Appendix D1: BSEE Underwater Calculator 3 (UWC-3) Report

WATER SHOCK ENVIRONMENT AND RESULTING ISOPLETHS FOR EXPLOSIVE REMOVAL OF OFFSHORE STRUCTURES: UNDERWATER CALCULATOR 3 (UWC3)

April 26, 2019

Prepared for:
Bureau of Safety and Environmental Enforcement
1201 Elmwood Park Blvd.
New Orleans, LA 70123

Prepared by:
Ted Argo, Ph.D.
Peter T. Dzwilewski, P.E.
Applied Research Associates, Inc.
7921 Shaffer Parkway
Littleton, Colorado 80127

Contract: GS00F341CA
Order: E17PD00144

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Acknowledgements

The work was performed for the Bureau of Safety and Environmental Enforcement under contract GS00F341CA, Order E17PD00144. The author would like to thank Mr. T.J. Broussard and Deborah Epperson, Ph.D. and Nikki Charpentier, the Contracting Officer Representatives, for their guidance, and Afua Serwah-Asibey, the Contracting Officer, for administering the contract.

Executive Summary

The UnderWater Calculator 3 (UWC3) is a spreadsheet-based tool that calculates the underwater shock, namely, Sound Pressure Level (SPL), Impulse, and Sound Exposure Level (SEL), caused by the use of explosives for removal of offshore structures (EROS), such as that simulated in Figure 1. The primary use of this tool is to calculate the isopleth (range) to specified criteria for permanent threshold shift (PTS), temporary threshold shift (TTS), behavioral effects, and injury for marine mammals.

The UWC3 range to effect is based on field data from Technical Assessment and Research 429 (TAR429), TAR570, and Pressure Wave and Acoustic Properties (PWAP) reports. The PTS and TTS criteria for marine mammals are based in terms of both SPL and SEL, while behavioral effects are based upon only SEL. The SEL criteria for this effort was specified by low-, mid-, and high-frequency cetacean hearing groups. To determine the SEL as function of range and explosive mass, the pressure-time histories were processed using provided auditory weighting functions for the three hearing groups. TAR429, TAR570, and PWAP had the required pressure time histories to allow this analysis to be accomplished.

An analysis of the field data shows that there is a considerable amount of variability due to difficult fielding conditions, variations in soil types and properties, pile properties, conductor construction, water depth, explosive depth below the mudline, and other unknown factors. To account for these variations and to be conservative in predictions, in order to reduce the chance of underpredicting the distances to thresholds, the relationships for the upper 90% percentile prediction were used in the UWC3.

Both isopleth and forward calculation options are provided in UWC3 spreadsheet. The isopleth calculation provides the onset ranges for the TTS, PTS, behavioral effects for the three hearing groups, and injury thresholds. Conversely, the forward calculation provides the SPL, SEL, and impulse for a given slant range, explosive mass, and main pile, conductor, and open-water scenarios.

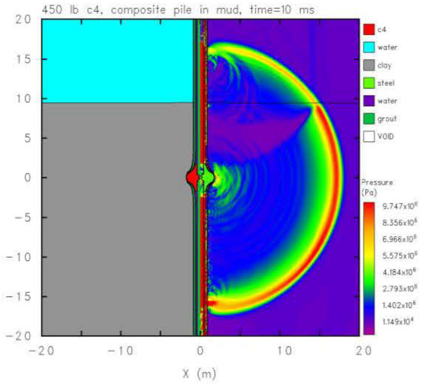


Figure 1. Simulation of explosive pile cutting showing the shock wave propagating into the sediment and water.

1. Introduction

The UnderWater Calculator 3 (UWC3) is a spreadsheet-based tool that calculates the underwater shock, namely, Sound Pressure Level (SPL), Impulse, and Sound Exposure Level (SEL), caused by the use of explosives for removal of offshore structures (EROS). The primary use of this tool is to calculate the isopleth (range) to specified criteria for permanent threshold shift (PTS), temporary threshold shift (TTS), behavioral effects, and injury for marine mammals.

The development of the UWC3 is based upon a list of recommendations by the National Marine Fisheries Service (NMFS) to the Bureau of Safety and Environmental Enforcement (BSEE) for updating Version 2.0 of the Underwater Calculator (UWC2). Suggestions were compiled from NMFS staff and the Center of Independent Experts review of the UWC2. Many of the recommendations concerned broadening the scope of water shock effects, adding conservativism to the procedures including more field data, and using updated criteria to determine the isopleth thresholds.

UWC2 only considered TTS based on a peak pressure of 23 psi and EFD of 182 dB re: 1 μPa^2-s 1/3-octave band and was based on field data from Technical Assessment and Research 570 (TAR570). UWC3 added PTS and injury effects. Additional data from TAR429 and Pressure Wave and Acoustic Properties (PWAP) field studies were used to define the peak pressure, impulse, and EFD as a function of the explosive mass, range, and pile scenario.

The UWC3 threshold distance criteria are from NMFS. The PTS and TTS criteria are based in terms of both SPL and SEL, while behavioral effects are based upon SEL. The SEL criteria is specified by the low-, mid-, and high-frequency cetacean hearing groups. To determine the SEL as function of range and explosive mass, the pressure-time histories were processed using the provided auditory weighting functions for the three hearing groups. TAR429, TAR570, and PWAP had the required pressure time histories available to allow this analysis to be accomplished. As we do not have the Connor data (TAR118) in digital form, we could not use that data in developing the relationships.

In the sections below, we present the major features of the UWC3, show examples of the UWC3 output, give the criteria, present the development of shock environment models and results, and show SPL and SEL versus range with criteria. Lastly, we provide our conclusions.

2. Major Features of the UWC3

Major features and organization of the UWC3 include the following.

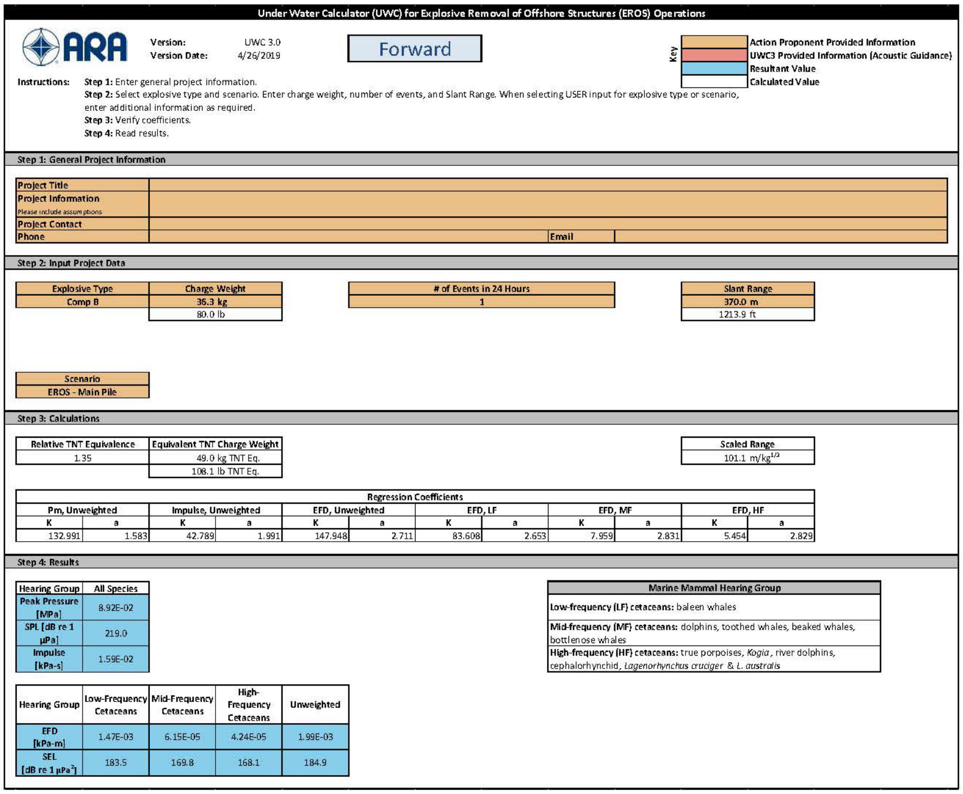
- The UWC3 is an Excel spreadsheet.
- The cell headings and values for the threshold criteria are protected. They can be changed by unlocking the sheets using a password provided by BSEE personnel.
- SI units are used with conversion to customary English units when deemed helpful.
- There are six sheets: Summary, isopleth calculation, forward calculation, tables, criteria, and glossary.
- For the isopleth calculation (slant ranges to PTS, TTS, behavioral, and injury criteria), the required inputs are explosive type, charge weight, number of events (SEL is cumulative), and pile scenario. Mammal mass and mammal depth are required for injury calculations.
- For the forward calculation (SPL, impulse and SEL at a given slant range), the required inputs are slant range, explosive type, charge weight, number of events, and pile scenario.
- Nine explosive types are provided with their respective TNT equivalency. The explosives are C-4, CH-6, Comp B, H-6, Octol-70/30, Octol-75/25, Pentolite-50/50, PETN, and TNT. A user option is also provided.
- The EROS scenarios include: 1) main pile and 2) well conductors. The open-water case (i.e., explosive in water with no pile present) is included for comparison purposes.
- The UWC3 threshold distance (isopleth) criteria is based on the NMFS recommendations (provided in a later section). The PTS and TTS criteria are based in terms of both SPL and SEL, while behavioral effects are based upon SEL. The SEL criteria is specified by the low-, mid-, and high-frequency cetacean hearing groups. To determine the SEL as a function of range and explosive mass, the pressure time histories were processed using the provided auditory weighting functions for the three hearing groups.
- The field data used in UWC3 include TAR429, TAR570, and PWAP as they had the required pressure-time histories to allow this analysis to be accomplished.
- The functional forms to relate explosive mass, distance and peak pressure, impulse, and Energy Flux Density (EFD) are those used traditionally as described by Cole (1965) and Swisdak (1978). In UWC3, the units are SI and then pressure is converted to SPL, and EFD is converted to SEL internally to the spreadsheet. For peak pressure, the relationship is

  $$P_m = K \cdot (W^{1/3} / R)^{\alpha}$$

  Where K is a constant and α is the attenuation with distance obtained by fitting the data. The impulse and EFD relationships are similar, except that they are scaled by the cube root of the explosive weight (i.e., $I/W^{1/3}$ and $EFD/W^{1/3}$, respectively). The explosive mass (W) is based on TNT equivalency.
- The coefficients for the relationships are provided in the Table sheet and are automatically populated based on the scenario chosen. Coefficients were developed for the mean, lower 90% prediction, and upper 90% prediction. The upper 90% prediction coefficients were implemented into UWC3 to account for site differences, test condition variations, and measurement uncertainties in a very difficult test environment. The use of the upper 90% prediction coefficients reduces the chance of under-predicting the distances to thresholds.
- The UWC3 also has an option for users to specify different coefficients to define the shock environments.

3. Examples UWC3 Output

Example output for the forward and isopleth calculations are shown in Figure 2 and Figure 3.



Under Water Calculator (UWC) for Explosive Removal of Offshore Structures (EROS) Operations

Version: UWC 3.0
Version Date: 4/26/2019

Forward

Key

🟧	**Action Proponent Provided Information**
🟥	**UWC3 Provided Information (Acoustic Guidance)**
🟦	**Resultant Value**
☐	**Calculated Value**

Instructions:
Step 1: Enter general project information.
Step 2: Select explosive type and scenario. Enter charge weight, number of events, and Slant Range. When selecting USER input for explosive type or scenario, enter additional information as required.
Step 3: Verify coefficients.
Step 4: Read results.

Step 1: General Project Information

Project Title			
Project Information Please include assumptions			
Project Contact			
Phone		**Email**	

Step 2: Input Project Data

Explosive Type	Charge Weight
Comp B	36.3 kg
	80.0 lb

# of Events in 24 Hours
1

Slant Range
370.0 m
1213.9 ft

Scenario
EROS - Main Pile

Step 3: Calculations

Relative TNT Equivalence	Equivalent TNT Charge Weight
1.35	49.0 kg TNT Eq.
	108.1 lb TNT Eq.

Scaled Range
101.1 m/kg$^{1/3}$

Regression Coefficients											
Pm, Unweighted		Impulse, Unweighted		EFD, Unweighted		EFD, LF		EFD, MF		EFD, HF	
K	a	K	a	K	a	K	a	K	a	K	a
132.991	1.583	42.789	1.991	147.948	2.711	83.608	2.653	7.959	2.831	5.454	2.829

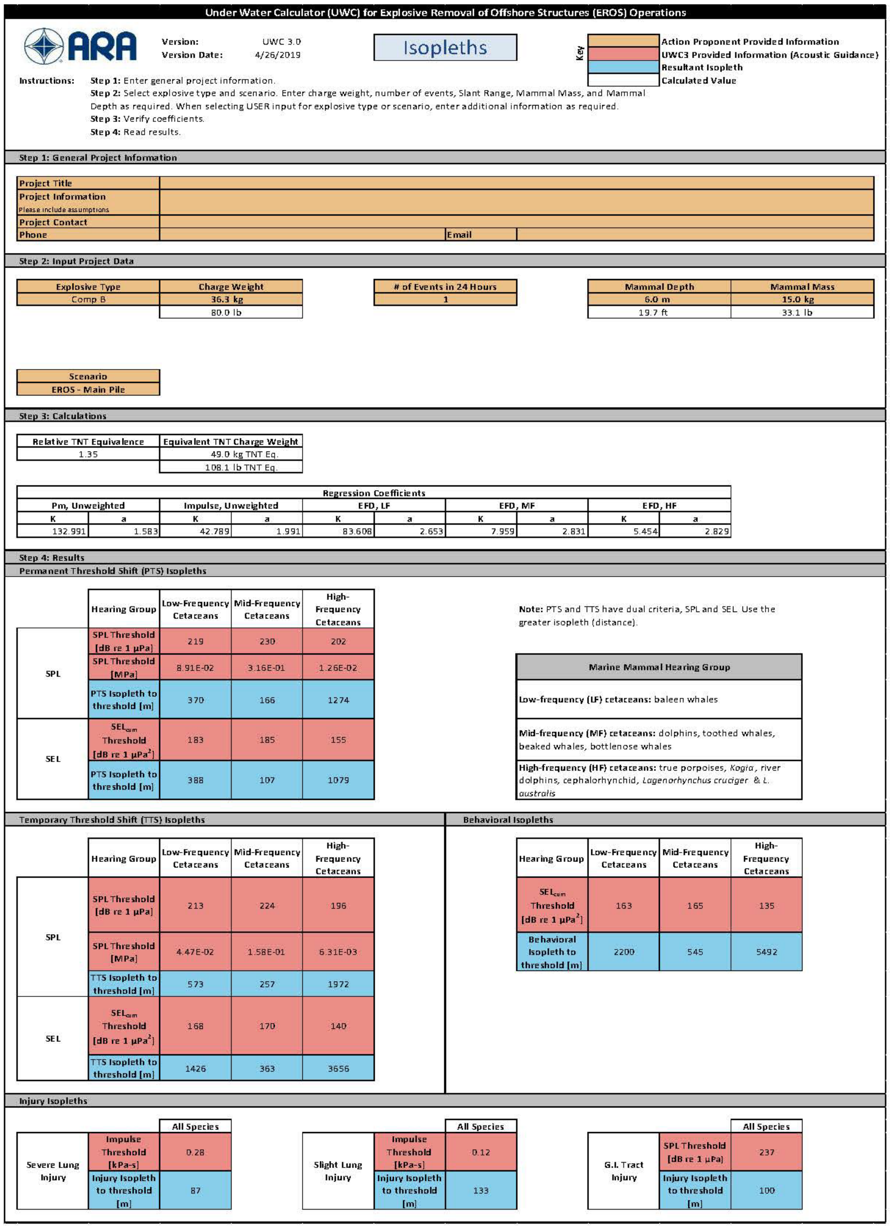
Step 4: Results

Hearing Group	All Species
Peak Pressure [MPa]	8.92E-02
SPL [dB re 1 μPa]	219.0
Impulse [kPa-s]	1.59E-02

Hearing Group	Low-Frequency Cetaceans	Mid-Frequency Cetaceans	High-Frequency Cetaceans	Unweighted
EFD [kPa-m]	1.47E-03	6.15E-05	4.24E-05	1.99E-03
SEL [dB re 1 μPa^2]	183.5	169.8	168.1	184.9

Marine Mammal Hearing Group
Low-frequency (LF) cetaceans: baleen whales
Mid-frequency (MF) cetaceans: dolphins, toothed whales, beaked whales, bottlenose whales
High-frequency (HF) cetaceans: true porpoises, *Kogia*, river dolphins, cephalorhynchid, *Lagenorhynchus cruciger* & *L. australis*

Figure 2. Output result of the forward calculation of the UWC3 for 80 lbs. of Comp B Explosive in a Main Pile.



Under Water Calculator (UWC) for Explosive Removal of Offshore Structures (EROS) Operations

Version: UWC 3.0
Version Date: 4/26/2019

Isopleths

Key

🟧	**Action Proponent Provided Information**
🟥	**UWC3 Provided Information (Acoustic Guidance)**
🟦	**Resultant Isopleth**
☐	**Calculated Value**

Instructions:
Step 1: Enter general project information.
Step 2: Select explosive type and scenario. Enter charge weight, number of events, Slant Range, Mammal Mass, and Mammal Depth as required. When selecting USER input for explosive type or scenario, enter additional information as required.
Step 3: Verify coefficients.
Step 4: Read results.

Step 1: General Project Information

Project Title			
Project Information Please include assumptions			
Project Contact			
Phone		**Email**	

Step 2: Input Project Data

Explosive Type	Charge Weight
Comp B	**36.3 kg**
	80.0 lb

# of Events in 24 Hours
1

Mammal Depth	Mammal Mass
6.0 m	**15.0 kg**
19.7 ft	33.1 lb

Scenario
EROS - Main Pile

Step 3: Calculations

Relative TNT Equivalence	Equivalent TNT Charge Weight
1.35	49.0 kg TNT Eq.
	108.1 lb TNT Eq.

Regression Coefficients

Pm, Unweighted		Impulse, Unweighted		EFD, LF		EFD, MF		EFD, HF	
K	a	K	a	K	a	K	a	K	a
132.991	1.583	42.789	1.991	83.608	2.653	7.959	2.831	5.454	2.829

Step 4: Results

Permanent Threshold Shift (PTS) Isopleths

	Hearing Group	Low-Frequency Cetaceans	Mid-Frequency Cetaceans	High-Frequency Cetaceans
SPL	SPL Threshold [dB re 1 µPa]	219	230	202
	SPL Threshold [MPa]	8.91E-02	3.16E-01	1.26E-02
	PTS Isopleth to threshold [m]	370	166	1274
SEL	SEL$_{cum}$ Threshold [dB re 1 µPa^2]	183	185	155
	PTS Isopleth to threshold [m]	388	107	1079

Note: PTS and TTS have dual criteria, SPL and SEL. Use the greater isopleth (distance).

Marine Mammal Hearing Group
Low-frequency (LF) cetaceans: baleen whales
Mid-frequency (MF) cetaceans: dolphins, toothed whales, beaked whales, bottlenose whales
High-frequency (HF) cetaceans: true porpoises, *Kogia*, river dolphins, cephalorhynchid, *Lagenorhynchus cruciger* & *L. australis*

Temporary Threshold Shift (TTS) Isopleths

	Hearing Group	Low-Frequency Cetaceans	Mid-Frequency Cetaceans	High-Frequency Cetaceans
SPL	SPL Threshold [dB re 1 µPa]	213	224	196
	SPL Threshold [MPa]	4.47E-02	1.58E-01	6.31E-03
	TTS Isopleth to threshold [m]	573	257	1972
SEL	SEL$_{cum}$ Threshold [dB re 1 µPa^2]	168	170	140
	TTS Isopleth to threshold [m]	1426	363	3656

Behavioral Isopleths

Hearing Group	Low-Frequency Cetaceans	Mid-Frequency Cetaceans	High-Frequency Cetaceans
SEL$_{cum}$ Threshold [dB re 1 µPa^2]	163	165	135
Behavioral Isopleth to threshold [m]	2200	545	5492

Injury Isopleths

		All Species
Severe Lung Injury	Impulse Threshold [kPa-s]	0.28
	Injury Isopleth to threshold [m]	87

		All Species
Slight Lung Injury	Impulse Threshold [kPa-s]	0.12
	Injury Isopleth to threshold [m]	133

		All Species
G.I. Tract Injury	SPL Threshold [dB re 1 µPa]	237
	Injury Isopleth to threshold [m]	100

Figure 3. Output result of the isopleth calculation of the UWC3 for 80 lbs. of Comp B Explosive in a Main Pile.

