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TNT EQUIVALENCE OF C-4 AND PE4: A REVIEW OF TRADITIONAL SOURCES AND RECENT DATA

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ABSTRACT

Since standard engineering-level blast models are typically developed to predict airblast parameters (pressure and impulse) from TNT bursts, prediction of airblast from other materials uses an equivalence factor by which an equivalent TNT weight is computed and used in the source term of the model. This approach is widespread in the industry and has been codified in numerous manuals, books, and papers.

A recent effort co-sponsored by TSWG (U.S.) and FSTD (Singapore) collected and compiled equivalence data for a wide variety of explosive materials (both military grade as well as home-made) into a single software tool named STREET. The database thus assembled provides a comprehensive and expandable repository for equivalence data. Two of the main achievements in STREET are the consideration of equivalence as a function of scaled standoff (rather than a scalar), and the documentation of uncertainty in the estimated value.

In this paper, we consider specifically the manual- and test-derived data related to Composition C-4, and as a first step, we draw some judgments regarding the equivalence implicit in blast curves provided by UFC 3-340-02, for both pressure and impulse.

Next, we consider PE4, which is similar in composition to C-4 and is used widely in the UK. A significant body of blast data for this explosive has been generated, from which equivalence is computed and is compared to the available data for C-4, with a view towards determining whether these two materials can in fact be considered as a single explosive (with two alternate names).

Finally, considering the combined data for both C-4 and PE4, new curve fits are provided that represent the pressure and impulse equivalence of the C-4/PE4 material (and its uncertainty) as a function of scaled standoff.

INTRODUCTION

Of all explosive materials, trinitrotoluene (TNT) remains the single most well-characterized explosive with regard to its airblast parameters such as time of arrival, peak pressure, and impulse. In particular, the Kingery-Bulmash model [1] has been widely accepted as providing reliable airblast metrics as a function of scaled standoff, and the corresponding curves have been adopted in numerous publications including government manuals for explosive safety design [2] and design of hardened structures [3]. Calculating blast loads from a TNT explosion, whether a spherical burst in free air or a hemispherical charge at ground surface, can thus be easily accomplished with these curves. Additionally, the uncertainty in the model has been well characterized with reference to a large body of experimental data, data not available at the time of the original model's derivation [4].

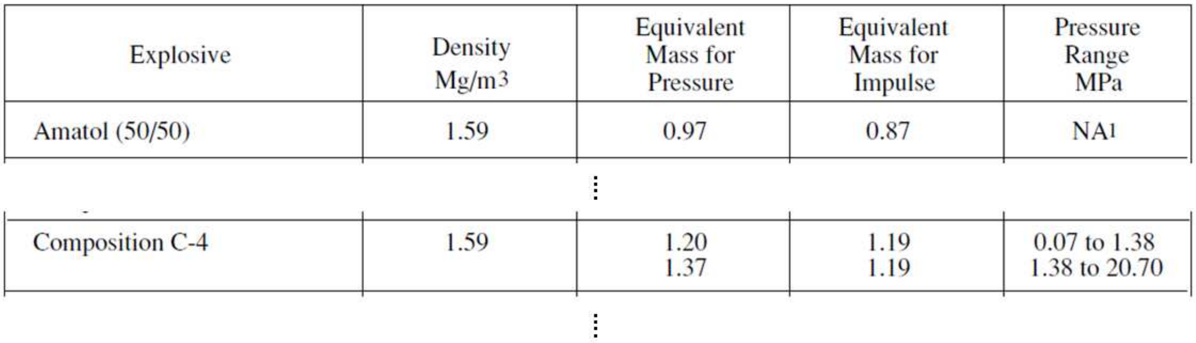
To predict the effects of an explosive other than TNT, recourse is generally made to the concept of an equivalence factor, a factor which, when multiplied by the weight of the explosive of interest, converts its weight to an equivalent TNT weight. When the equivalent TNT weight is used in the engineering models, a reasonable approximation of the airblast from the subject explosive can be obtained. In equation form, then:

$$W_{eq\text{-}TNT} = K\, W_{mat} \tag{1}$$

where W_{mat} is the weight of the material, K is the equivalence factor, and $W_{eq\text{-}TNT}$ is the equivalent TNT weight.

In most practical contexts, the selection of K for a particular explosive proceeds to tables found in common references. For example, the DAHS Manual [3] provides a table listing the equivalence of 50 different materials, most of them military grade explosives; a portion of this table is reproduced in Table **1**. Different equivalence values are provided for pressure than for impulse, and these are typically given as scalars. In a few instances (such as C-4 in our extract), two different domains are defined in terms of pressure (or its analog, scaled standoff) with the equivalence essentially exhibiting a step function from one to the other.

Table 1: Sample equivalence factors from DAHS Manual [3] (extract).



Explosive	Density Mg/m^3	Equivalent Mass for Pressure	Equivalent Mass for Impulse	Pressure Range MPa
Amatol (50/50)	1.59	0.97	0.87	NA[1]
		⋮		
Composition C-4	1.59	1.20 1.37	1.19 1.19	0.07 to 1.38 1.38 to 20.70
		⋮		

In recent work jointly sponsored by the U.S. Department of Defense (TSWG) and Singapore Ministry of Defence, a new code has been developed which incorporates a wide range of both manual data (as above) as well as experimental data on the explosive equivalence of nearly 200 different materials, including not only military grade explosives but also homemade explosives (HMEs). The Scenario- and Target-Relevant Explosive Equivalence Tool (STREET) [5] improves on the prior status quo of equivalence in three important ways:

- It provides equivalence as a function of scaled standoff, rather than a scalar, by fitting numerical functions to the available data.
- It provides uncertainty in the equivalence, due to both measurement uncertainty as well as fitting uncertainty.
- It gathers, under a common umbrella, data from both tests and published references related to the equivalence of hundreds of military and home-made explosives.

The third bullet cited above, in particular, allows comparison between equivalence data from various sources that would have been difficult previously. Taking advantage of this convenience, this paper seeks to re-evaluate the data for one explosive in particular, Composition C-4, and draw some conclusions regarding the validity of data from one traditional and well-regarded source. Following that discussion, we consider a new source of data (new even to STREET) using the material PE4 which is a variant of C-4 and draw conclusions as to whether those two materials can in fact be treated as a single material. Finally, we provide recommended equivalence curves for C-4/PE4 to be used in future applications.

UFC 3-340-02 EQUIVALENCE FOR C-4

Within the STREET database, C-4 equivalence data is available from two manuals (UFC 3-340-01 as shown earlier in Table **1**, and a 1975 publication by Swisdak [6]). On the experimental side, two papers [7][8] provide test data, one of which (Veldman) has both pressure and impulse while the other (Nansteel) only documents impulse equivalence; the D-BREIE III study [9] is the other source of experimental data. The resulting plots are shown in Figure **1** and Figure **2** for pressure and impulse, respectively. The step function from the DAHS manual is clearly seen in Figure **1**, while for impulse the value is flat. The Swisdak data for pressure is relatively smooth and shows a pronounced decrease with increasing standoff, but although shifted to the right, it is close in value to the data from DAHS. For impulse, Swisdak indicates a sine wave–like shape that defies explanation; the average of that curve, however, agrees quite well with DAHS.

