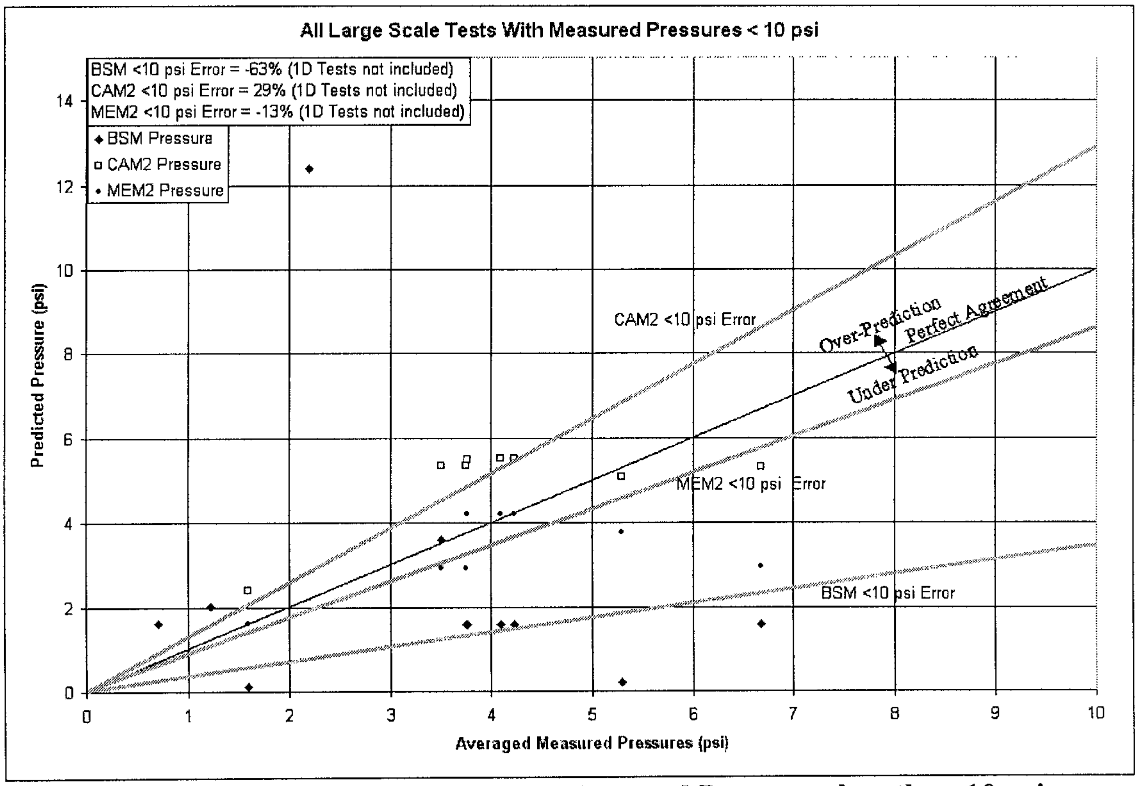

Figure 5 – Plot of Large-scale Averaged Measured Pressures less than 10 psi versus Predicted Pressures

5.1.1. BFETS2 Experimental Comparisons

The BFETS2 experiments used in this comparison were all 1D confinement tests. The CAM2 and MEM2 predictions were performed using the calculations for 2D confinement because neither method provides calculations for 1D confinement. This was done for information only to compare to the BSM, which does allow for 1D confinement.

Figure 6 and Figure 7 show the BSM over predicted the 1D low congestion pressure predictions while it provided a good prediction for the 1D medium congestion pressure predictions. Like the BSM pressure predictions, the figures also show the CAM2 1D low congestion pressure predictions were high and the 1D medium congestion pressure predictions were good. The MEM2 pressure predictions were good for both the 1D low and medium congestion experiments as shown in the same figures. The CAM2 and MEM2 results imply that the 2D calculations may be applicable in some 1D situations. However, the extent of situations where they could be applied cannot be stated until a more comprehensive evaluation is performed.

Blast wave duration predictions as compared to measured data are shown in Figure 8 and Figure 9. These plots show the low congestion test durations were under predicted by all three methods while the medium congestion test durations were adequately predicted by all three methods.

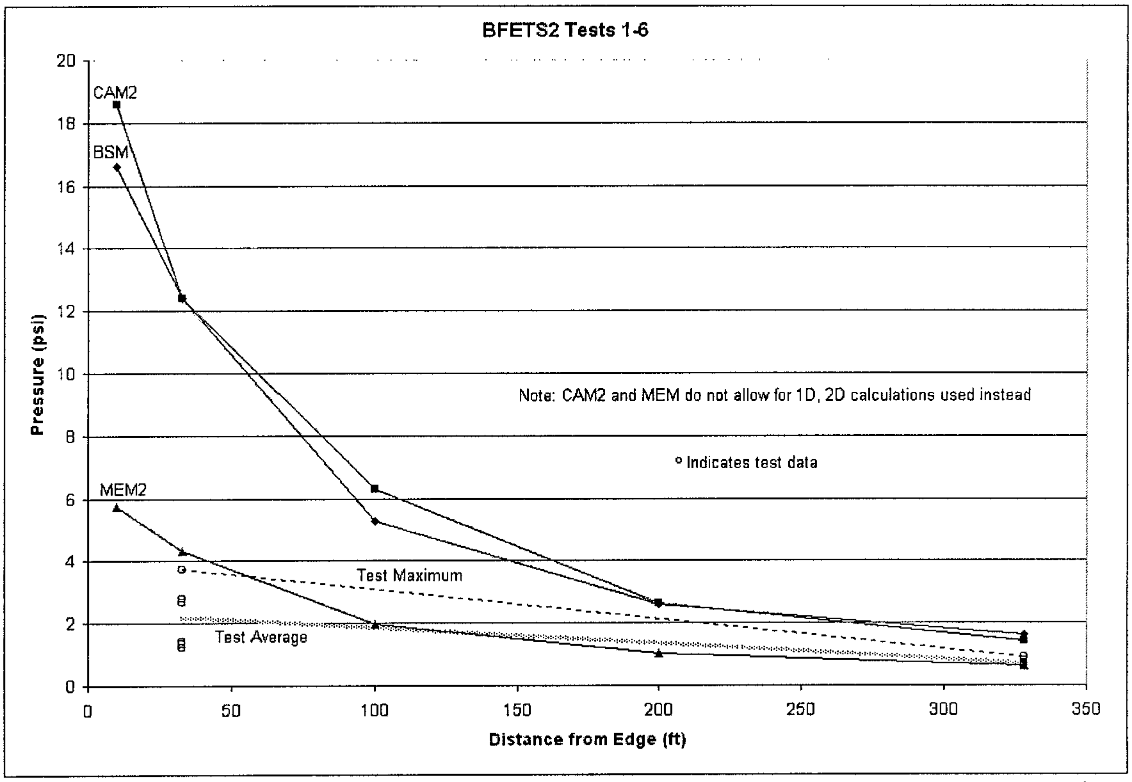

Figure 6 – Plot of BFETS2 1D Low Congestion Measured Pressures versus Predicted Pressures

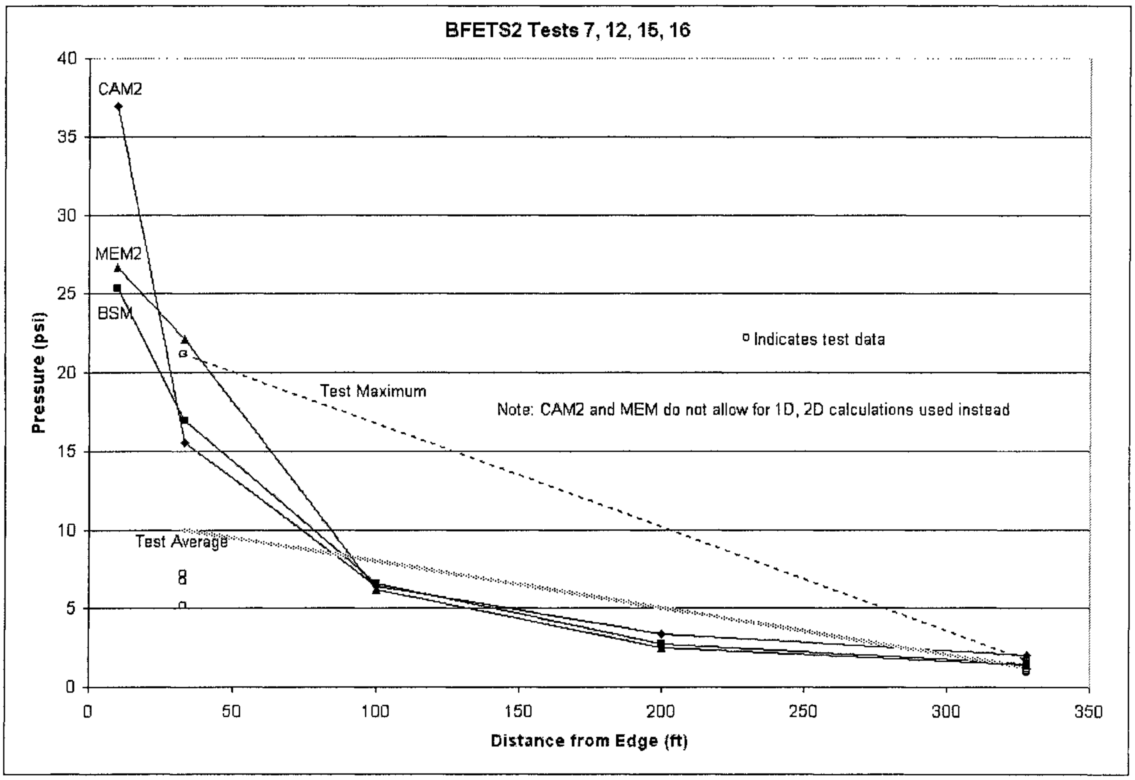

Figure 7 – Plot of BFETS2 Tests 1D Medium Congestion Measured Pressures versus Predicted Pressures

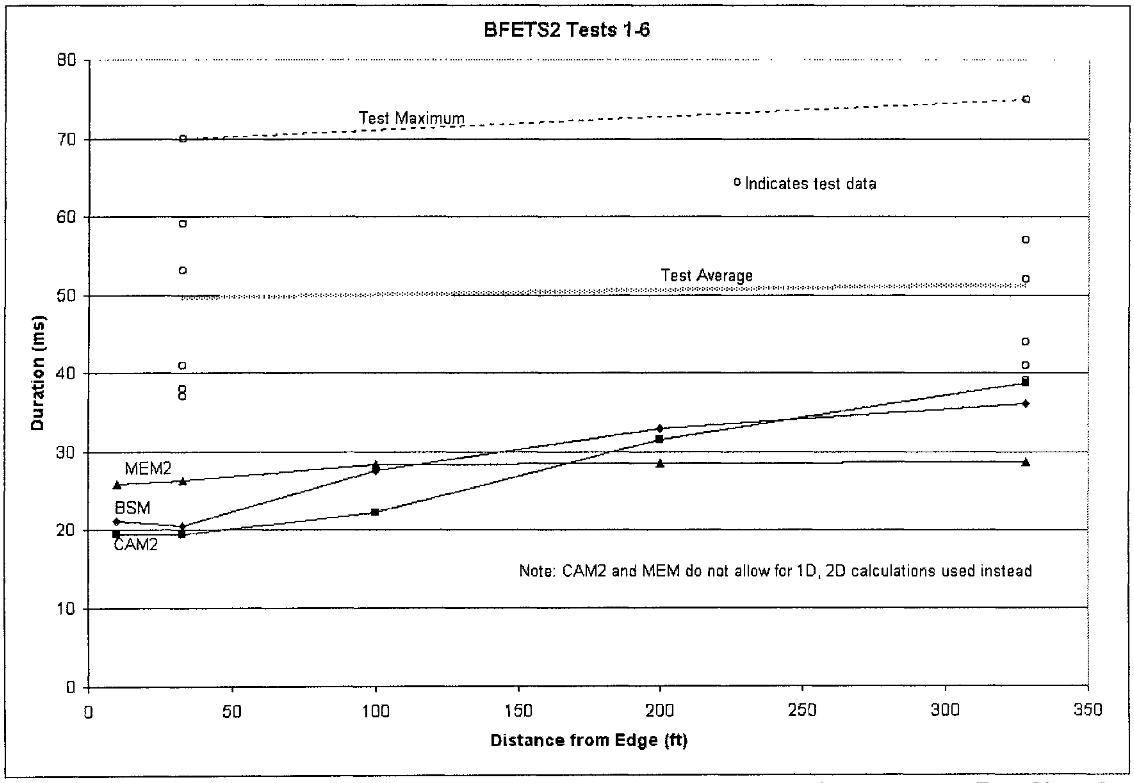

Figure 8 – Plot of BFETS2 1D Low Congestion Measured Durations versus Predicted Durations

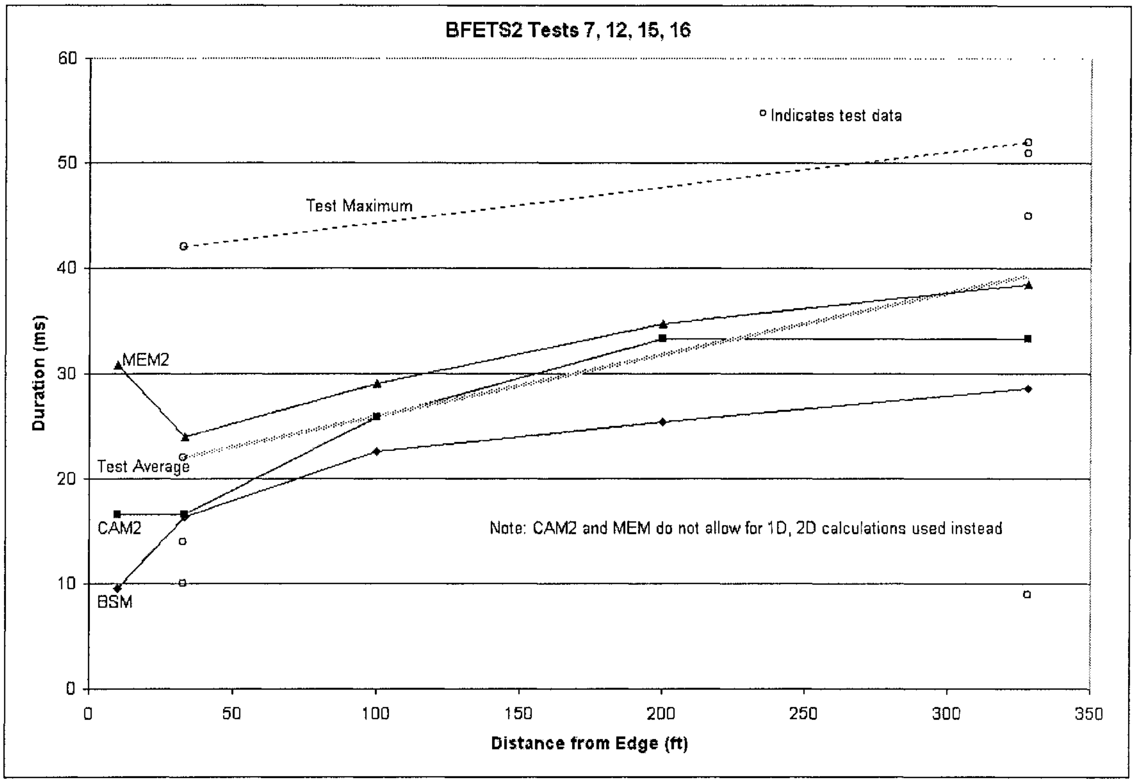

Figure 9 – Plot of BFETS2 1D Medium Congestion Measured Durations versus Predicted Durations

5.1.2. BFETS3a Experimental Comparisons

The BFETS3a tests included in this comparison were either 2D or 2½D confinement according to the BSM confinement definitions. The CAM2 and MEM2 confinement definitions categorize these tests as 3D because the flame front from a center ignited cloud would be the same distance from a vent plane as it would be from the roof. Figures 10-14 shows the plots of the predictions versus measured pressures. The CAM2 and MEM2 predictions were both relatively good for these tests. Overall, the BSM predictions were low. Figures 28-32 at the end of the paper show the predicted durations. Measured durations were not reported in the BFETS3a report, thus the predicted durations are plotted only for comparison with each other. In general, the BSM predicted durations about 2-3 times those predicted by the CAM2 and MEM2 while CAM2 and MEM2 tended to predict similar durations.