4. Criteria Used for the UWC3

Table 1. Updated PTS onset, TTS onset, and behavioral thresholds (multiple detonations) for underwater explosives based on NMFS 2018.

Hearing Group	**PTS Impulsive Thresholds**	**TTS Impulsive Thresholds**	**Behavioral Threshold (multiple detonations)**
Low-Frequency (LF) Cetaceans	Cell 1 $L_{pk,flat}$: 219 dB $L_{E,LF,24h}$: 183 dB	Cell 2 $L_{pk,flat}$: 213 dB $L_{E,LF,24h}$: 168 dB	Cell 3 $L_{E,LF,24h}$: 163 dB
Mid-Frequency (MF) Cetaceans	Cell 4 $L_{pk,flat}$: 230 dB $L_{E,MF,24h}$: 185 dB	Cell 5 $L_{pk,flat}$: 224 dB $L_{E,MF,24h}$: 170 dB	Cell 6 $L_{E,MF,24h}$: 165 dB
High-Frequency (HF) Cetaceans	Cell 7 $L_{pk,flat}$: 202 dB $L_{E,HF,24h}$: 155 dB	Cell 8 $L_{pk,flat}$: 196 dB $L_{E,HF,24h}$: 140 dB	Cell 9 $L_{E,HF,24h}$: 135 dB
Phocid Pinnipeds (PW) (Underwater)	Cell 10 Lpk,flat: 218 dB LE,PW,24h: 185 dB	Cell 11 $L_{pk,flat}$: 212 dB $L_{E,PW,24h}$: 170 dB	Cell 12 $L_{E,PW,24h}$: 165 dB
Otariid Pinnipeds (OW) (Underwater)	Cell 13 $L_{pk,flat}$: 232 dB $L_{E,OW,24h}$: 203 dB	Cell 14 $L_{pk,flat}$: 226 dB $L_{E,OW,24h}$: 188 dB	Cell 15 $L_{E,OW,24h}$: 183 dB

* Dual metric acoustic thresholds for impulsive sounds: Use whichever results in the largest isopleth for calculating PTS/TTS onset.

Note: Peak sound pressure (L_{pk}) has a reference value of 1 μPa, and cumulative sound exposure level (L_E) has a reference value of 1μPa^{2}s. In this Table, thresholds are abbreviated to reflect American National Standards Institute standards (ANSI 2013); however, peak sound pressure is defined by ANSI as incorporating frequency weighting, which is not the intent for this Technical Guidance. Hence, the subscript "flat" is being included to indicate peak sound pressure should be flat weighted or unweighted within the generalized hearing range. The subscript associated with cumulative sound exposure level thresholds indicates the designated marine mammal auditory weighting function (LF, MF, and HF cetaceans, and PW and OW pinnipeds) and that the recommended accumulation period is 24 hours. The cumulative sound exposure level thresholds could be exceeded in a multitude of ways (i.e., varying exposure levels and durations, duty cycle). When possible, it is valuable for action proponents to indicate the conditions under which these acoustic thresholds will be exceeded.

Table 2. Summary of weighting and exposure function parameters from NMFS 2018.*

Hearing Group	**a**	**b**	**f_1 (kHz)**	**f_2 (kHz)**	**C (dB)**	**K (dB)**
Low-frequency (LF) cetaceans	1.0	2	0.2	19	0.13	179
Mid-frequency (MF) cetaceans	1.6	2	8.8	110	1.20	177
High-frequency (HF) cetaceans	1.8	2	12	140	1.36	152
Phocid pinnipeds (PW) (underwater)	1.0	2	1.9	30	0.75	180
Otariid pinnipeds (OW) (underwater)	2.0	2	0.94	25	0.64	198

* Equations associated with Technical Guidance's weighting (*W(f)*) and exposure functions (*E(f)*):

$$W(f) = C + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a\,[1+(f/f_2)^2]^b}\right\}$$

$$E(f) = K - 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right\}$$

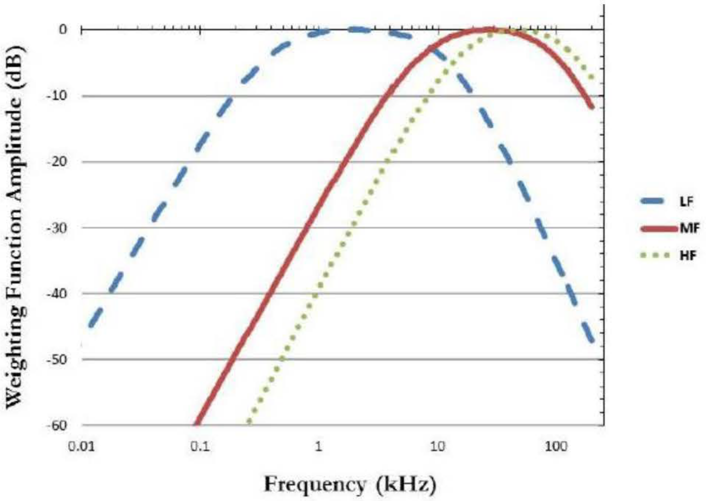


Figure 4. Auditory weighting functions for low-frequency (LF), mid-frequency (MF), and high-frequency (HF) cetaceans.

5. Development of Shock Environment Models

The physics of EROS is demonstrated in the two figures below from a shock physics calculation modeled after one of the field tests from TAR570. The material plot, Figure 5 (explosive shown in red), is shown first and the pressure field is shown at 15.5 ms in Figure 6. The top of the mudline is at zero and the explosive is at 5 m (15 ft.) below mudline (BML). The wave structure is complex, with stress running up the steel pile and emanating outward, the direct pressure from the explosive propagating through the soil and then into the water, the interaction of the soil-water interface, the reflection off a harder soil or rock layer below the saturated soil that was put into this problem to show this effect, and the rarefaction off the water-air interface. These elements can be modeled quite adequately. The difficulty, however, is that the actual *in situ* soil conditions and properties and their variability with depth and range are generally not known. In particular, the energy losses in the soil due the presence of air or gasses in the voids have a significant impact on the attenuation and shock environment in the water. Hence, there is a great need to base the models on field data.

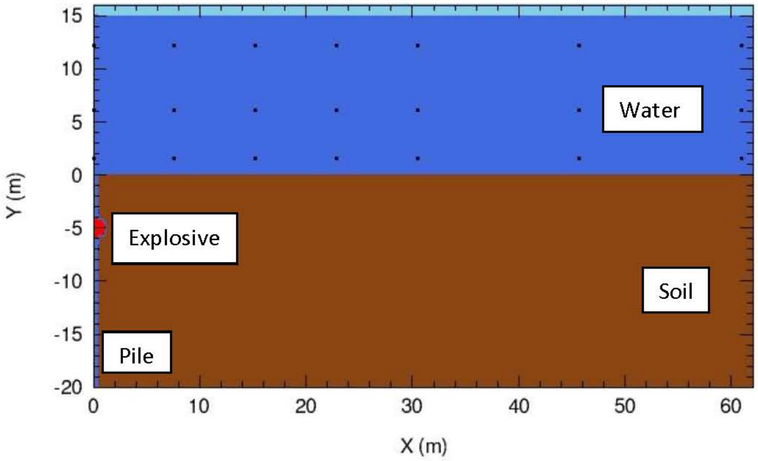


Figure 5. Material plot for an EROS numerical simulation.

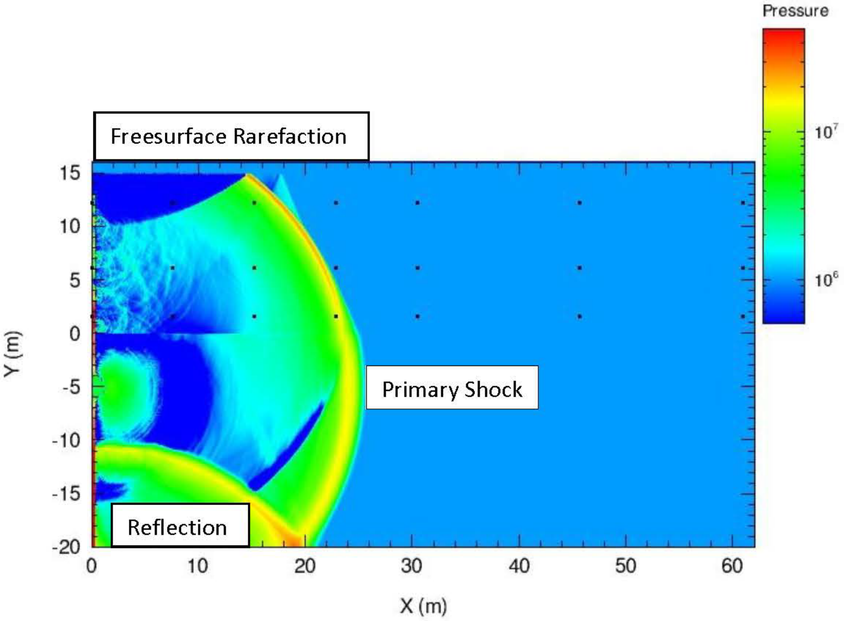


Figure 6. Pressure plot at 15.5 ms for an EROS numerical simulation.

The overall approach to development of the UWC3 was to study the TAR429, TAR570, and PWAP data to develop the shock environment. The results of this review were used to develop new models of SPL, impulse, and EFD (SEL) as a function of explosive mass, range, and pile (main pile and conductor), and open-water scenarios. The peak data versus scaled (or reduced) range (i.e., range divided by the cube root of the explosive weight) were plotted and fit in log-log space. These resulting fits became the basis for the models that were implemented into UWC3.

The form of the relationships for peak pressure, impulse, and EFD is the same as used by Cole Cole (1965), Swisdak (1978), and Connor (1990). The relationship has two constants: one for the magnitude (K) and one for the attenuation rate with scaled range (α). For peak pressure, the relationship is as follows:

$$P_m = K \cdot (W^{1/3} / R)^{\alpha}.$$

The impulse and EFD relationships are similar except that they are scaled by the cube root of the explosive weight, i.e., $I/W^{1/3}$ and $EFD/W^{1/3}$, respectively. Fits to the data included the 90% lower prediction, the mean, and the upper 90% prediction. The upper 90% prediction coefficients as specified by NMFS are used in UWC3 to account for uncertainty.

The approach using MATLAB was as follows: (1) starting with the digitized pressure time histories, determine the peak compressional pressure; (2) integrate the pressure time histories to obtain the peak impulse; (3) using the pressure time histories, calculated the total or unweighted EFD according to

$$E_f(t) = \frac{1}{\rho_o c_o} \cdot \int_0^{\tau} P^2(t)dt \quad ;$$

and (4) using the pressure time histories, determine the frequency-weighted auditory EFD (SEL) for low-, mid-, and high-frequency cetacean hearing groups.

Steps 1–3 are relatively straightforward; however, Step 4, requiring the frequency-weighted SEL, was the largest complication and challenge in developing the coefficients for the UWC3. As shown above, the auditory weighting amplitude depends upon the frequency and the frequency of the pressure-time histories depend upon the explosive mass. Large explosive masses have longer time duration; hence, lower frequency content. Conversely, smaller explosive masses have shorter time durations; hence, higher frequency content. To make the UWC3 applicable to various charge weights, we analyzed each pressure waveform nine times, once for each hearing group and once for three charge weights. We picked charge weights of 20 lb., 80 lb., and 200 lb. of C as typical for EROS operations and scaled the times of the pressure waveforms by the ratio of the cube root of the charge weights (e.g., Hopkinson-Cranz Scaling Law).

The procedure to obtain the hearing group SELs was to transform the pressure waveform into the frequency domain, apply the weighting factors, and then transform back into the time domain. The resulting pressure time histories were then processed to obtain the frequency-weighted SEL for the three hearing groups. The resulting coefficients were fit with a linear relationship in log-log space, which was implemented in UWC3. The explosive masses chosen were 20 lb., 80 lb., and 200 lb. Comp B because they were common for EROS operations. We did not explore the range of validity for explosive masses above and below the 20 lb.–200 lb. in this study.

Examples of the analysis method for two pressure-time histories are presented here. The first example, Figure 7, gave results as expected, while the second example, Figure 8, demonstrates the problem that arises for very low amplitude signals that have a very significant noise component.

An example of a strong signal for one channel and one explosive event is shown in Figure 7. The upper left pane shows the pressure waveform filtered according to each of the auditory weighting functions; the unfiltered signal is blue, the LF is purple, MF is yellow, and HF is orange. As shown, the unfiltered and LF signals are similar in shape/peak pressure and the MF and HF signals are similar in shape/peak pressure. The impulse calculation is shown for the unfiltered signal and is taken to be the maximum of the integral of the pressure with respect to time. The EFD, which translates to the SEL, is shown in the remaining panes for each of the filtering cases. For all three weighted EFD (SEL), the peak values are associated with the main shock pulse as expected.

In contrast, for a weak signal with significant noise, shown in Figure 8, the impulse, unweighted EFD, and weighted EFD are dominated by noise and baseline shift. The EFD for the high-frequency weighting was a particular concern. The weighted pressure wave form is dominated by recorded noise after the low frequency components are removed. The noise, both positive and negative excursions, contributes as p^2 to the calculation of energy flux density and SEL. The resulting EFD keeps increasing with time long after the shock wave physics has ended. Data similar to those shown in Figure 8 were not included in determining the relationships used in UWC3.

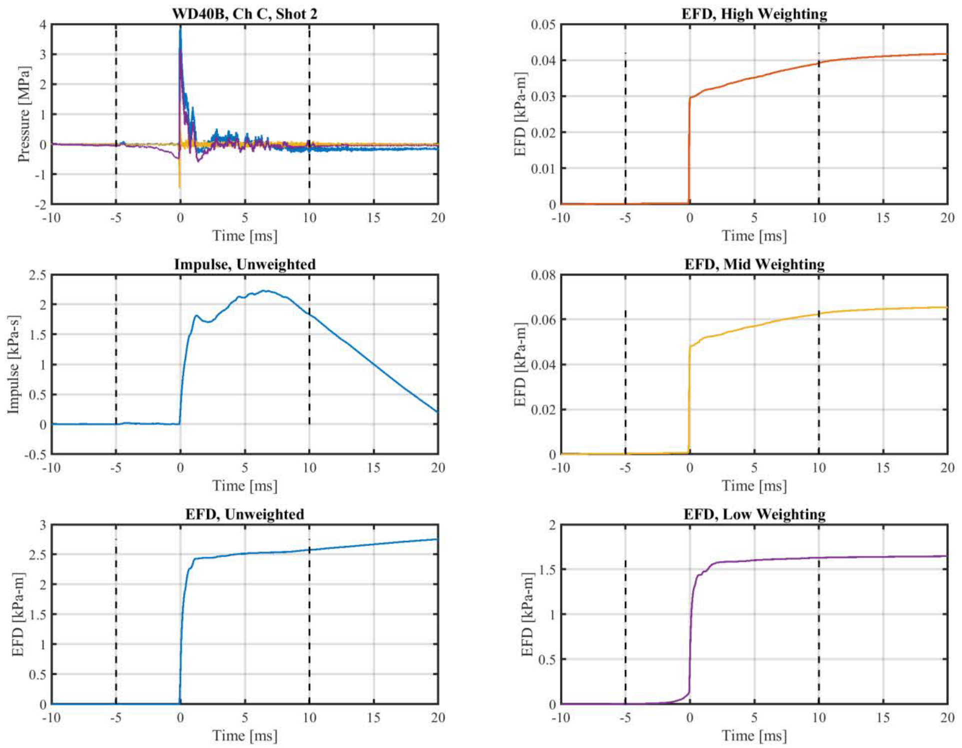


Figure 7. Data with a strong pressure-time history filtered using the auditory weighting functions demonstrates a clear blast wave arrival.

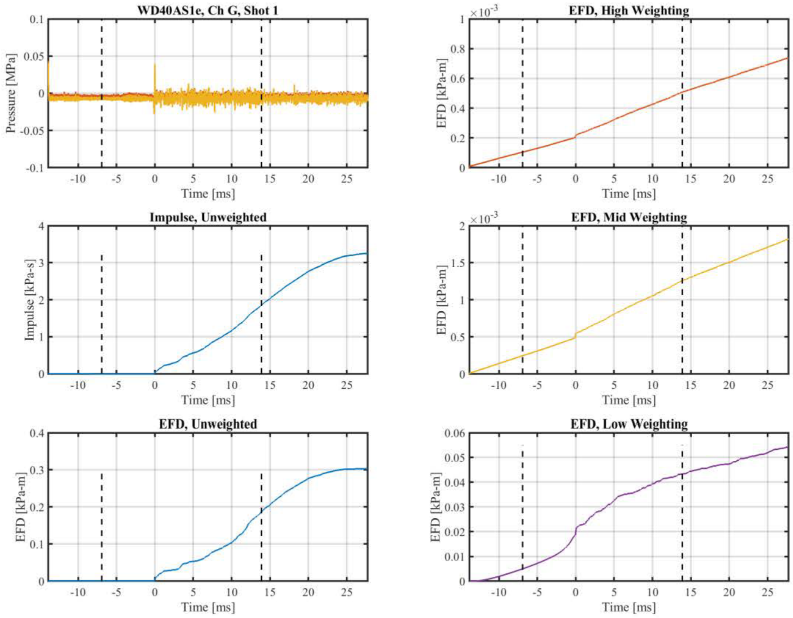


Figure 8. A low amplitude pressure-time history filtered using the auditory weighting functions produces data which is corrupted by noise.

Models for open water are included in UWC3 for reference purposes. The same procedure was used to develop the models with two exceptions; because we did not have actual open water time histories, we used synthesized pressure time histories based upon Cole (1965) and Swisdak (1978) equations. An equation of the form $P = P_m e^{-t/\theta}$ was used with coefficients from Swisdak for TNT.

The second exception was that mean values for the coefficients were used as that is what we had and there is a lot less variability in the open water data. This is demonstrated in Figure 9 from Soloway and Dahl (2014).

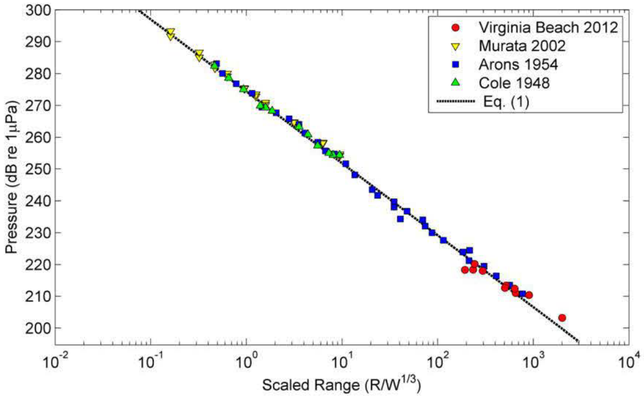


Figure 9. Open water measurements from Soloway 2014.

The distance that an explosive detonation point is below the mudline (BML) was considered in this study. Previously, in the Connor study (Connor 1990) and TAR570 (Poe 2009), tests were conducted with the explosives detonated at various distance BML. Connor concluded for main piles, "Within the precision of the data, there was no difference between the pressure pulses observed near the main pile detonations with the charges at depths of 8, 16, and 26 feet below the mud line." For TAR570 main piles (80-lb. charges), a similar conclusion can be reached, as shown in the following plot (Figure 10). The impulse and EFD for the two TAR570 BML tests were also similar (Dzwilewski 2014).