The test data is far more scattered than the manual data, as one might expect. The Veldman data for pressure roughly agrees with the DAHS value at close standoffs, but the D-BREIE data spans a much larger range of standoffs and is quite scattered. Broadly speaking, though, its values are only slightly higher than the DAHS value, if one excludes the apparent outlier at about 2.5. In the impulse plot, the Nansteel data is very internally consistent and also in excellent agreement with DAHS, particularly considering its very small standoff. The Veldman impulse data is somewhat lower than DAHS, as is D-BREIE III overall. Generally speaking, considering all the data together, both plots are suggestive of an essentially flat-line relationship between equivalence and standoff; in other words, they suggest a scalar relationship that is not markedly dependent on standoff.

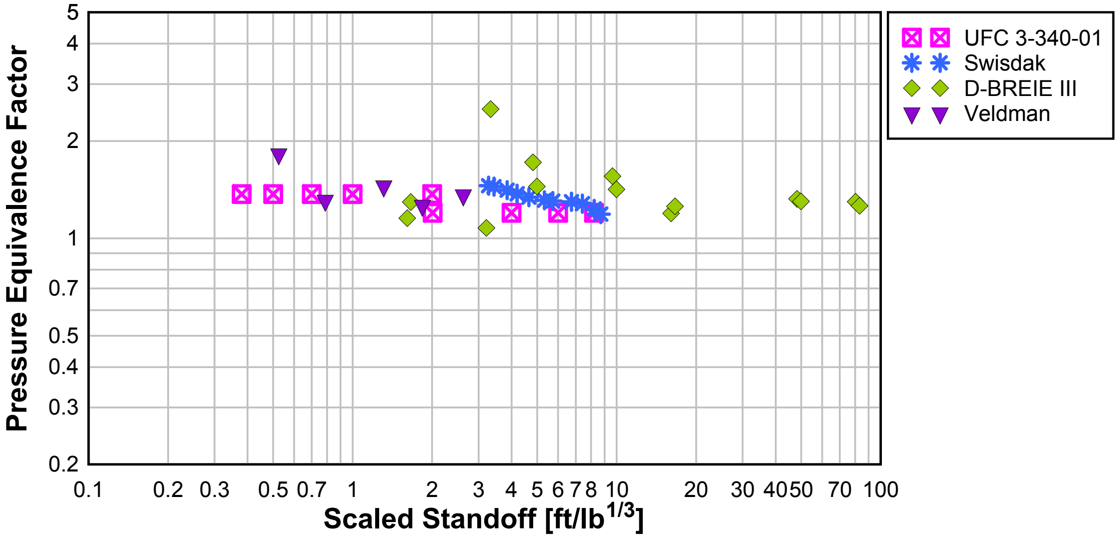


Figure 1: Pressure equivalence data for C-4 in STREET.

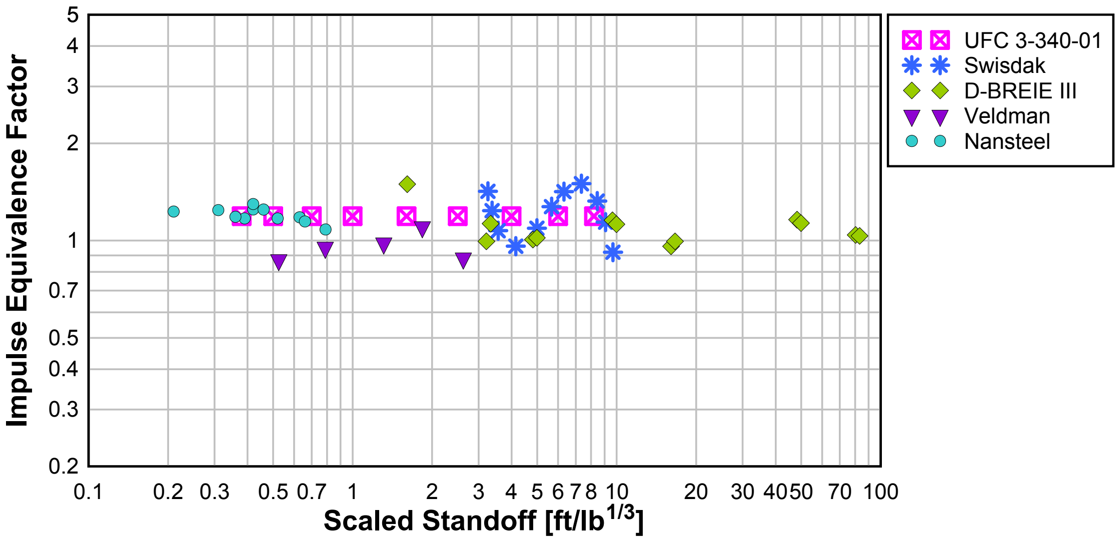


Figure 2: Impulse equivalence data for C-4 in STREET.

We turn now to UFC 3-340-02, whose approach to calculating blast from non-TNT charges differs markedly from all the sources cited earlier. Rather than providing a table of equivalence factors for converting the explosive to TNT, UFC 3-340-02 provides curves of pressure and impulse as a function of scaled standoff, such as the example shown in Figure **3** for C-4. Note from the graph heading in that figure that the curve applies to an orthorhombic (i.e., brick-shaped) charge with aspect ratio of 1.6:1:1.3, which is to say roughly cubic.

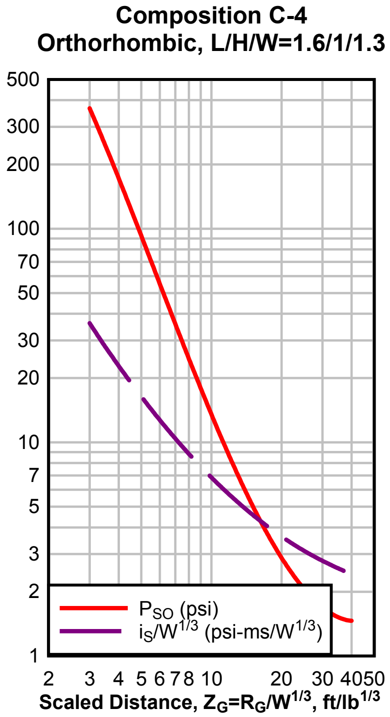


Figure 3: Pressure and impulse from a C-4 charge, from [2].

We note that the curves in Figure **3** are exactly analogous to those of Kingery-Bulmash for TNT. Thus, one can directly get pressure and impulse for C-4 without the need to obtain an equivalence, convert the C-4 to TNT, and then use the TNT curves for the appropriate scaled standoff. Nevertheless, the existence of these C-4 curves implies an equivalence between the two, and the implicit equivalence can be calculated as demonstrated in Figure **4**.