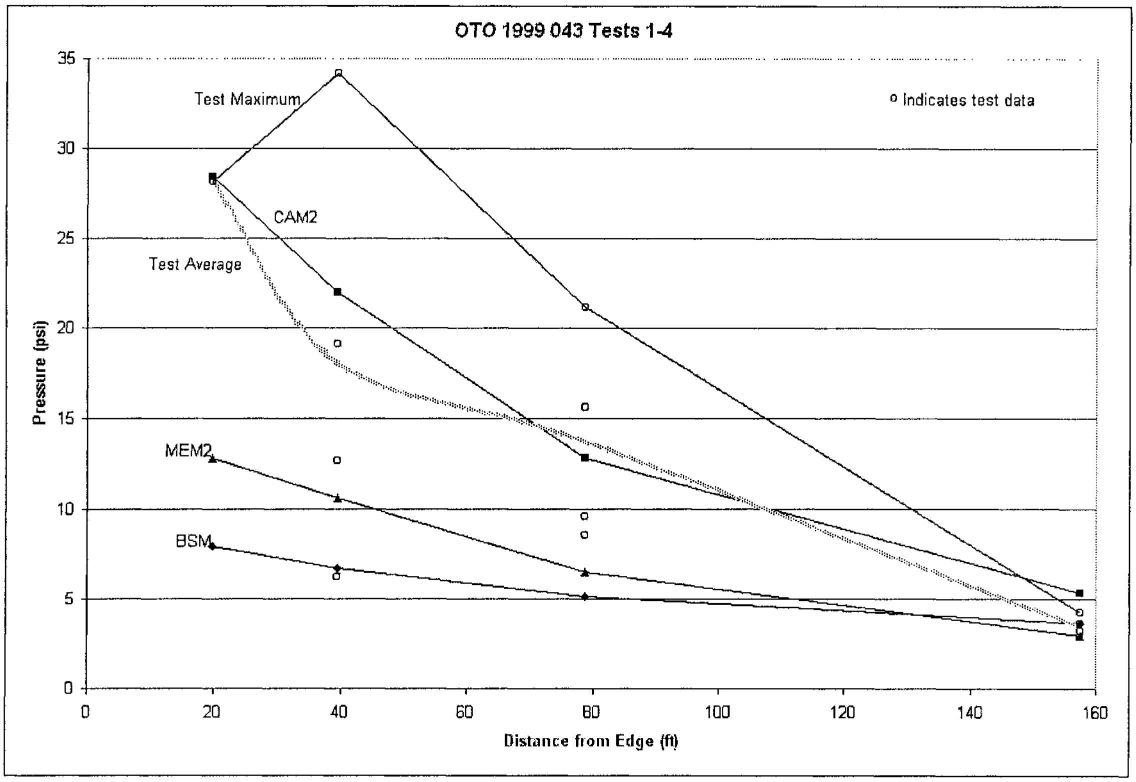

Figure 10 –Plot of BFETS3a 2D High Congestion Methane Tests Measured Pressures versus Predicted Pressures

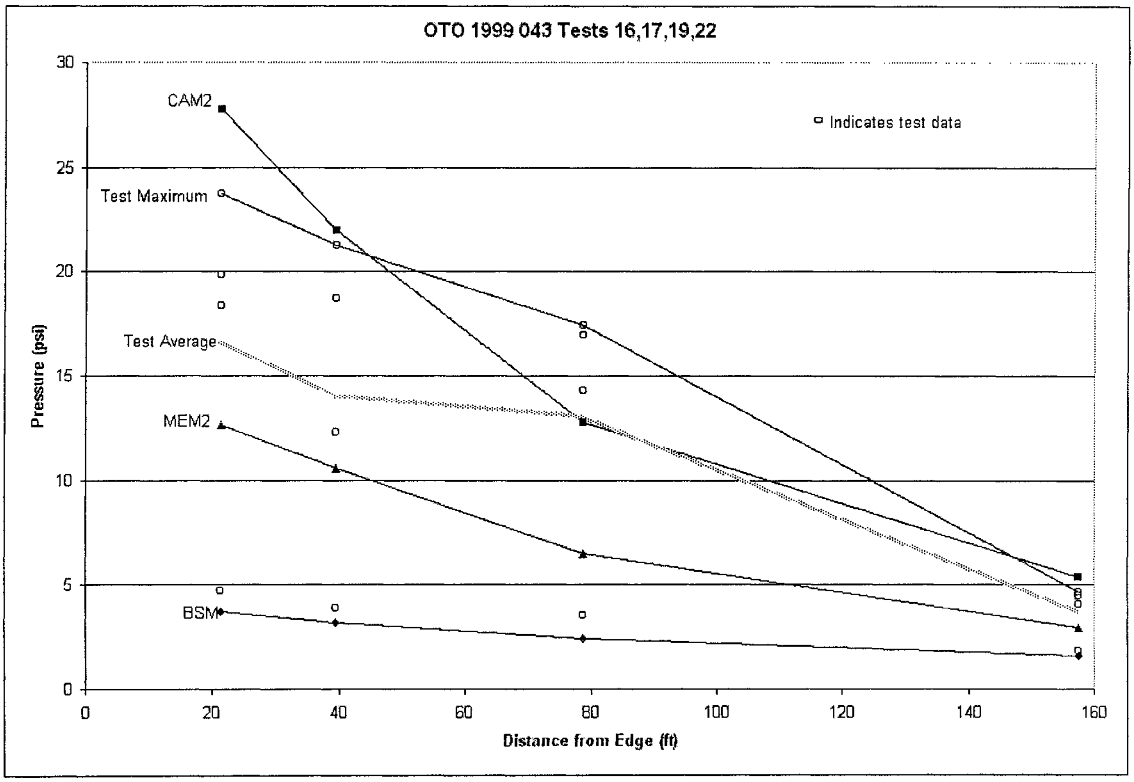

Figure 11 –Plot of BFETS3a 2½D High Congestion Methane Tests Measured Pressures versus Predicted Pressures

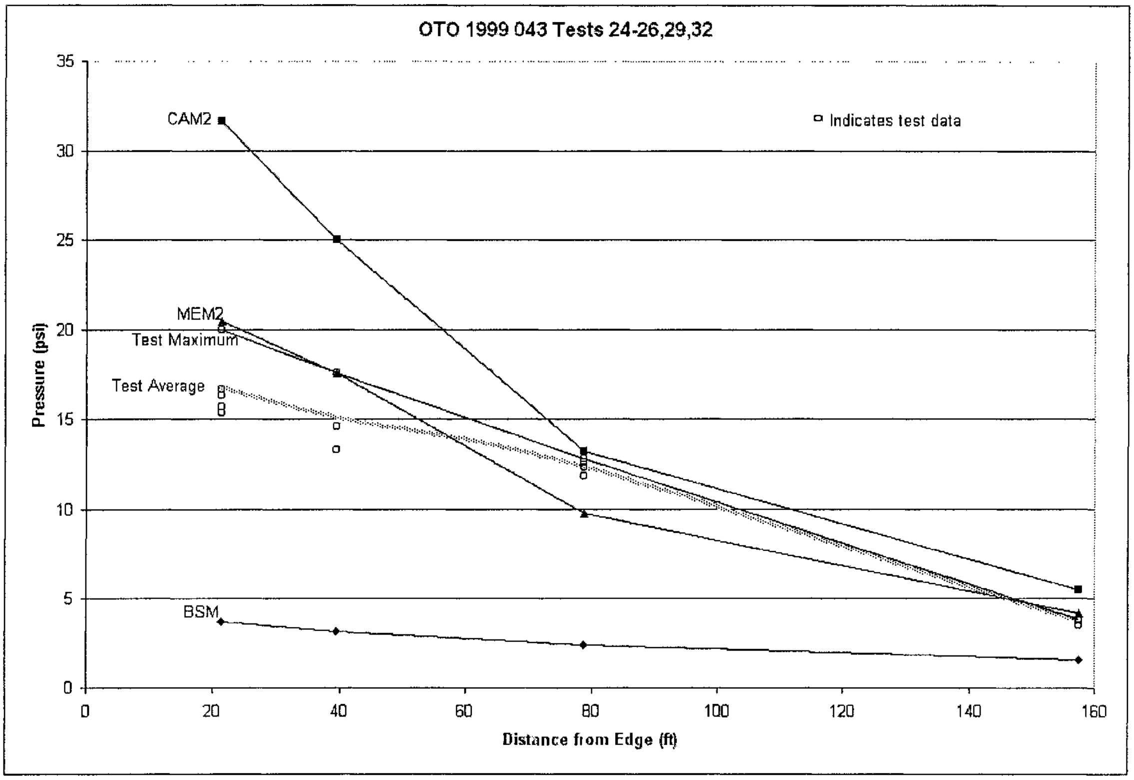

Figure 12 –Plot of BFETS3a 2½D High Congestion Methane Tests Measured Pressures versus Predicted Pressures

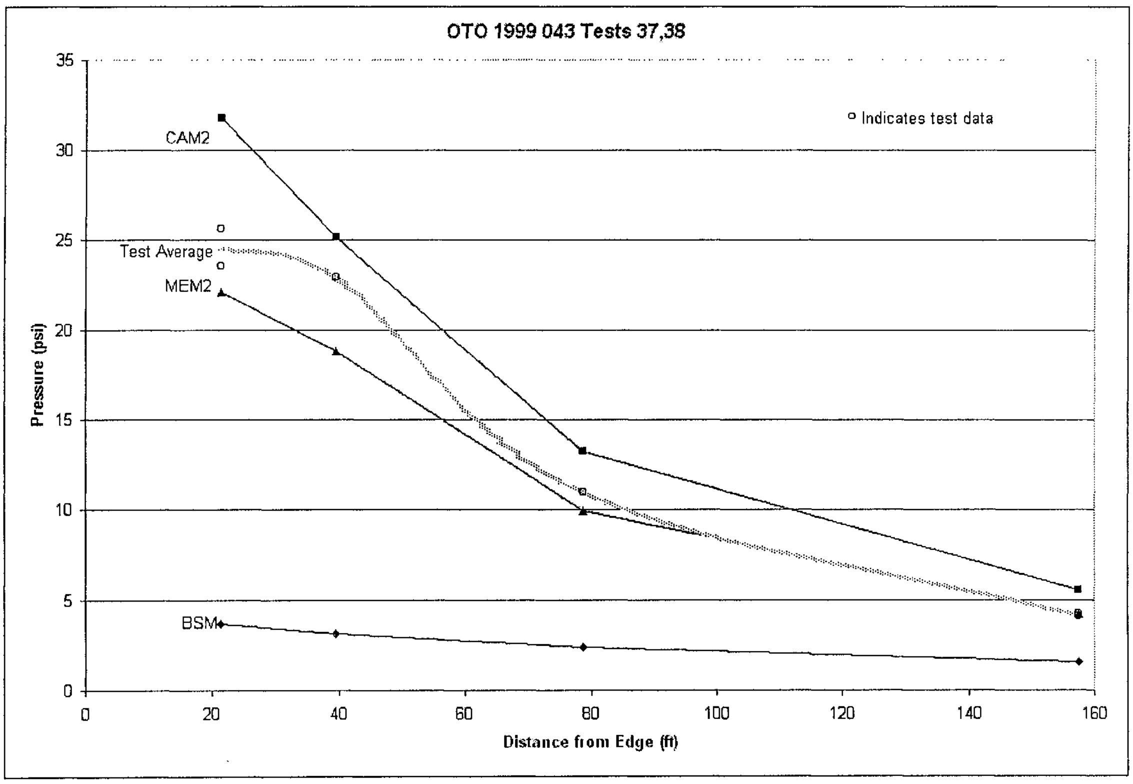

Figure 13 –Plot of BFETS3a 2½D High Congestion Methane Tests Measured Pressures versus Predicted Pressures

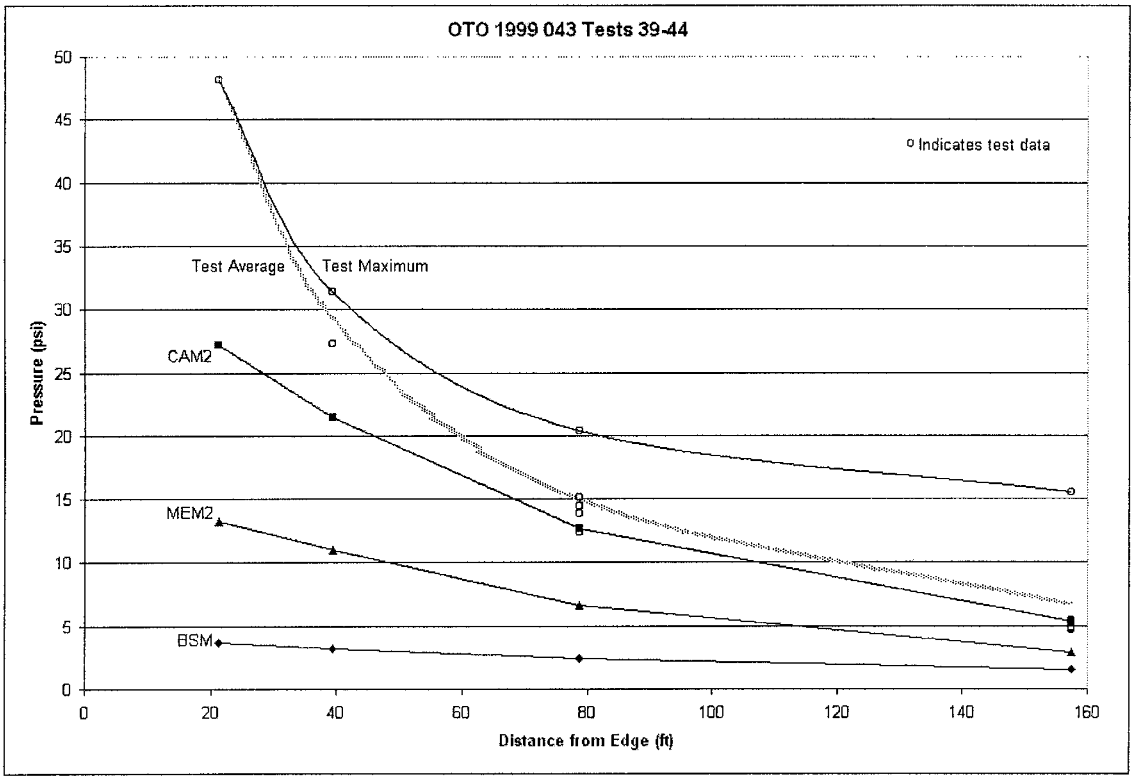

Figure 14 –Plot of BFETS3a 2½D High Congestion Methane Tests Measured Pressures versus Predicted Pressures

5.1.3. Emerge Experimental Comparisons

The EMERGE tests were conducted with methane and propane for three different sizes. Figure 15 and Figure 16 show the large-scale experiment comparisons. The methane tests in Figure 15 show MEM2 provides the best correlation. The propane tests were reported to have transitioned to detonation and the part of the pressure wave due to deflagration could not be extracted from the recorded data. Thus, there are not any measured results plotted in Figure 16. The amount of induced turbulence was concluded by the EMERGE report to have not affected the results. Thus, that variable should not be considered when evaluating the test data. Note that all EMERGE tests were performed with round obstacles and it is known that no sharp edged obstacles were present. Thus, as previously discussed, the confidence in the CAM2 predictions are higher for the EMERGE tests than for the other tests since none of the CAM2 predictions accounted for any sharp edged obstacles.

The plots for the small- and medium-scale EMERGE comparisons are included in the appendix at the end of this paper since they were not used in the overall comparison. They show none of the methods are reliable for use at these sizes. Also included in the appendix are figures that show the EMERGE predicted durations. Measured durations were not reported in the EMERGE report. Thus, the predicted durations are plotted only for comparison with each other. For the large-scale EMERGE tests, the BSM predicted durations were much greater those predicted by the CAM2 and MEM2 while CAM2 and MEM2 tended to predict similar durations.

