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MEASURING UNCERTAINTY AND CONSERVATISM IN SIMPLIFIED BLAST MODELS

David Bogosian
Karagozian & Case
625 North Maryland Avenue, Glendale, CA 91206
Phone (818) 240-1919; Fax (818) 240-4966; E-mail: bogosian@kcse.com

John Ferritto
Karagozian & Case
E-mail: ferritto@kcse.com

Yongjiang Shi
Karagozian & Case
E-mail: shi@kcse.com

Engineers performing assessments or designs of structures to blast effects usually begin by computing blast loads for the explosive event under consideration. In almost all cases, this computation involves the use of one of a number of simplified engineering level tools, including PC codes as well as lookup curves. Unfortunately, the tools only provide a deterministic prediction, without giving engineers any sense of the inherent uncertainties in the loading. To further complicate matters, each technical community seems to prefer one particular tool over the others, which often leads to discrepancies when two such communities with different models are required to interact or cooperate on a single project.

This paper compares blast predictions (both reflected and incident loads, both for pressure and impulse, and both positive and negative phases) from a number of popular simplified models, including BlastX, ConWep, SHOCK, to a wide range of test data spanning three decades and comprising a total of nearly 300 individual measurements. All of these were taken at low heights above the ground, some on small cubicles and others on larger buildings. The comparison is restricted to a scaled range of 3–100 ft/lb$^{1/3}$, a regime where variations in the details of the test arrangement should be more or less irrelevant. The results provide quantitative assessment of the inherent uncertainty in any blast prediction tool, even for these relatively simple geometric conditions. Relative comparison between models and test data support the determination of biases and trends within each of the models. Using these results, it is possible to quantify the bias and uncertainty in the models for each of the load metrics, and also to compare uncertainties between the various metrics.

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INTRODUCTION

For structural engineers performing designs or assessments of facilities for blast effects, calculation of the blast loads is the inevitable first step in the process. In a very few cases, that calculation involves high-level computational fluid dynamics (CFD) computer codes which model the explosive release of energy, the resulting thermal and pressure histories, and finally the pressure of interest on the structure being considered. Yet this approach is seldom used because of its cost and complexity: CFD codes are very computationally intensive, and their use requires high-level specialized knowledge.

As a result, the vast majority of loading estimates are made by using any of a number of simple engineering models. The one with greatest overall acceptance is the Kingery-Bulmash model [1] which has been incorporated as the standard blast model in numerous government manuals, including TM 5-1300. This basic mathematical model has been automated within the ConWep computer code [2], as well as in the more sophisticated (yet still engineering-level) BlastX [3]. BlastX allows users the option of either the Kingery-Bulmash (K-B) basic model, or as an alternative, a tabular TNT model which is based on a series of one-dimensional CFD calculations. Yet another simple code for such calculations is SHOCK [4]. Because of the differing provenance of each of these codes, they tend to be favored by different communities. And because of differences in approach and implementation, the models inevitably produce different results.

As a result, engineers are often faced by a quandary when determining loads: which model should I use? If I were to compare results to other models and find differences, which one should I believe? How much uncertainty is there in the blast loads that I'm using? And ultimately, how conservative is this model compared to reality?

The scope of this study is restricted to on- or near-ground bursts at some significant distance from the wall (i.e., scaled standoff of 3 ft/lb$^{1/3}$ or greater). This configuration represents a very common situation for structural response analysis and design, hence it was of primary interest (as opposed to the smaller standoffs which generate very intense, close-in loads). Within this context, the purpose of this paper is threefold:

- To compare the output from the three major blast model codes (ConWep, SHOCK, and BlastX) against the K-B model.
- To compare the output of the K-B model (and others) against a broad set of experimental results and assess the bias, if any, in the model.
- To quantitatively estimate the uncertainty in the test data which may be applied to predictions obtained from K-B or any other model.

These comparisons are performed for a total of eight metrics, each a combination of the following three items: reflected or incident, positive or negative, pressure or impulse; for example, incident positive impulse, etc. Clearly, designers are most interested in reflected positive pressure and impulse, but the others have been included for reference and thoroughness.

In this paper, we have approached our subject in blissful ignorance of the many details and nuances of blast propagation and shock physics. While certainly real and applicable, those refinements lie beyond the scope of our study. Our approach is essentially empirical, since as structural engineers our interest in blast loads is purely utilitarian rather than theoretical. Our hope is to provide some basic guidance to engineers with regard to the applicability of various blast models and the bias and uncertainty associated with each blast load computation involving these simple tools.

ENGINEERING MODEL DESCRIPTION

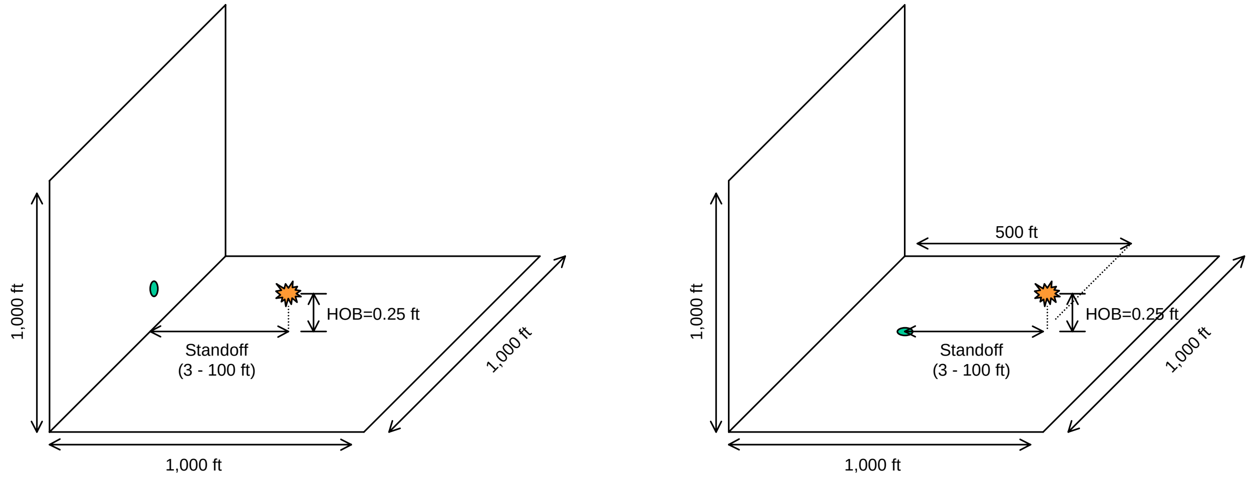
Our first task is to compare the results of our three candidate engineering models (ConWep, BlastX, and SHOCK) to the K-B model. A brief description of the methods used to obtain each set of data is provided below.

The K-B data for the *positive* pressures and impulses was calculated by taking the original 9th order polynomial equations and coding them within an Excel worksheet. Thus, this implementation goes directly back to the source relationships and, as will be shown later, can be verified against the results of the ConWep code. However, since the K-B formulation does not provide a set of relationships for *negative* pressures and impulses, those were obtained by manual digitization from the curves in TM 5-1300. The precise provenance of these curves is unknown at the present time. However, they are reproduced identically in virtually every major design manual that involves blast loads.

ConWep data was obtained simply by running the code and tabulating the resulting pressure and impulse provided. This code (as well as all the others) was exercised using a 1.0 lb TNT charge to eliminate the need for scaling. The “aboveground detonation” was selected, followed by the “hemispherical surface burst” option; the standoff was input, and the resulting pressure and impulse values obtained. One limitation of ConWep is that negative pressures and impulses are not calculated.

Running BlastX was a bit more involved, as the code allows the placement of charges and targets (measurement locations) at arbitrary positions. Version 4.2.3 of the code, the most current available at the time of this study, was used in all the calculations. A very large (e.g., 1,000 ft on each side) single-room model was utilized to eliminate any reflections from the side walls. All the calculations were made using MAXORD (the maximum order of reflected rays to be included) of 3. For reflected pressures and impulses, the 1.0 lb charge was placed at the required standoff from one of the side walls; the target was placed on the side wall at a height of 0.25 ft. For incident pressures and impulses, the charge was placed in the middle of the room with targets on the floor at all the selected ranges where results were needed. In all the runs, the charge height-of-burst (HOB) was set at 0.25 ft. Earlier verification studies [5] had shown that these values of the HOB and the target height produce the most stable and reliable results. A sketch of the models is shown in Figure 1.

BlastX includes two basic blast models, one being K-B and the other a tabular TNT model. Each was exercised independently to obtain two separate sets of results. Of the models considered, BlastX (both the tabular and K-B forms) is the only one to calculate negative pressure and impulse.



(a) Reflected pressure and impulse. **(b) Incident pressure and impulse.**

Figure 1. BlastX models used to generate data.

Perhaps least amenable to the large charge at large distance scenario being studied was SHOCK, whose primary purpose is to calculate shock loads from internal explosions inside a cubicle with perhaps some of the side walls missing. To adapt it for our purposes, the following approaches were contrived:

- A charge weight of 1.0 lb was used throughout.
- The HOB was set to 0.01 ft.
- The size of the wall at which pressure and impulse are being measured was set at 1 ft square.
- Reflections were enabled only from the ground (floor); reflections from the two side walls and the ceiling were disabled. In this way, the near-ground exterior burst condition is mimicked.
- The peak pressure and impulse at a point near the ground and directly opposite the charge were extracted from the grid of outputs by the program.

Version 1.0 of the program (running as a DOS executable) was utilized. The program is limited to computing reflected positive pressures and impulses, hence only those outputs were available.