First, we plot the pressure and scaled impulse curves for the two materials (TNT and C-4) against one another. For pressure, we note that the C-4 curve is consistently higher than that for TNT (except for a small portion around 15-25 ft/lb$^{1/3}$). This indicates that over most of the domain, C-4 will have a pressure equivalence greater than 1.0 (i.e., it produces a higher pressure for the same charge weight and standoff). For impulse, however, the situation is somewhat reversed, as C-4 underperforms TNT over most of the domain and is going to have an equivalence lower than 1.0.

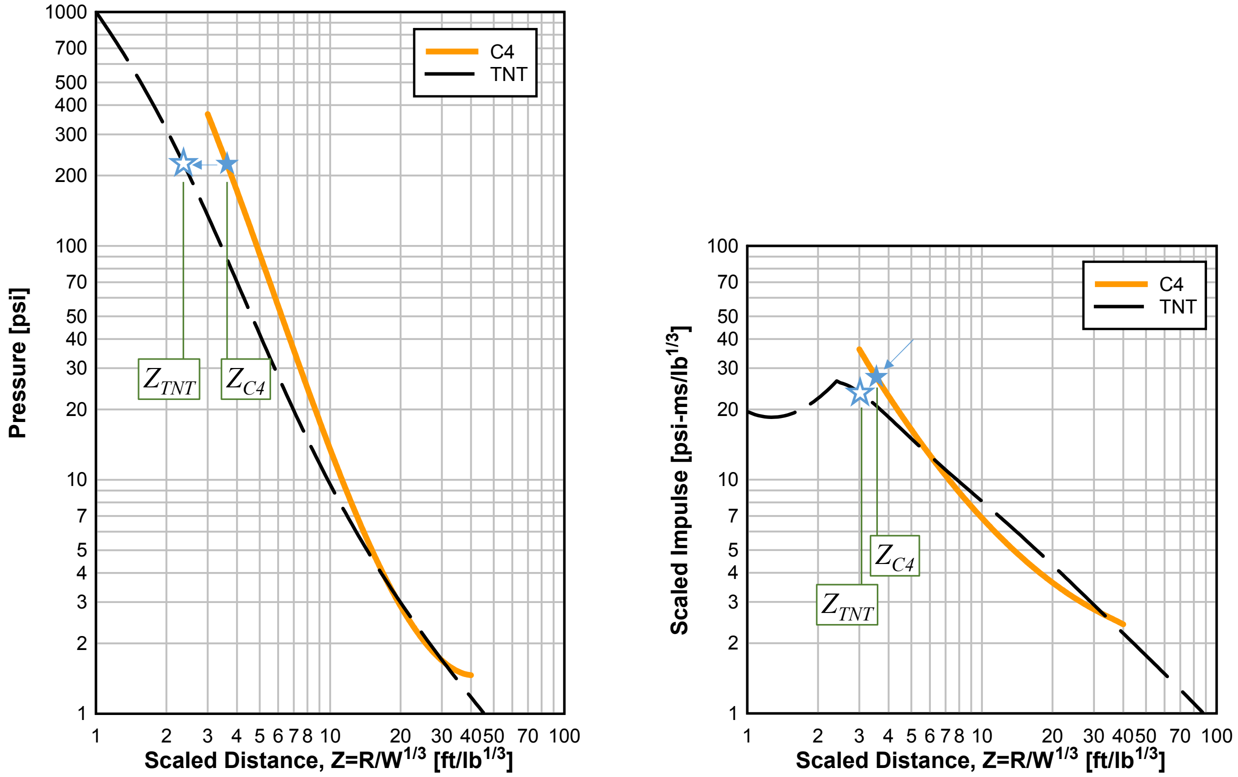


Figure 4: Calculation of equivalent scaled standoffs for C-4 relative to TNT.

It may be demonstrated, from the definition of equivalence, that the equivalence factor is simply:

$$K = \left(\frac{Z_{C4}}{Z_{TNT}} \right)^3 \tag{2}$$

For peak pressure, the values of the two standoffs are easily obtained by taking a horizontal line at constant pressure and determining where that line intersects the two curves, as shown graphically in Figure **4**. For impulse, since the value provided is the scaled impulse, the line is not horizontal but angled at 45° so that both impulse and standoff are scaled by the same amount as the shift is made. Taking these values across the spectrum of scaled standoff, we can obtain curves of equivalence vs. scaled standoff, which can then be plotted against the available data from the sources shown earlier.[1]

These plots are shown in Figure **5** for pressure, and in Figure **6** for impulse. In both cases, the UFC curve seems to diverge drastically from all of the remaining data, not only in terms of magnitude but also in its basic shape. The curves indicate an equivalence that is highest at the two ends of the domain but lowest in the middle (around 25 ft/lb$^{1/3}$ for pressure, or 15 ft/lb$^{1/3}$ for impulse); this sort of behavior is not easily explained in physical terms. Additionally, the curves

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[1] Note that to perform this transformation, the Kingery-Bulmash curves for a hemisphere at ground surface were utilized. Clearly the C-4 curves in UFC 3-340-02 are applicable to a brick rather than to a hemisphere, however the aspect ratio of the brick is not far from that of a hemisphere (2:2:1) and at distances greater than a few scaled feet, one would not expect the charge ^{shape} to be of any significance.

reach very high values (as much as 4 in the case of pressure) that are not entirely credible. One might suppose that these relationships were chosen out of a desire for conservatism.[2] However, using the UFC's curves would lead to significant *non-conservatism* if one's problem was in the regime of 15–25 ft/lb$^{1/3}$.

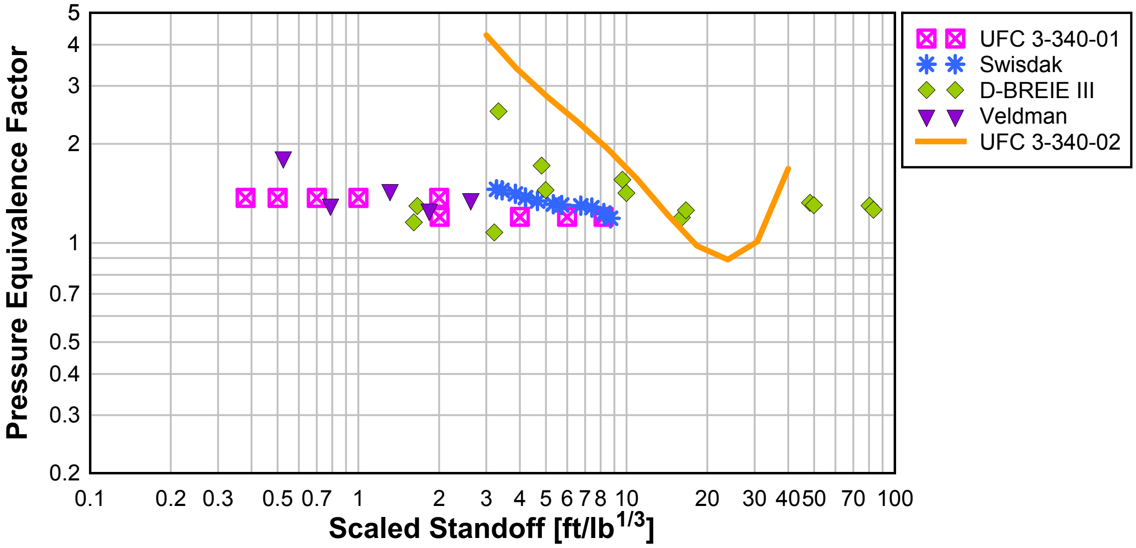

Figure 5: Pressure equivalence from UFC 3-340-02 compared to other sources.