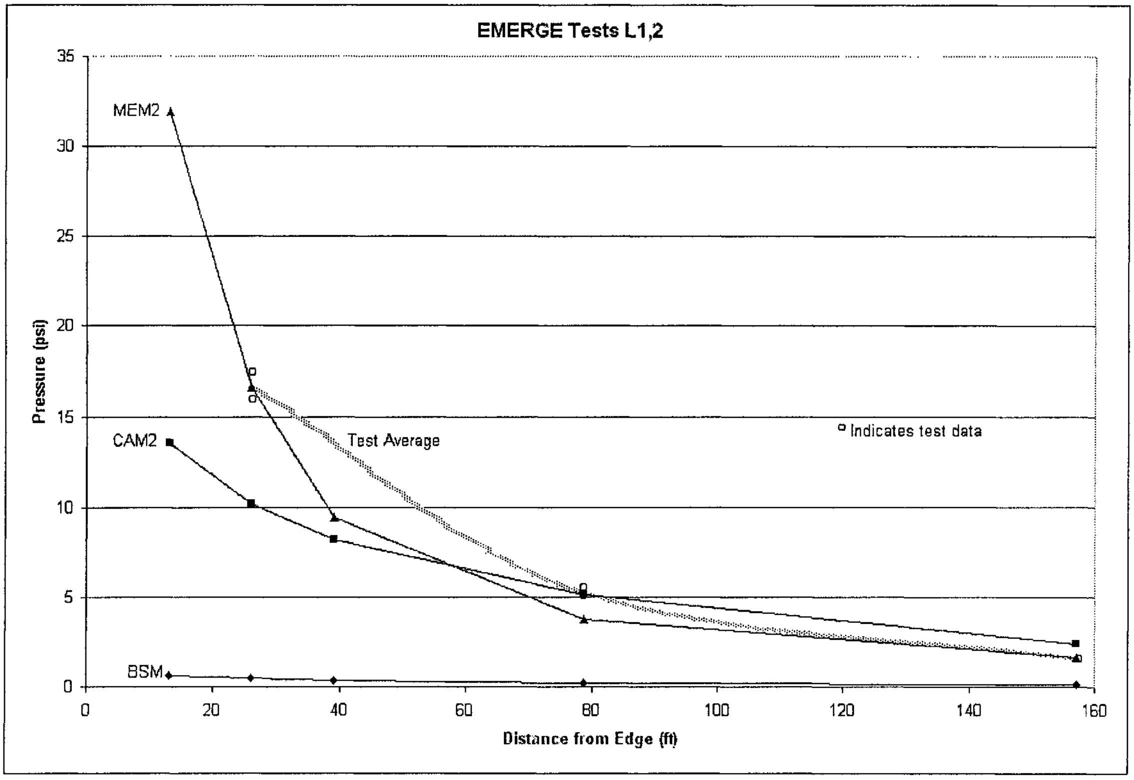

Figure 15 –Plot of EMERGE Large Scale 3D High Congestion Methane Tests Measured Pressures versus Predicted Pressures

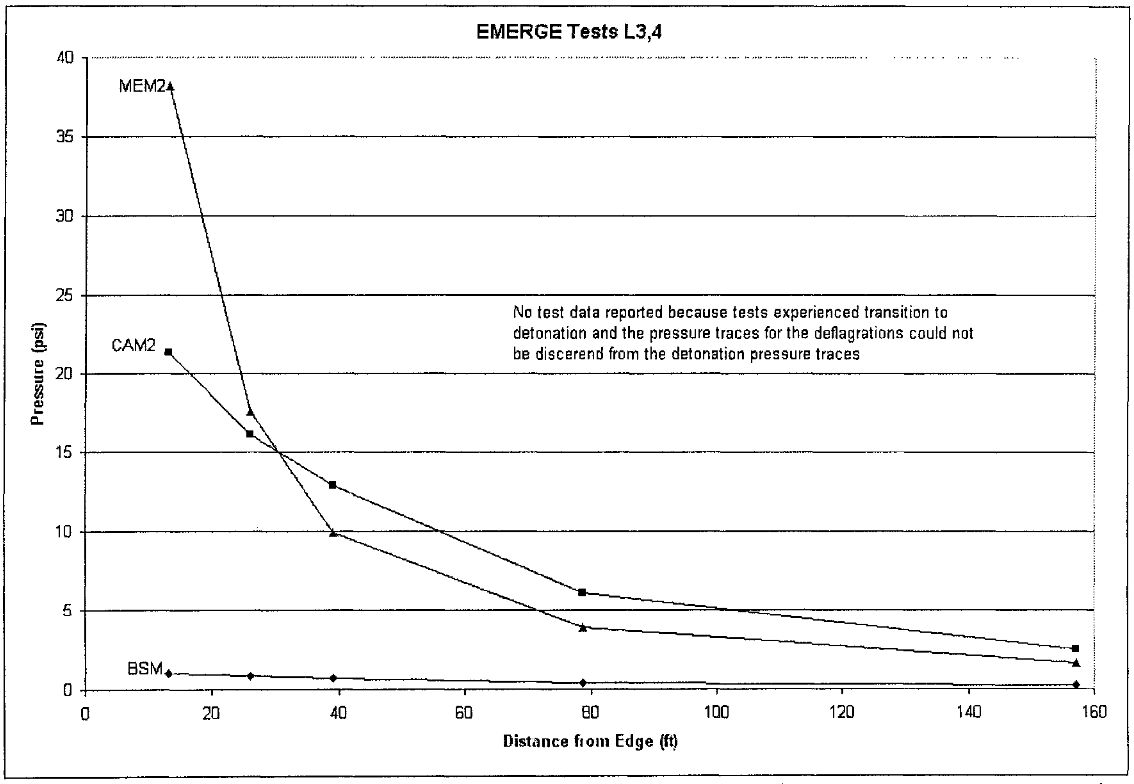

Figure 16 –Plot of EMERGE Large Scale 3D High Congestion Propane Tests Predicted Pressures

5.1.4. BSM Experimental Predictions

Figure 17 and Figure 18 show the BSM predictions plotted against the experimental results and grouped according to their confinement and congestion categories. Figure 17 shows all of the predicted data while Figure 18 only shows that data corresponding to measured pressures less than 10 psi. With a calculated average error of 54%, the BSM does a fair job of predicting 1D confinement with medium congestion for low reactivity fuel. The BSM significantly over predicted the 1D confinement, low congestion tests at an average error of +296%. Overall, the remaining tests were significantly under predicted. The dotted lines indicate a factor of two about the diagonal line for perfect agreement. Only a few BSM predictions fall within the factor of two range.

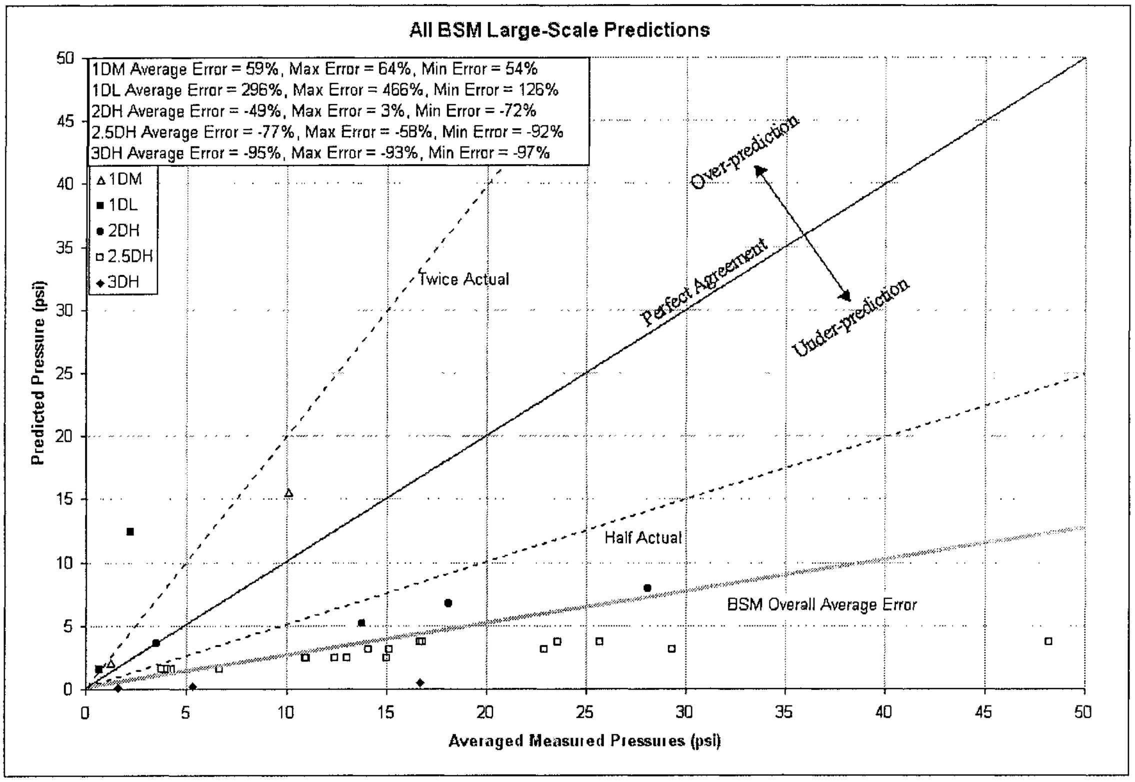

Figure 17 – Plot of Large-scale Averaged Measured Pressures versus BSM Predicted Pressures

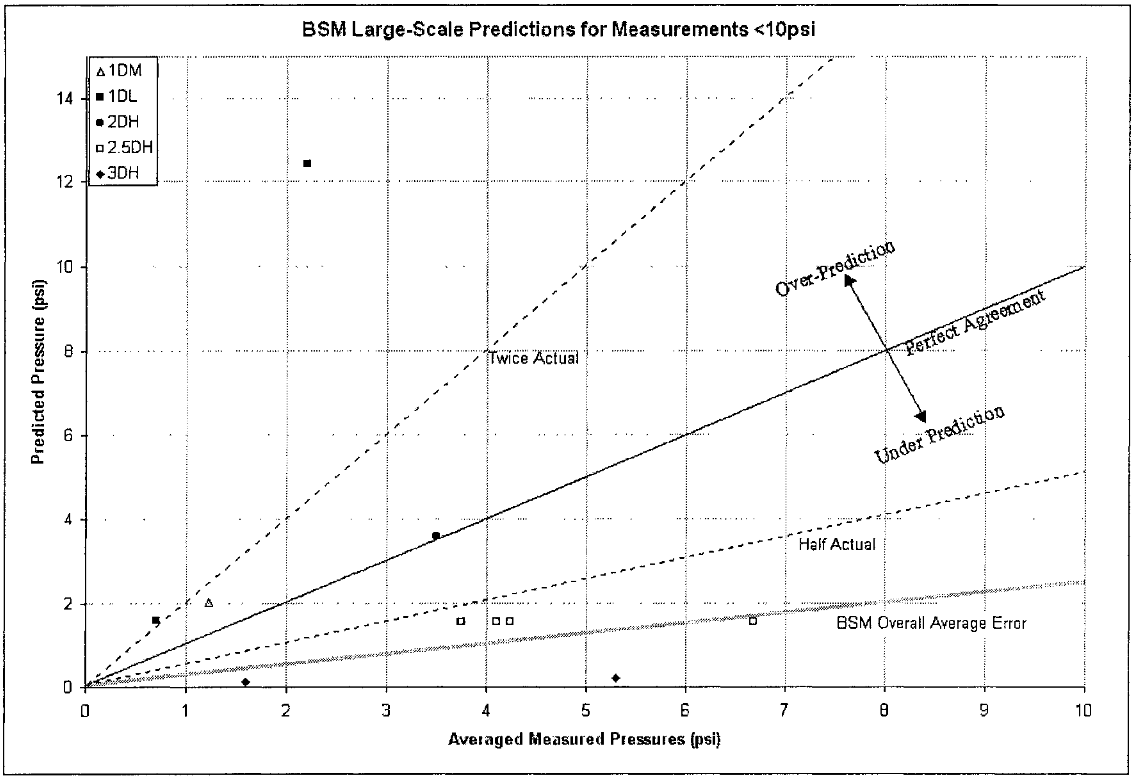

Figure 18 – Plot of Large-scale Averaged Measured Pressures less than 10 psi versus BSM Predicted Pressures

5.1.5. CAM2 Experimental Predictions

Figure 19 and Figure 20 show the CAM2 predictions plotted against the experimental results and grouped according to the BSM confinement and congestion categories. Figure 19 shows all of the predicted data while Figure 20 only shows that data corresponding to measured pressures less than 10 psi. With a calculated average error of between 2% and 23%, the CAM2 does a very good job of predicting all the experiments. All of the predictions fell within the factor of two range.

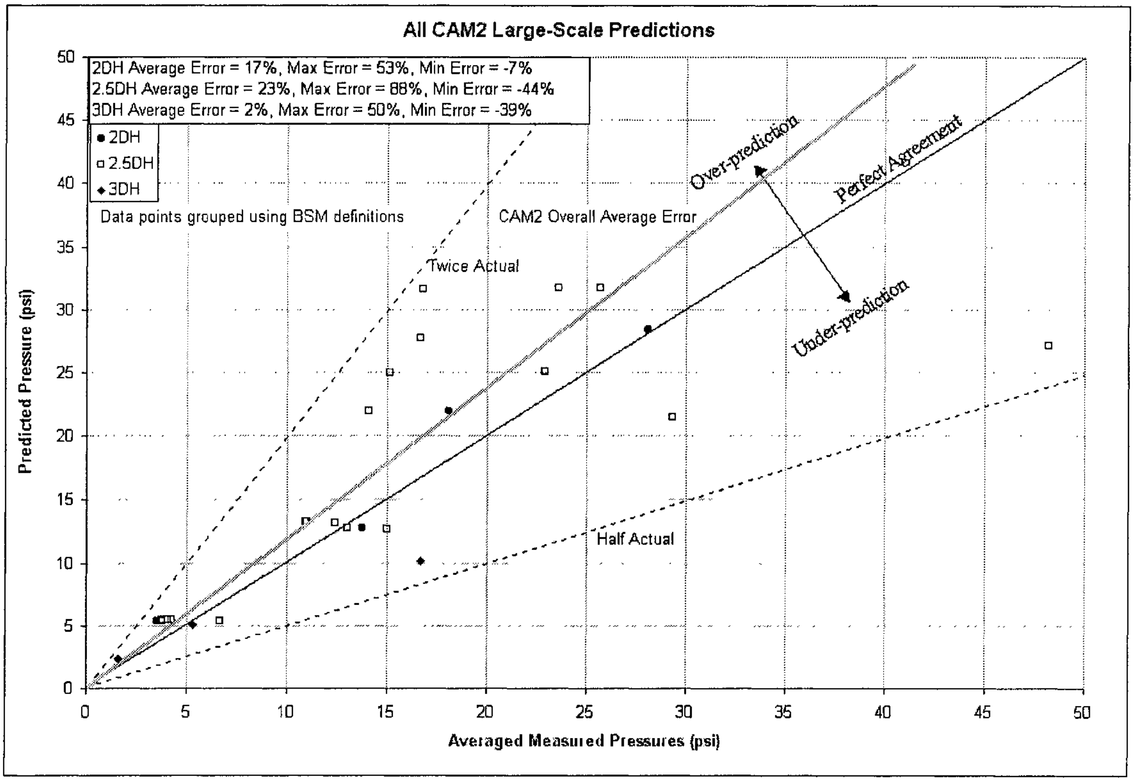

Figure 19 – Plot of Large-scale Averaged Measured Pressures versus CAM2 Predicted Pressures

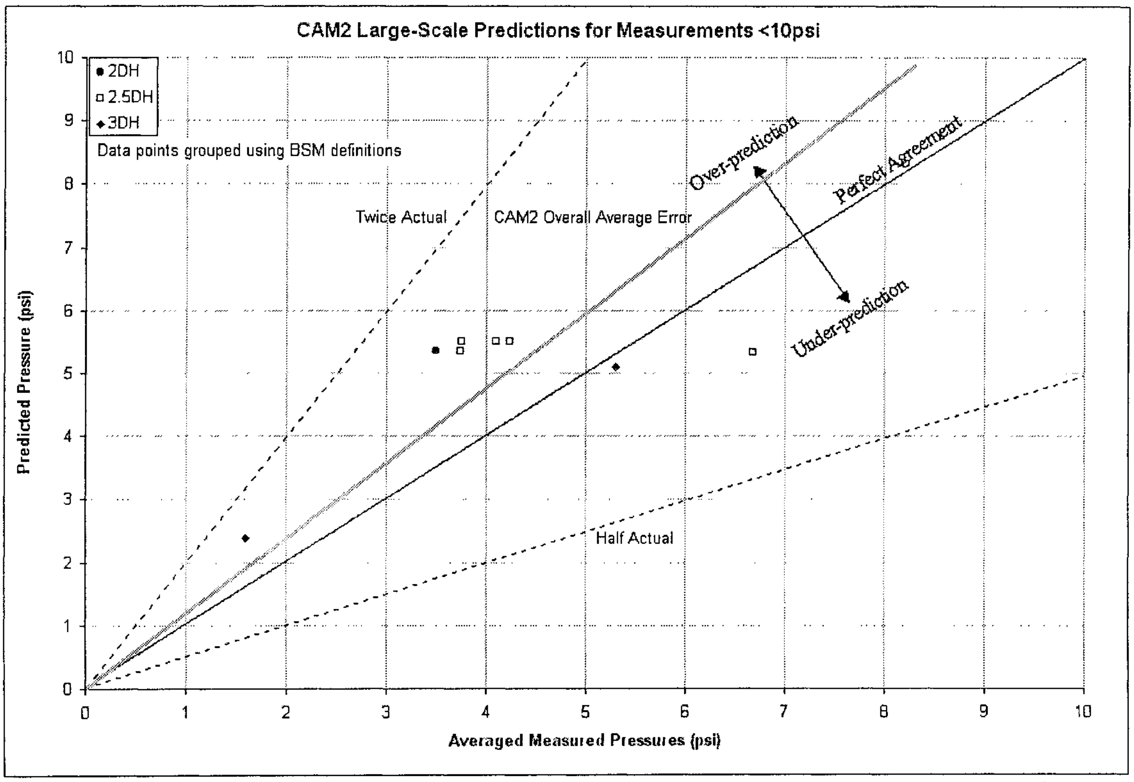

Figure 20 – Plot of Large-scale Averaged Measured Pressures less than 10 psi versus CAM2 Predicted Pressures

5.1.6. MEM2 Experimental Predictions

Figure 21 and Figure 22 show the MEM2 predictions plotted against the experimental results and grouped according to the BSM confinement and congestion categories. Figure 21 shows all of the predicted data while Figure 22 only shows that data corresponding to measured pressures less than 10 psi. With a calculated average error of between –10 and -41%, the MEM2 predictions tend to under predict the measurements, but still do a fair job of predicting all the experiments. The predictions shown in Figure 21 indicate better agreement when less than 10 psi. Most of the predictions fell within the factor of two range.