ENGINEERING MODEL RESULT COMPARISON

Our first set of graphs compares the results of the various engineering models and the K-B model against one another. Figure 2, 3, 4, and 5 show, respectively, the reflected positive, incident positive, reflected negative, and incident negative pressure and impulse. The plots for each metric reflect the models from which data were available. The most complete comparisons are for positive reflected values which all the models could calculate.

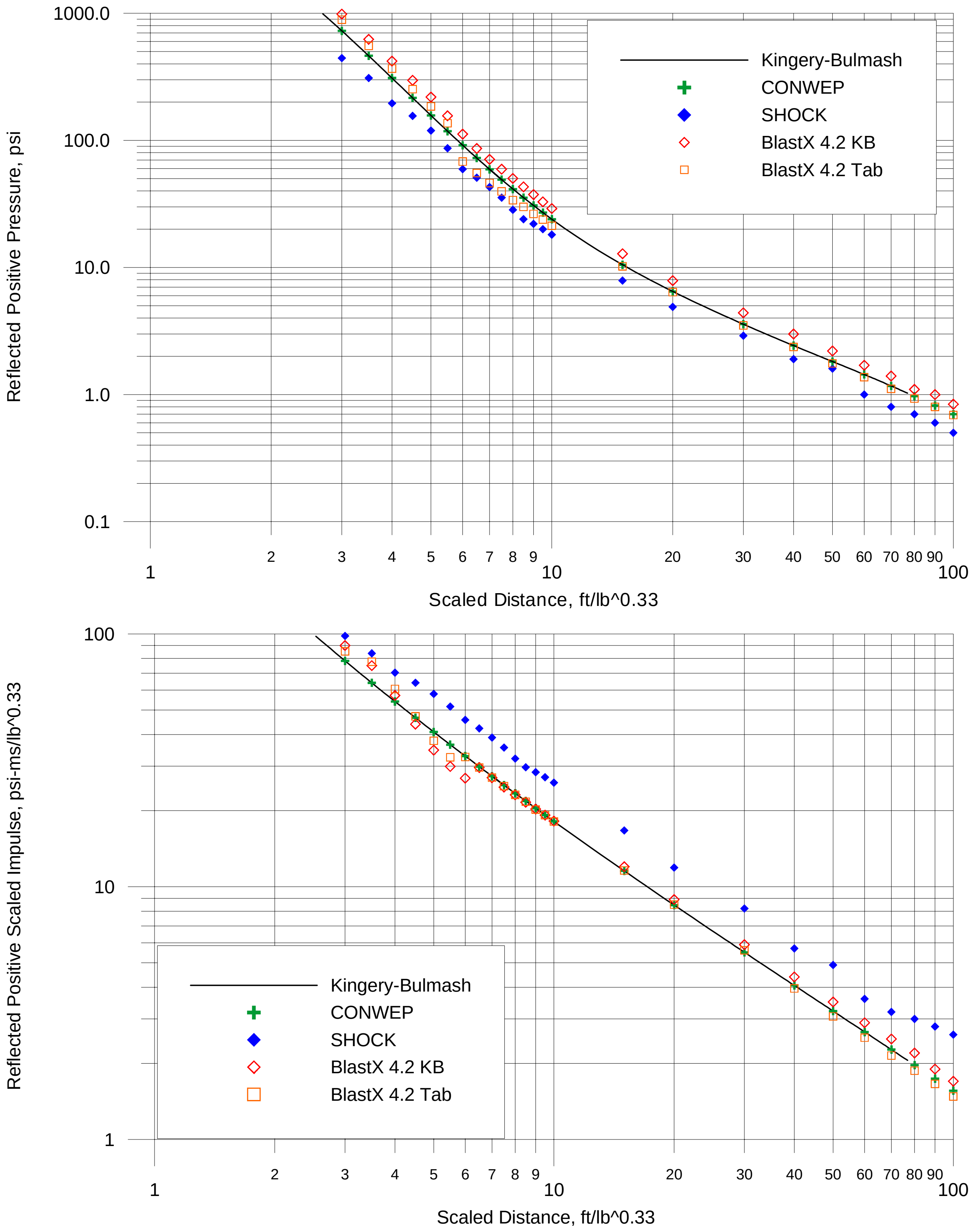


Figure 2. Reflected positive pressure and impulse comparison among models.

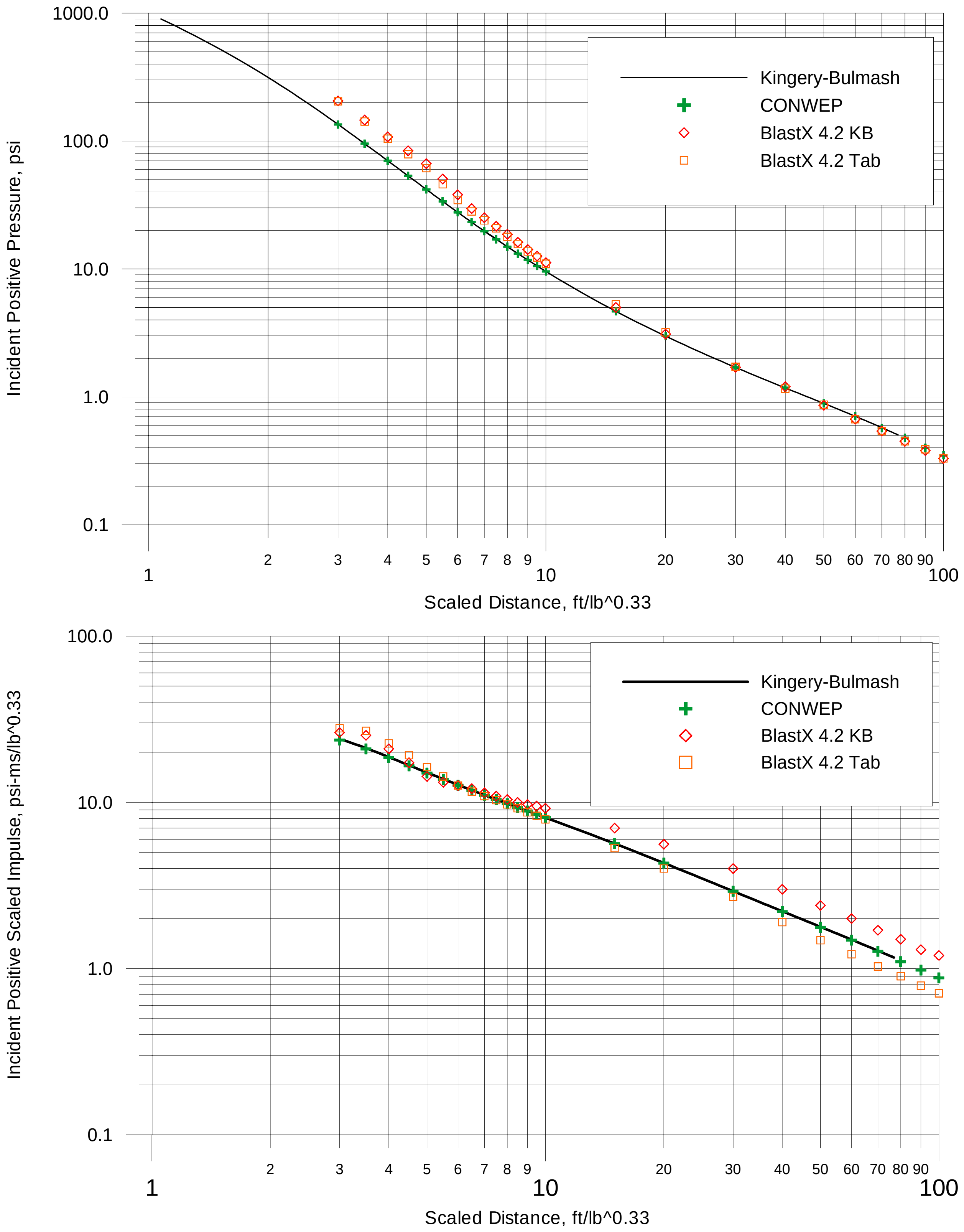


Figure 3. Incident positive pressure and impulse comparison among models.