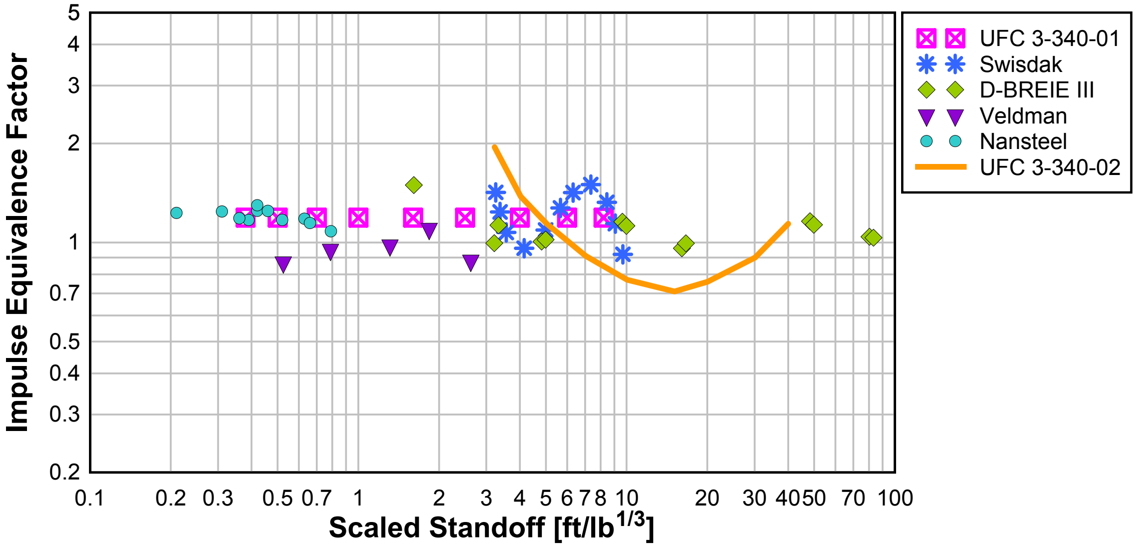

Figure 6: Impulse equivalence from UFC 3-340-02 compared to other sources.

In our judgment, this comparison indicates that the UFC 3-340-02 pressure and impulse curves should only be used—if they are used at all—with extreme caution, as they produce airblast parameters that disagree quite visibly from the community's consensus on the equivalence of C-4. Perhaps the curves could be used in the very limited case of a brick with aspect 1.6:1:1.3, but even then, the dip observed in the middle range of the curves would seem counter-intuitive.

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[2] UFC 3-340-02 is well known for its overall conservatism in such areas as response criteria.

With regard to STREET, the curve fits provided for C-4 were re-calculated after excluding the UFC 3-340-02 data, which had a modest effect on the median curve but had a very pronounced effect in reducing the fitting uncertainties.

PE4 BLAST DATA AND EQUIVALENCE

We turn next to a consideration of PE4 as an explosive material similar to C-4. Like C-4, PE4 is composed of RDX mixed with a plasticizer, but the proportion of RDX may vary slightly (91% in C-4, 88% in PE4) as would the plasticizing compound. In most descriptions, PE4 is stated to be "nearly identical" or "very similar" to C-4 in its explosive properties. An earlier study using numerical simulations of TNT charges to replicate experimental measurements from PE4 charges [10] concluded that an equivalence of about 1.2 is appropriate for both pressure and impulse, a value fully consistent with those in the DAHS manual for C-4 (1.20 for pressure, 1.19 for impulse). Our interest here is to determine whether the equivalence of PE4 is sufficiently similar to C-4 (i.e., within the statistical uncertainty associated with C-4 equivalence) that it may be considered the same material.

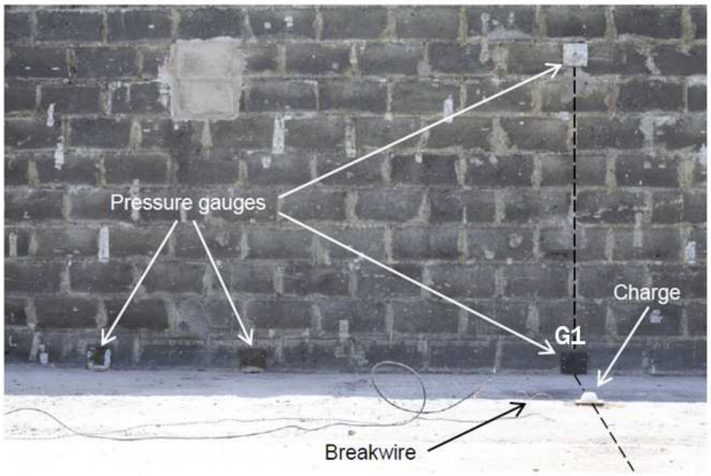

Figure 7: Typical experimental setup for PE4 tests (from [13]).

A voluminous body of blast data was obtained from four separate series of trials conducted by researchers at Sheffield University, and documented in four different papers ([11], [12], [13], [14]) which we shall identify by the prime author and year of publication. The trials used hemispheres of PE4 weighing between 180 and 350 g and positioned on a concrete slab. Active pressure gauges were fielded in rigid, non-responding walls between 4 and 10 m from the charge. A typical test setup is shown in Figure **7**. Even though gauges were often positioned at varying angles of incidence, only the G1 gauge (normal to the charge) was used in the current study. In some cases, the walls were of sufficient size to prevent clearing effects; in others, clearing effects were observed and measured. For the current study, data from gauges fielded in tests with clearing effects were considered for *peak pressure only*; impulse from those records was not utilized.

The test series produced a quantitatively substantial body of data. A summary of the number of measurements is provided in Table **2**. Due to some of the tests having a finite reflector, the number of impulse points is about half that of the pressure points, but the numbers are still respectable.

For each gauge record, a peak pressure was determined by fitting a Friedlander waveform to the bulk of the active gauge data, excluding the initial early-time spikes, which can be subject to noise from gauge ringing and overshoot. An example of such a fit is shown in Figure **8**, where the measured peak is close to 70 kPa while the curve fit produces a much more meaningful peak pressure estimate of 58 kPa. The impulse for the gauge was then calculated by integrating the fitted curve, rather than the original data, although the two produce essentially identical impulses.

Table 2: Number of measurements from PE4 tests.