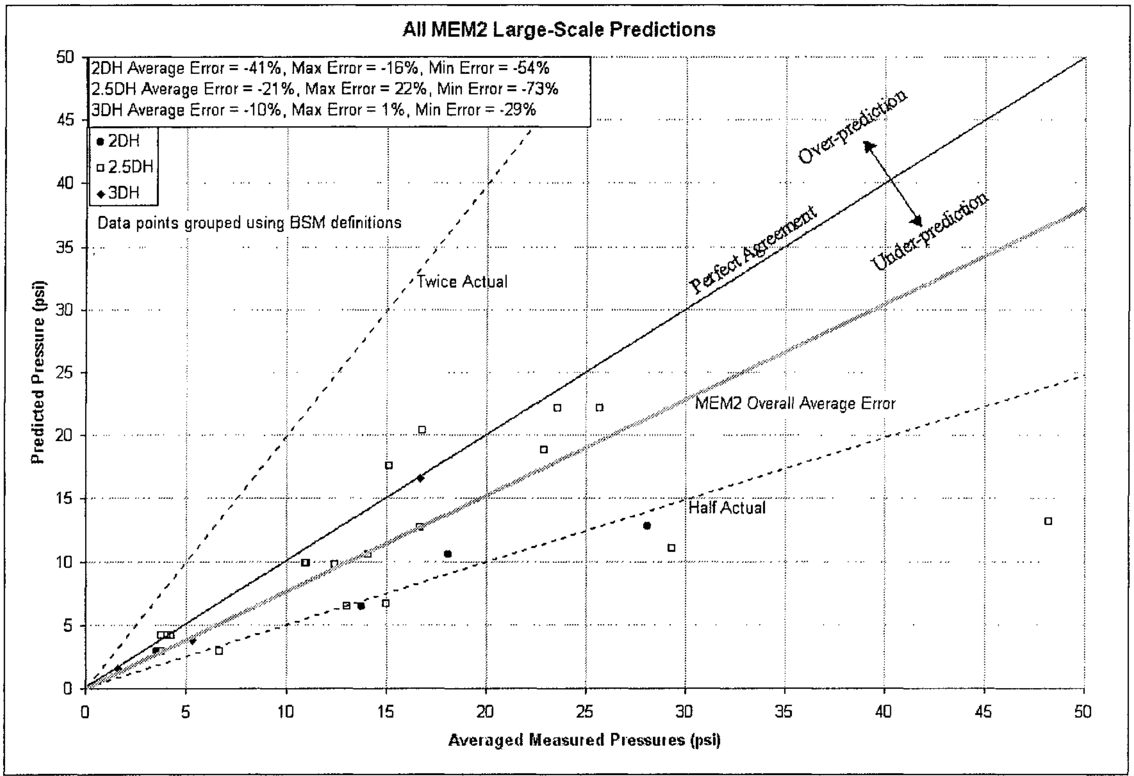

Figure 21 – Plot of Large-scale Averaged Measured Pressures versus MEM2 Predicted Pressures

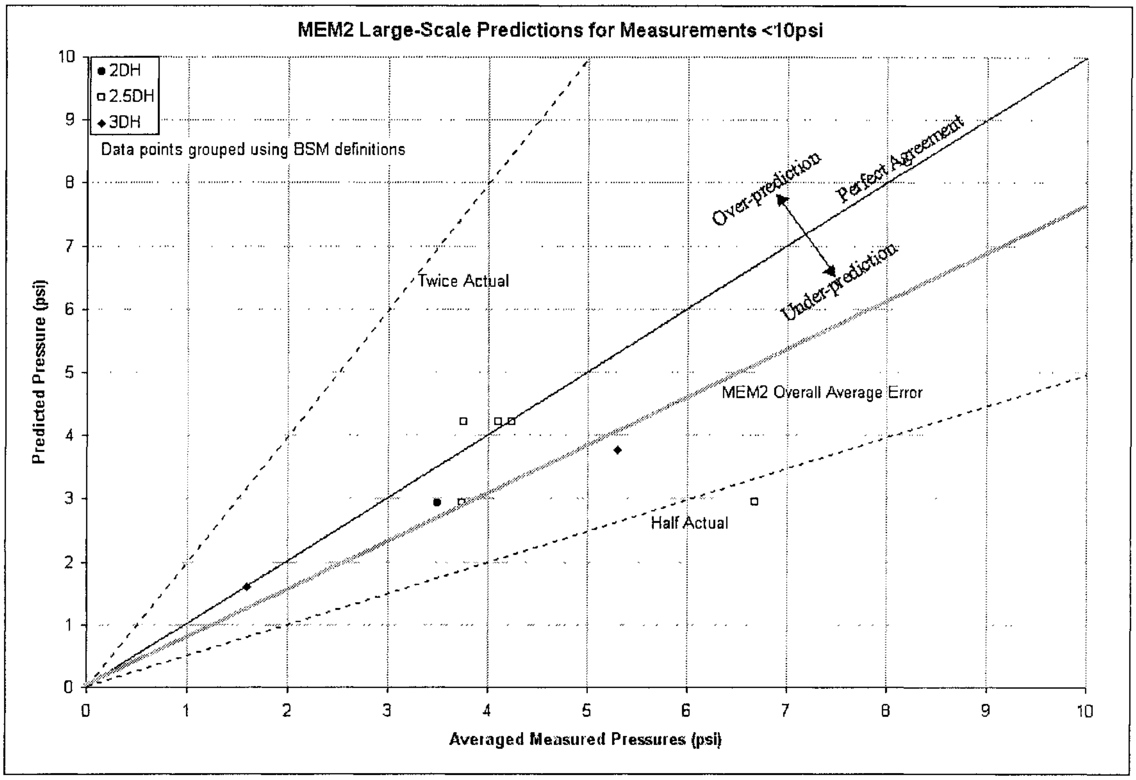

Figure 22 – Plot of Large-scale Averaged Measured Pressures less than 10 psi versus MEM2 Predicted Pressures

5.2. Industry Case Study Comparison

The industry case study comparison indicates all three method provide good far field predictions (distances greater than 1350 feet) as shown in Figure 23. This was the closest distance where both a lower pressure limit and an upper pressure limit to have caused the observed damage was reported. The EPA/OSHA report indicated 50% window breakage was observed at about 1350 feet from the explosion. The report indicated this level of damage could be in the range of 0.3 to 0.5 psi, based on the window thickness and area. 100% window breakage was reported at 500 feet from the explosion. The report also indicated that pressures greater than 1 psi will result in 100% window breakage. Thus, 1 psi was a minimum pressure at the distance of 500 feet. The report continued to state that window breakage was observed at more than one mile. The average minimum pressure for window breakage is usually about 0.15 psi. No detailed window information was included in the report that would provide for better estimates. It is possible that more detailed window information could have changed these pressure estimates for damage. However, all predictions are close to the pressure estimates so they are all believed correct in the very far field.

All three methods produced similar results as close as 400 feet as shown in Figure 24. Since all predictions correlated to the very far field damage predictions, and had similar results at 400 feet from the explosion, one could have confidence that any of the methods would produce acceptable results at distances greater than 400 feet. However, the methods diverge at less than 400 feet. At 100 feet, the CAM2 predicted pressure was almost 2.5 times the BSM pressure and the MEM2 predicted pressure was about 3.5 times the BSM pressure. The experimental comparisons indicate the BSM tends to under predict in the near field, suggesting the MEM2 or CAM2 may be more accurate for this case study. Unfortunately, damage data was not available in the near field, so conclusions cannot be made about which method is best at distances close to the explosion.

Figure 25 shows a plot of the predicted durations. No data was available from the EPA/OSHA report to make any comparisons with observed durations. All three predictions start at about the same value. However, as the distance increases the BSM and MEM2 predictions increase while the CAM2 predictions remain constant. This is contrary to that observed with the experimental results. Without further data, this discontinuity cannot be resolved and no conclusions can be reached regarding durations.

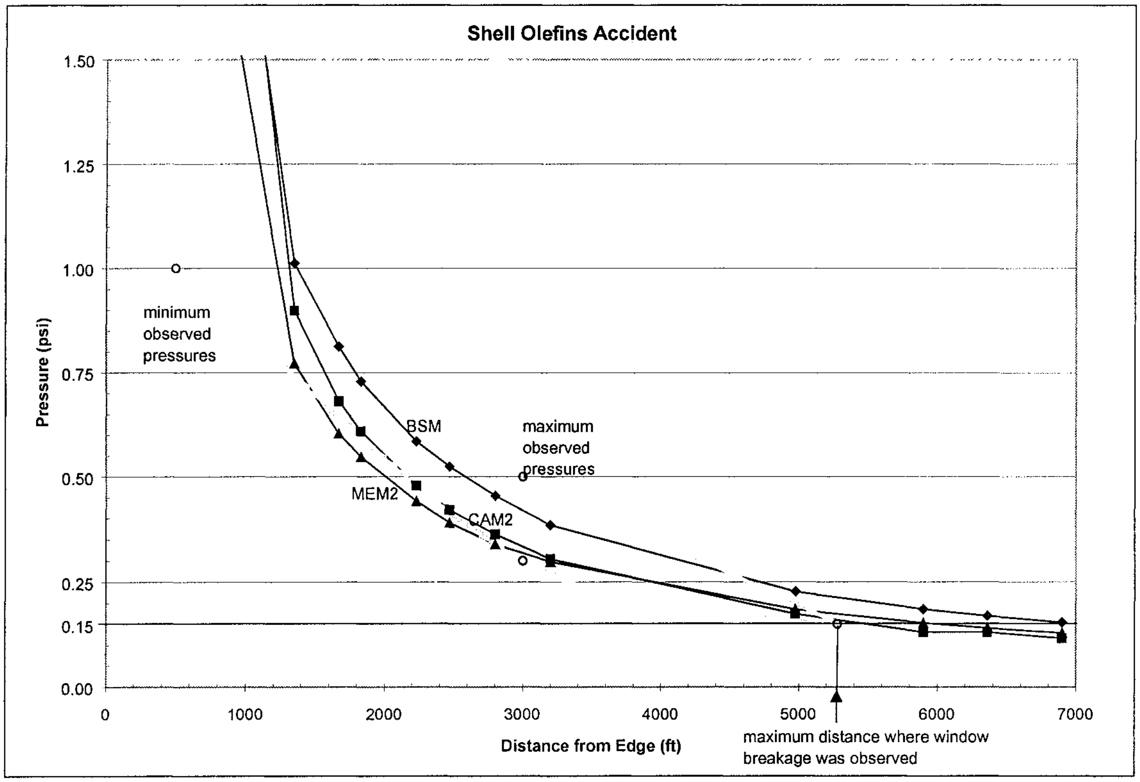

Figure 23 –Plot of Industry Case Study Observed Pressures versus Predicted Pressures in the Far Field

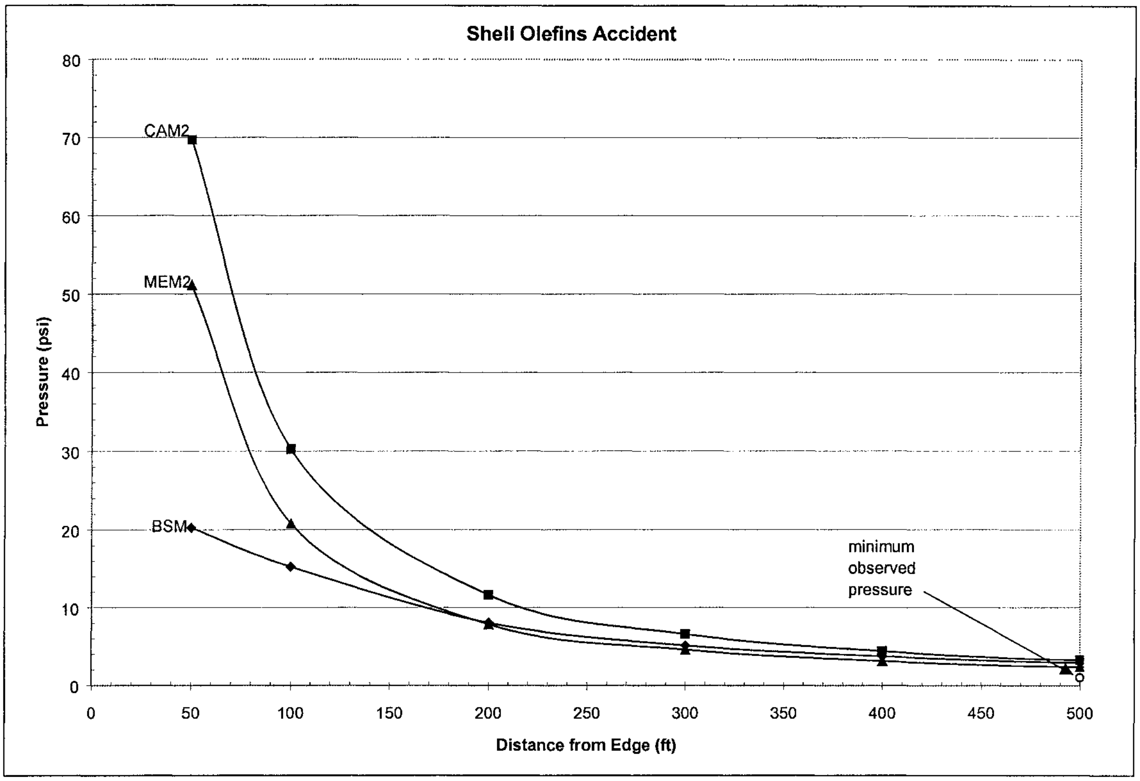

Figure 24 –Plot of Industry Case Study Near-Field Predicted Pressures

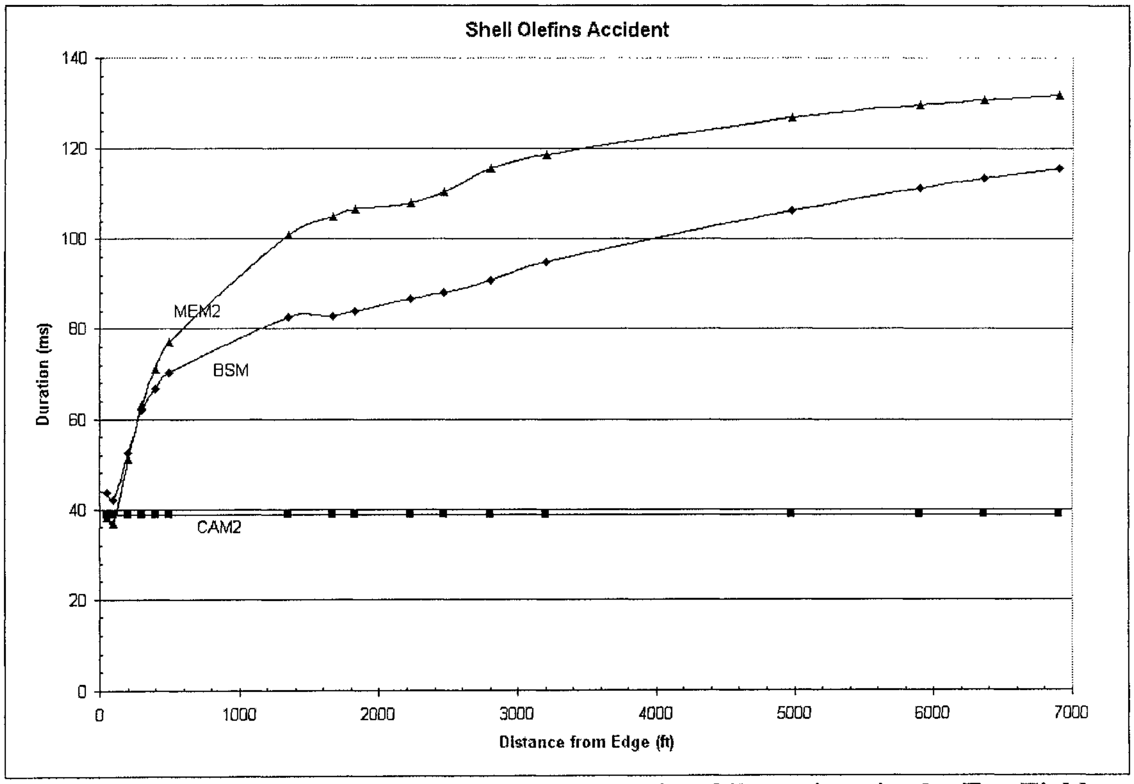

Figure 25 –Plot of Industry Case Study Predicted Durations in the Far Field

To ensure confidence in the accuracy of the predictions, a sensitivity analysis was conducted. In applying the MEM2 method to the industry case study, a severity level of 10 was used. Thus, no changes were possible that would increase pressures further. Changes that would reduce the severity level would have to have been much more severe than reasonable since severity levels 6-10 are identical in the far field. Calculations were performed to determine the VBR needed with the given congested volume to result a severity level of less than 6. It was found that a VBR of no greater than 1.8% was needed to obtain less than a severity level of 6. For the average obstacle diameter from the experiments that replicated process layouts, an ABR of 17% resulted. This is much less than what would be considered highly congested. Thus, the MEM2 analysis is considered to be representative in the very far field.