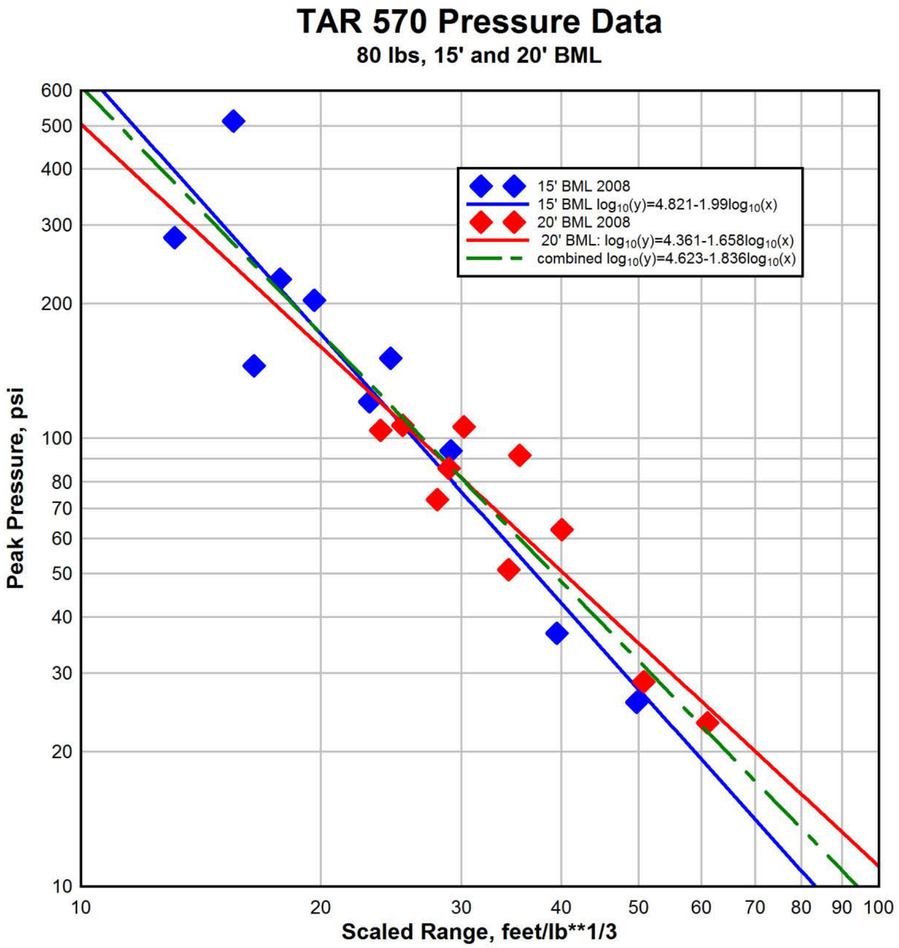


Figure 10. Peak Pressure versus Scaled Range for 80-lb. Main Pile Shots demonstrating the effect of charge placement below mudline.

In contrast to the main pile scenario, the TAR570 conductor tests (145-lb. charges) at 25 ft. and 30 ft. BML, the peak pressure, impulse, and EFD show a distinct dependence on the explosive depth BML. The values for the smaller BML are higher than the greater BML. The peak pressure versus distance relationship is shown in Figure 11. The black and red data points are for 25 ft. BML, and the blue and green data points are for 30 ft. BML.

Although it is reasonable that BML may have an effect, the field data has not been consistent enough to include in the UWC3 models.

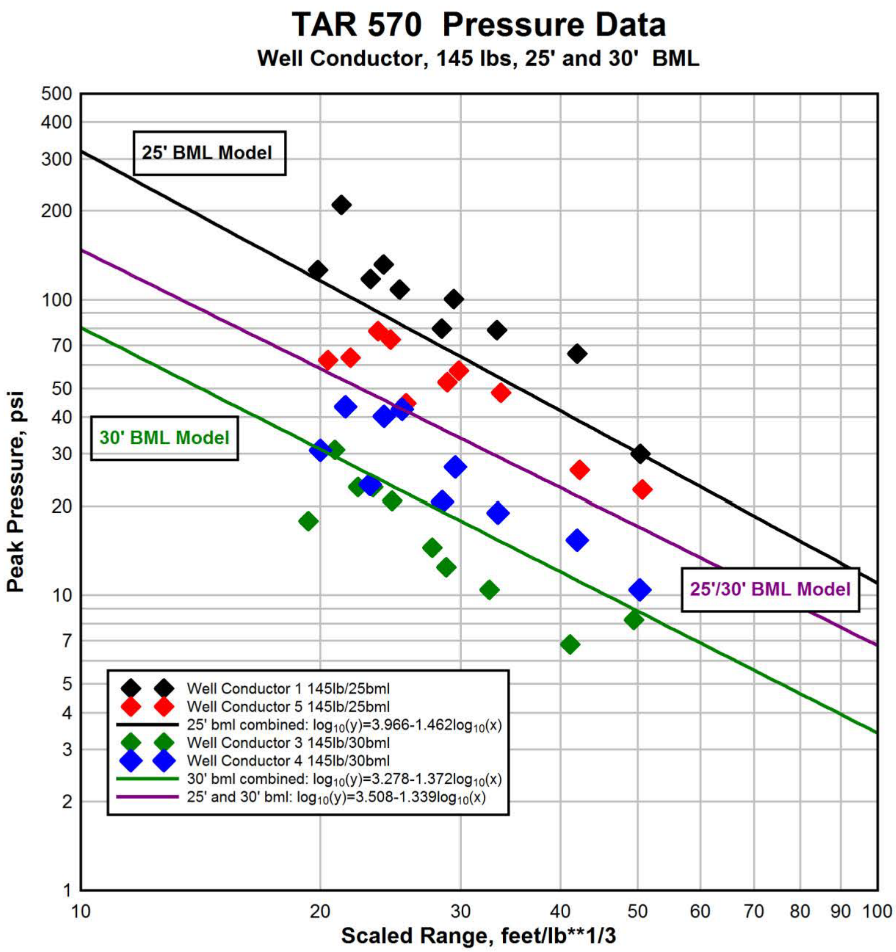


Figure 11. Peak Pressure versus Scaled Range for 145-lb. Well Conductor Shots demonstrating the effect of charge placement below mudline.

6. Shock Environment Models

The shock environment (P, I, EFD) distance relationships were developed from field data from TAR429, TAR570, and PWAP. Some of the main parameters and conditions are listed in Table 3 below. A map with the locations of the projects is shown below in Figure 12.

Table 3. Comparison of parameters of past and current studies.

Experiment	Water Depth (ft.)	Charge Size (lb.)	Depth BML (ft.)	Wall Thickness (in.)
TAR118 (Connor)	53	25–50	8–26	1.0
TAR429	38–50	50	15	1.0
TAR570	50	75–145	15–30	0.625–1.5
PWAP	92	75–200	15–25	1.0–2.25

Figure 12. Approximate locations of TAR118, TAR429, TAR570, and PWAP projects (map from Barkaszi 2016).

In the sections below, the peak pressure, impulse, unweighted EFD, and weighted EFD versus scaled range fitted relationships for the three charge weights (20 lb., 80 lb., and 200 lb. of Comp B). The data from TAR429, TAR570, and PWAP are also plotted. Note that the pressure, impulse, and unweighted plots are the same for all charge weights due to scaled the x-axis (range) and the y-axis for impulse and EFD is scaled. Peak pressure does not need to be scaled. The upper 90% prediction fit parameters are the ones incorporated in UWC3. The 20-lb. results are given first, followed by the 80-lb. results, and then the 200-lb. results.

For the main piles, the data was collected from 2–55 m/kg$^{1/3}$ scaled range. For the conductors, the data was collected from 3–30 m/kg$^{1/3}$ scaled range. Note that the prediction relationships need to be extended out to distances beyond the available data to determine the isopleth threshold distances for the SPL and SEL.

In general, the data show that the TAR570 peak data is lower than the PWAP data at any given range. This may indicate that the TAR570 soil is more energy absorbent than that of the PWAP site.

7. Plots of Analyzed Data

7.1. Main Pile: 20 lb. Comp B Pressure, Impulse, Total EFD, and Frequency-weighted versus Scaled Distance Plots

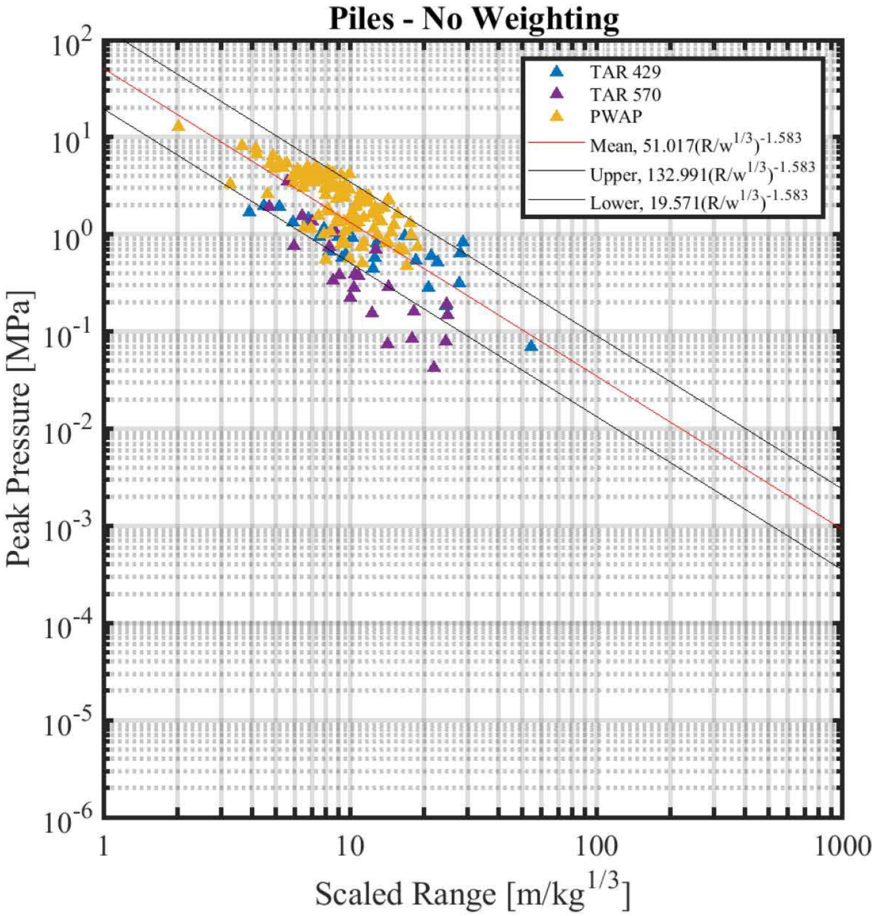


Figure 13. Peak Pressure versus Scaled Range calculated for 20 lbs. of Comp B explosive in a main pile.

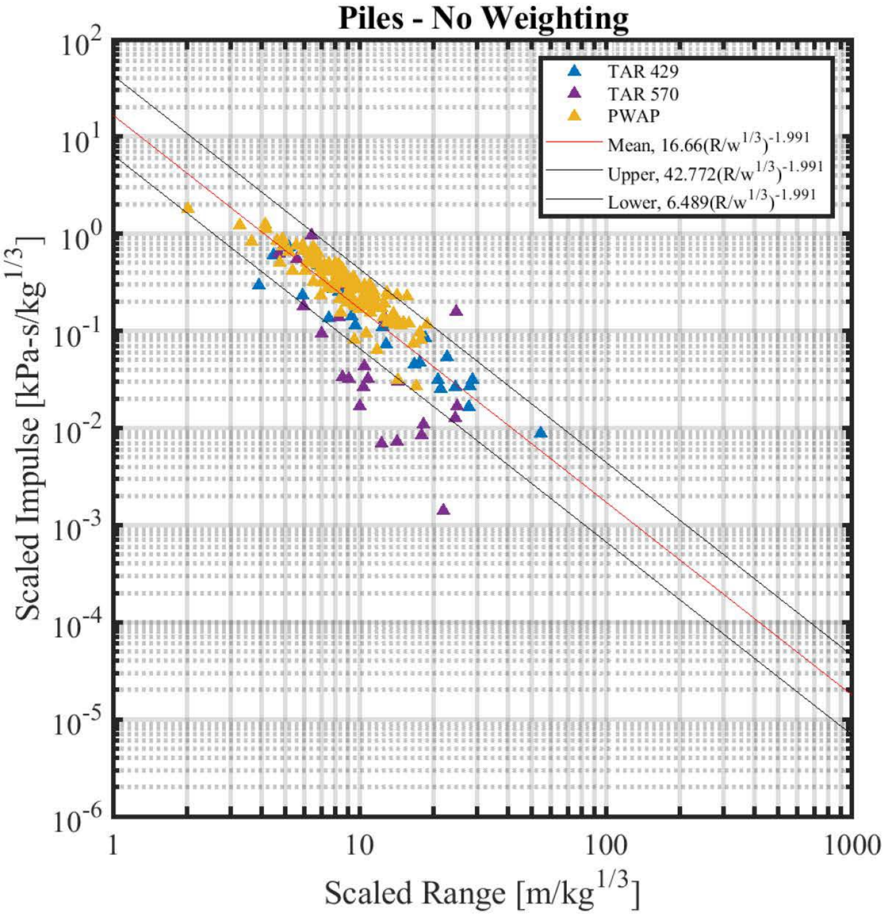


Figure 14 Scaled Impulse versus Scaled Range calculated for 20 lbs. of Comp B explosive in a main pile.

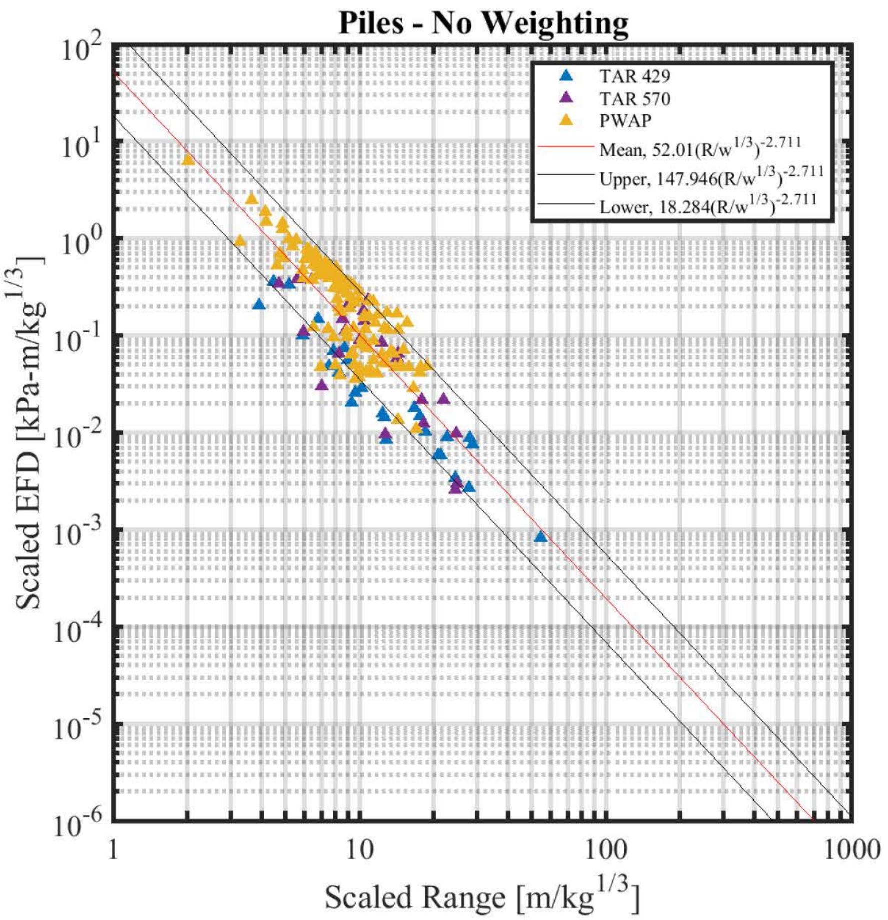


Figure 15. Unweighted Scaled EFD versus Scaled Range calculated for 20 lbs. of Comp B explosive in a main pile.

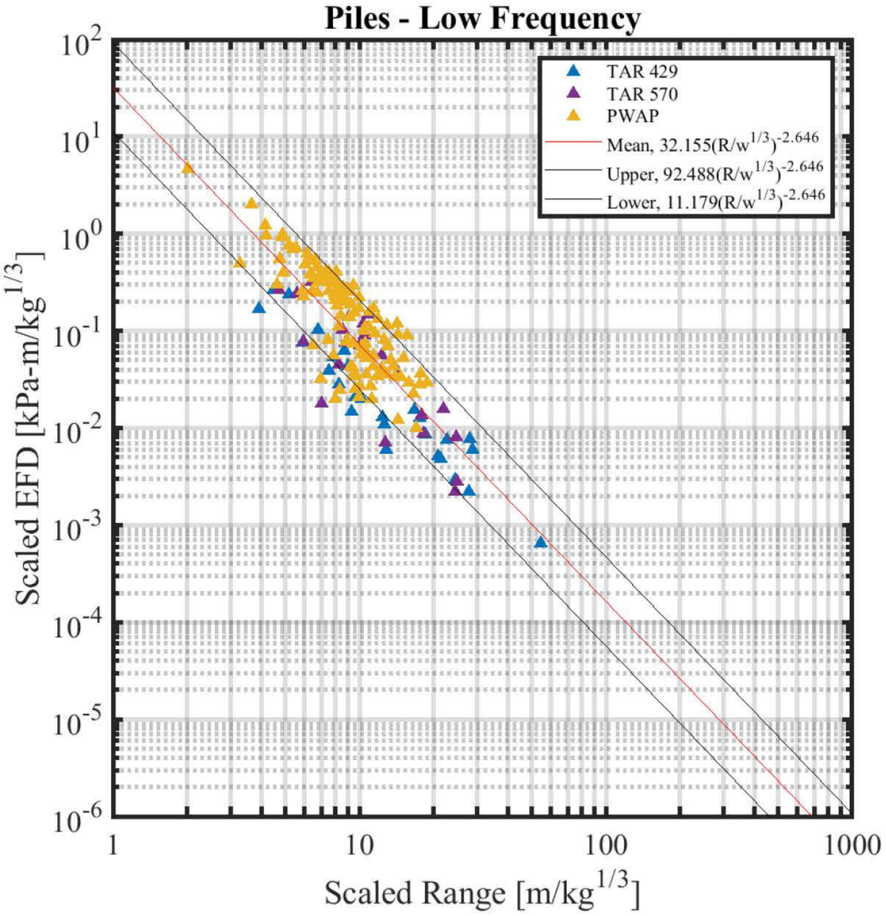


Figure 16. Low Frequency Weighted Scaled EFD versus Scaled Range calculated for 20 lbs. of Comp B explosive in a main pile.

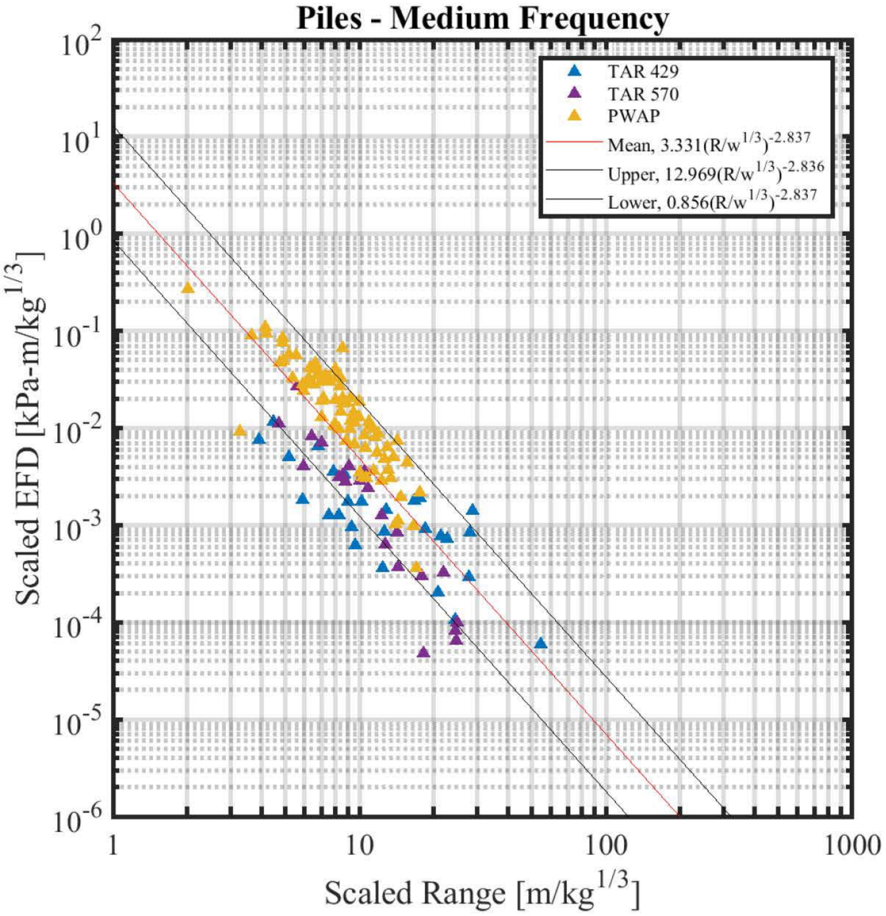


Figure 17. Mid Frequency Weighted Scaled EFD versus Scaled Range calculated for 20 lbs. of Comp B explosive in a main pile.