		Number of measurements	
Reference	**Study**	**Pressure**	**Impulse**
[11]	Tyas 2011	16	—
[12]	Rigby 2012	4	4
[13]	Rigby 2014	14	14
[14]	Rigby 2015	4	—
	TOTAL	38	18

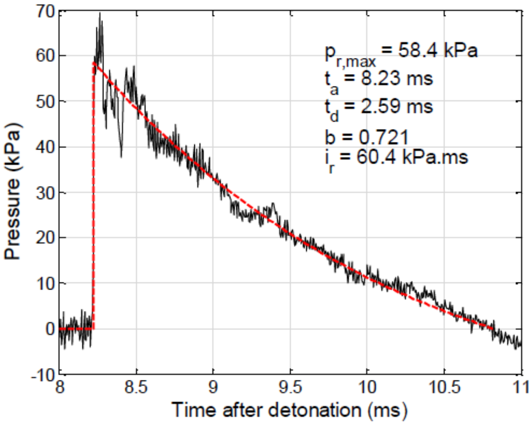

Figure 8: Typical curve fit used to determine peak pressure from gauge record (from [13]).

To estimate TNT equivalence for each gauge, a similar approach was used as was described earlier for the data from UFC 3-340-02. Namely, the pressure and impulse were compared to the Kingery-Bulmash curves for a hemispherical charge at ground surface, the corresponding scaled standoffs were determined for either a constant pressure or an impulse along a 45° line, and the equivalence calculated as the cube of the ratio of scaled standoffs. We thus obtained 38 data points for the pressure equivalence of PE4 and 18 data points for its impulse equivalence.

These results are now plotted, as a function of the scaled standoff, in Figure **9** and Figure **10**. As the plots show, the covered range of scaled standoffs is fairly small relative to our overall range of interest, and the data fall in the regime of far field (roughly 10-40 ft/lb$^{1/3}$). The pressure data is somewhat more scattered than the impulse, but both form reasonably consistent data sets. An exponential function was fit to the data and is shown in each plot as a black line; the arrangement of the data led to a nearly straight-line fit (in log-log space) for both sets. In both cases, the line has a slight downward slope (decreasing equivalence at farther standoffs).

Using the curve fit for pressure, the PE4 equivalence is between 1.20 at the closest standoff and 1.15 at the farthest. For impulse, once again using the curve fit, the equivalence ranges from 1.19 to 1.18 (i.e., is essentially flat). These values are generally similar to those provided by DAHS for C-4, and we are therefore encouraged that PE4 may indeed be compared favorably to C-4 with regard to equivalence.

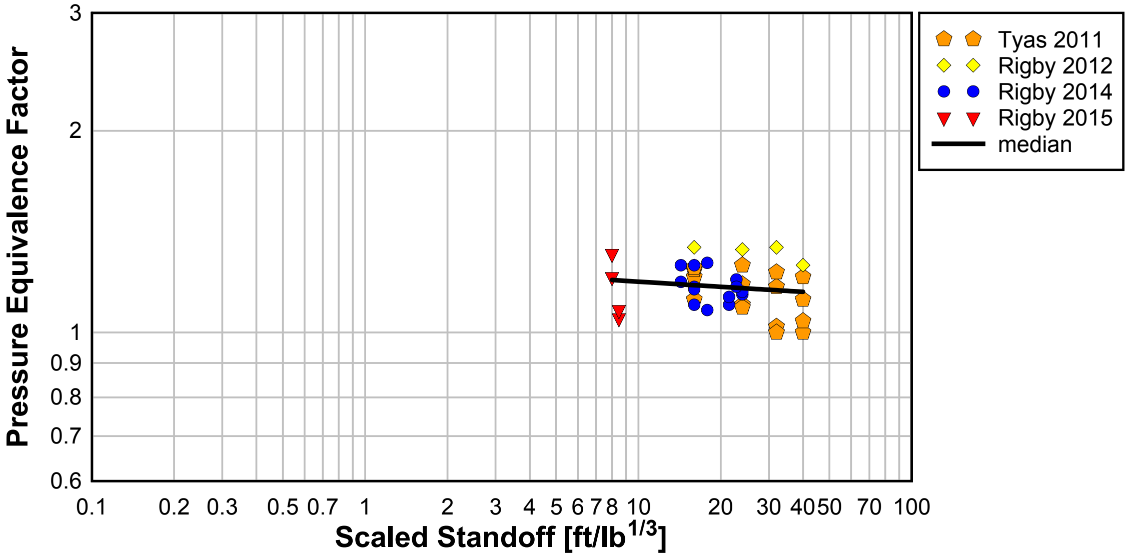

Figure 9: Pressure equivalence data for PE4 vs. scaled standoff.

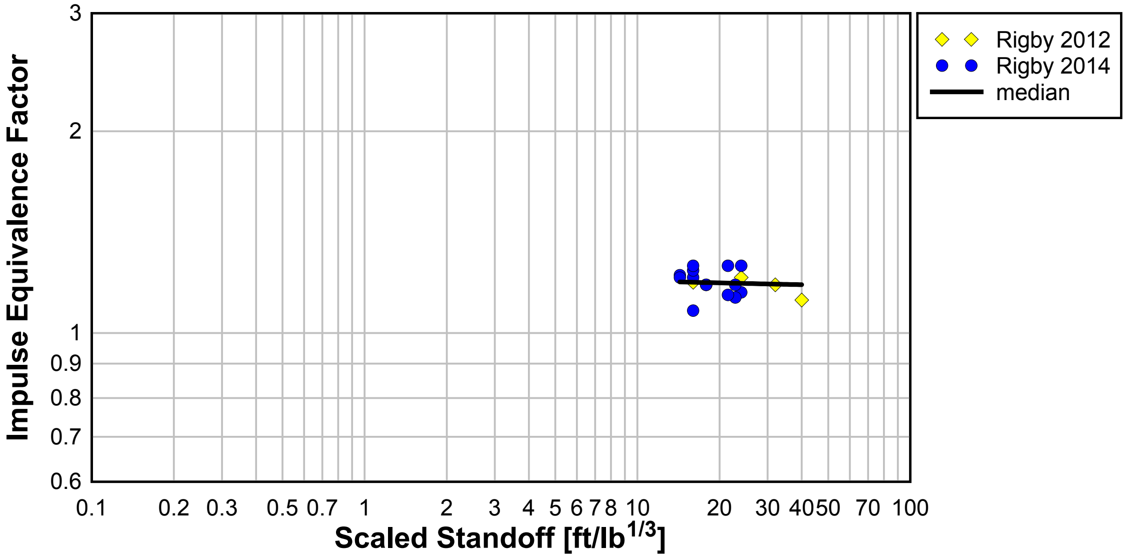

Figure 10: Impulse equivalence data for PE4 vs. scaled standoff.

COMPARING PE4 TO C-4

We are now prepared to address the question of whether PE4 is “similar to” or “the same as” C-4 with regard to its TNT equivalence. The plots in Figure **11** and Figure **12** provide the necessary data for this determination. In those plots, the original C-4 data are plotted in gray, while the new data for PE4 is plotted in color. The straight lines shown in the plots are the curve fits used in STREET to represent C-4, along with the ±2-sigma uncertainty bounds. The uncertainty bounds represent a 95% confidence interval due to fitting of the functional curve to the scattered data.[3]

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[3] Note that an entirely separate source of uncertainty is due to scatter in the individual gauges measuring pressure and impulse. That uncertainty is not included in the bounds being plotted and the values of the uncertainty factor reported below, but it has been quantified in STREET.