The BSM comparison evaluated the area at 2.5D confinement, high congestion and high fuel reactivity. A reduction in congestion is not reasonable given the accident report descriptions and photographs provided in the report. An increase in congestion is not likely since the fin fan cooler was elevated and did not cover the entire congested volume. A change in fuel reactivity was not possible given the BSM criteria. A reduction in confinement could be argued due to the elevated fin fans. However, the area clearly fit the BSM 2½D definition and thus a reduction in confinement was not considered. Alternatively, one could argue that 2D confinement would be a reasonable assumption. An increase from 2.5D confinement to 2D confinement would increase pressure by 0.17 psi at 1350 feet and 0.02 psi at 6900 feet. These changes are negligible given the range of observed pressures and uncertainties with the pressures reported to cause window damage. Thus, the BSM analysis is also considered to be representative in the very far field.

The CAM2 calculations were repeated for a range of ABRs between 30% and 70% without a change in pressure prediction in the very far field. The numbers of obstacles was also varied significantly without a change in the pressure prediction. Thus, there is a high degree of confidence that the CAM2 prediction is valid for the far field.

5.3. Fictional Case Study Comparison

This case was taken from an example given in the original BSM paper with two exceptions. The example in the paper assumed high congestion. The majority of comparisons made thus far were for high congestion, so it was assumed that the area would have medium congestion to provide an indication of how the methods perform at lower explosion severity. Another change from the original example is that this comparison takes the fuel at average reactivity. The example described the fuel as a mixed hydrocarbon fuel with 10% hydrogen. Using the method given in the 1997 BSM update paper, this mixture would be an average reactivity fuel. Since CAM2 does not allow for fuel mixtures, the fuel was taken to be propane since it is a typical light hydrocarbon, average reactivity fuel. The resulting pressure predictions are shown in Figure 26.

The BSM and MEM2 predictions are relatively close to each other very close to the edge of the explosion and almost identical at greater than 30 feet. The CAM2 resulted in much greater predictions than either the BSM or MEM2. Without actual test data, it is unknown which is correct. However, a comparison of the congested size, VBR and ABR show close similarities to the EMERGE medium scale propane tests, except the fictional process is about 3 times longer, 50% wider and 50% taller than the EMERGE tests. Figure 43 at the end of this paper shows the EMERGE medium scale propane tests indicated closest agreement with the MEM2 prediction while the BSM under predicted and the CAM2 over predicted. Thus, when reviewing the fictional process predictions, one could conclude that the MEM2 should provide the best agreement with an actual explosion in this environment. The BSM would be the next best choice and the CAM2 would be the last choice for this environment. This suggests the CAM2 is not well suited for very low explosion severity or smaller sized processes.

Figure 27 show the predicted blast wave durations. This plot shows the BSM results in much greater durations than either the CAM2 or MEM2 while the MEM2 is about twice that of CAM2.

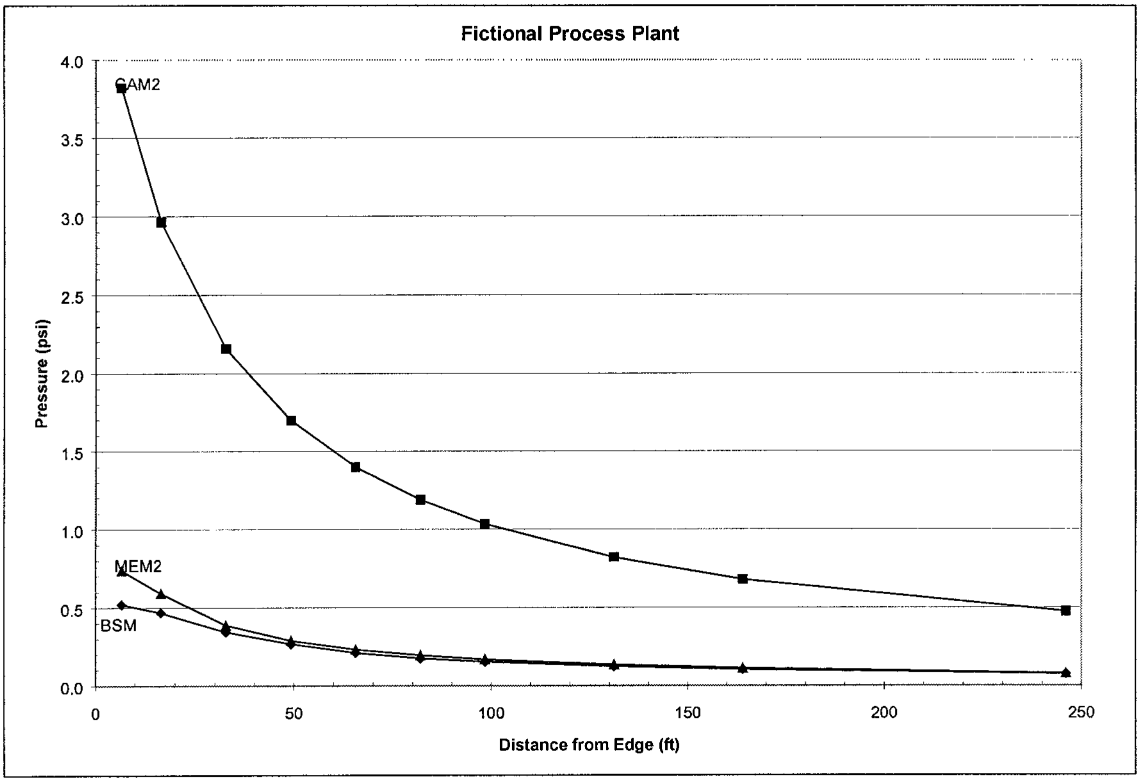

Figure 26 –Plot of Fictional Case Study Predicted Pressures

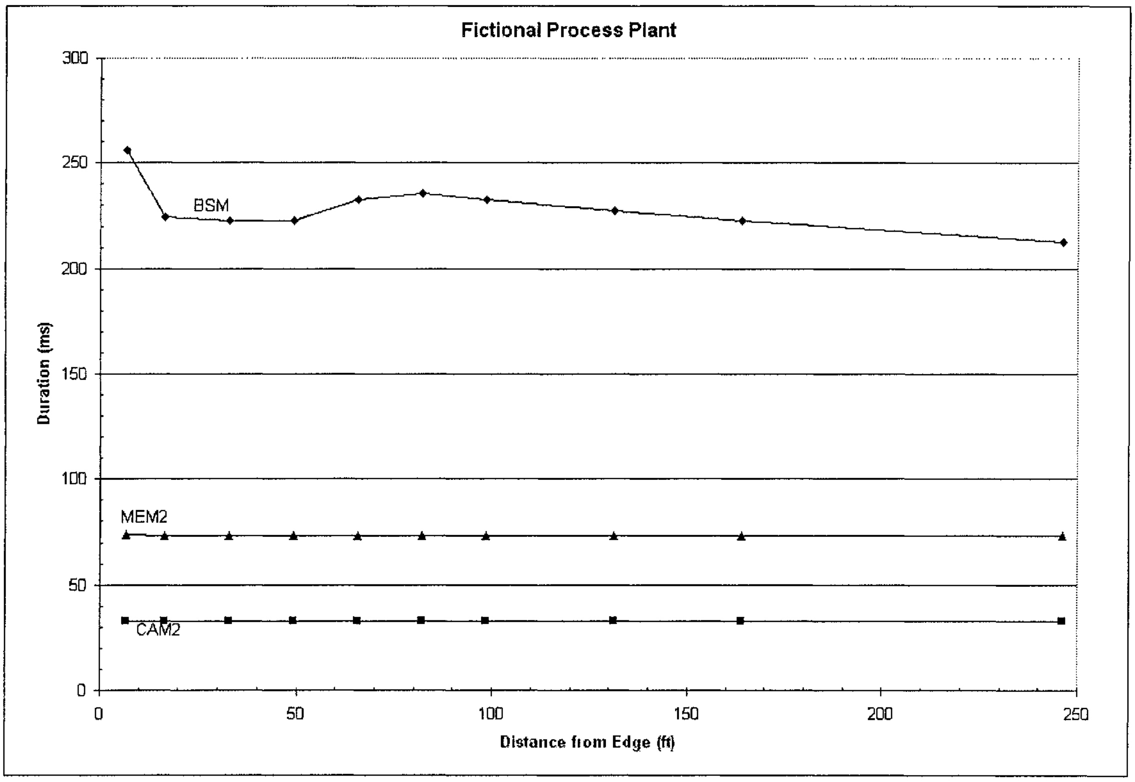

Figure 27 –Plot of Fictional Case Study Predicted Durations

6. Conclusions

Vapor cloud explosions are complex events with numerous variables. The lack of data from industry events requires experimental data obtained under controlled conditions be used for method improvement and validation. However, it is debatable if experiments produce representative data or worst case data. Experiments are typically conducted with fuels that are homogeneously mixed and at near stoichiometric concentrations. Some experiments use idealized congestion with constant pitch to simulate process environments. These conditions tend to produce more severe explosions than non-homogeneously mixed fuels closer to the rich or lean limits in a real process plant. Conversely, the experiments are also typically performed with a quiescent mixture, which produces a less severe explosion than if there were a high velocity jet release. Since the majority of releases that produce significant vapor clouds in industry are pressurized, it is believed that the explosion experiments do not necessarily produce worst case data. The experiments are believed to be most representative of an average of events that would result under similar conditions.

It has been found that some methods might over predict the experiments while others may be closer to the experimental average. Thus, in deciding which method to apply, the user needs to determine if the goal of the prediction is to provide a worst-case prediction or a prediction of the average of nearly identical explosions.

The experimental comparisons showed the following

- BSM provided good pressure predictions for 1D confinement with medium congestion and high predictions for the 1D low congestion environments, both with a low reactivity fuel.

- BSM tended to severely under predict pressures in 2D, 2½D and 3D confinement tests with medium and high congestion and with low and medium reactivity fuels. The average prediction error for these cases was –75%.
- CAM2 tended to provide the best pressure predictions for the experimental data. All predictions were within a factor of two from the measured values. The average prediction error was +20%.
- MEM2 provided relatively good predictions to the experimental data, though not quite as good as the CAM2 predictions. The average prediction error was –23%. When only measured pressures less than 10 psi were evaluated, the average prediction error was –13%.
- Overall, BSM predicted durations much greater than the CAM2 and MEM2 predictions while the CAM2 and MEM2 predictions were similar.

The industry case study indicated the following:

- All three methods provided good correlations with pressures predicted to cause observed damage in the very far field for an incident believed to be very severe.
- The near field predicted pressures diverged with the BSM predicted pressure being much lower than CAM2 and MEM2 predictions.

The fictional case study comparisons indicted the following:

- CAM2 predicted pressures that were much greater than either the MEM2 or the BSM predictions. This indicates CAM2 may not be well suited for smaller sized explosions or potentially less severe explosions. More data is needed to be sure.
- BSM and MEM2 predictions were very similar in the near field and were identical in the far field.
- MEM2 prediction would probably be most accurate due to the good correlation made with the medium scale EMERGE propane tests, a test similar to, but smaller than the fictional case study.
- The predicted durations were consistent with the test comparisons with the BSM being much larger than either CAM2 or MEM2.

The overall conclusions are that the BSM is best used for predictions where high reactivity fuel is involved, 1D confinement is present or where only far field measurements are needed. Very poor correlations with most other conditions indicate great caution should be exercised any time this method is used. Predicted BSM durations were overall much greater than the other methods.

The CAM2 provided the best overall correlations. CAM2 tended to over predict most large-scale situations, but not significantly. CAM2 allows the user to account for increased turbulence effects from sharp edged obstacles. It was known that sharp edged obstacles were not present in the EMERGE tests, but it was not known if, or how much, sharp edged blockage was present in the other experiments and case studies. Thus, the effect of sharp edged obstacles was not taken into account for any of the CAM2 predictions. Ignoring sharp edged obstacles provided good CAM2 correlations in this paper, but that approach cannot be recommended unless further work is done to evaluate the experiment layouts in more detail. Accounting for sharp edged obstacles would increase the CAM2 pressure predictions. Thus, there is some uncertainty as to if the CAM2 predictions are artificially low for some of the experiments. It would be tempting to recommend CAM2 for the user that wanted to predict an average explosion result since the comparisons indicated low overall errors. However, the uncertainty in the predictions because of sharp edged obstacles prevents that recommendation at this time. Alternatively, if the goal of the user were to predict a worst case event, then the CAM2 method would likely be the best choice since it gave a slight over prediction, even while ignoring potential sharp edged obstacles.

The MEM2 provided good overall correlations for all of the explosions, tending to under predict most situations, but not significantly and with a high degree of confidence in the predictions. Thus, if the user wants to predict the average result for a set of explosion conditions, then the MEM2 would be the best choice. This together with the lower level of complexity when compared to CAM2 makes it an attractive prediction method.

The BSM predicted durations tended to be much greater than CAM2 and MEM2 while the CAM2 and MEM2 predicted durations tended to be similar. No conclusions regarding the predicted durations can be made at this time due to the low availability of measured durations.