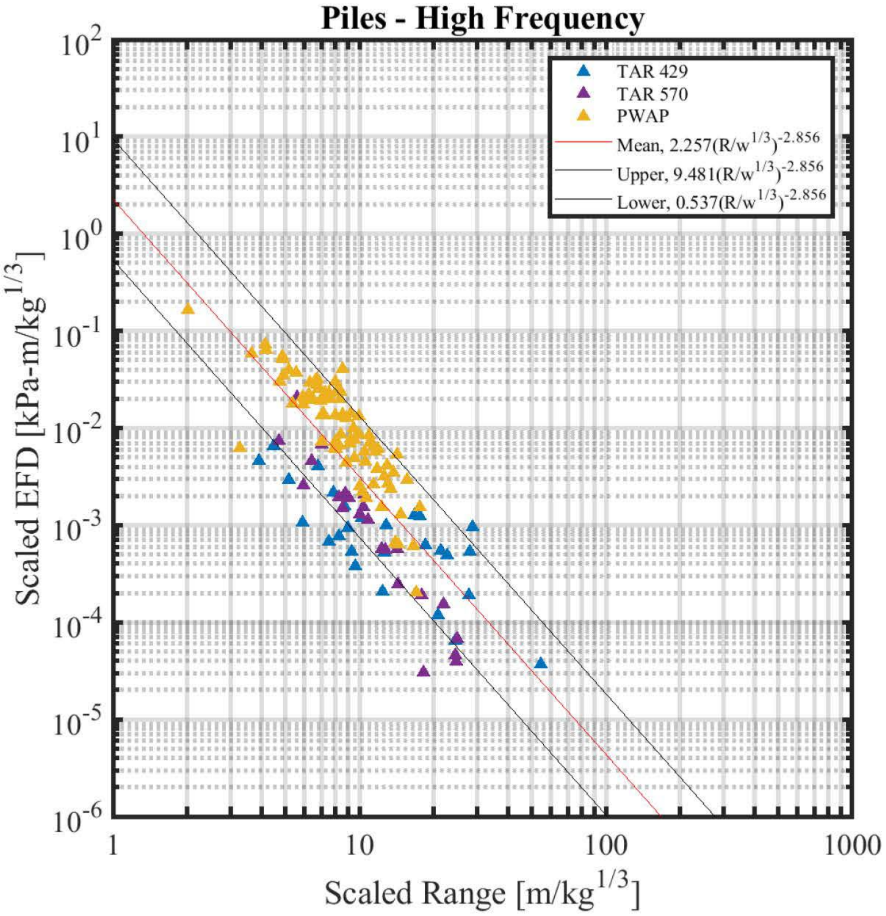


Figure 18. High Frequency Weighted Scaled EFD versus Scaled Range calculated for 20 lbs. of Comp B explosive in a main pile.

7.2. Main Pile: 80 lb. Comp B Pressure, Impulse, Total EFD, and Frequency-weighted versus Scaled Distance Plots

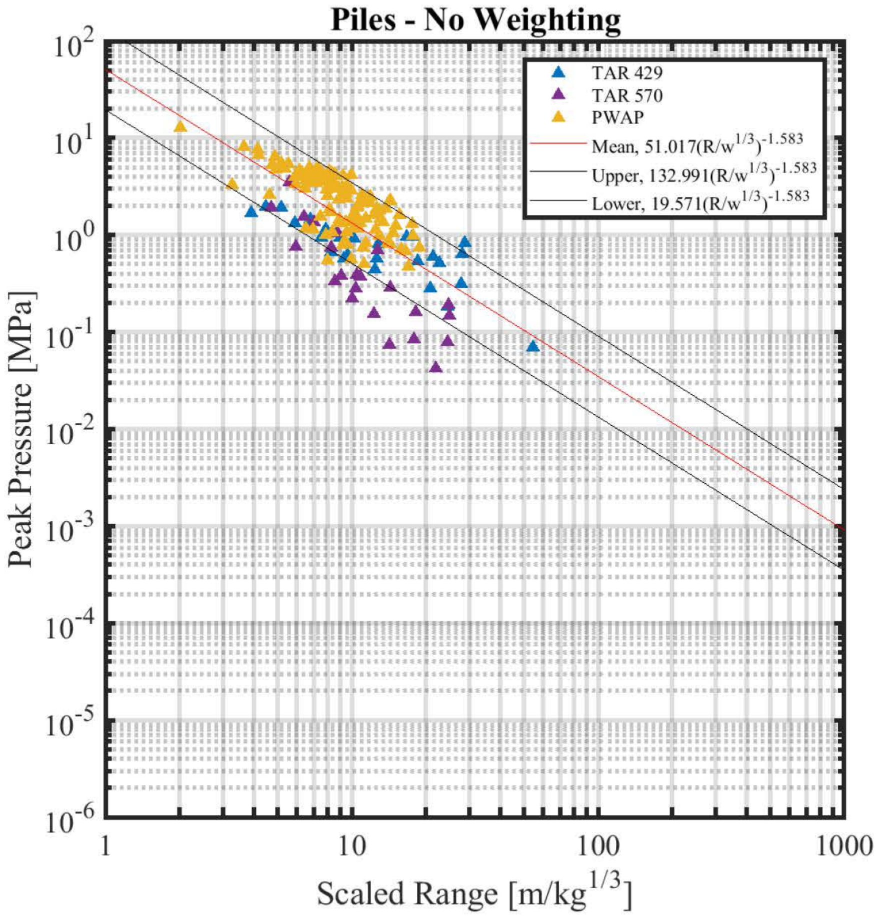


Figure 19. Peak Pressure versus Scaled Range calculated for 80 lbs. of Comp B explosive in a main pile.

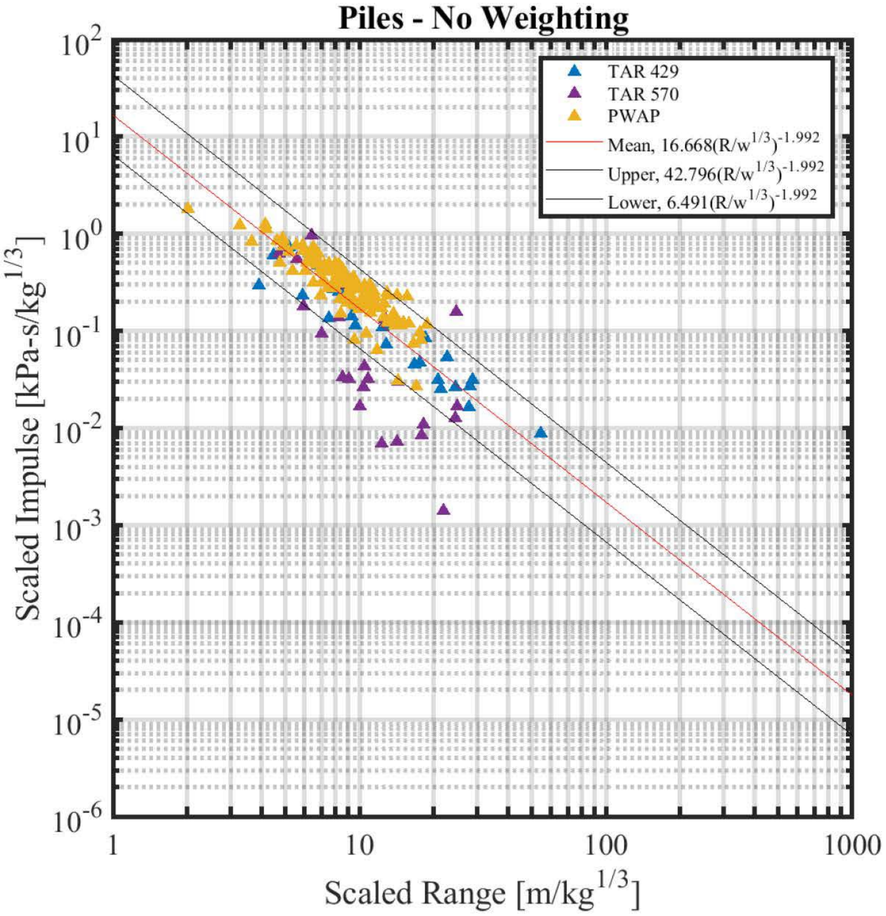


Figure 20. Scaled Impulse versus Scaled Range calculated for 80 lbs. of Comp B explosive in a main pile.

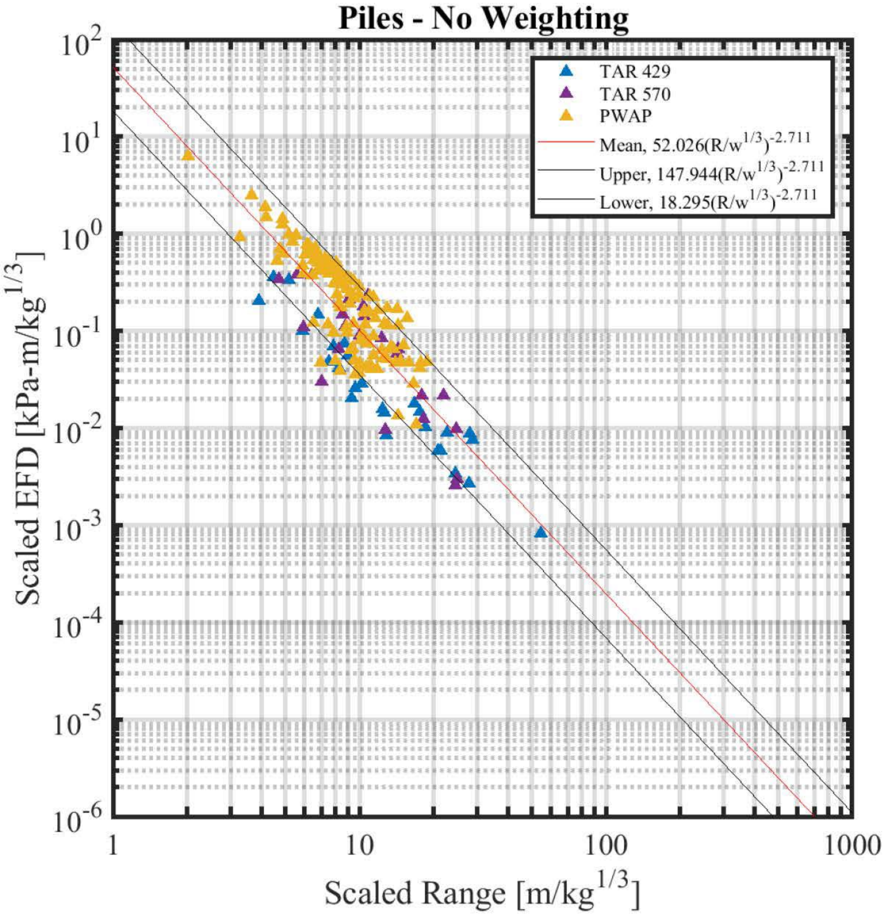


Figure 21. Unweighted Scaled EFD versus Scaled Range calculated for 80 lbs. of Comp B explosive in a main pile.

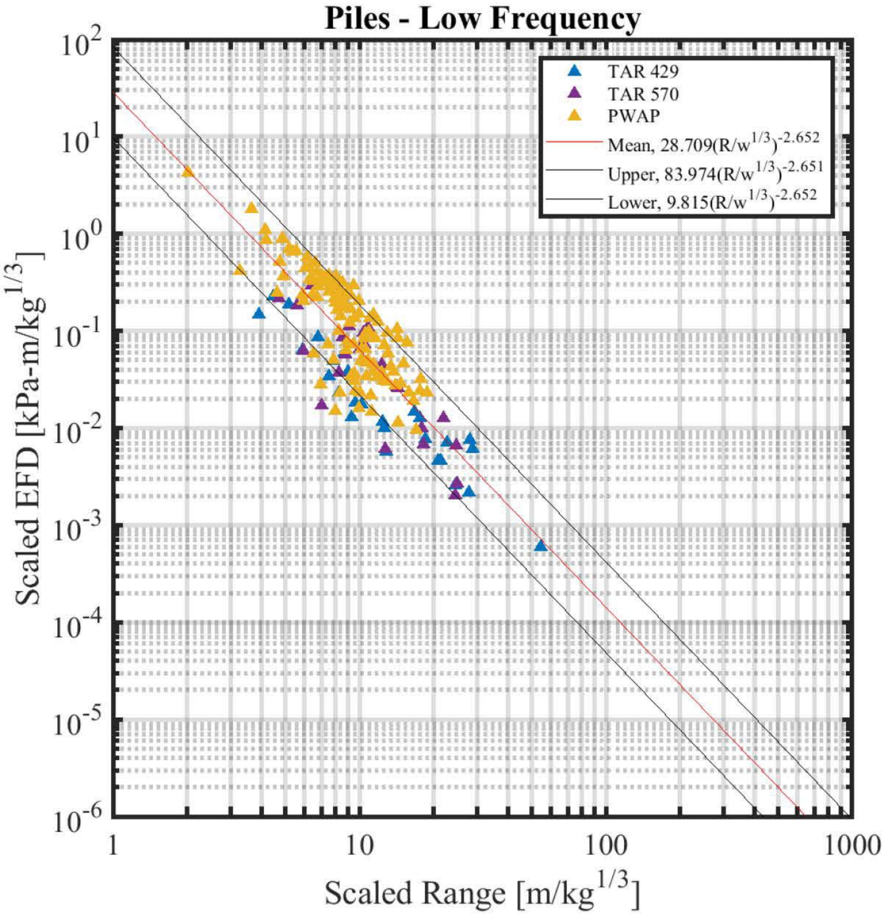


Figure 22. Low Frequency Weighted Scaled EFD versus Scaled Range calculated for 80 lbs. of Comp B explosive in a main pile.

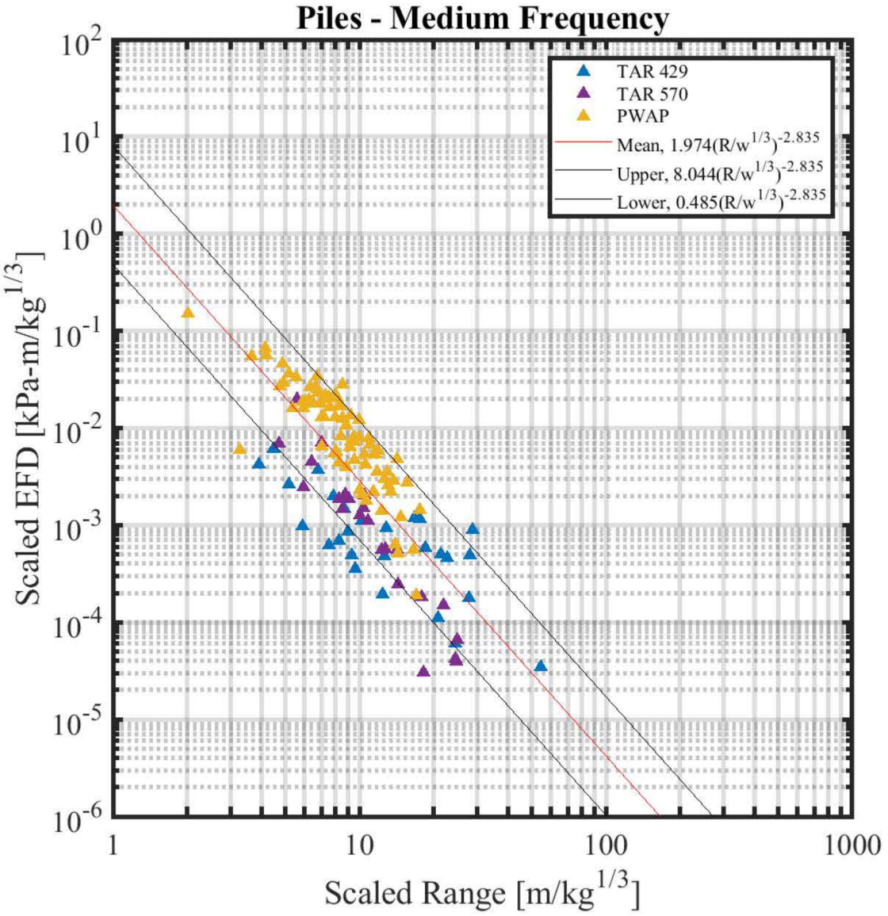


Figure 23. Mid Frequency Weighted Scaled EFD versus Scaled Range calculated for 80 lbs. of Comp B explosive in a main pile.

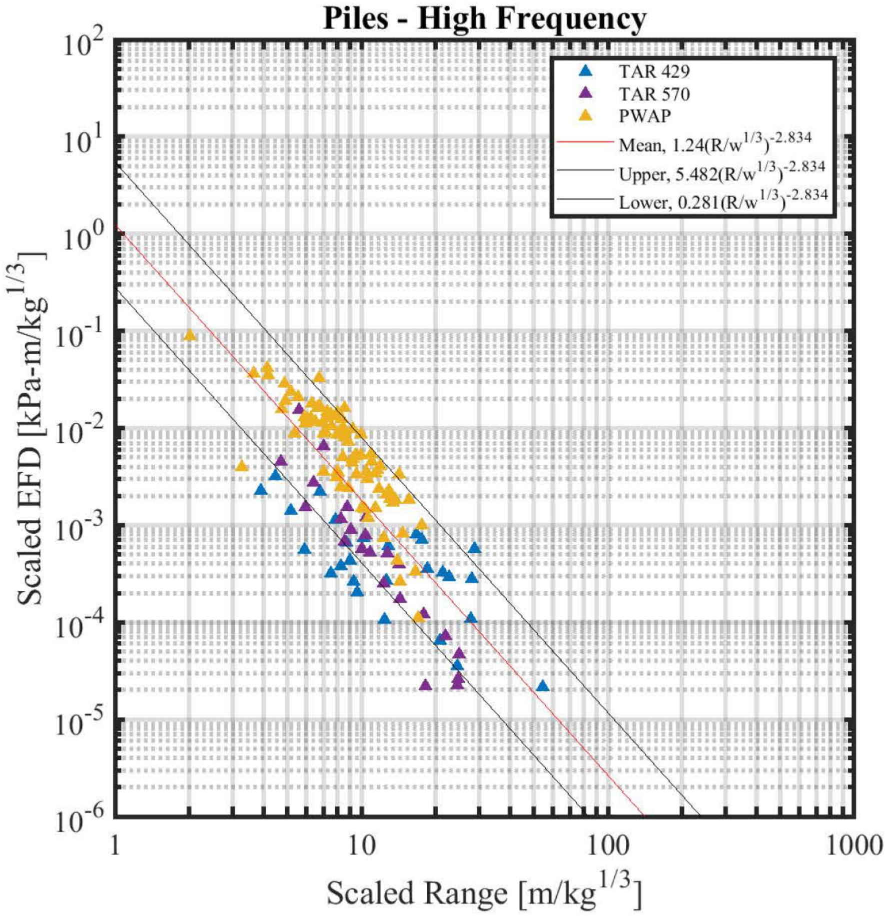


Figure 24. High Frequency Weighted Scaled EFD versus Scaled Range calculated for 80 lbs. of Comp B explosive in a main pile.