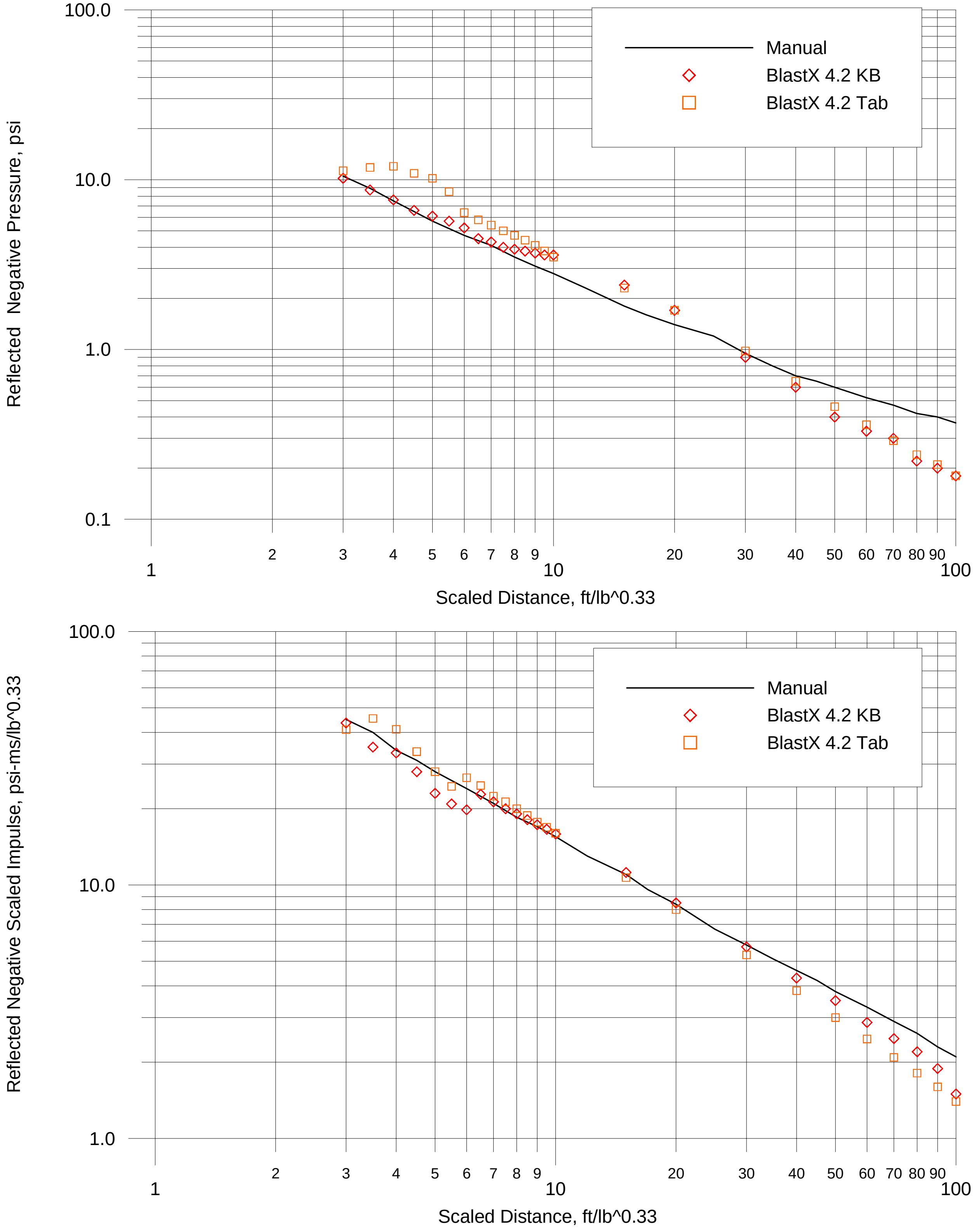


Figure 4. Reflected negative pressure and impulse comparison among models.

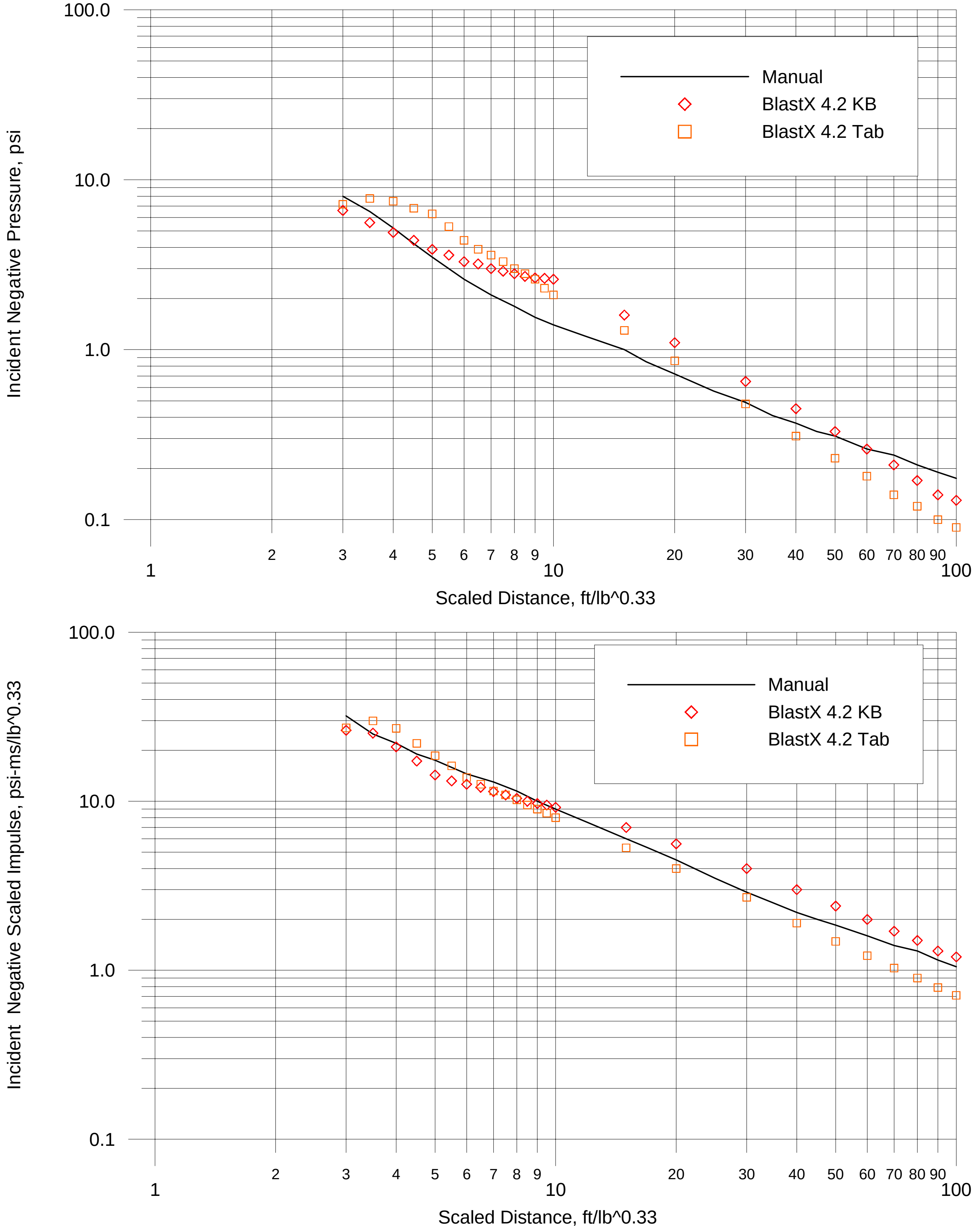


Figure 5. Incident negative pressure and impulse comparison among models.

As might have been expected, the different models do not predict loads with unanimity. In fact, the only pair of models that are numerically identical are ConWep and K-B, with regard to the positive pressures and impulses, both reflected and incident. We can therefore safely conclude that the ConWep implementation of the K-B model is accurate and verified.

SHOCK output for reflected positive metrics diverges significantly from K-B. In terms of pressure, SHOCK is consistently low by a factor of roughly 0.7 (i.e., 30% lower). On the other hand, with regard to impulse, SHOCK is consistently high by a factor of roughly 1.4 (i.e., 40% higher). Such a disparity is noteworthy, especially because it is present across the entire range of scaled standoffs under consideration.

The BlastX output is available for all eight metrics, both from the K-B as from its tabular model. In none of the eight metrics does the BlastX K-B result exactly match the actual K-B (or manual) data, presumably due to geometric effects in setting up the BlastX model. For example, all the reflected positive pressures are about 10-20% high; incident pressures are as much as 30% high for scaled ranges between 3 and 6 ft/lb$^{1/3}$, but the margin of overprediction diminishes with distance, and for ranges greater than 15 ft/lb$^{1/3}$ the comparison is almost perfect. Interestingly, this trend is reversed for the incident positive impulse: the BlastX tabular results are too high at the larger standoffs, but compare well at the smaller standoffs.

With regard to the negative metrics, the two BlastX-generated curves tend to cross one another and the manual curves at several points across the domain. Generally speaking for these negative metrics, the BlastX K-B results are higher than the BlastX tabular results for smaller standoffs, but the reverse holds at larger standoffs.

K-B MODEL VALIDATION AGAINST TEST DATA

To reach meaningful conclusions about the validity of any of these models, it is necessary to turn to experimental results. A large body of blast tests has been conducted in the past several decades, hence a statistically significant number of test results can be assembled for this purpose. The final test database comprised a total of 303 individual gage records, though these were then divided among the different metrics being considered (reflected vs. incident, etc.). Not all were of sufficient duration and/or quality as to be able to extract negative as well as positive values, and while some had dubious peak pressure readings, others became suspect at later time and therefore could not produce reliable impulses. Table 1 summarizes the distribution of the data points from the various test series considered. Data was obtained from published test reports [6–11], published reports that include analysis or representation of the test data [12, 13], other documentation issued by the testing agencies [14–21], or in one case, a test database included within a computer code [22].

The tests included comprise a wide range of configurations and conditions which, to a purist, would be difficult to consider as a unified data set. Some of the charges were cylindrical, others spherical, others hemispherical. Some of the charges were in contact with the ground, others at small heights of burst. Charge weights ranged from a few pounds to over a million. A variety of explosives were used, including TNT, C-4, and ANFO, each of which was converted to its TNT equivalence (using handbook values) before computing the scaling factors. The measurements of incident pressure were generally on the ground, but reflected pressures were measured on structures with a wide range of sizes: from small cubicles up to large four-story buildings. Also, for the larger buildings, gages were included which were approximately though not exactly perpendicular to the charge, which in turn introduces some additional variability in the results.

Table 1. Summary of blast test data points (number of individual measurements).