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Appendix – Additional Plots

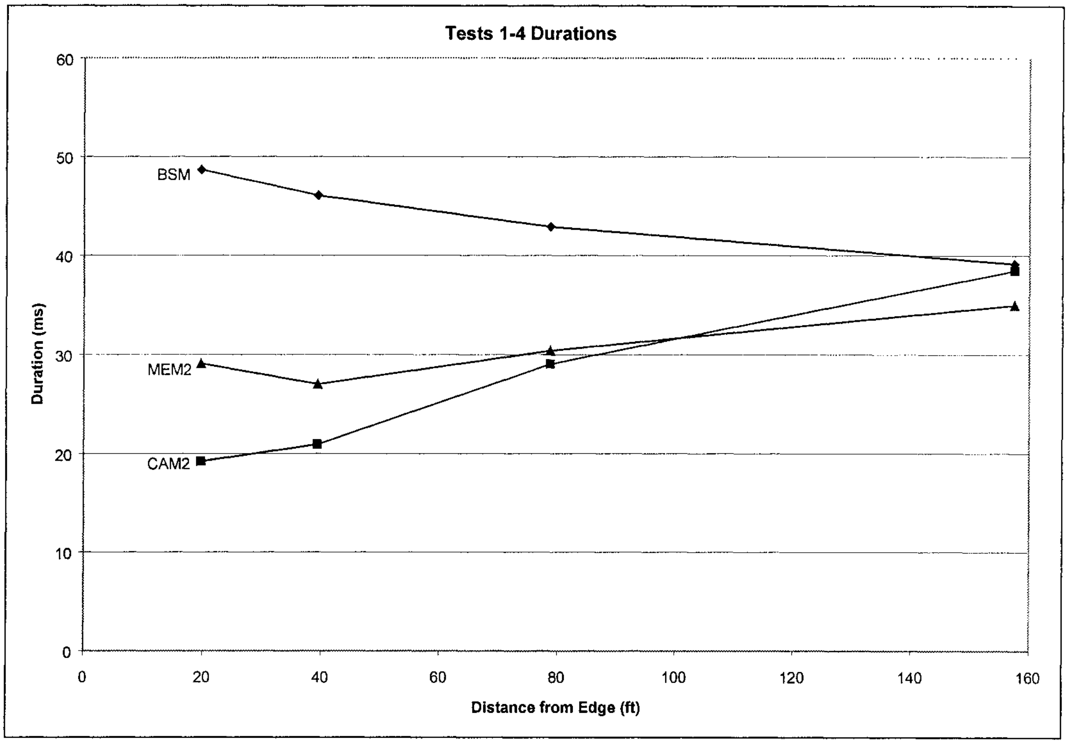

Figure 28 –Plot of BFETS3a 2D High Congestion Methane Tests Predicted Durations

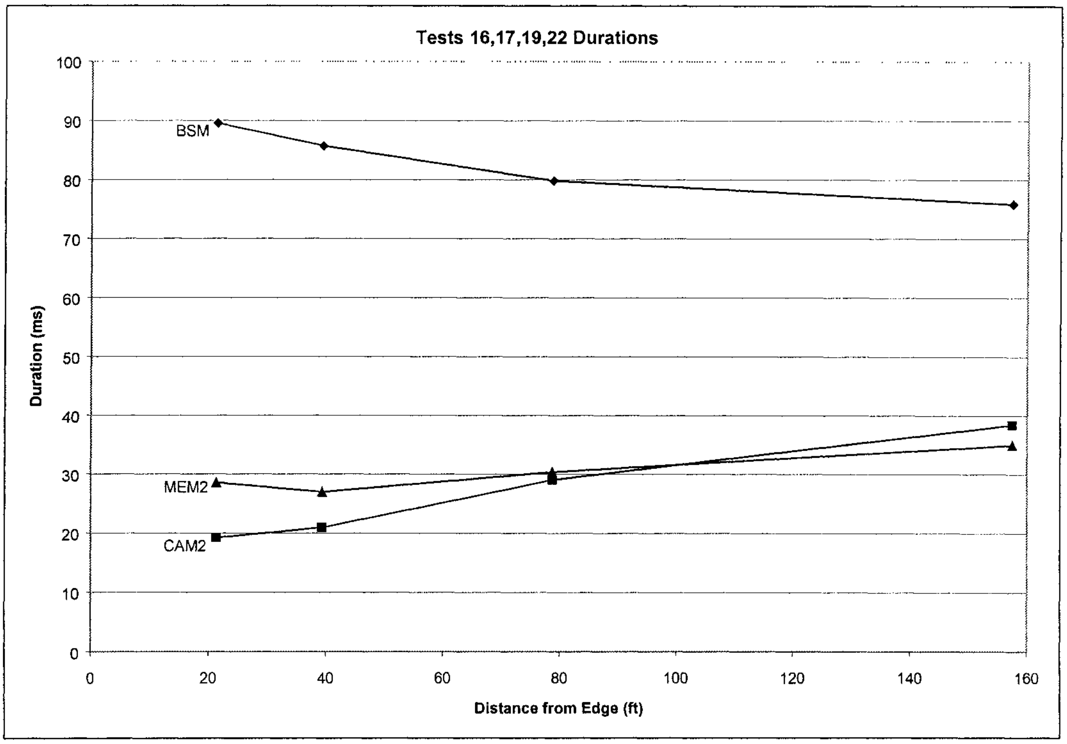

Figure 29 –Plot of BFETS3a 2½D High Congestion Methane Tests Predicted Durations

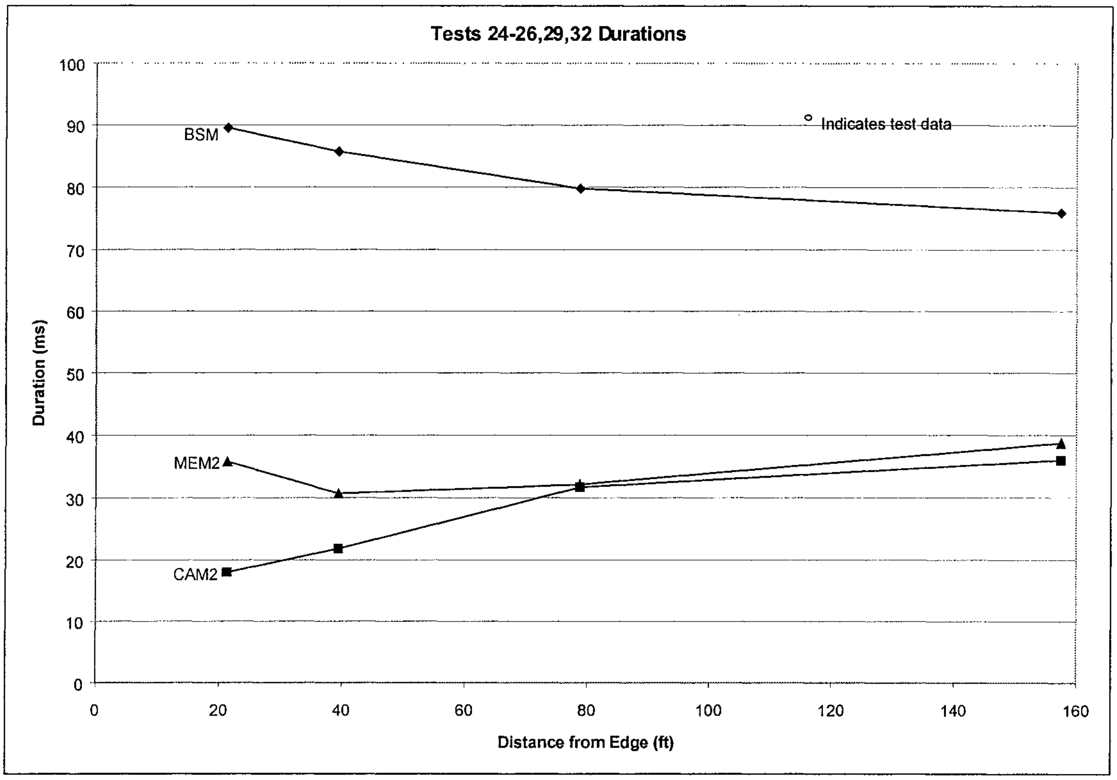

Figure 30 –Plot of BFETS3a 2½D High Congestion Methane Tests Predicted Durations

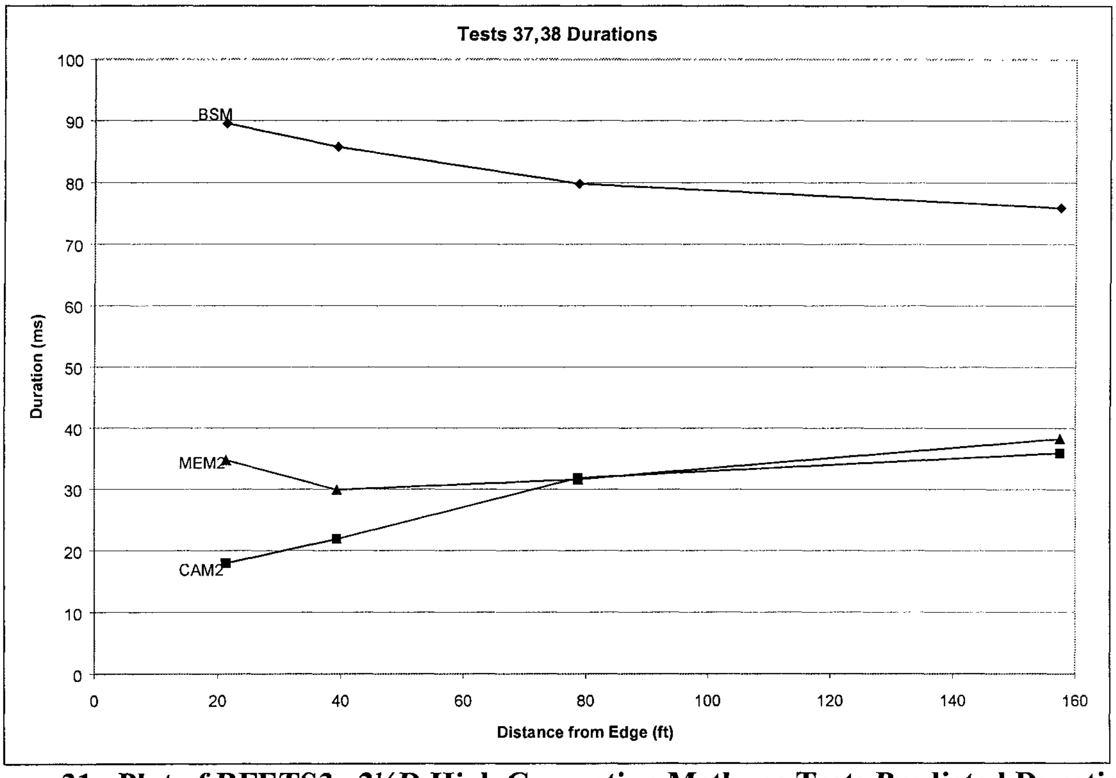

Figure 31 –Plot of BFETS3a 2½D High Congestion Methane Tests Predicted Durations

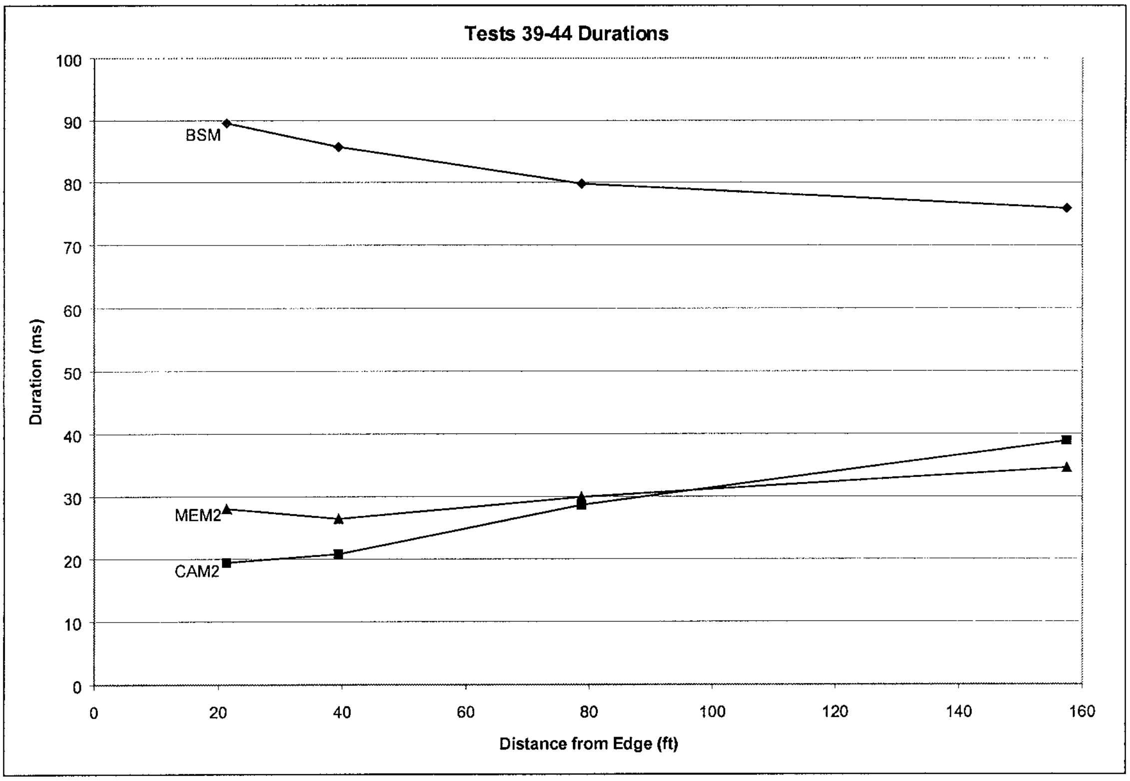

Figure 32 –Plot of BFETS3a 2½D High Congestion Methane Tests Predicted Durations

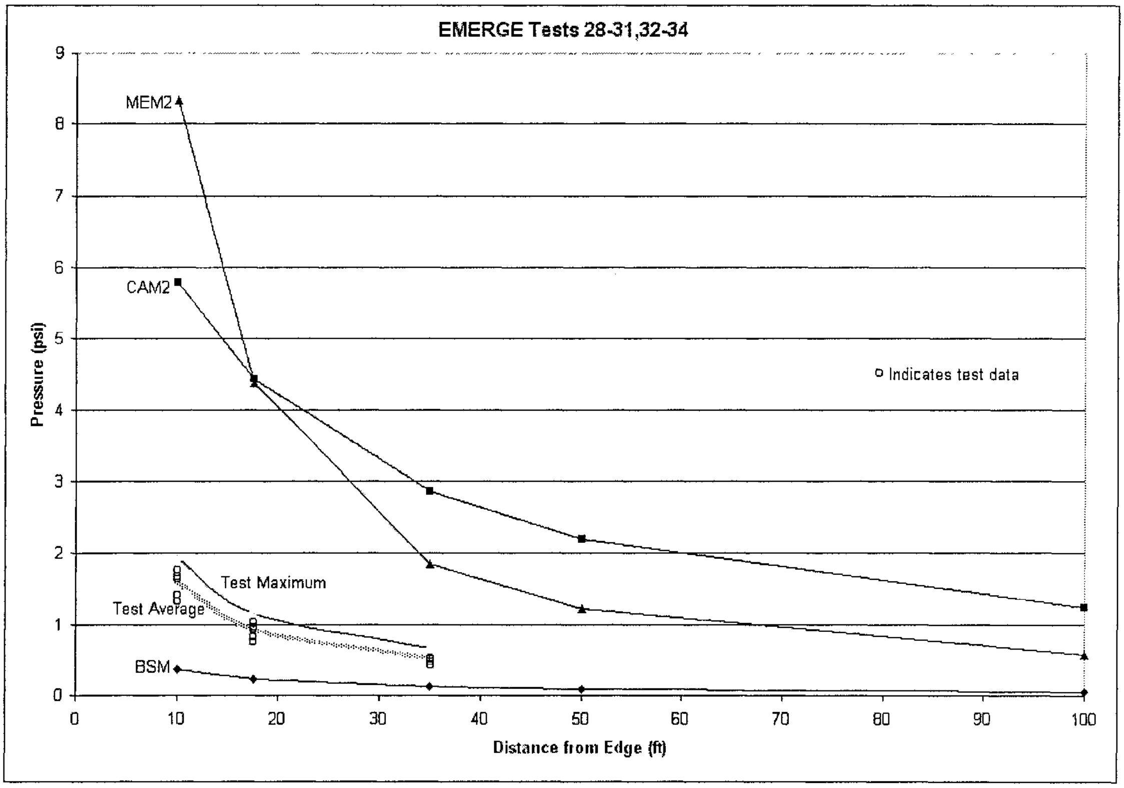

Figure 33 –Plot of EMERGE Small Scale 3D High Congestion Methane Tests Measured Pressures versus Predicted Pressures

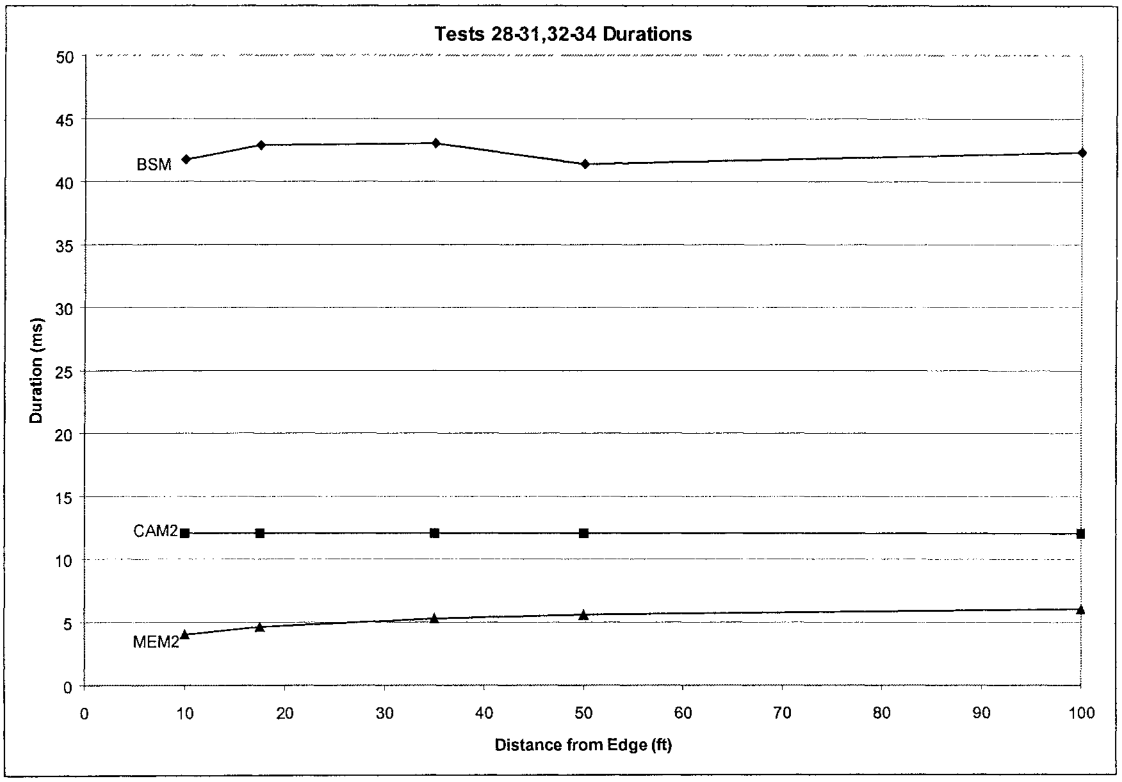

Figure 34 –Plot of EMERGE Small Scale 3D High Congestion Methane Tests Predicted Durations