7.3. Main Pile: 200 lb. Comp B Pressure, Impulse, Total EFD, and Frequency-weighted versus Scaled Distance Plots

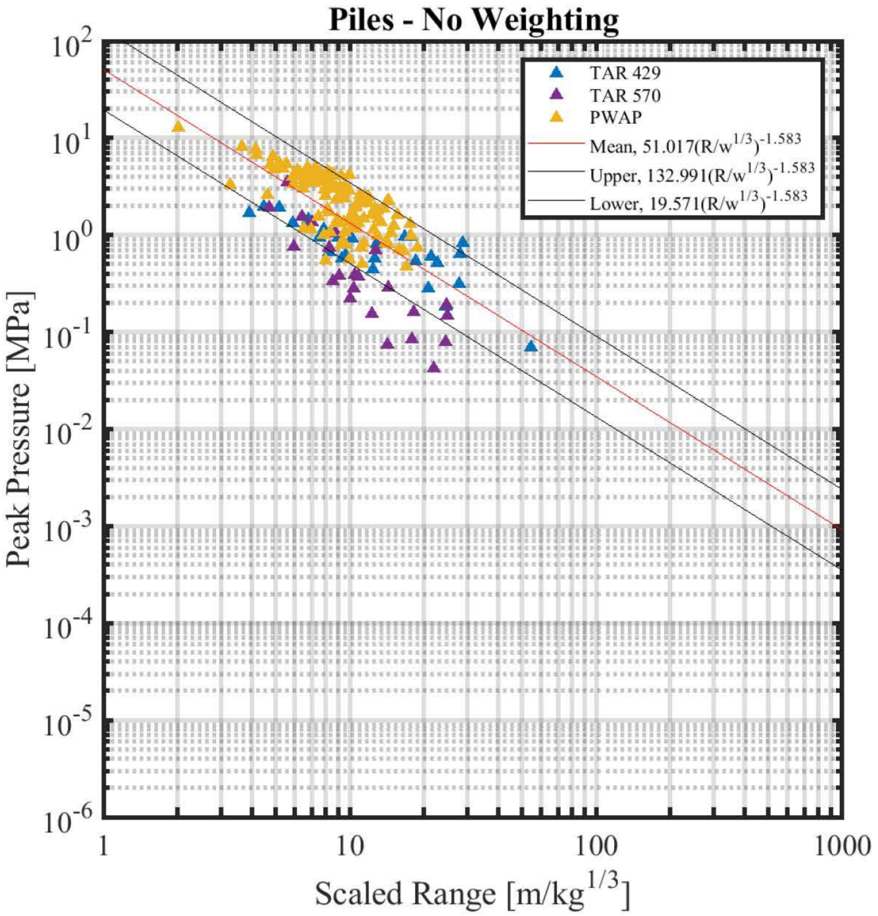


Figure 25. Peak Pressure versus Scaled Range calculated for 200 lbs. of Comp B explosive in a main pile.

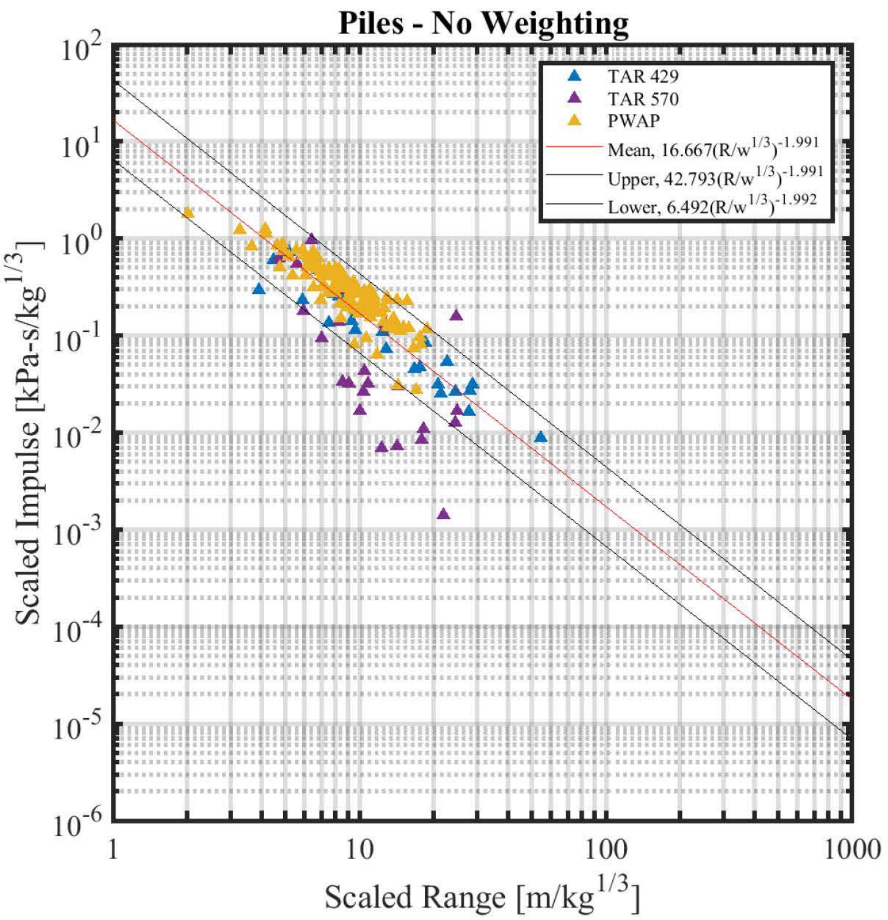


Figure 26. Scaled Impulse versus Scaled Range calculated for 200 lbs. of Comp B explosive in a main pile.

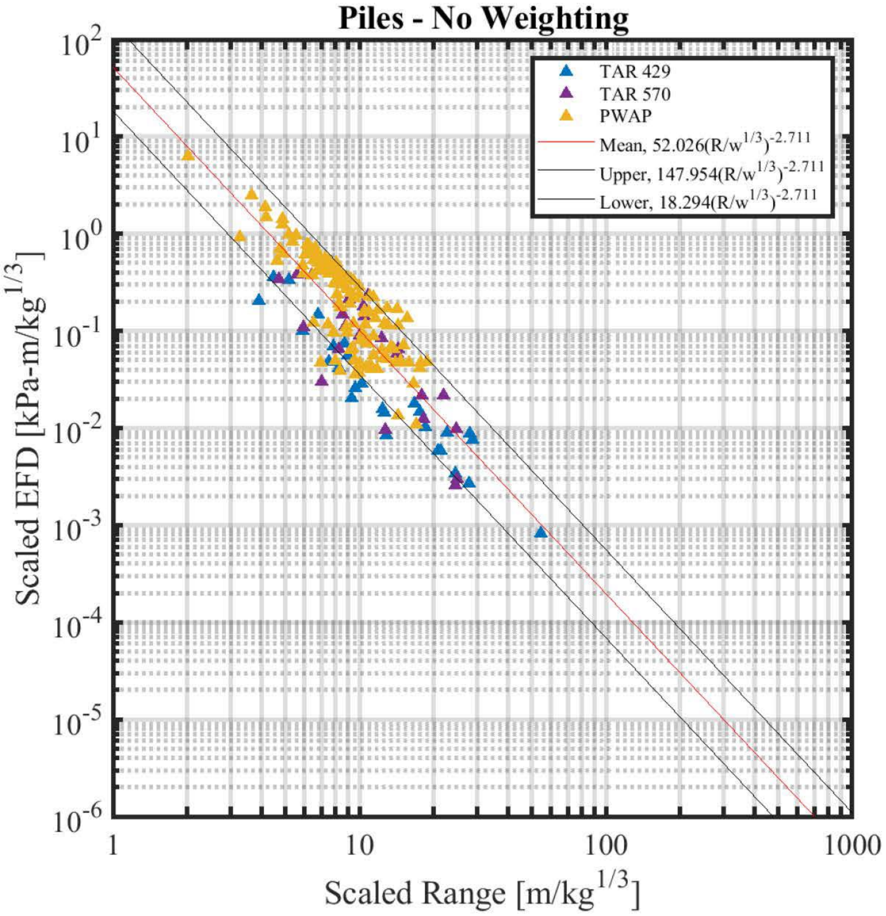


Figure 27. Unweighted Scaled EFD versus Scaled Range calculated for 200 lbs. of Comp B explosive in a main pile.

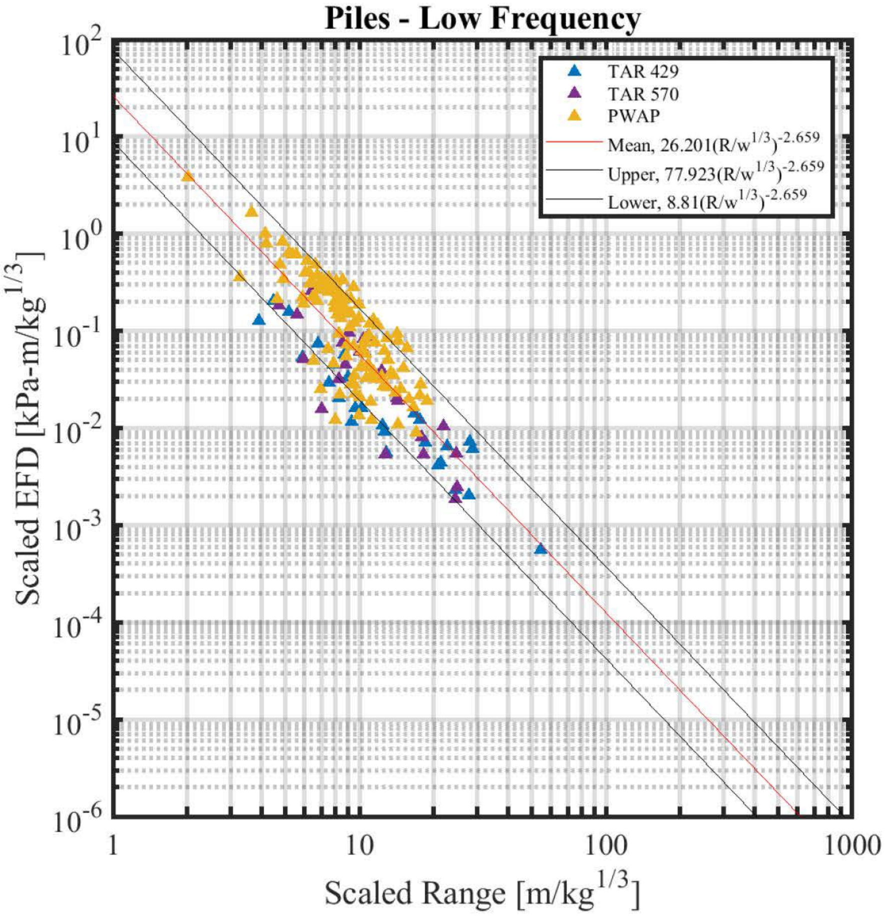


Figure 28. Low Frequency Weighted Scaled EFD versus Scaled Range calculated for 200 lbs. of Comp B explosive in a main pile.

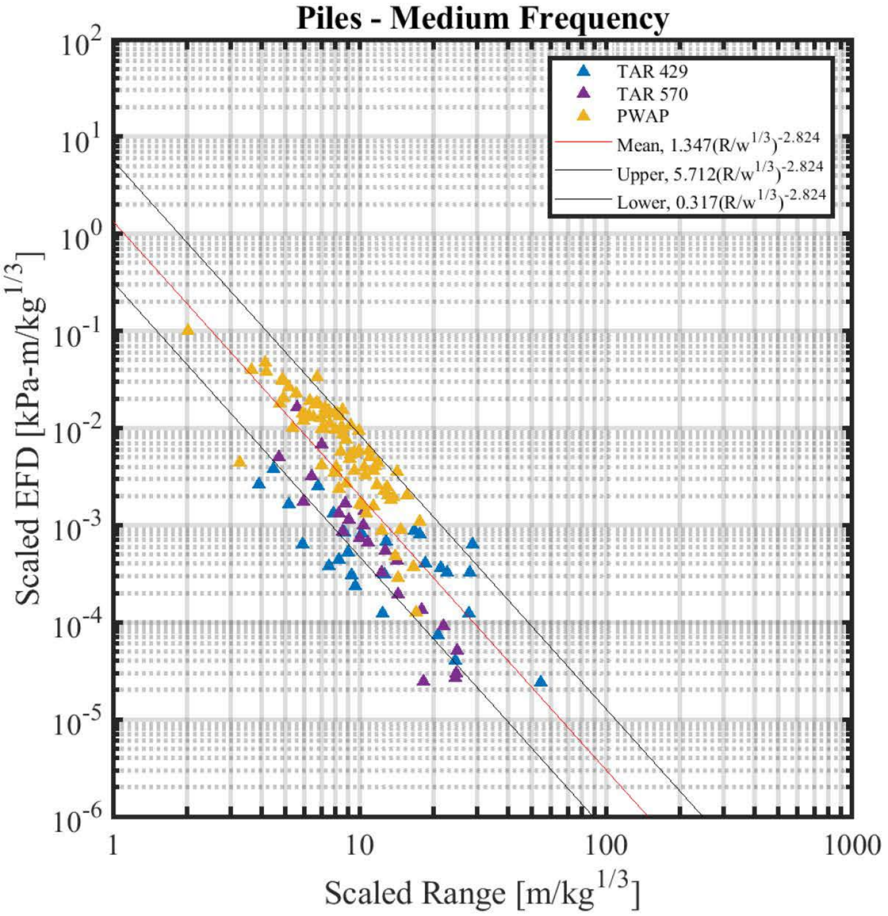


Figure 29. Mid Frequency Weighted Scaled EFD versus Scaled Range calculated for 200 lbs. of Comp B explosive in a main pile.

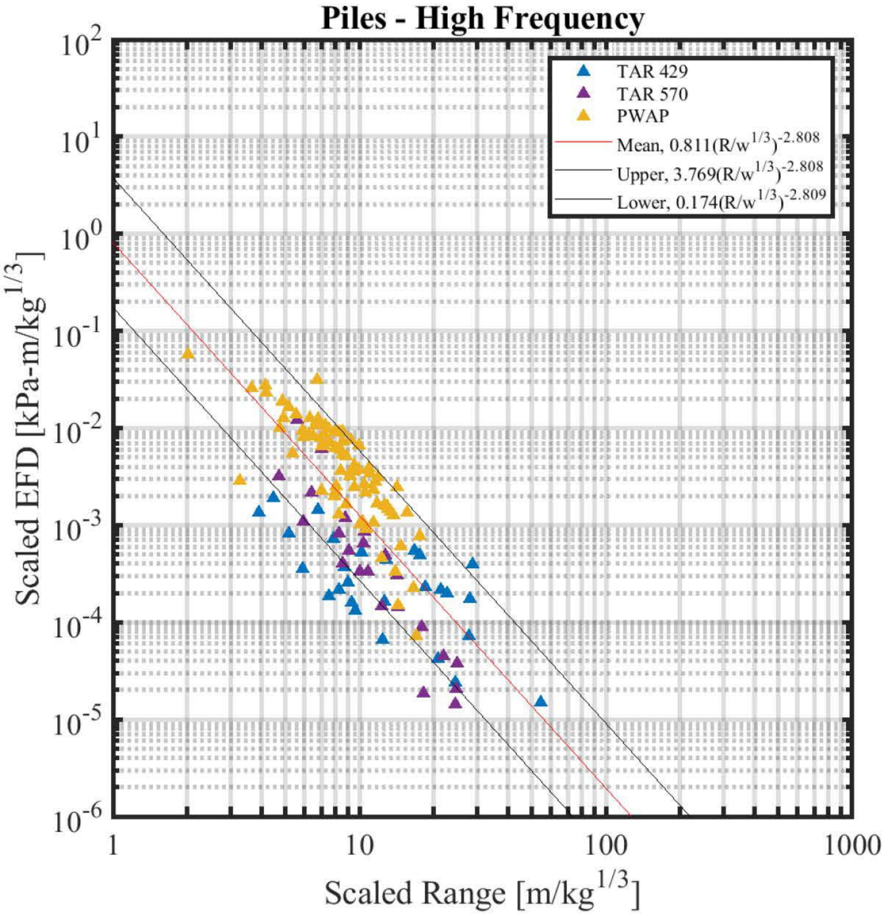


Figure 30. High Frequency Weighted Scaled EFD versus Scaled Range calculated for 200 lbs. of Comp B explosive in a main pile.

7.4. Conductor: 20 lb. Comp B Pressure, Impulse, Total EFD, and Frequency-weighted versus Scaled Distance Plots

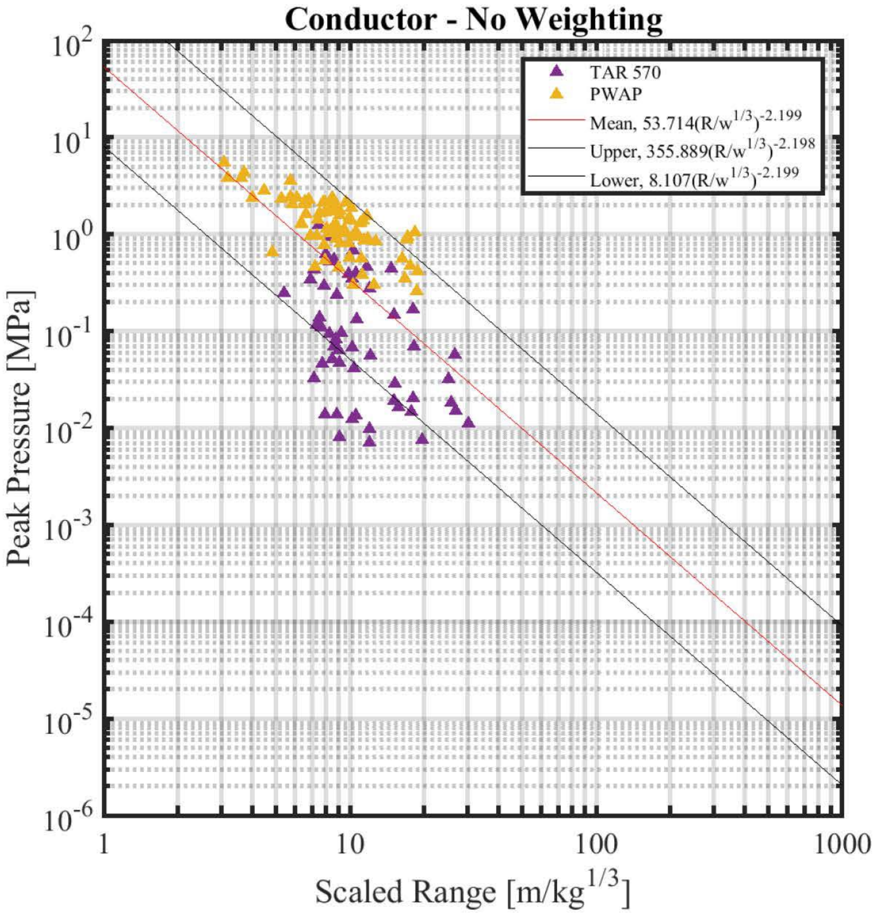


Figure 31. Peak Pressure versus Scaled Range calculated for 20 lbs. of Comp B explosive in a well conductor.

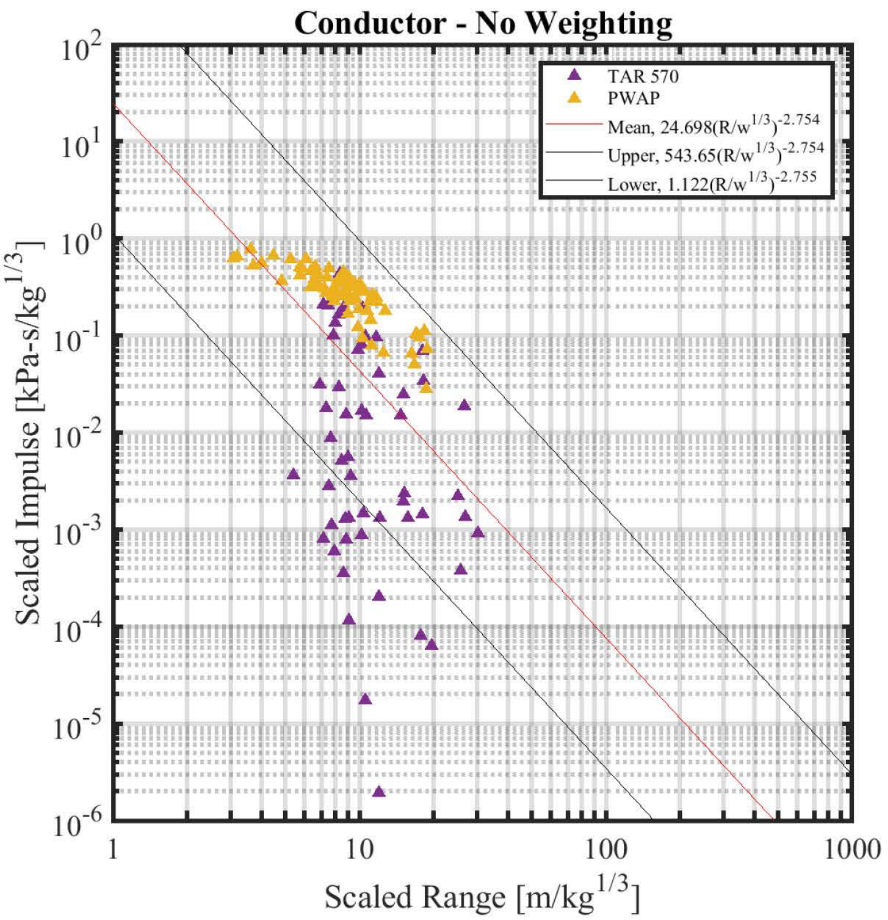


Figure 32. Scaled Impulse versus Scaled Range calculated for 20 lbs. of Comp B explosive in a well conductor.