	Positive				**Negative**			
	Reflected		**Incident**		**Reflected**		**Incident**	
Test Series	**Pressure**	**Impulse**	**Pressure**	**Impulse**	**Pressure**	**Impulse**	**Pressure**	**Impulse**
Fabric Test 2	2	2	0	0	2	2	0	0
DIVINE BUFFALO 1, 4, 9, 19	40	39	15	15	39	38	15	15
Joist Tests 1-4	4	4	4	4	4	4	4	3
EMRTC CMU Tests	19	19	27	27	0	0	0	0
WINDAS Database	67	60	0	0	0	0	0	0
Swedish-Norwegian Tests	8	8	0	0	0	0	0	0
PRAIRIE FLAT	0	0	17	17	0	0	16	0
DICE THROW	0	0	40	36	0	0	0	0
SAIC Barrier Tests	5	6	5	2	5	3	2	0
WES CMU 1-5	25	25	0	0	25	25	0	0
DIVINE BUFFALO 21-24, 28, 29	20	20	0	0	20	20	0	0
Total	190	183	108	101	95	92	37	18

To include this many individual measurements in one study does necessitate the relaxation of strict guidelines regarding such parameters as the charge size, charge composition, angle of incidence, size of reflecting building, etc. However, this range of conditions is actually representative of a realistic design or assessment situation, since the typical project does not conform to the idealizations necessitated by these simplified models. Consequently, it is appropriate to take this somewhat heterogeneous data set and use it to draw conclusions regarding the accuracy and uncertainty in simplified blast model predictions, since it is precisely in such heterogeneous situations that those models are often applied.

Comparisons of the test data against K-B are presented in Figures 6, 7, 8, and 9 for the reflected positive, incident positive, reflected negative, and incident negative pressure and impulse, respectively. In these plots, different colors and marker types are used to represent each of the test series, in order to identify potential biases that might be present in any one of the data sets. The black line represents K-B or manual values in all eight graphs.

Figure 6 presents the positive reflected pressure and impulse data. The K-B model passes nicely through the center of the cloud of peak pressure data. It is also reassuring to note that there is no strong bias in any one of the data sets, suggesting that in fact the variability in charge composition, angle of incidence, etc. is insignificant compared to the random scatter in the measurements. In fact, considering any one of the data sets, we observe that the test data is sometimes above and sometimes below the K-B line, which further eliminates the possibility of some systematic bias.

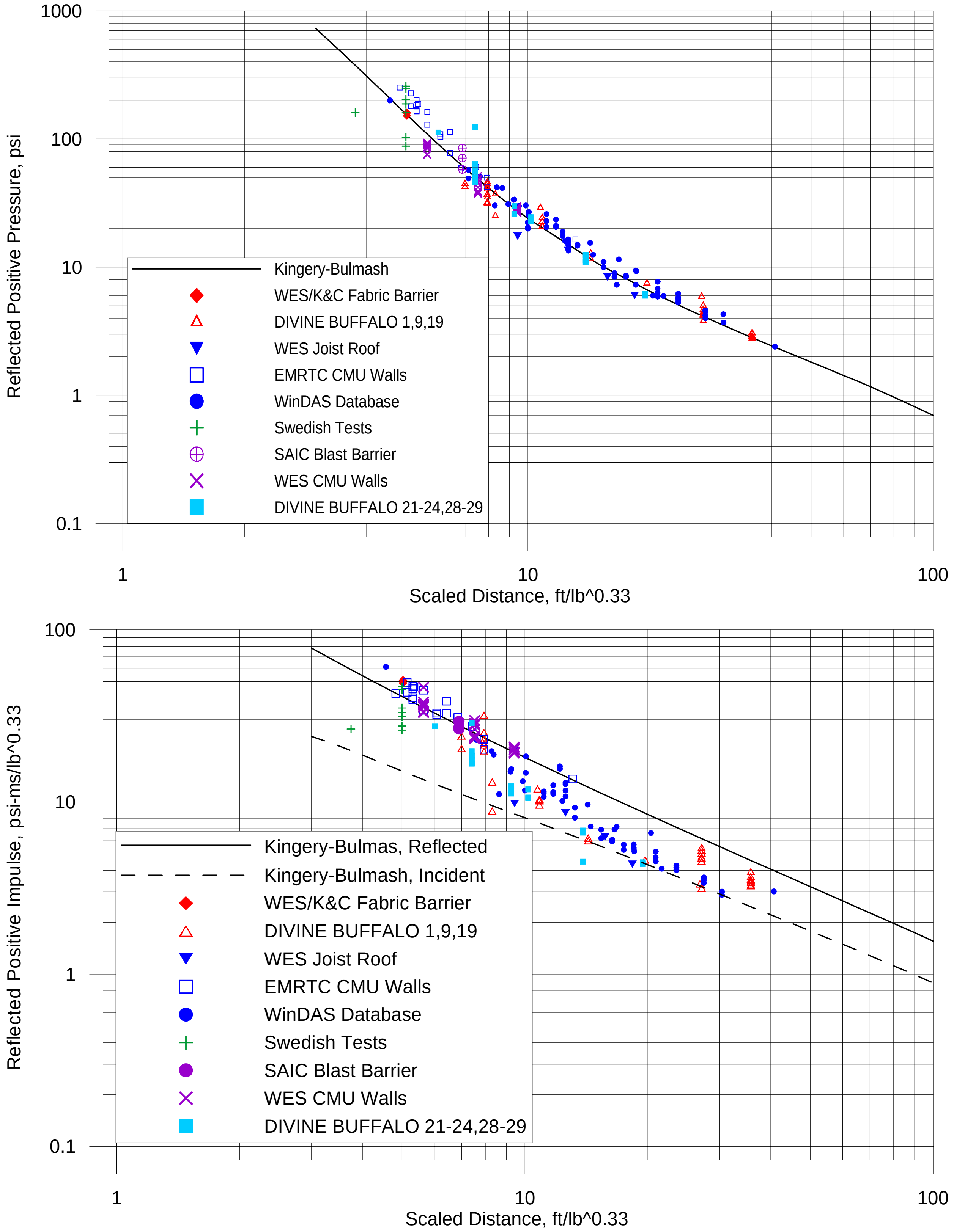


Figure 6. Reflected positive pressure and impulse test data comparison.

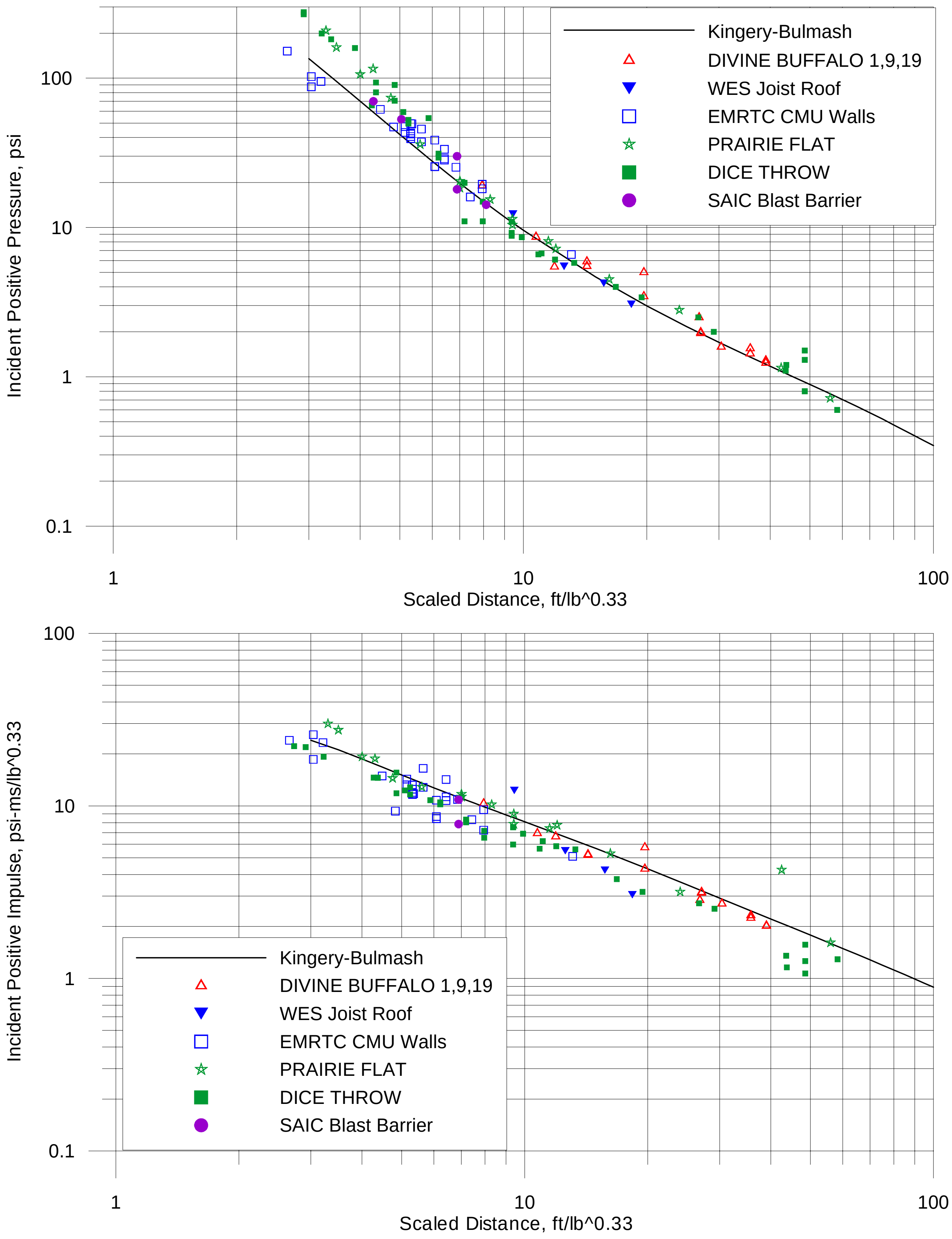


Figure 7. Incident positive pressure and impulse test data comparison.