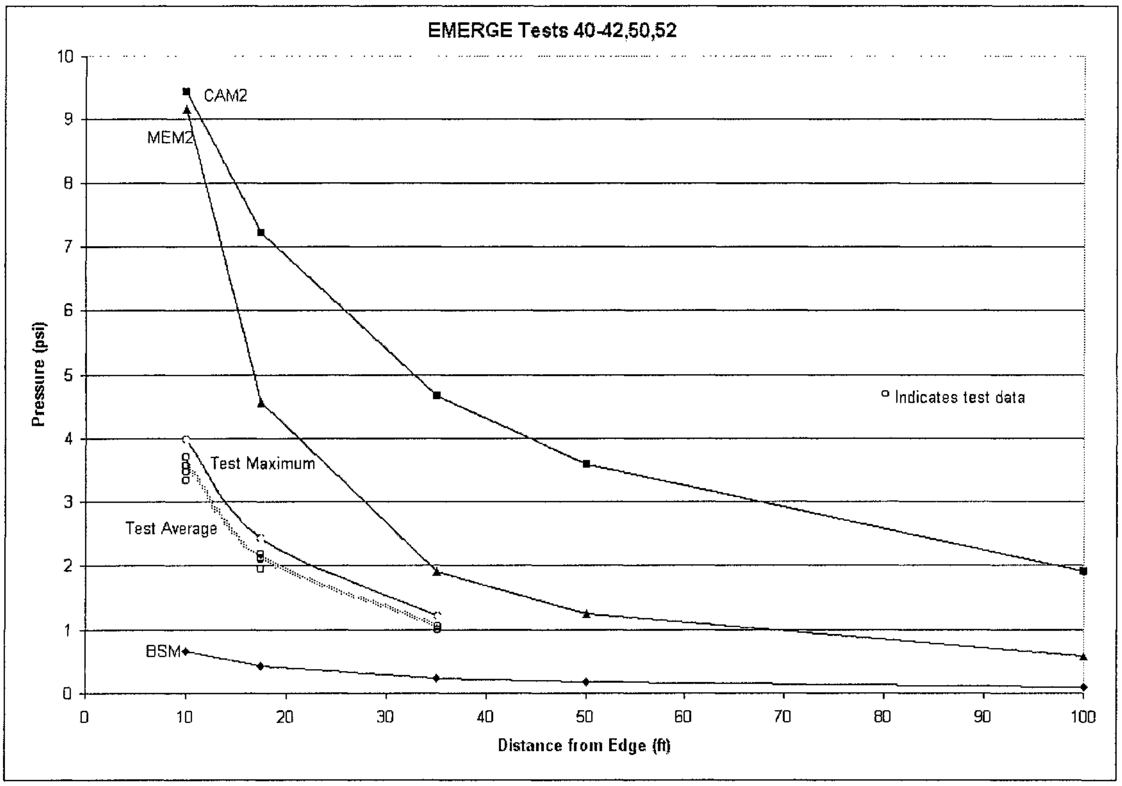

Figure 35 –Plot of EMERGE Small Scale 3D High Congestion Propane Tests Measured Pressures versus Predicted Pressures

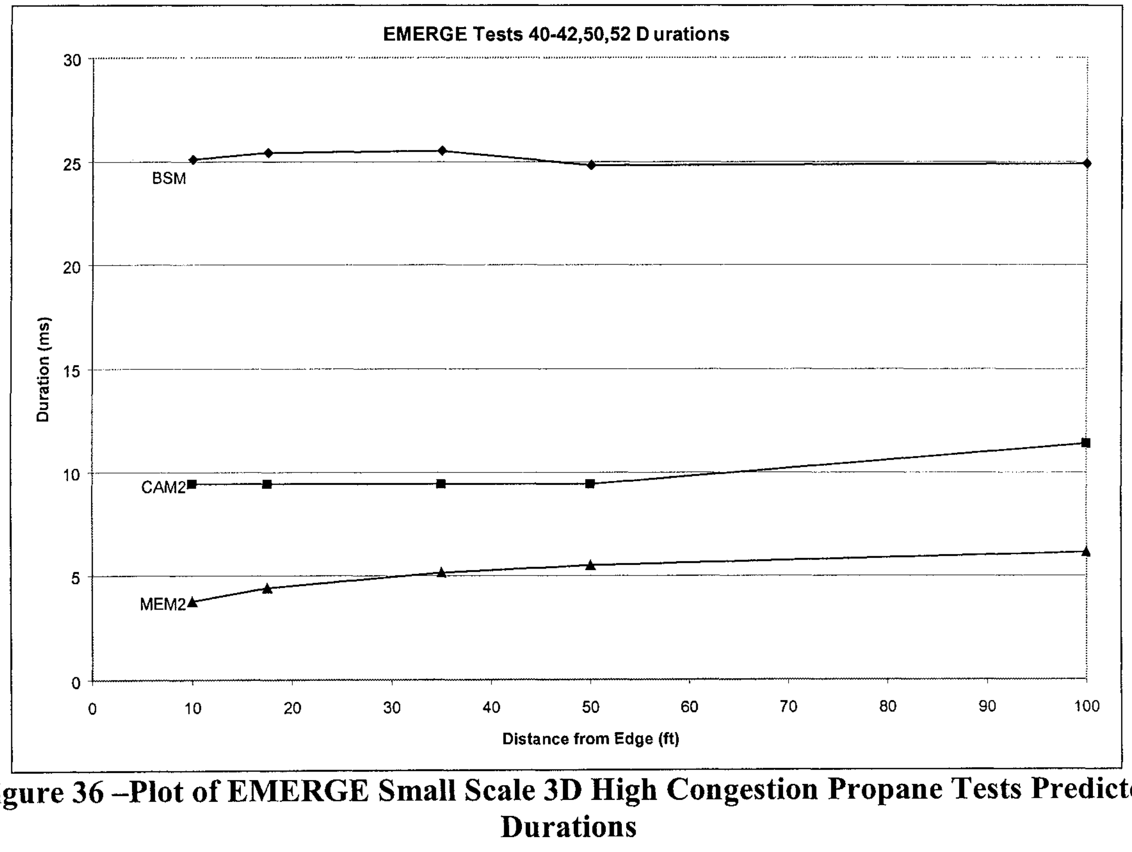

Figure 36 –Plot of EMERGE Small Scale 3D High Congestion Propane Tests Predicted Durations

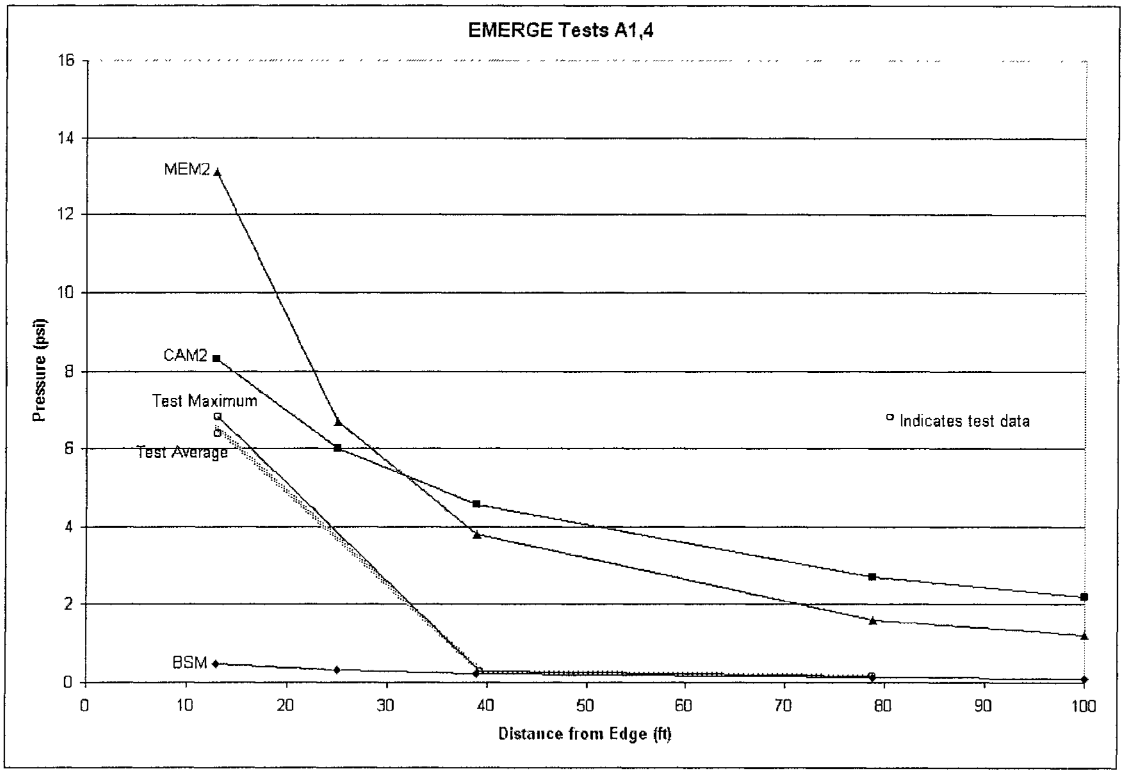

Figure 37 –Plot of EMERGE Medium Scale 3D High Congestion Methane Tests Measured Pressures versus Predicted Pressures

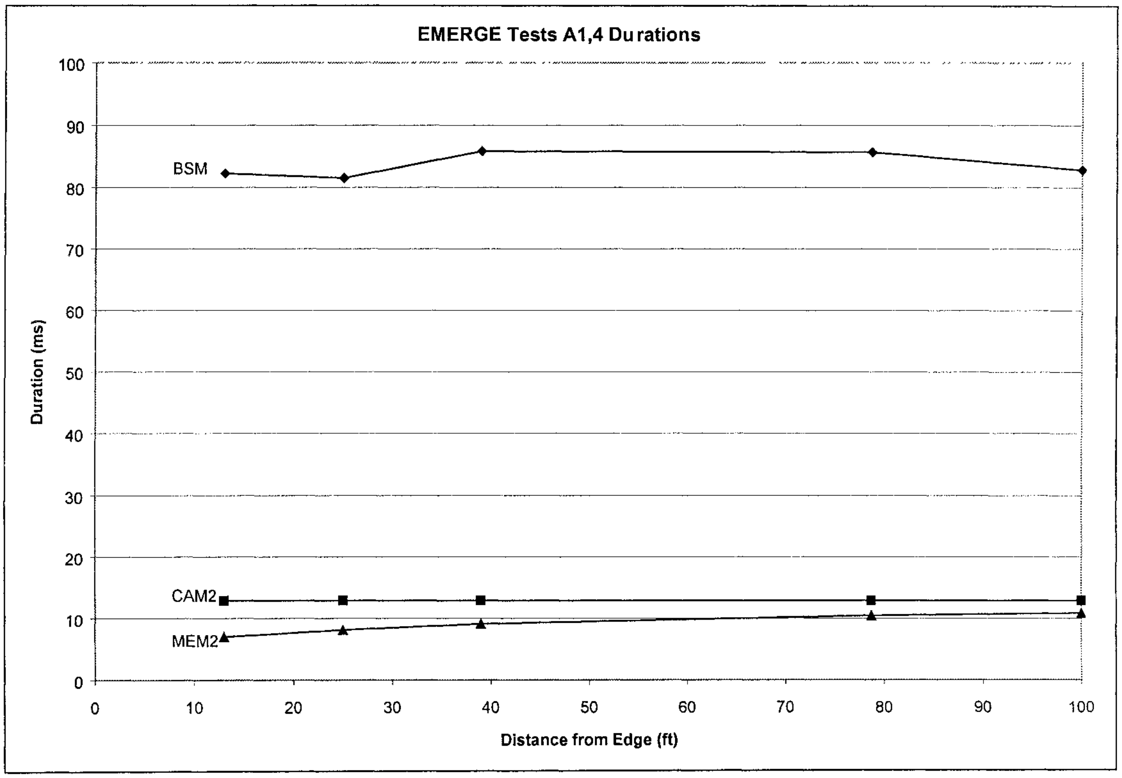

Figure 38 –Plot of EMERGE Medium Scale 3D High Congestion Methane Tests Predicted Durations

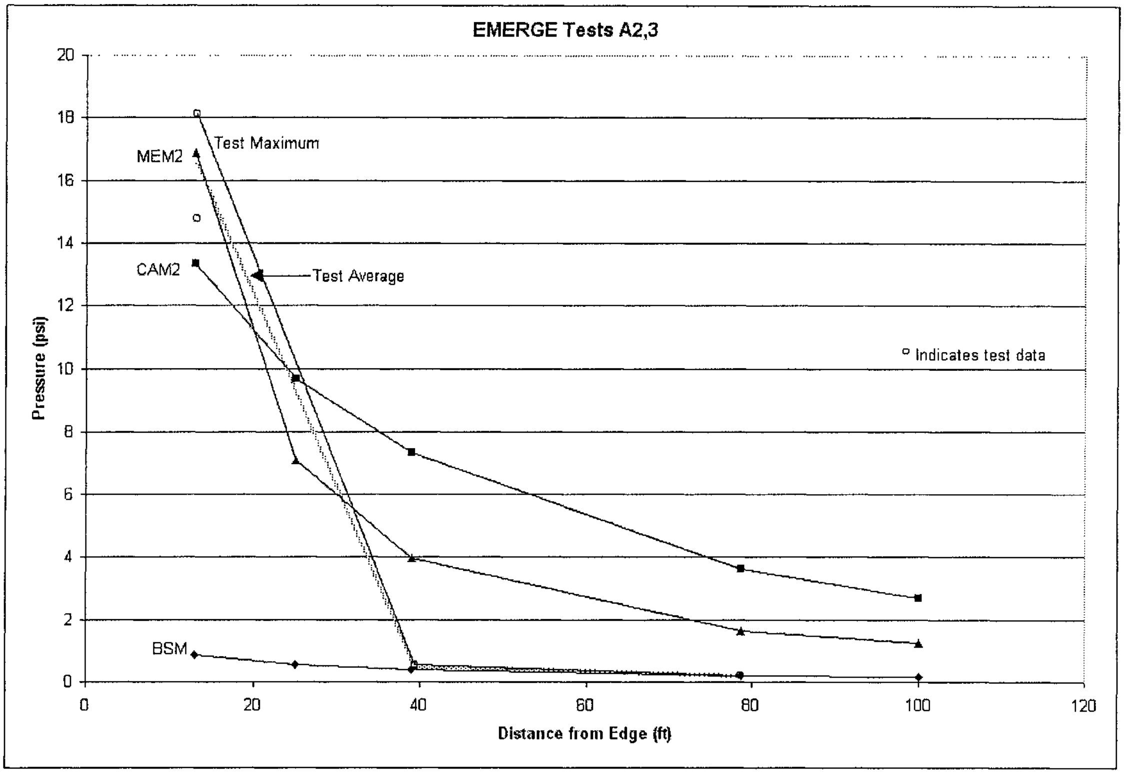

Figure 39 –Plot of EMERGE Medium Scale 3D High Congestion Propane Tests Measured Pressures versus Predicted Pressures

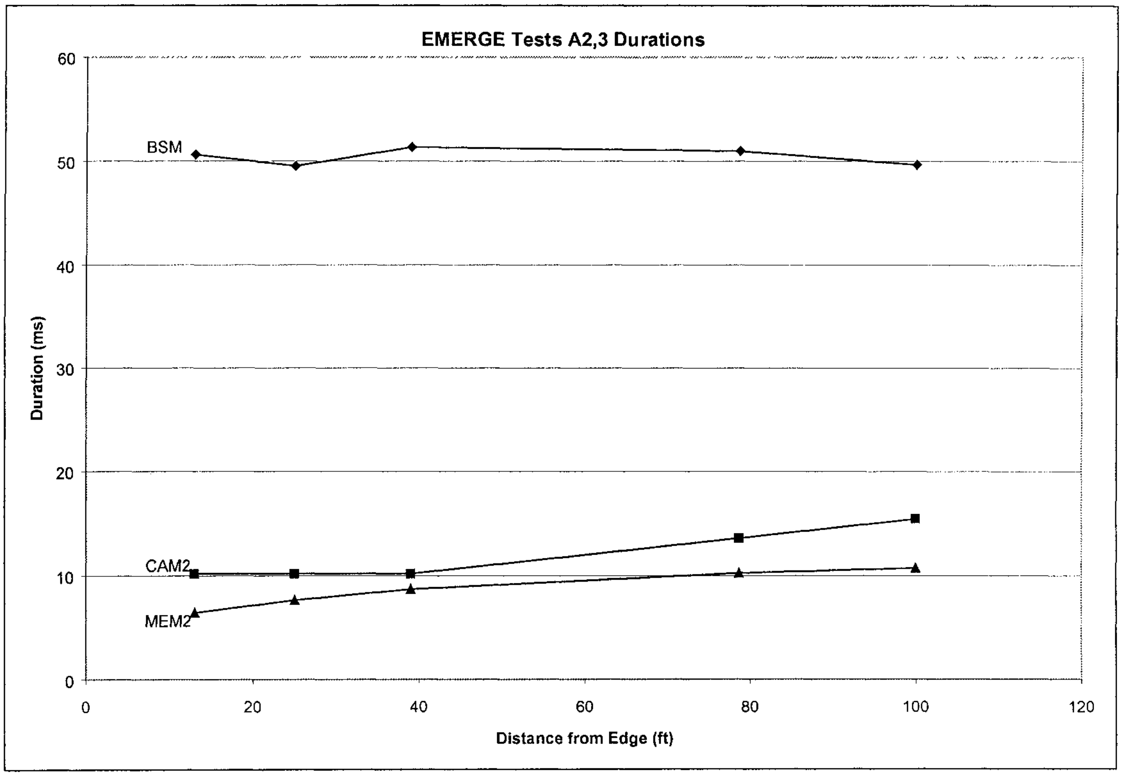

Figure 40 –Plot of EMERGE Medium Scale 3D High Congestion Propane Tests Predicted Durations