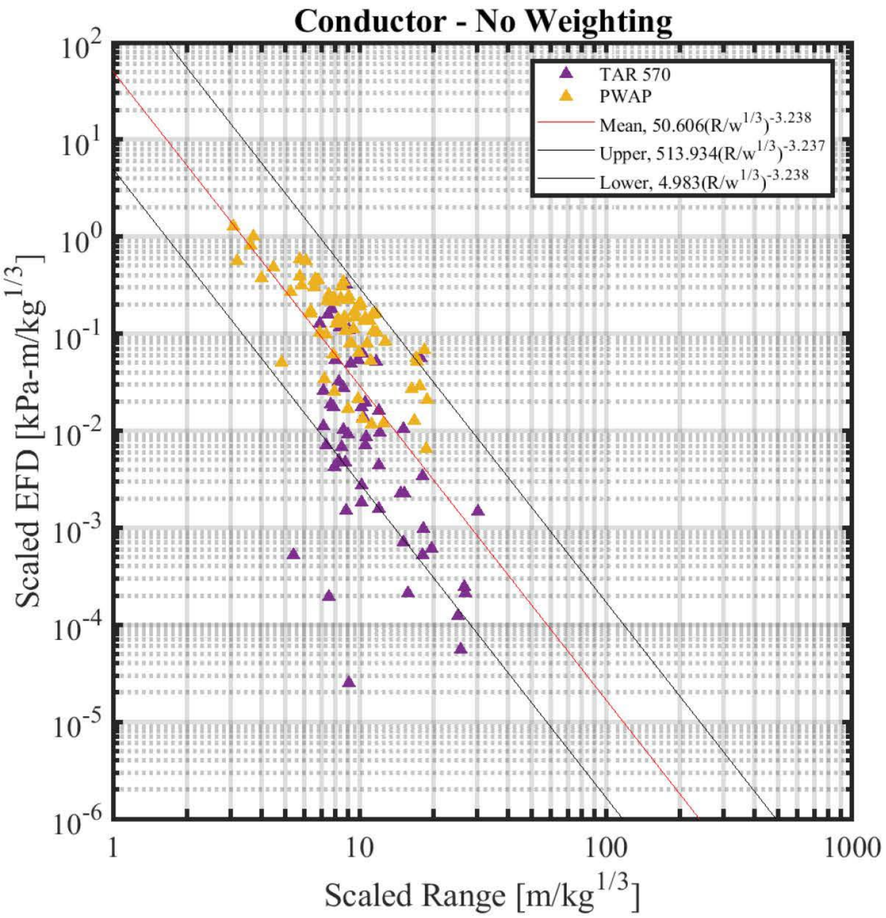


Figure 33. Unweighted Scaled EFD versus Scaled Range calculated for 20 lbs. of Comp B explosive in a well conductor.

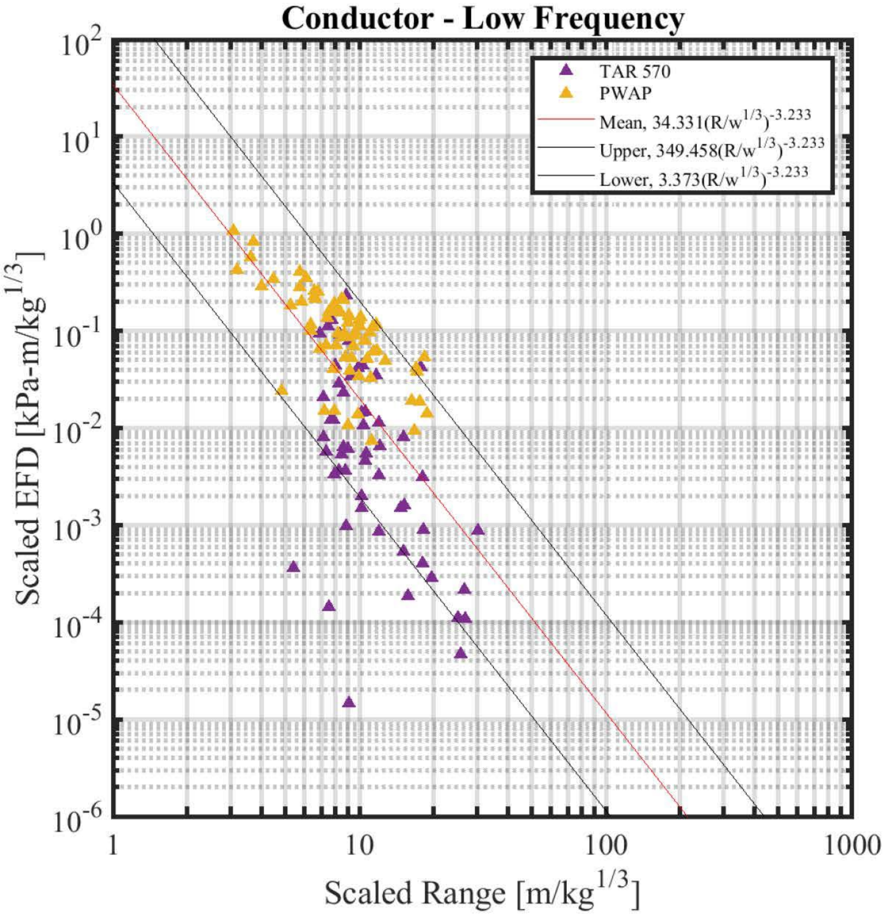


Figure 34. Low Frequency Weighted Scaled EFD versus Scaled Range calculated for 20 lbs. of Comp B explosive in a well conductor.

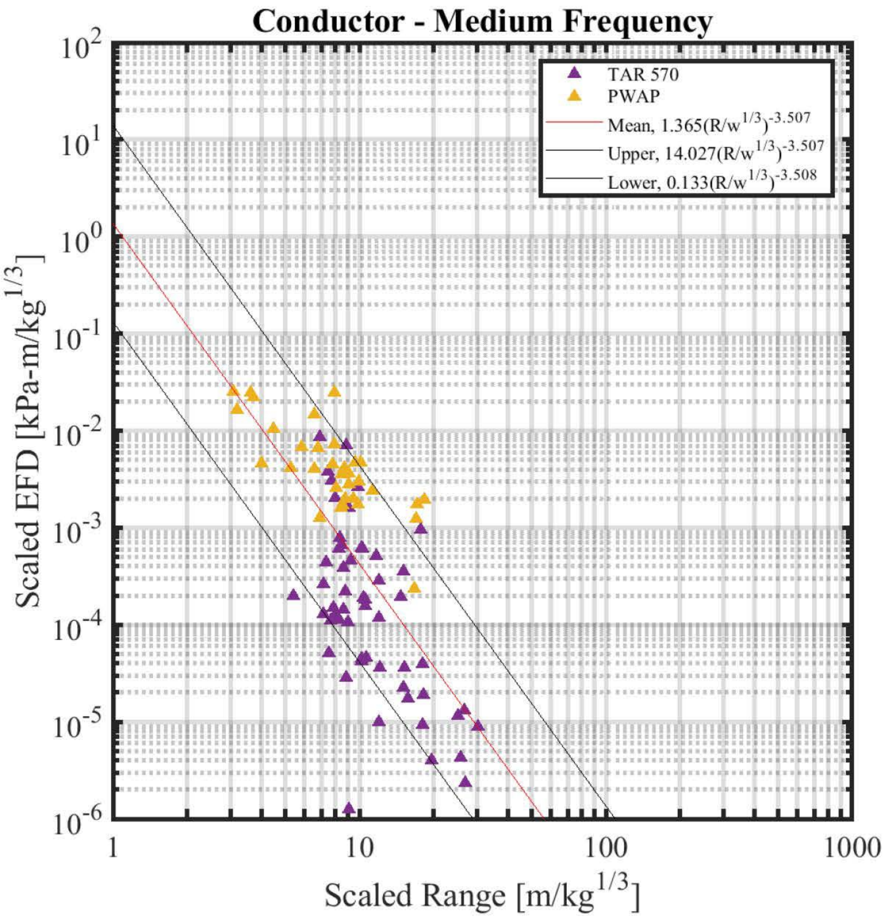


Figure 35. Mid Frequency Weighted Scaled EFD versus Scaled Range calculated for 20 lbs. of Comp B explosive in a well conductor.

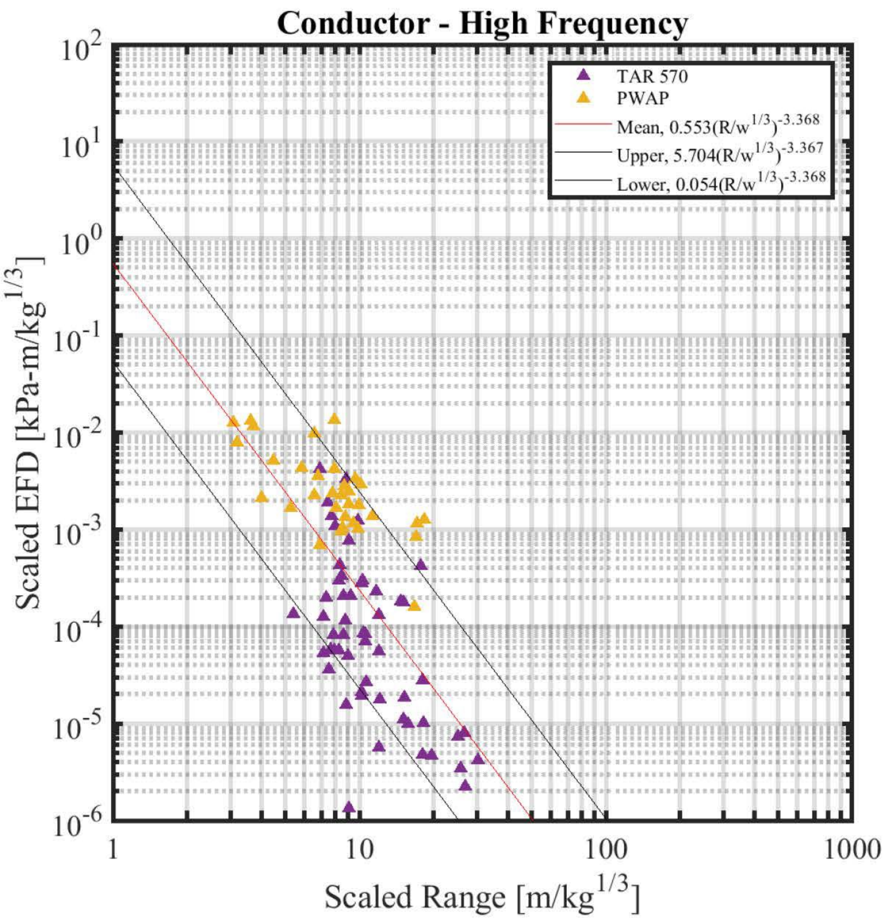


Figure 36. High Frequency Weighted Scaled EFD versus Scaled Range calculated for 20 lbs. of Comp B explosive in a well conductor.

7.5. Conductor: 80 lb. Comp B Pressure, Impulse, Total EFD, and Frequency-weighted versus Scaled Distance Plots

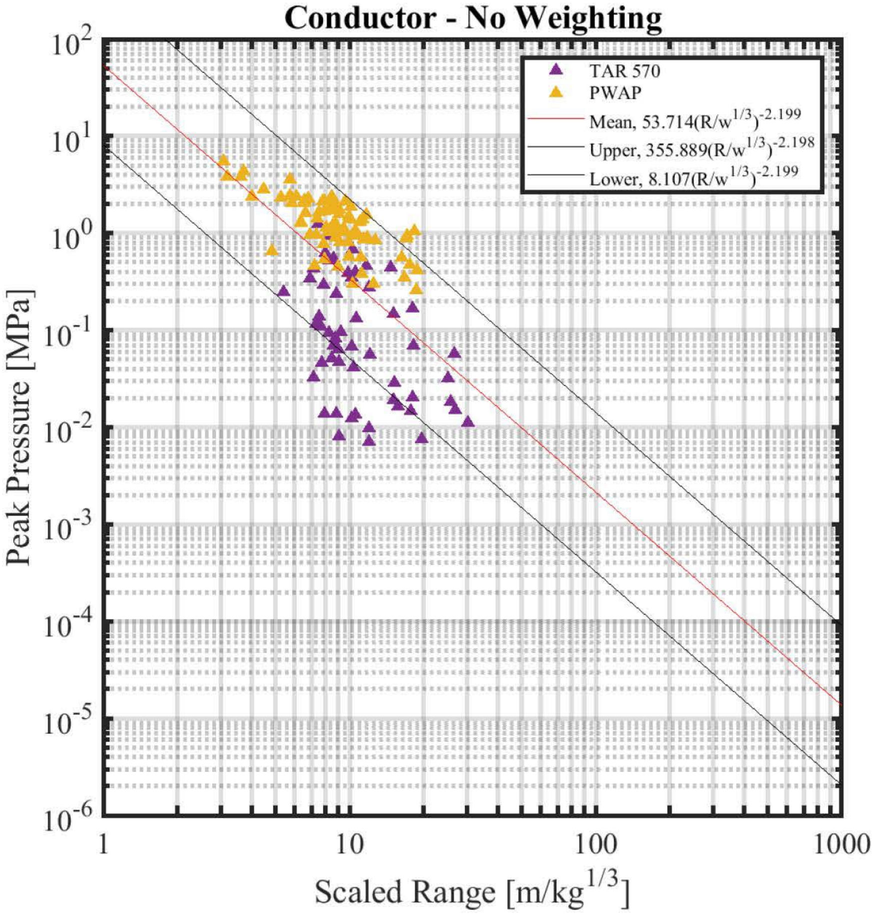


Figure 37. Peak Pressure versus Scaled Range calculated for 80 lbs. of Comp B explosive in a well conductor.

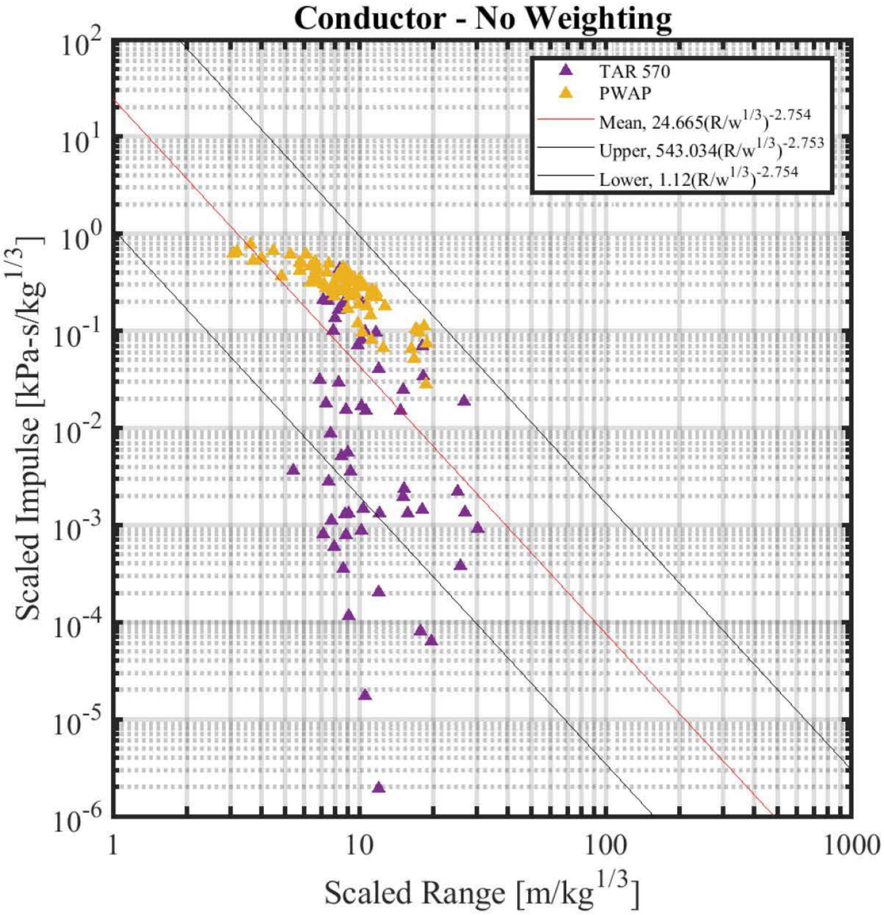


Figure 38. Scaled Impulse versus Scaled Range calculated for 80 lbs. of Comp B explosive in a well conductor.

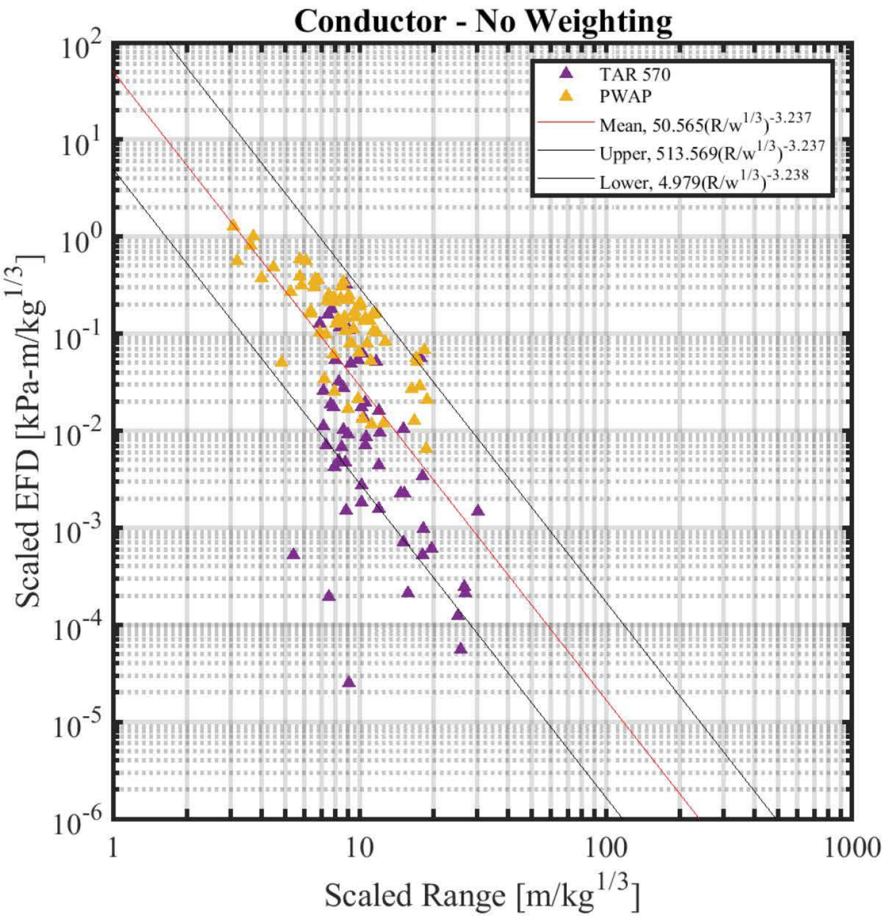


Figure 39. Unweighted Scaled EFD versus Scaled Range calculated for 80 lbs. of Comp B explosive in a well conductor.