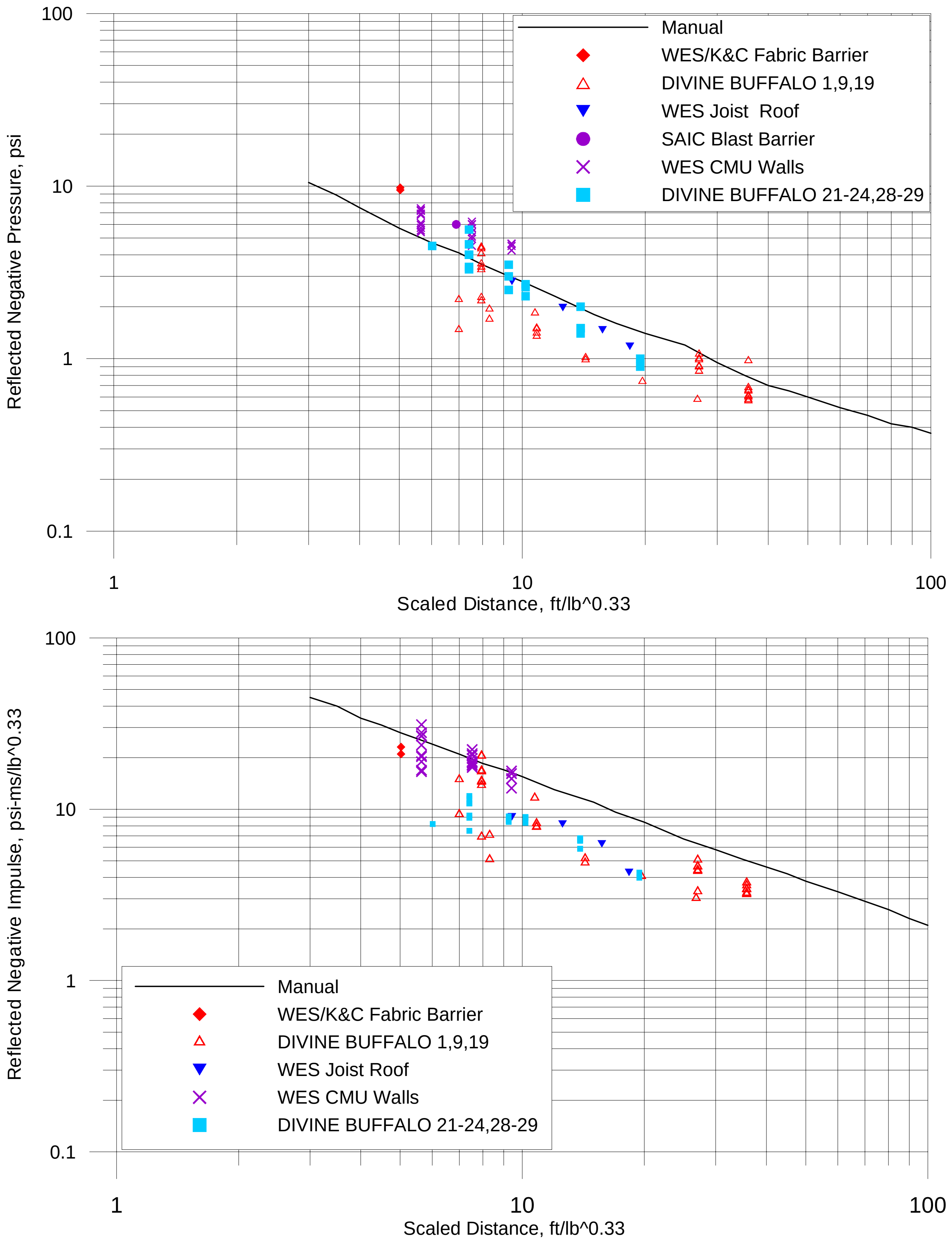


Figure 8. Reflected negative pressure and impulse test data comparison.

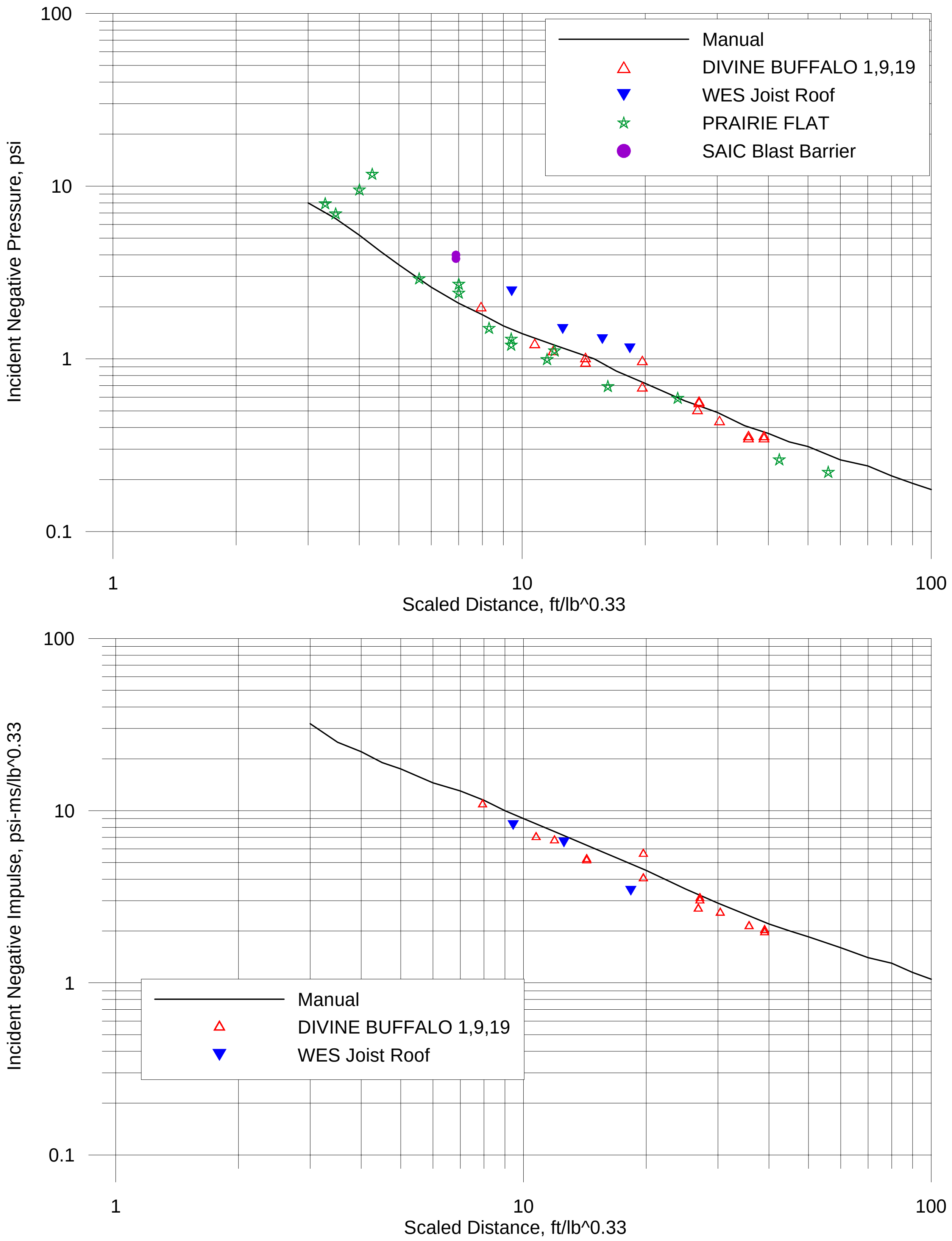


Figure 9. Incident negative pressure and impulse test data comparison.

But when it comes to positive reflected impulse, the test data lies significantly below the K-B line for standoffs above roughly 7 ft/lb$^{1/3}$. For reference, the K-B incident impulse is also shown in this graph (using a dashed line). As the standoff increases, the test data tends to diverge from the reflected line and approach the incident line.

Such a trend is consistent with the fact that, given a particular (and realistic) building size, as the standoff is increased, the pulse duration increases, and the effect of clearing from the edges becomes more pronounced. At small standoffs, by the time clearing effects arrive, the pulse is virtually over, and the effect on impulse is unnoticed.

In the reflected impulse as the reflected pressure data, there is no apparent trend or bias in any one of the data sets.

We turn next to the incident positive pressure and impulse data in Figure 7. With regard to the pressures, here we note that K-B is adequate at larger standoffs, but at smaller standoffs it significantly underpredicts the test data. And the data at these smaller standoffs come from a number of different test series, so that it cannot simply be explained as an anomaly in a particular data set. With regard to impulse, however, K-B overpredicts by a more or less consistent margin over the entire range of standoffs considered.

Negative phase loads, presented in Figures 8 and 9, are typically of less significance to engineers and shall only be dealt with herein in cursory fashion. In general, K-B predicts the results reasonably well, except for the reflected impulse which is significantly overpredicted. The spread in the data appears somewhat larger, but to a great extent that is an artifact of the scaling used for the ordinate of the plots for the negative phase metrics. The different data sets seem to overlie one another quite well, and there is no clear indication of a systematic bias in any one data set.