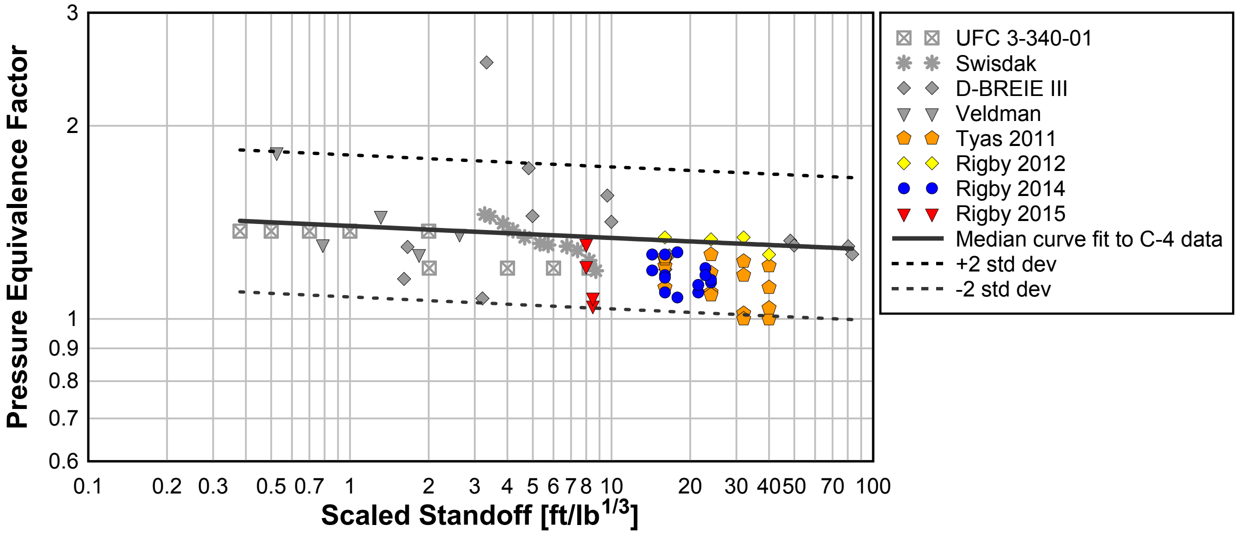

Figure 11: Comparison of PE4 pressure equivalence data to C-4 data and curve fit.

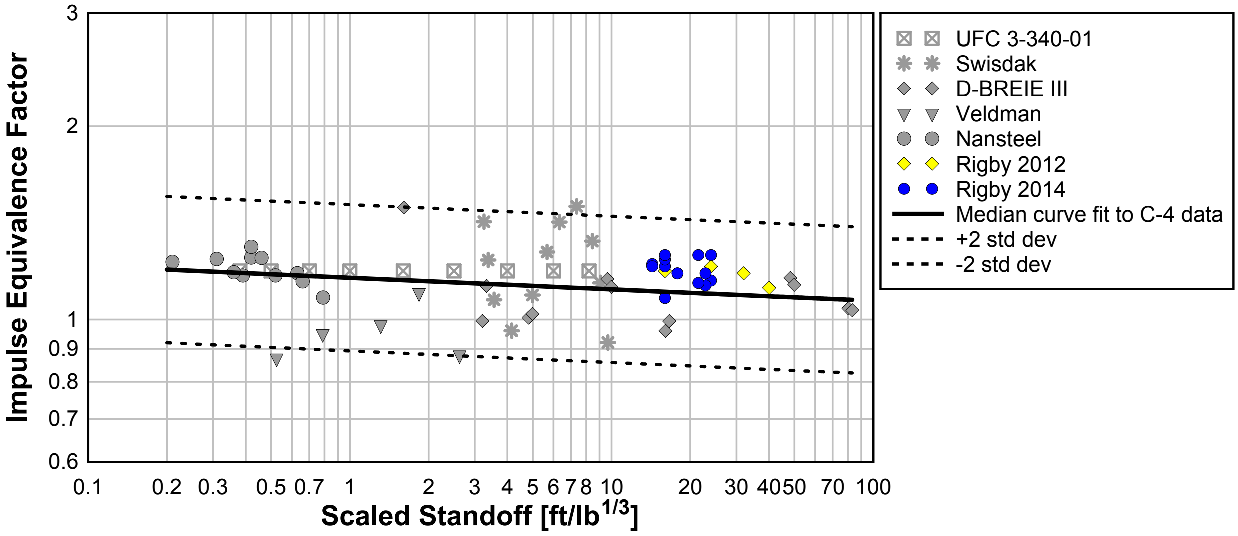

Figure 12: Comparison of PE4 impulse equivalence data to C-4 data and curve fit.

From the pressure plot, we see that most of the PE4 data points lie within the 95% confidence interval. In fact, 2 of the 38 points lie (just) below the lower bound, which happens to coincide exactly with the proportion of points (5%) that would be expected to fall outside the two-sigma bounds. The PE4 data does tend to be low compared to the curve fit, with only 3 of the 38 points being above the median. Nonetheless, the fact that 95% of the points are within the 95% confidence interval indicates excellent consistency. Turning to the impulse plot, the consistency is even more pronounced: none of the 18 points lie outside the two-sigma bounds. Here, most of the PE4 data lies above the median (only one point lies below), but again, the comparison is most favorable.

Consequently, we can conclude that *PE4 is in fact the same as C-4 with regard to its pressure and impulse equivalence*, within the reasonable scatter observed in the data. This conclusion is, of necessity, limited to the far-field standoffs where PE4 data was available for the current study, and it remains to be determined through future analysis of existing data (or testing to generate new data) whether it is equally applicable in the mid- and near-field regimes.

UPDATED CURVE FITS FOR C-4/PE4

Now that C-4 and PE4 are considered as a single material, we can re-calculate the curve fits for both pressure and impulse equivalence, using all the data combined into a single data set. We first see the pressure curve fit in Figure **13**, in which all the C-4 data is in purple while the PE4 data is in orange. The two-sigma uncertainty bounds are also shown parallel to the median curve fit. The curve represents the data quite well, even though there is a significant amount of scatter. It is worth noting that the new PE4 complements the older C-4 data quite well, since there was only one study (D-BREIE III) that provided data in the > 10 ft/lb$^{1/3}$ regime, and none of it was in the 18–45 ft/lb$^{1/3}$ range (compare to Figure **1**).