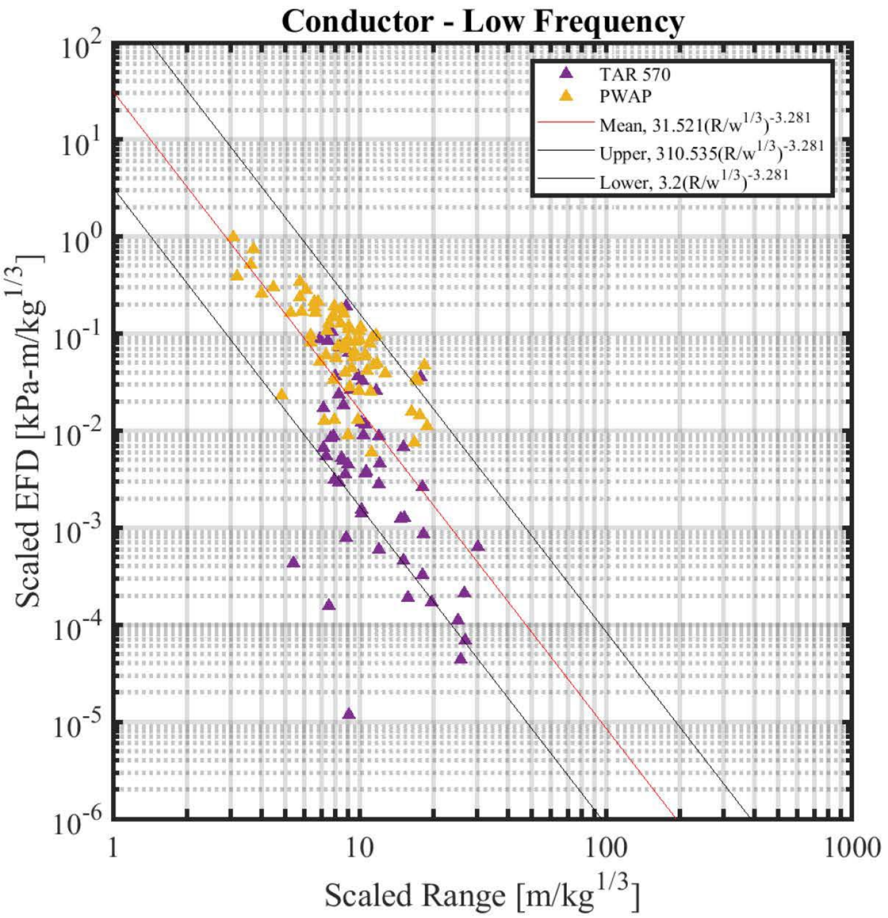


Figure 40. Low Frequency Weighted Scaled EFD versus Scaled Range calculated for 80 lbs. of Comp B explosive in a well conductor.

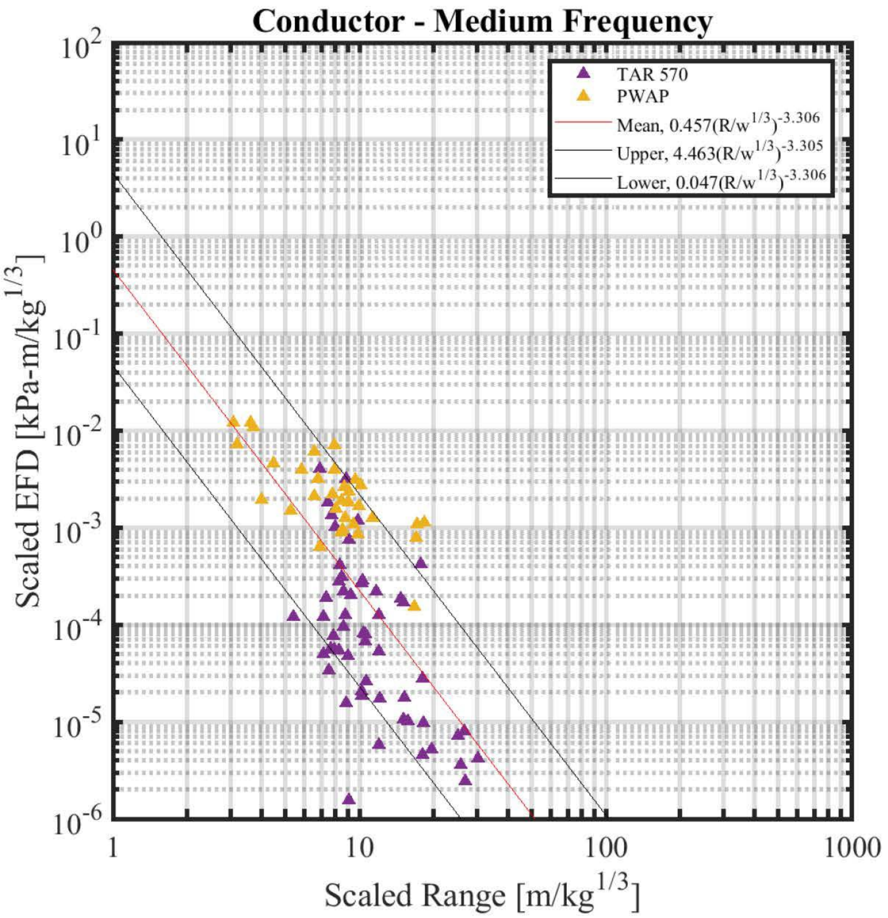


Figure 41. Mid Frequency Weighted Scaled EFD versus Scaled Range calculated for 80 lbs. of Comp B explosive in a well conductor.

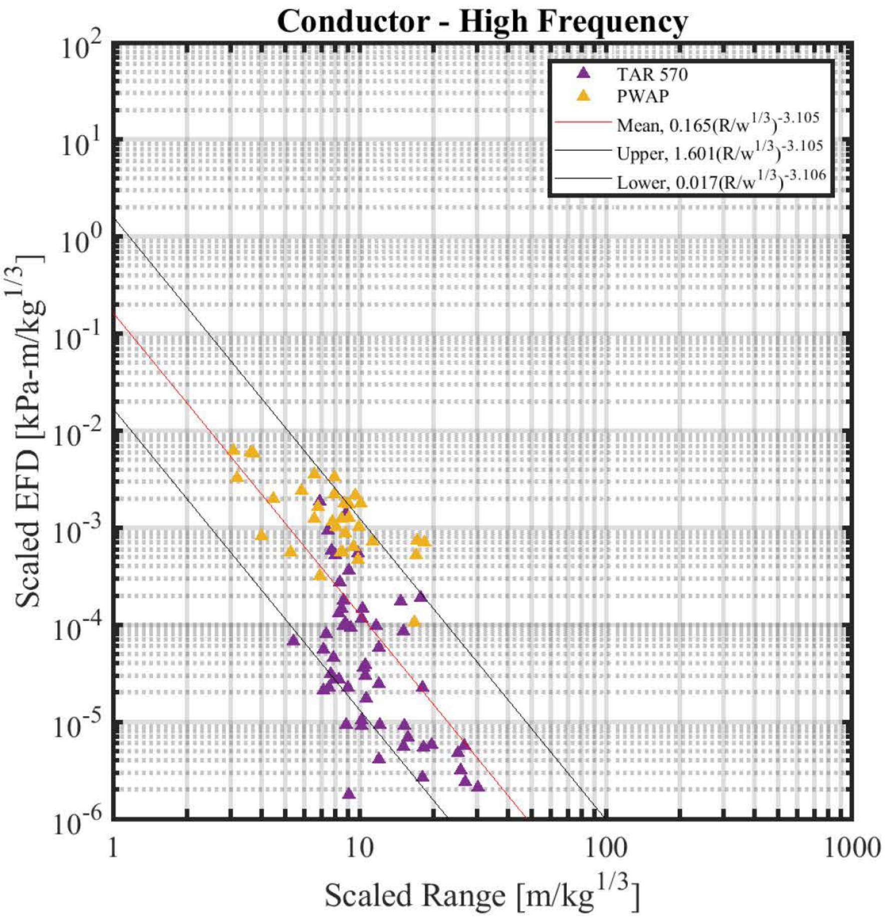


Figure 42. High Frequency Weighted Scaled EFD versus Scaled Range calculated for 80 lbs. of Comp B explosive in a well conductor.

7.6. Conductor: 200 lb. Comp B Pressure, Impulse, Total EFD, and Frequency-weighted versus Scaled Distance Plots

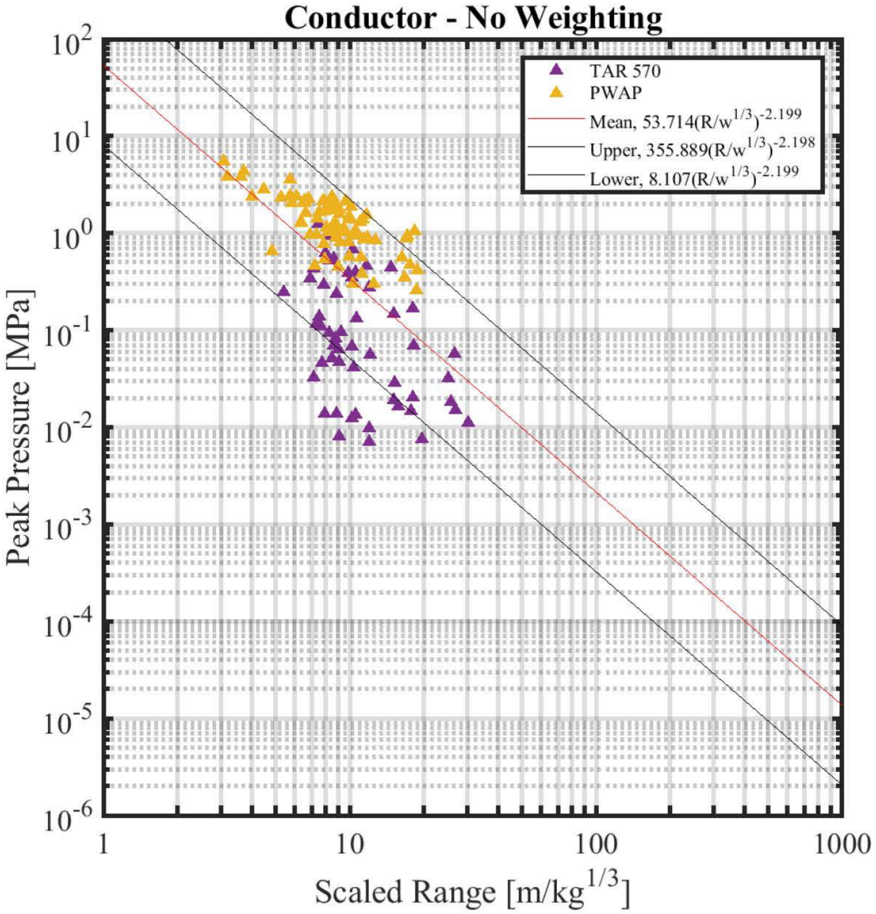


Figure 43. Peak Pressure versus Scaled Range calculated for 200 lbs. of Comp B explosive in a well conductor.

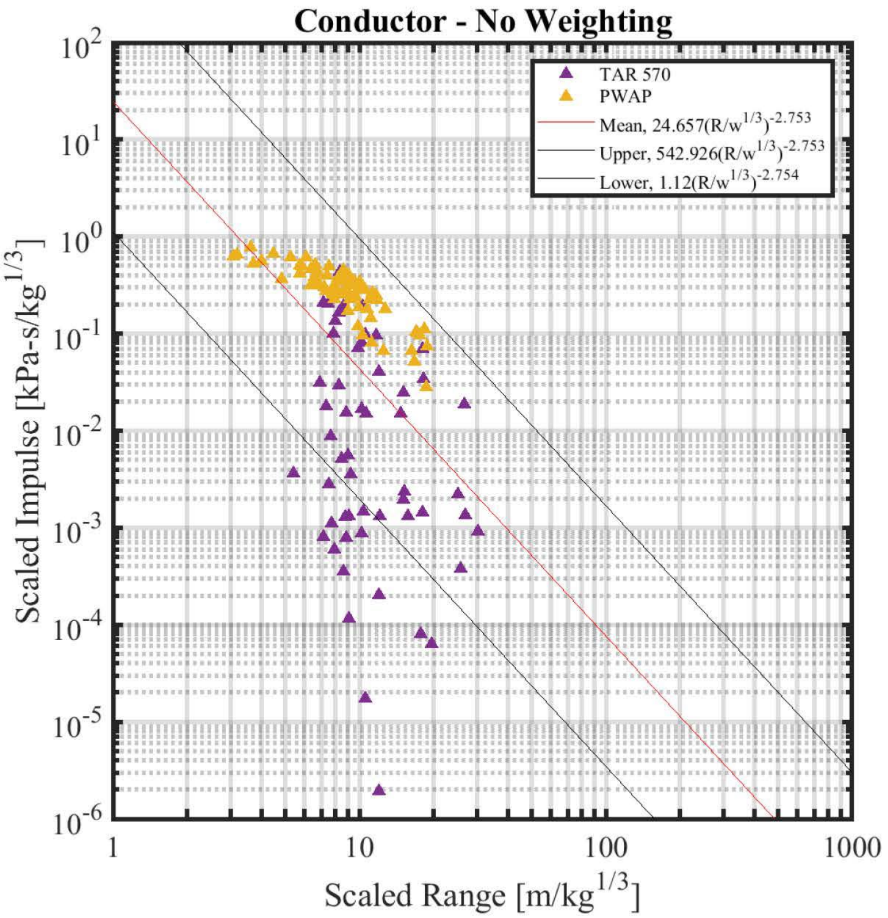


Figure 44. Scaled Impulse versus Scaled Range calculated for 200 lbs. of Comp B explosive in a well conductor.

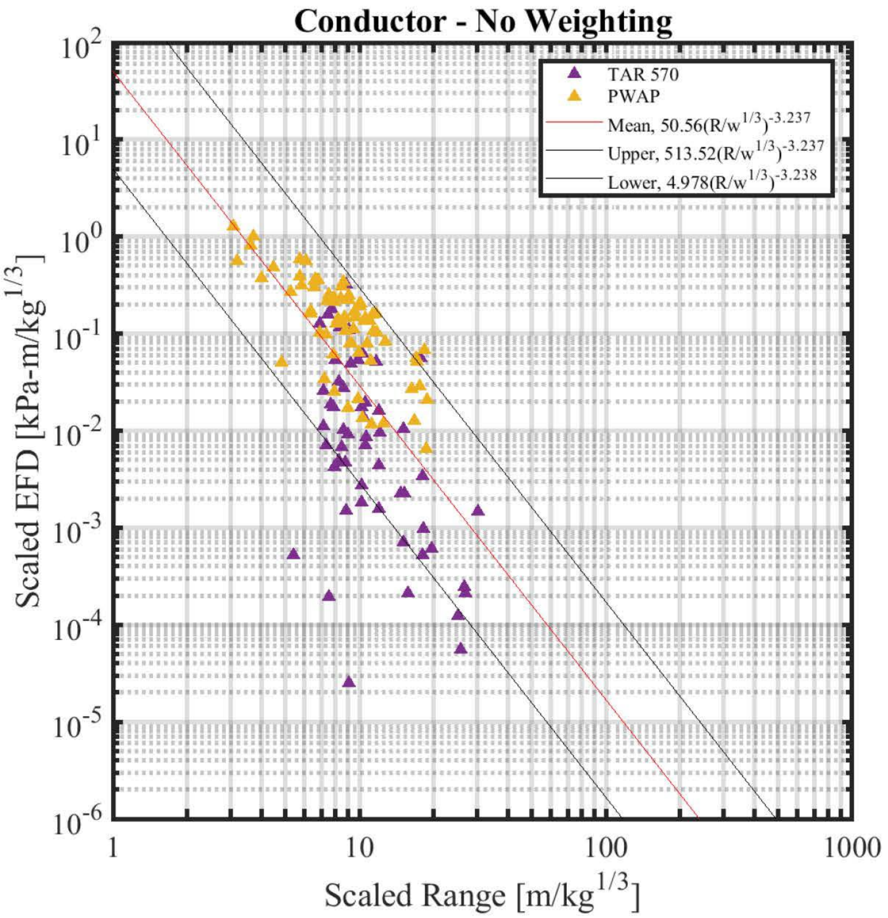


Figure 45. Unweighted Scaled EFD versus Scaled Range calculated for 200 lbs. of Comp B explosive in a well conductor.

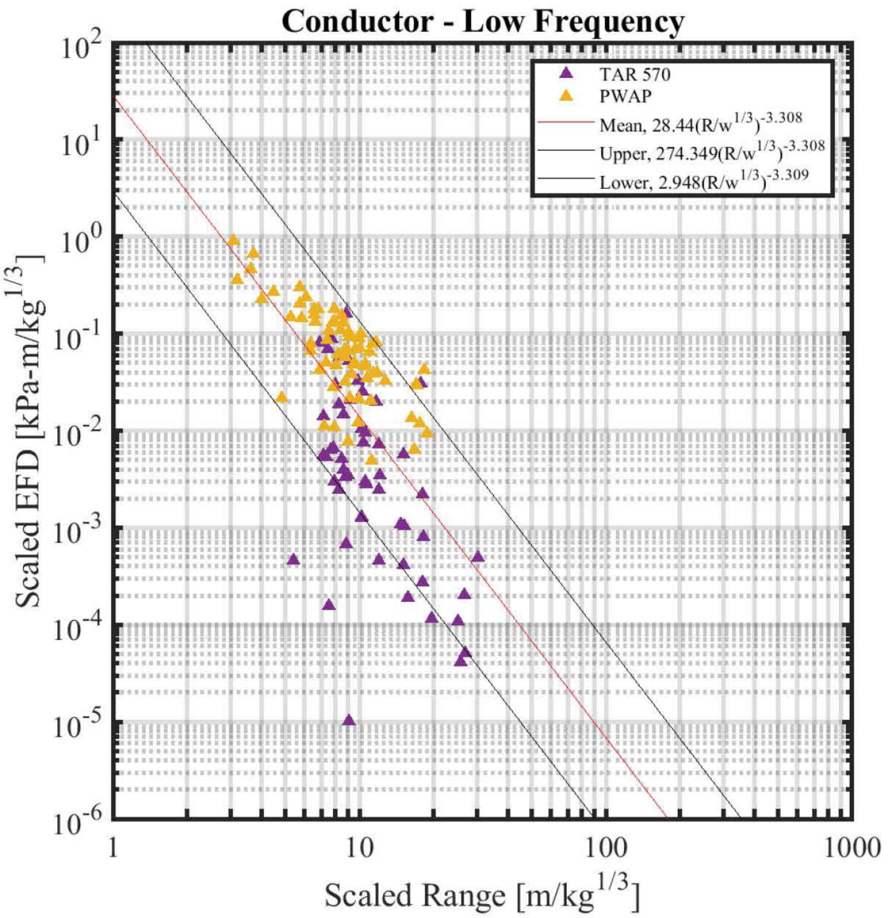


Figure 46. Low Frequency Weighted Scaled EFD versus Scaled Range calculated for 200 lbs. of Comp B explosive in a well conductor.

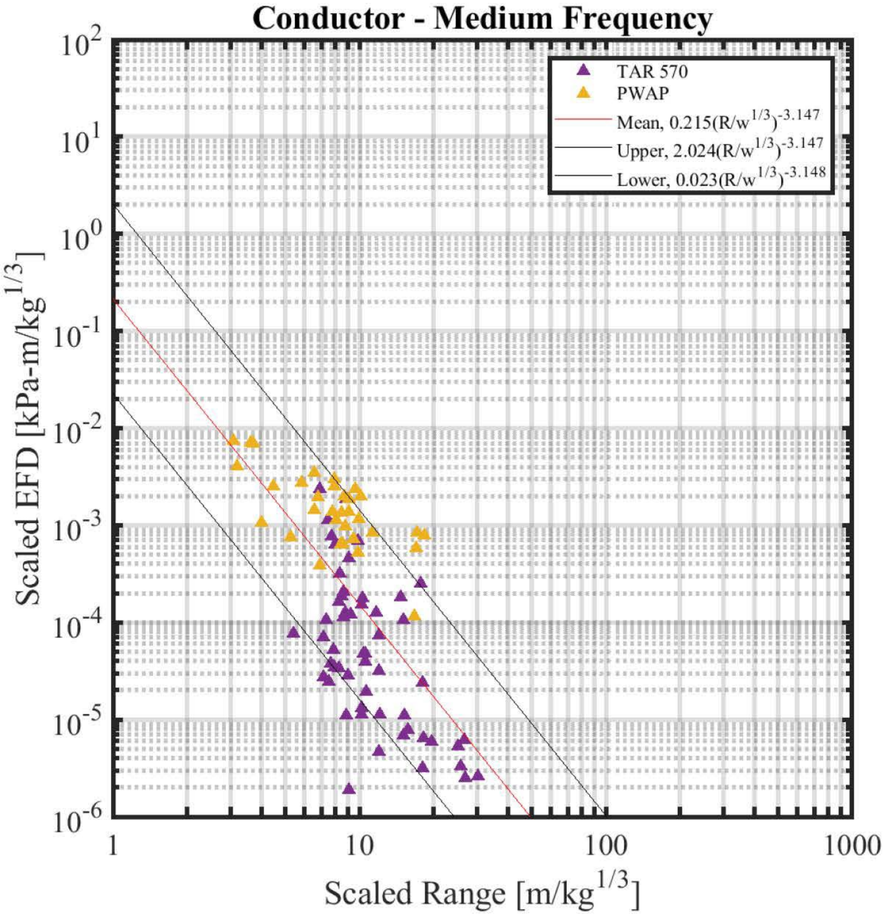


Figure 47. Mid Frequency Weighted Scaled EFD versus Scaled Range calculated for 200 lbs. of Comp B explosive in a well conductor.