ALL MODELS COMPARED TO TEST RESULTS

For the two most important metrics, reflected positive reflected pressure and reflected positive impulse, it is helpful to plot the results of all the engineering models against the test data, this time without discriminating the different test series. In these plots, shown in Figure 10, we may use the ConWep results to also indicate K-B, since earlier comparisons already verified that ConWep accurately reproduces K-B.

Considering the pressure, it is evident that ConWep (or K-B) provides the overall best representation of the data over the range of standoffs. SHOCK is clearly a lower bound prediction with the vast majority of the test data lying above the curve. On the other hand, the BlastX K-B model clearly bounds the data on the upper side. BlastX tabular results are reasonably close to ConWep and form a good middle range prediction. It is curious that, around 6 ft/lb$^{1/3}$, the tabular BlastX curve steps up from below ConWep to above Conwep. This is likely due to some more complex physical phenomenon that BlastX is representing. Nevertheless, over the range of standoffs considered, the overall best fit lies with ConWep.

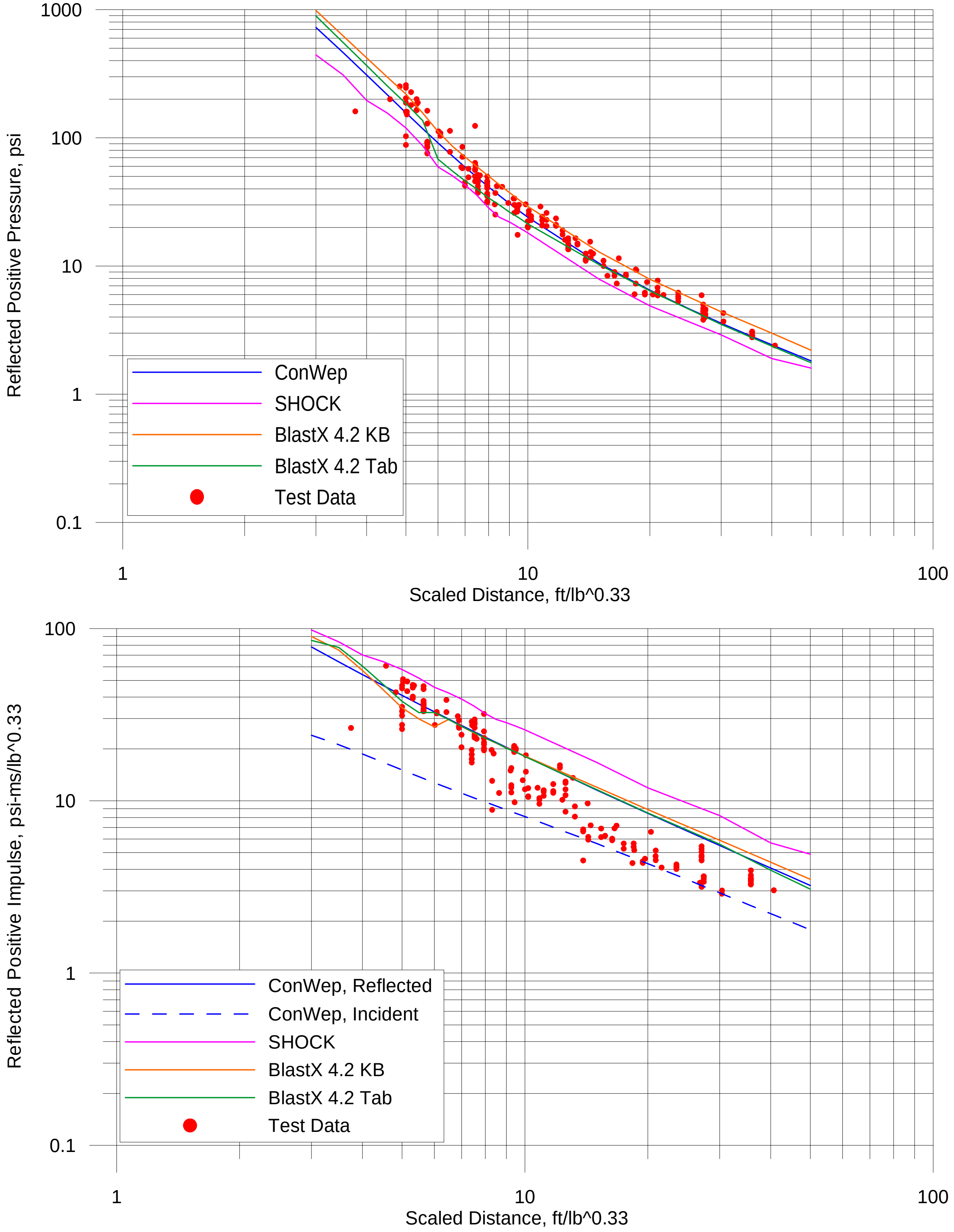


Figure 10. Reflected positive pressure and impulse test data compared to various models.

Turning next to the impulses, we see SHOCK as the clear upper bound; in fact not one single test point lies above the SHOCK curve. Both BlastX models produce data that is very closely comparable to ConWep, except for standoffs less than 6 ft/lb$^{1/3}$. The main feature in the data is the gradual drift from the reflected to the incident impulse curve as the standoff is increased, and this effect overwhelms any minor differences between the two models. So overall, aside from SHOCK, the remaining models fit the data well, provided one is able to account for clearing effects at the larger standoffs.

BIAS AND UNCERTAINTY ESTIMATES

Our final task is to estimate the uncertainty in the test data, and also any bias that is evident in the engineering models. Since, of all the models considered, the K-B model fits the test data most consistently and over the broadest range of metrics, the calculations are limited to that model, or more precisely, the ConWep results which reproduce K-B. For the negative metrics where ConWep results are unavailable, the manual curves were utilized.

For each load metric where this approach is feasible, the approach utilized was to calculate the ratio between the value measured in the test and that predicted by ConWep. Thus, a large number of test-to-ConWep ratio values are computed for each metric since a large number of test points are available. Next, using standard statistical functions, the mean and standard deviation of these ratios was computed. The mean (or best estimate) value gives us an indication of the bias, if any, in ConWep. A mean of 1.0 says that ConWep, on average, predicts the test results down the middle (i.e., overpredicts as much as it underpredicts). A best estimate less than 1.0 implies that the ConWep values are too high and need to be brought down by that value to better match the tests; a value above 1.0 implies that ConWep is too low and needs to be raised overall.

The sigma values are an indication of the spread in the data about this best estimate. The larger sigma, the greater the spread and the uncertainty. Since two-sigma represents approximately 95% of a normal distribution, it is helpful to consider the two-sigma values. Using the best estimate value to adjust ConWep, the upper and lower bounds can be generated as follows:

$$p_{upper} = p_{conwep} (M + 2\sigma)$$

$$p_{lower} = p_{conwep} (M - 2\sigma)$$

where M is the mean (or best estimate) value, σ is the standard deviation, and p_{conwep} is the pressure calculated by ConWep. Impulse can also be substituted for pressure in the above formulation.

An overview of the mean and sigma values computed is provided in Table 2. This analysis was not performed for the reflected impulses (positive and negative), as the earlier analyses had shown a significant systematic effect due to clearing effects. Analysis of this kind would result in a best estimate significantly lower than 1.0, yet which did not appropriately reflect on the accuracy with which the model predicted reality. Also, the number of data points for the incident negative impulse were insufficient to consider statistically; thus the only impulse considered was the incident positive impulse. Of the pressures, all the metrics had sufficient data points except the incident negative pressure which was omitted.

Table 2. Summary of statistical measures for (test/ConWep) ratios.

	Results of Statistical Analysis		Recommended Factor for Application to ConWep Results		
Metric	**Mean**	**Two-sigma**	**Lower bound**	**Best estimate**	**Upper bound**
Reflected positive pressure	1.06	0.48	0.7	1.0	1.5
Incident positive pressure	1.19	0.66	0.6	1.2	1.9
Incident positive impulse	0.86	0.36	0.5	0.85	1.2
Reflected negative pressure	1.03	0.68	0.4	1.0	1.7

The statistical measures indicate that the bias in ConWep was in no case greater than 20%, which essentially validates ConWep since the two-sigma uncertainty in the data is always greater than that. The data indicates that to get a good representation of the test data, ConWep results should be essentially taken as-is for reflected positive and negative pressure; for incident positive pressure, they should be increased by 20%, while for incident positive impulse, they should be reduced by 15%.

A set of graphs presents the (test/ConWep) ratios, along with the best estimate and the bounds, as a function of standoff. Figures 11-14 also plot the resulting best-estimate curves (after adjusting ConWep by the mean value) and the bounding curves.

We first consider the reflected positive pressure data (Figure 11). Here the adjustment for the best estimate is very minor and can be considered negligible. The curves for the upper and lower bounds do reasonably bound the data, with only a very few outliers on either side. Since the two-sigma value is 0.48, the bounds are roughly at 0.7 and 1.5 times the ConWep result. These bounds seem small visually due to the compression afforded by the logarithmic scale, but in terms of numeric magnitude they are quite significant. To put it differently, if ConWep predicts a value of 10 psi for a particular charge weight-standoff combination, the actual value could be anywhere from 7 to 15 psi.