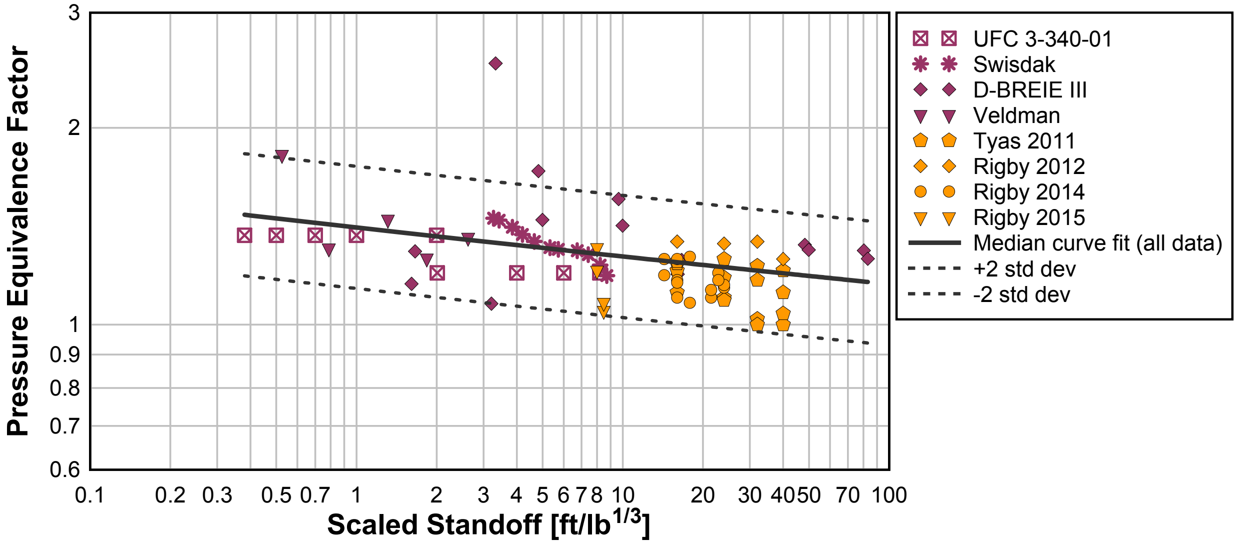

Figure 13: Curve fit to combined C-4 and PE4 data for pressure equivalence.

We might ask what difference the additional data made in the curve fits. First, in Figure **14** we compare the two curve fits and observe that the new fit (in red) has a distinctly steeper slope. This results in a slightly higher equivalence at the very close-in range, but a lower value at the far range. It's not surprising that the new data has had this effect since, as we noted, the pressure data from PE4 was lower than the old curve fit to C-4 data only (see Figure **12**). We also note that the uncertainty has been reduced somewhat, as can be seen most clearly at 1.6 ft/lb$^{1/3}$ where the two curves intersect and the width of the uncertainty bands is easily compared.

Next, looking at impulse, Figure **15** plots all available data (C-4 in purple, PE4 in orange) and the best-fitting curve along with uncertainty bounds. Once again, the PE4 data nicely fills a significant gap in the C-4 data set, with minimal overlap with existing data. The median curve represents the data quite well. The Swisdak points are inherently of lower credibility than the others, but removing them would have minimal effect on the median curve fit; it might reduce the uncertainty bounds somewhat, however.

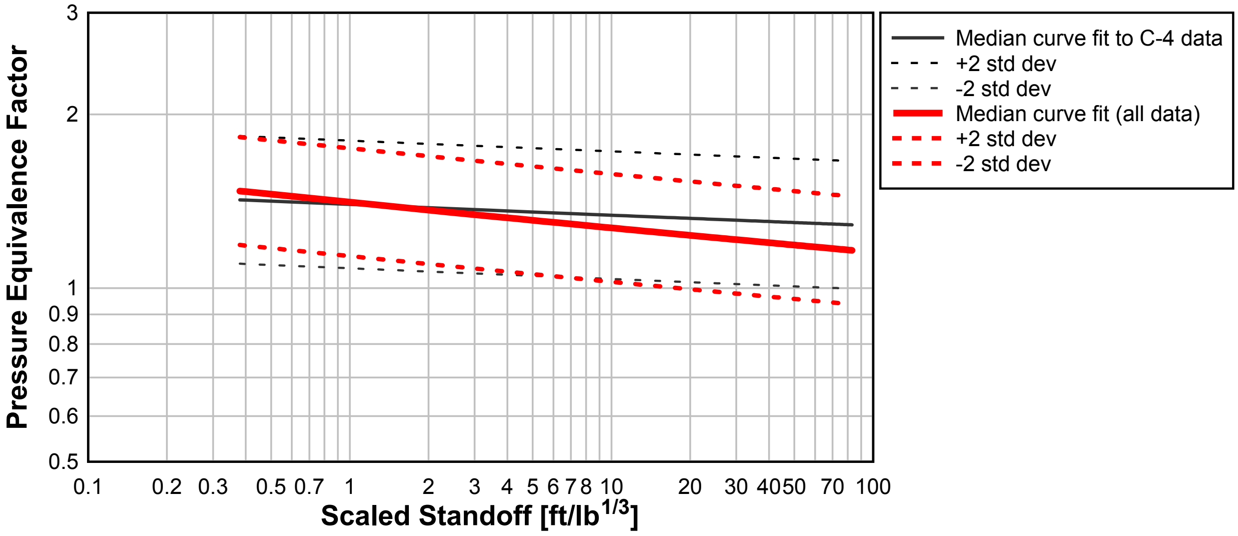

Figure 14: Comparison of original (C-4) and combined (C-4 + PE4) curve fits for pressure.

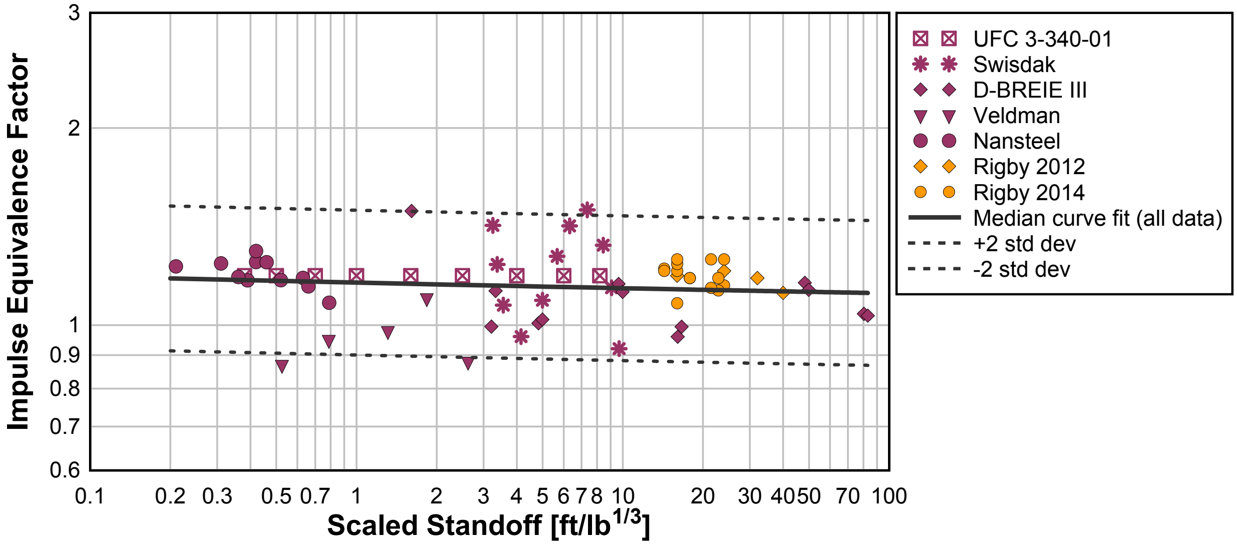

Figure 15: Curve fit to combined C-4 and PE4 data for impulse equivalence.