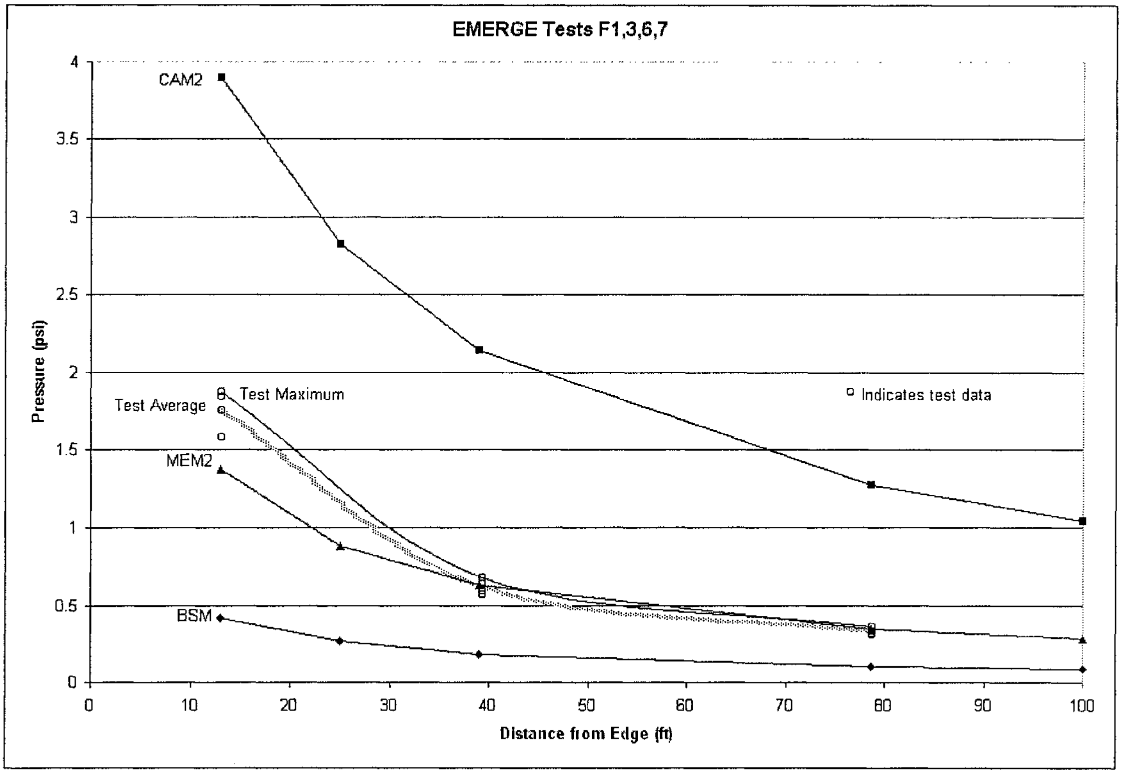

Figure 41 –Plot of EMERGE Medium Scale 3D Medium Congestion Methane Tests Measured Pressures versus Predicted Pressures

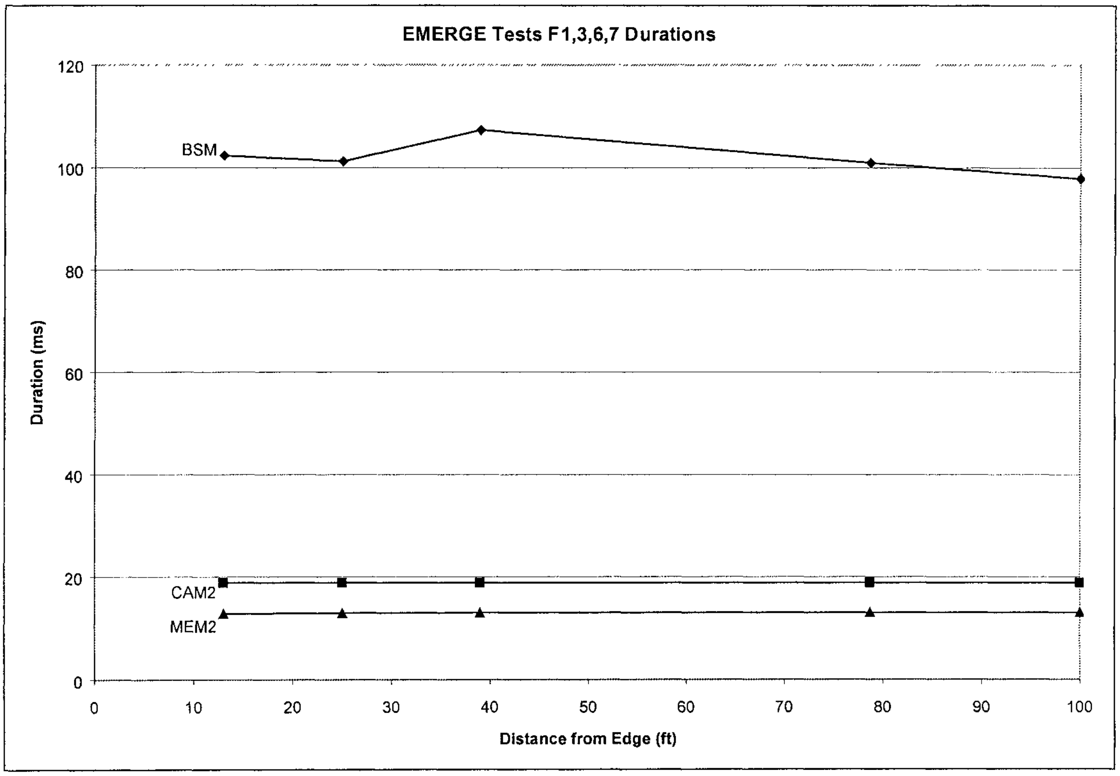

Figure 42 –Plot of EMERGE Medium Scale 3D Medium Congestion Methane Tests Predicted Durations

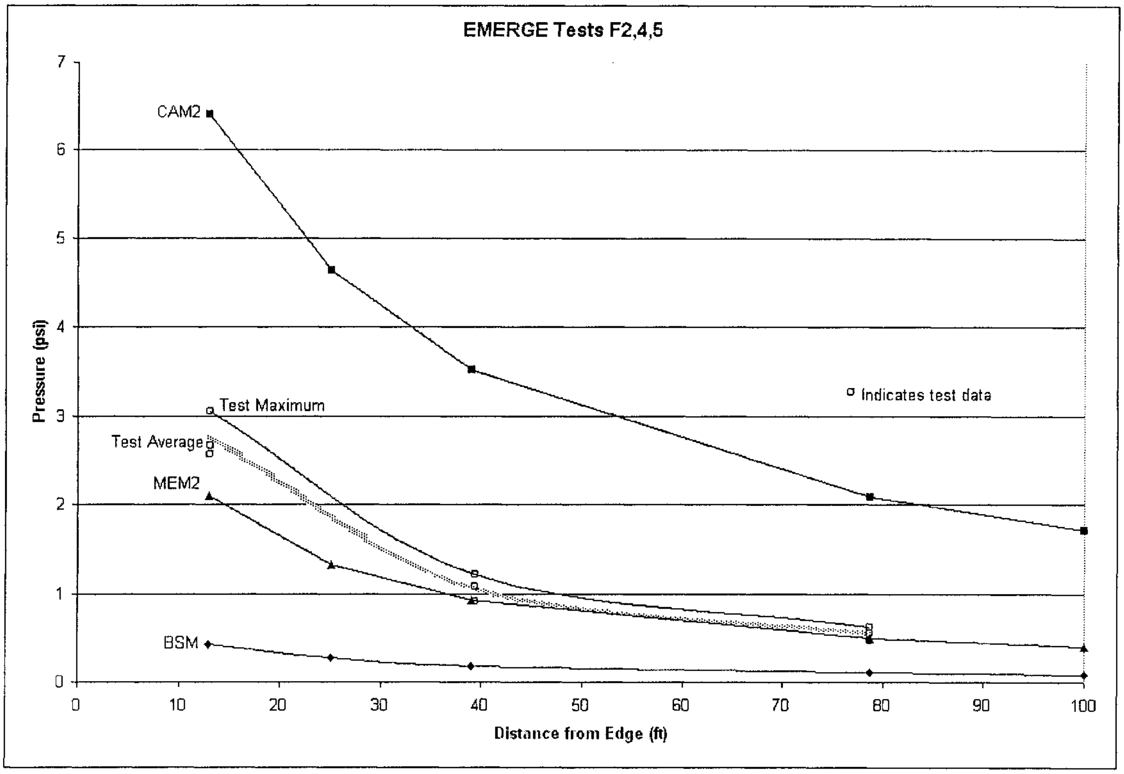

Figure 43 –Plot of EMERGE Medium Scale 3D Medium Congestion Propane Tests Measured Pressures versus Predicted Pressures

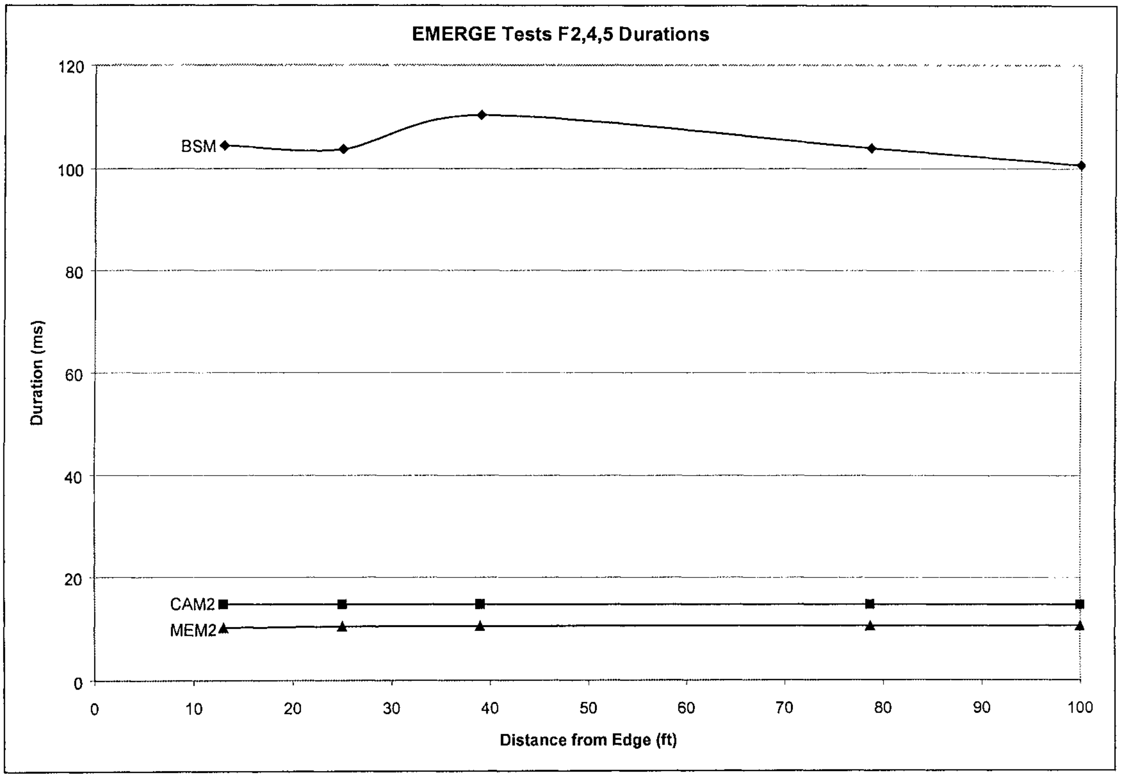

Figure 44 –Plot of EMERGE Medium Scale 3D Medium Congestion Propane Tests Predicted Durations

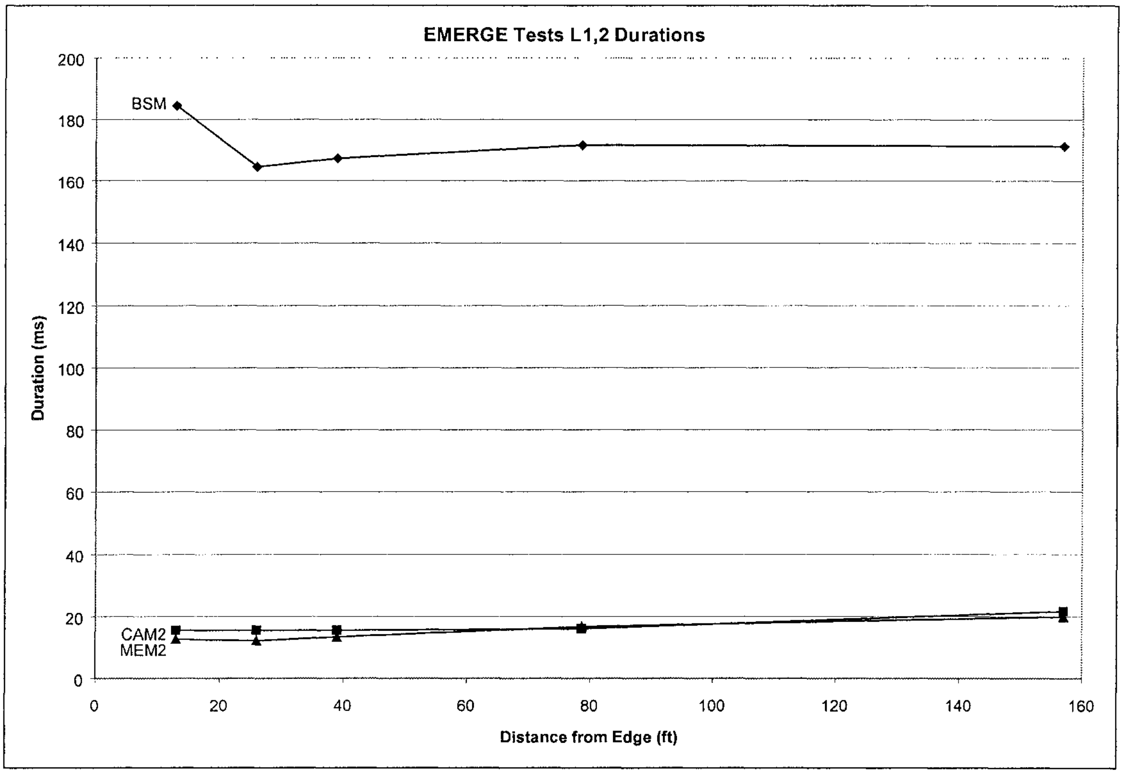

Figure 45 –Plot of EMERGE Large Scale 3D Medium Congestion Methane Tests Predicted Durations

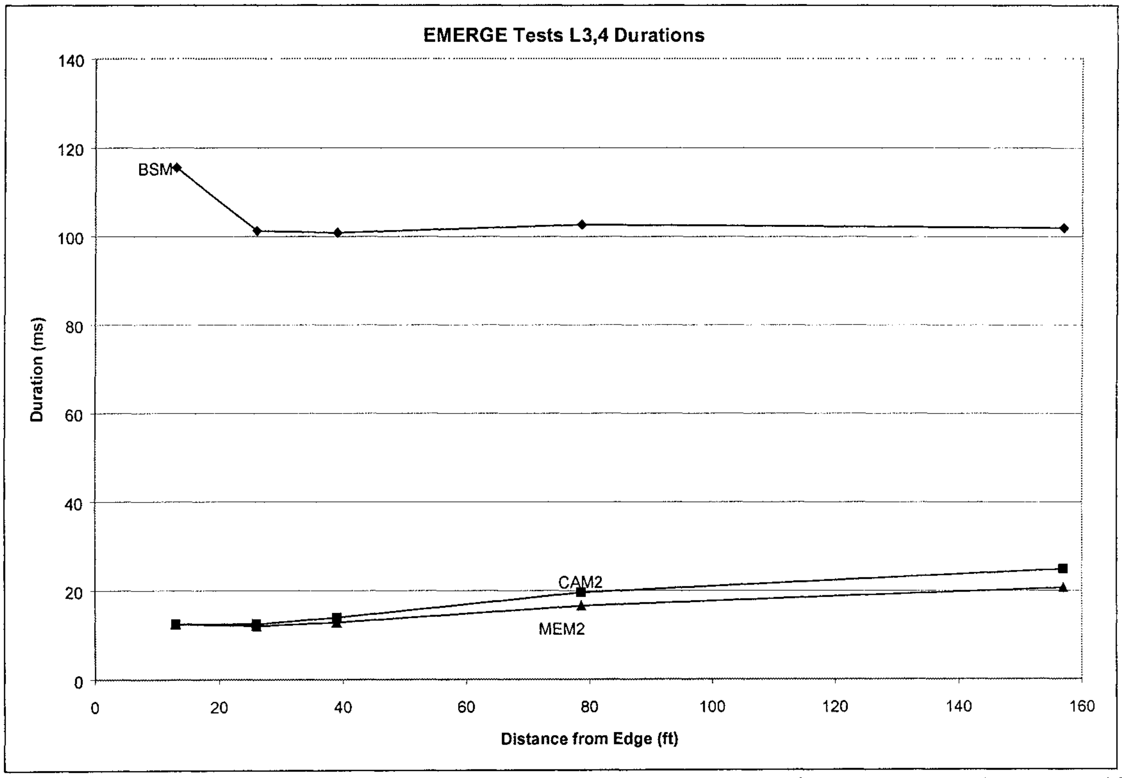

Figure 46 –Plot of EMERGE Large Scale 3D Medium Congestion Propane Tests Predicted Durations