Turning to the incident positive pressure (Figure 12), the bias here is somewhat visible, requiring a nearly 20% adjustment upward to properly represent the test data. Here the two-sigma bounds are even broader, roughly 1.9 and 0.6, indicating greater uncertainty. Following our example above, a ConWep prediction of 10 psi incident pressure would result in a best estimate of 12 psi, an upper bound of 19 psi and a lower bound of 6 psi.

For incident positive impulse (Figure 13), the bias is in the opposite direction, and ConWep results need to be adjusted downward by 15%. The two-sigma bounds, however, are considerably smaller, 0.5 and 1.2. Of the metrics considered, this one provided the tightest bounds, which one might expect considering that impulse is taken as an integral over time which tends to smooth out local anomalies in the measurements. For a ConWep prediction of 10 psi-ms of impulse, our best estimate would be 8.5 psi-ms, the lower bound would be 5 psi-ms, and the upper bound 12 psi-ms.

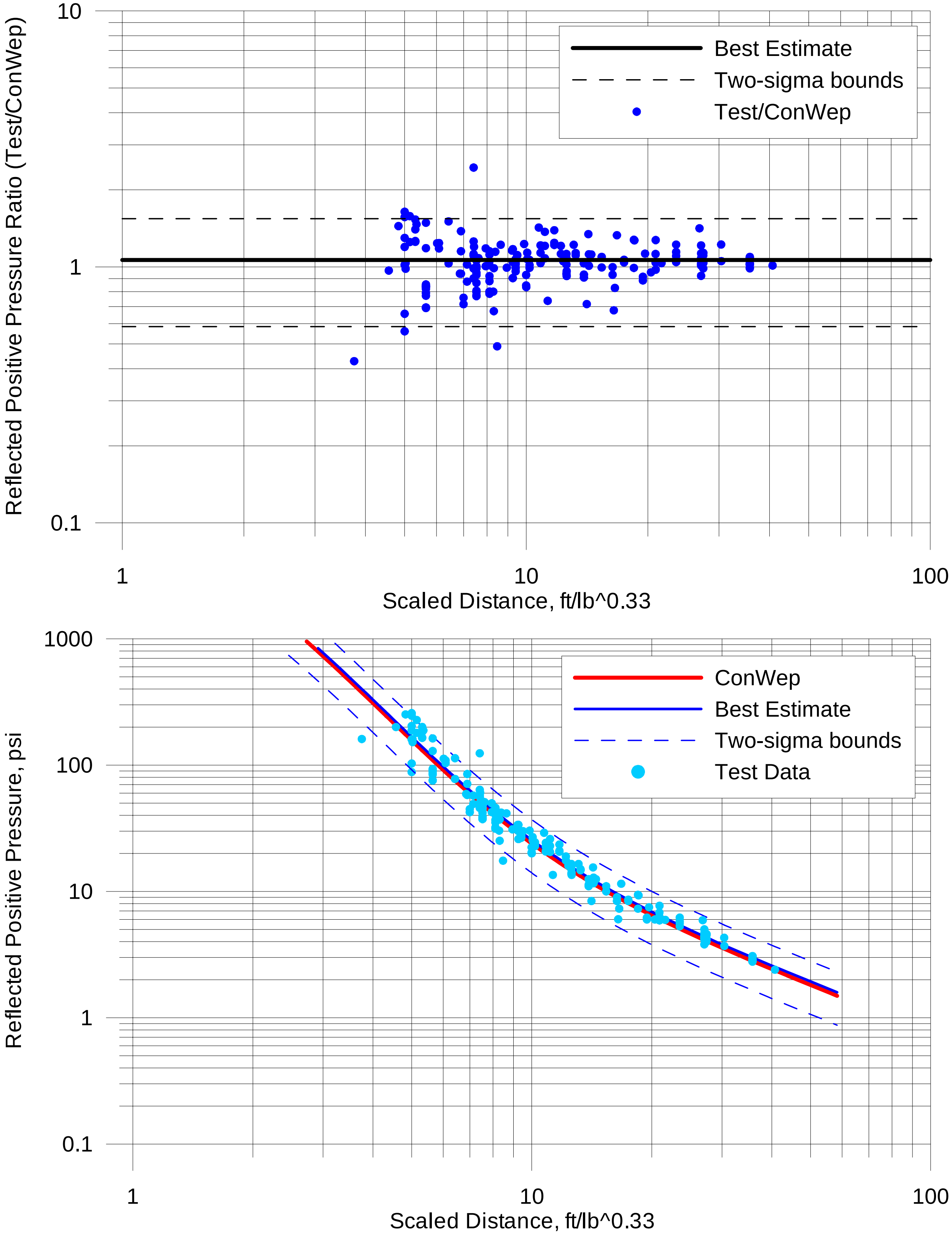


Figure 11. Uncertainty analysis results for reflected positive pressure.

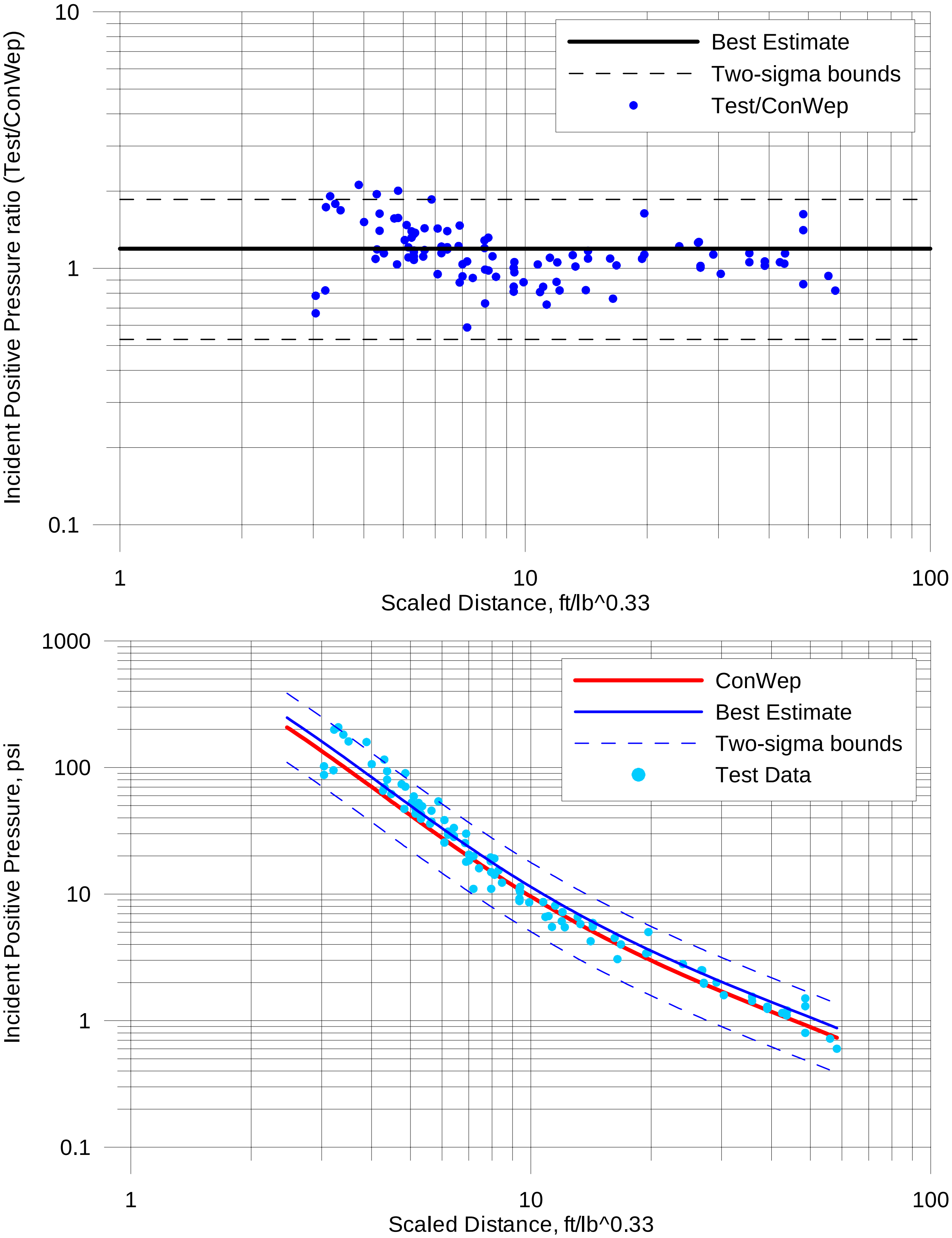


Figure 12. Uncertainty analysis results for incident positive pressure.