In Figure **16** we plot the original (C-4 only) and new (combined PE4 and C-4) curve fits to understand the impact of the new data on the resulting curve. Since the new PE4 impulse data lies mostly above the old curve fit (see Figure **12**), it is no surprise that the new curve is higher than the old at large standoffs, but only by a slight amount. The uncertainties are roughly the same, though the new curve has very slightly smaller confidence bounds.

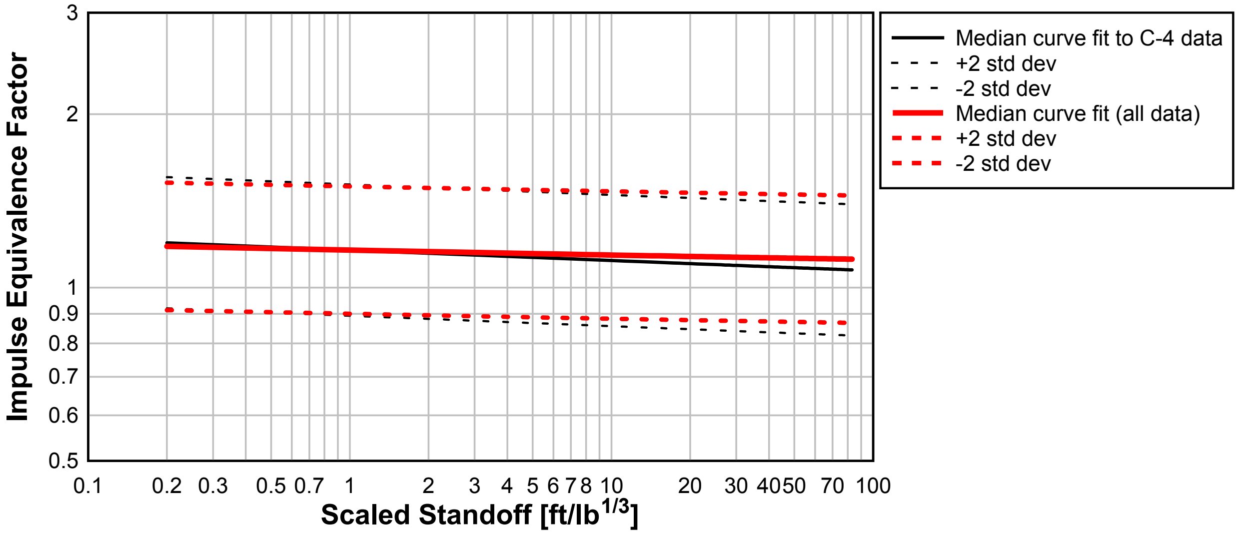

Figure 16: Comparison of original (C-4) and combined (C-4 + PE4) curve fits for impulse.

RECOMMENDED EQUIVALENCE VALUES FOR C-4/PE4

Ultimately, what values of equivalence should users plug into their models if calculating airblast from a C-4 or PE4 explosion? First, with regard to pressure, it is evident that there is a distinct standoff dependence to the equivalence: closer distances require a higher equivalence than more distant ones. The best fit curve ranges from 1.47 at 0.4 ft/lb$^{1/3}$ to 1.16 at 80 ft/lb$^{1/3}$, which is too large a variation to simply ignore. Impulse, however, is nearly flat, ranging from 1.18 to 1.12 across the domain; thus, approximating this with a constant 1.15 would be a reasonable simplification.

For those wishing to implement the curves into an automated model, the relevant equations for the best-fit curves are provided below:

$$
\begin{aligned}
y &= a_1 \exp(a_2 x) + a_3 \\
x &= \log_{10}\left(\frac{R}{W^{1/3}}\right) \\
y &= \log_{10}(K) \\
\text{where } a_1, a_2, a_3 &= \text{fitting constants} \qquad (3) \\
K &= \text{equivalence factor (pressure or impulse)} \\
W &= \text{charge weight [lb]} \\
R &= \text{standoff [ft]}
\end{aligned}
$$

For the new combined fits,[4] the parameters of the equations are listed in Table **3**. The two-sigma uncertainty factor is provided in the table, and can be used to determine a lower- and upper-bound value as follows:

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[4] For clarity, note that the curve fit for C-4 provided in the current version of STREET (ver. 1.0.2) is still the older form of the equation which was fit to C-4 data only (the black curve in Figure 14 and Figure 16).

$$\begin{aligned} K_{UB} &= K \cdot UF \\ K_{LB} &= K / UF \end{aligned} \tag{4}$$

If one wishes to define the one-sigma confidence interval, this can also be computed by:

$$UF_{1\sigma} = \sqrt{UF_{2\sigma}} \tag{5}$$

Table 3: Parameter values for equivalence curve fits.

Parameter	Value	
	Pressure	**Impulse**
a_1	0.8927	0.08607
a_2	-0.0511	-0.10546
a_3	-0.7440	-0.02105
UF (2σ)	1.24	1.29

It is worth noting that the uncertainty bounds are not trivial; choosing to use a conservative two-sigma upper bound would add 24% and 29% to the pressure and impulse equivalences, respectively. For example, the upper bound pressure equivalence at the 0.4 ft/lb$^{1/3}$ range is 1.83, a value quite a bit higher than the traditionally accepted 1.2, or even the 1.37 specified in DAHS. It is also interesting, and somewhat counter-intuitive, that the uncertainty bound on impulse is slightly larger than that on pressure. Traditionally, pressure measurements have had greater uncertainty than impulse, but perhaps the process of determining equivalence and then fitting a curve to that data negates that inherent uncertainty in measuring peak pressures. As well, the new PE4 data now included in these fits uses a Friedlander fit to determine the peak rather than the measurement (as illustrated in Figure **8**) which eliminates the scatter due to the initial overshoot of the gauge.

CONCLUSIONS

In this paper, we have examined the curves provided by UFC 3-340-02 for pressure and impulse from C-4 orthorhombic charges, and concluded that the curves are suspect and should be used only with the greatest caution. Use of equivalence factors such as those provided in the DAHS manual or in this paper is more reliable and defensible.

We have also examined whether, in terms of its performance in producing airblast, PE4 can be considered the same explosive as C-4, and the analysis shows emphatically that it can. In the future, then, C-4/PE4 can be considered the same explosive.

Finally, we have provided updated curves that define standoff-dependent values of pressure and impulse equivalence, along with the two-sigma confidence bounds. For conservative applications, use of the two-sigma upper bound is a reasonable approach.

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