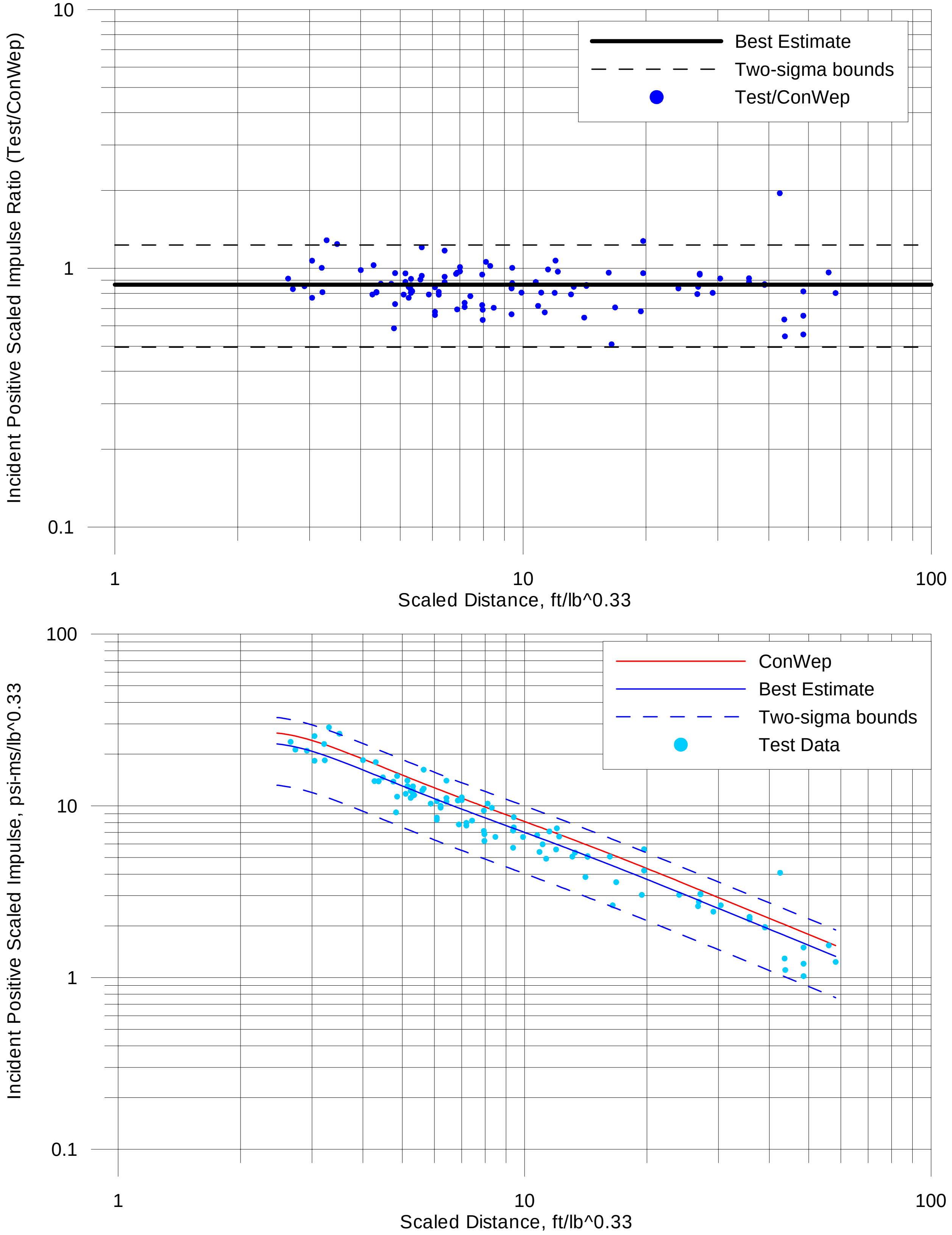


Figure 13. Uncertainty analysis results for incident positive impulse.

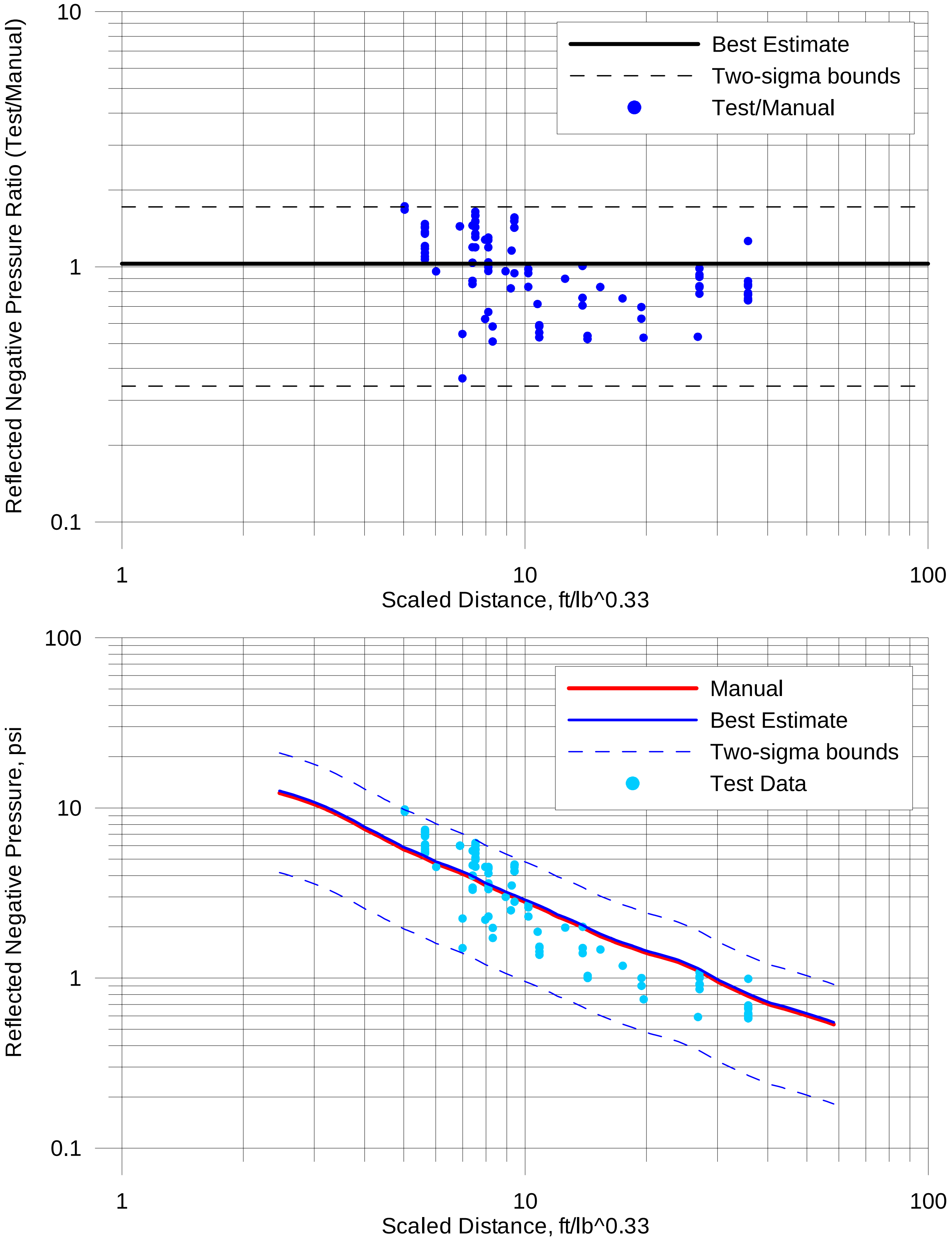


Figure 14. Uncertainty analysis results for reflected negative pressure.

Finally, the reflected negative pressure (Figure 14) requires no adjustment for its best estimate. The uncertainty, however, is quite large, as reflected in the two-sigma bounds. Thus factors of 0.4 and 1.7 must be applied to the manual curve data to approximate the range of variability seen in the test data.

The values of factors for best estimates and upper and lower bounds discussed above are summarized in Table 2 for ready reference. Note that these values, while based on the statistical analysis, are also tempered somewhat by engineering judgment and the desire for simplicity.

It is also interesting to consider that, in all four metrics, there is no clear evidence of a trend towards greater or lesser uncertainty as the standoff is increased or decreased. In some cases (e.g., Figure 11), there seems to be somewhat more scatter at the smaller standoffs than at the larger ones. However, this may also be due to the larger number of data points present in that regime. Hence, it is reasonable to suggest that the uncertainty bounds recommended above be used throughout the range of standoffs under consideration.

Although quantitative measures of uncertainty on reflected impulse could not be computed for the reasons noted above, a qualitative comparison of the scatter in the data between Figures 6 and 7 (reflected and incident impulse, respectively) suggests that the bounds for reflected impulse would be even broader than those for incident impulse. That would be expected since the distance from the gage to the free edge of the building would be an additional factor in the measurement. Since the incident positive impulse was computed to have a two-sigma value of 0.36, one might expect two-sigma values of roughly 0.5 or more for the reflected positive impulse.

CONCLUSIONS

The chief conclusions reached in this study are summarized below. As with all the results of this study, they are limited to scaled standoffs of 3 to 100 ft/lb$^{1/3}$.

- ConWep accurately reproduces the K-B model for all positive phase metrics.
- Of the models tested and with regard to the experimental results considered, ConWep (and manual curves for negative phase metrics) best represent the test data in an overall sense.
- For reflected impulse, consideration of clearing effects is essential for standoffs greater than 7 ft/lb$^{1/3}$. If detailed calculations cannot be performed, a simplistic approach would be to gradually transition from the reflected positive impulse (at 7 ft/lb$^{1/3}$) to the incident poisitive impulse (at 20 ft/lb$^{1/3}$) for typical building sizes and measurement locations.
- SHOCK significantly and consistently underpredicts reflected positive pressure and overpredicts reflected positive impulse. These results should only be used as lower and upper bounds, respectively.
- BlastX tabular results are in better agreement with ConWep (and the test data) than BlastX K-B results for positive reflected pressure and impulse, but both are reasonably close to the data.

- Statistical bias in the ConWep results compared to test data has been computed and does not exceed 20%. Specific recommended values are listed in Table 2 (on page 18).

- Statistical uncertainties in the test data have been computed and are listed in Table 2 (p. 18). The normalized two-sigma values are of significant magnitude, ranging from 1/3 to 2/3 and indicating a very wide range of uncertainty in the predicted blast metrics.

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DISCLAIMER

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