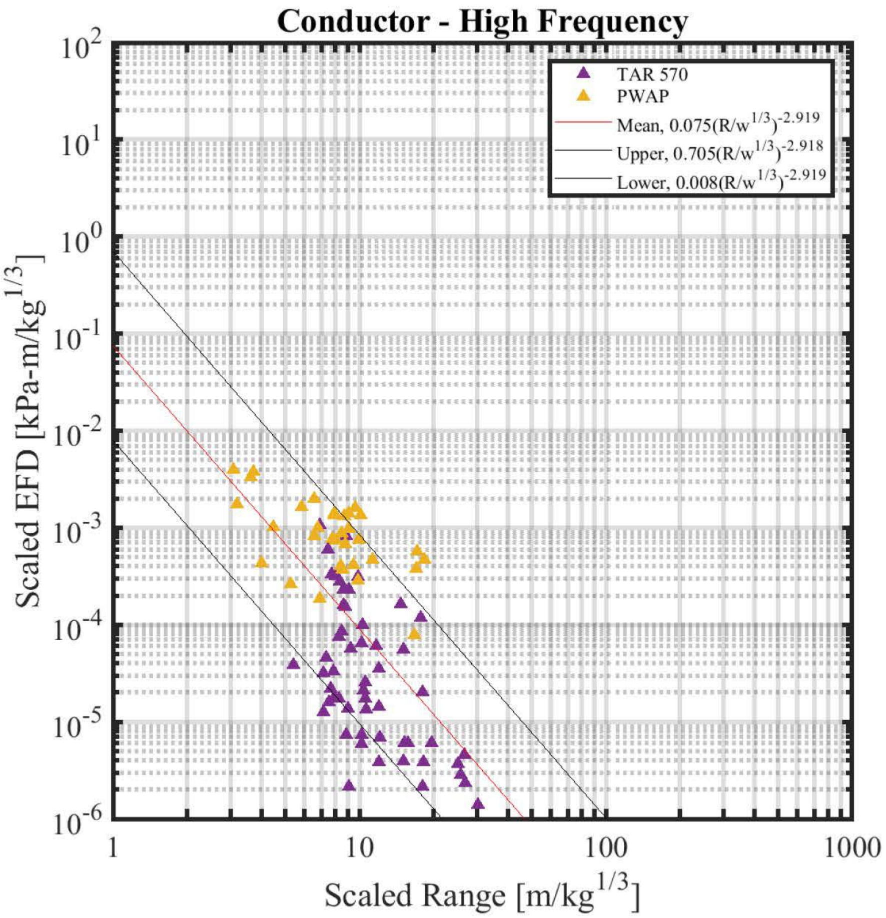


Figure 48. High Frequency Weighted Scaled EFD versus Scaled Range calculated for 200 lbs. of Comp B explosive in a well conductor.

7. SPL and SEL versus Range with Criteria

Using UWC3, the results of the data analysis can be presented in terms of SPL and SEL versus range and compared to the isopleth threshold criteria. This was done for SPL for PTS and TTS in Section 7.1. The SPL plots can be presented as a function of scaled range, so they are appropriate for a variety of explosive yields.

In contrast, the SEL vs. range plots are not independent of explosive mass, so the main pile and conductor PTS and TTS plots were developed for one typical explosive mass of 80 lb. Comp B. These plots with criteria are in Section 7.2.

7.1. SPL versus Range with Criteria

The SPL versus scaled range plot with PTS criteria for the three hearing groups is shown in Figure 49 for main piles and conductors. Similarly, the relationship for TTS is shown in Figure 50. These two SPL plots are applicable for all explosive masses as peak pressure is not weighted by frequency; however, each of the three hearing groups has its own threshold as indicated on the figure.

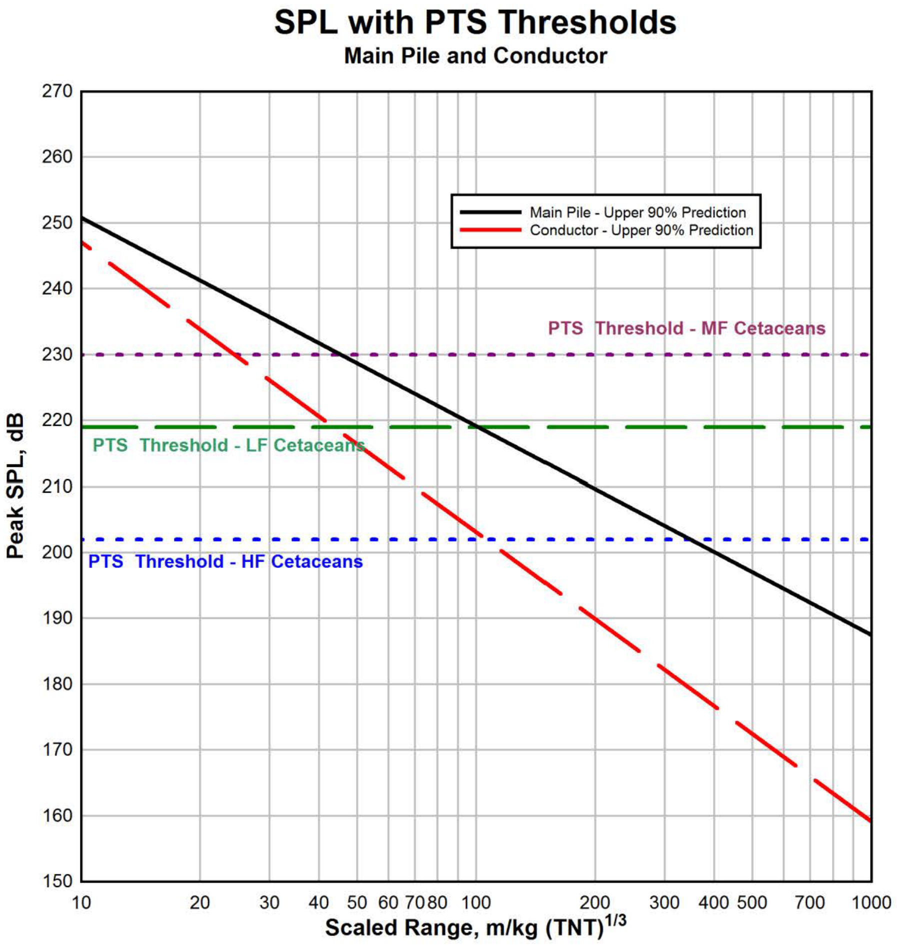


Figure 49. UWC3 peak pressure predictions for main piles and well conductors compared with the PTS thresholds.

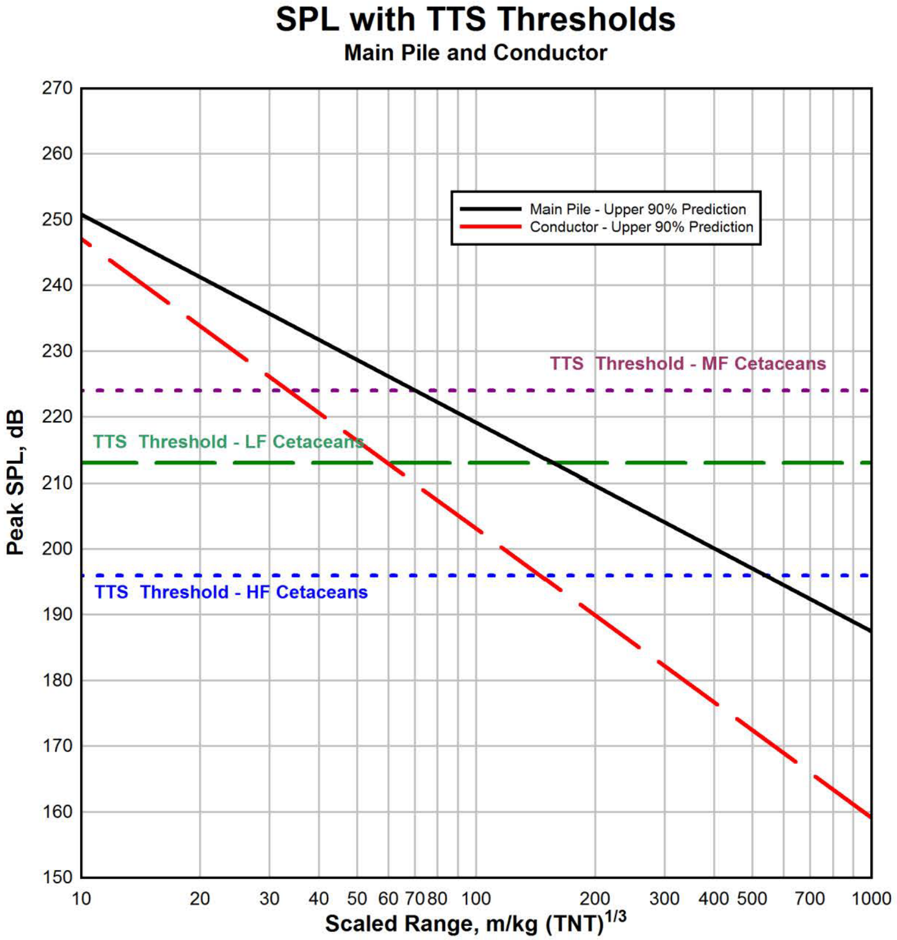


Figure 50. UWC3 peak pressure predictions for main piles and well conductors compared with the TTS thresholds.

In order to give the reader an idea of the PTS and TTS isopleths for common EROS operations, the following tables are presented for 80 lb. and 200 lb. Comp B explosive charges for both main pile and conductor scenarios. The threshold distances increase with charge size and scenario, with the main charge pile having larger distances than the conductor.

Table 3. 80 lb. Comp B Isopleths for SPL Criteria, Main Piles

Criteria	Low- Frequency	Mid-Frequency	High-Frequency
PTS	377 m	166 m	1274 m
TTS	573 m	257 m	1972 m

Table 4. 80 lb. Comp B Isopleths for SPL Criteria, Well Conductors

Criteria	Low- Frequency	Mid-Frequency	High-Frequency
PTS	159 m	89 m	388 m
TTS	218	122 m	531 m

Table 5. 200 lb. Comp B Isopleths for SPL Criteria, Main Piles

Criteria	Low- Frequency	Mid-Frequency	High-Frequency
PTS	502 m	226 m	1729 m
TTS	777 m	349 m	2675 m

Table 6. 200 lb. Comp B Isopleths for SPL Criteria, Well Conductors

Criteria	Low- Frequency	Mid-Frequency	High-Frequency
PTS	216 m	121 m	526 m
TTS	296 m	166 m	720 m

7.2. SEL versus Range with Criteria

The four plots below (Figures 51-54) show the SEL-distance relationships for an 80 lb. Comp B charge severing both a main pile and a conductor compared to the PTS and TTS thresholds for the three hearing groups. These are for a single explosive event. If there are multiple events during the EROS operation or within a 24-hour period, UWC3 is set up to handle the cumulative nature of SEL. To determine the various isopleths from these plots, one matches the color of the threshold line to the color of the SEL-distance relationship and reads off the distance.

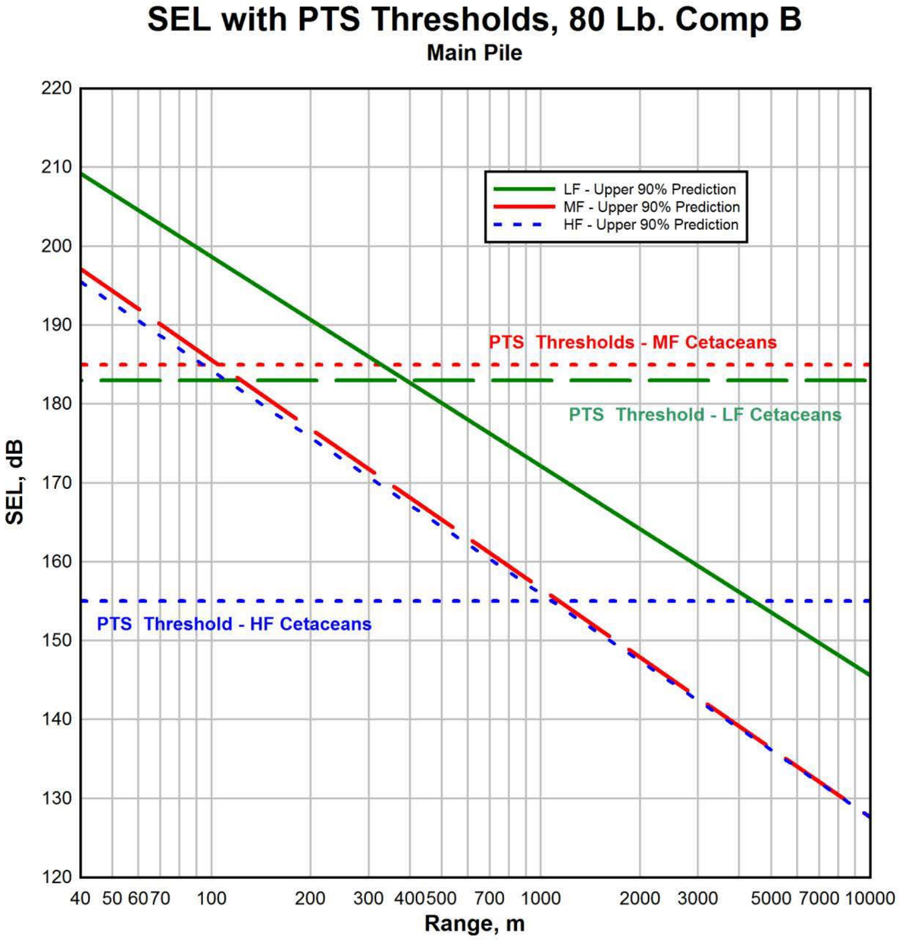


Figure 51. UWC3 SEL predictions for main piles compared with the PTS thresholds.

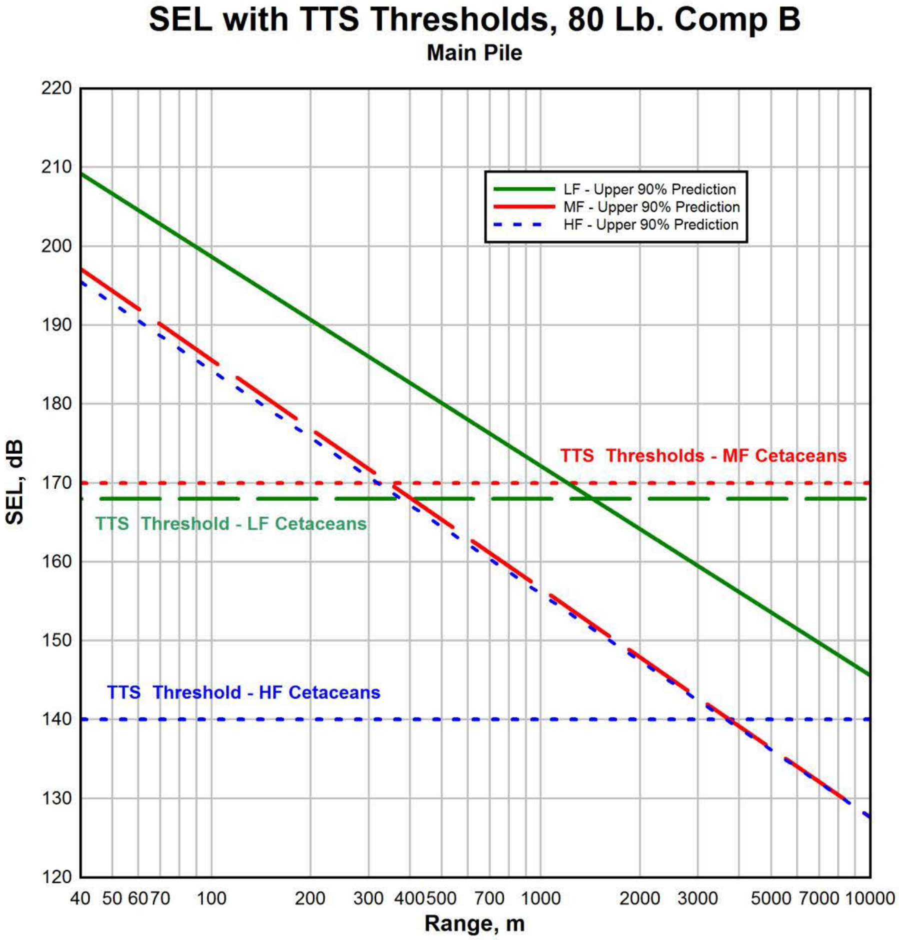


Figure 52. UWC3 SEL predictions for main piles compared with the TTS thresholds.

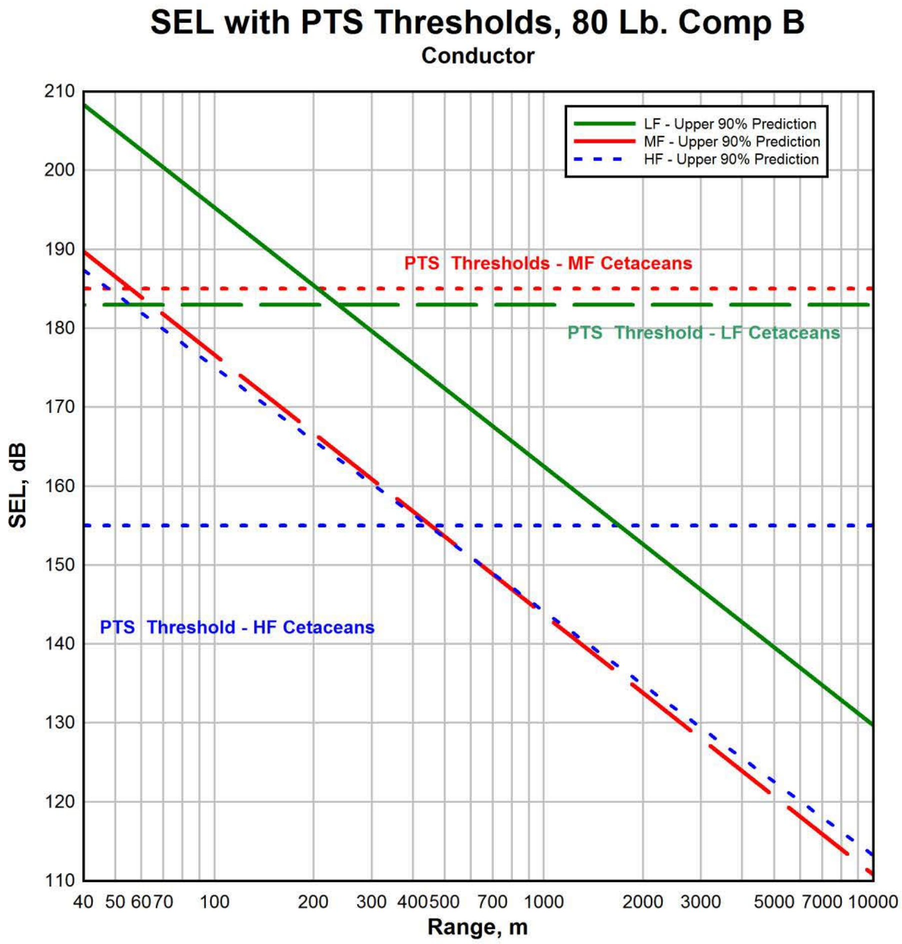


Figure 53. UWC3 SEL predictions for well conductors compared with the PTS thresholds.

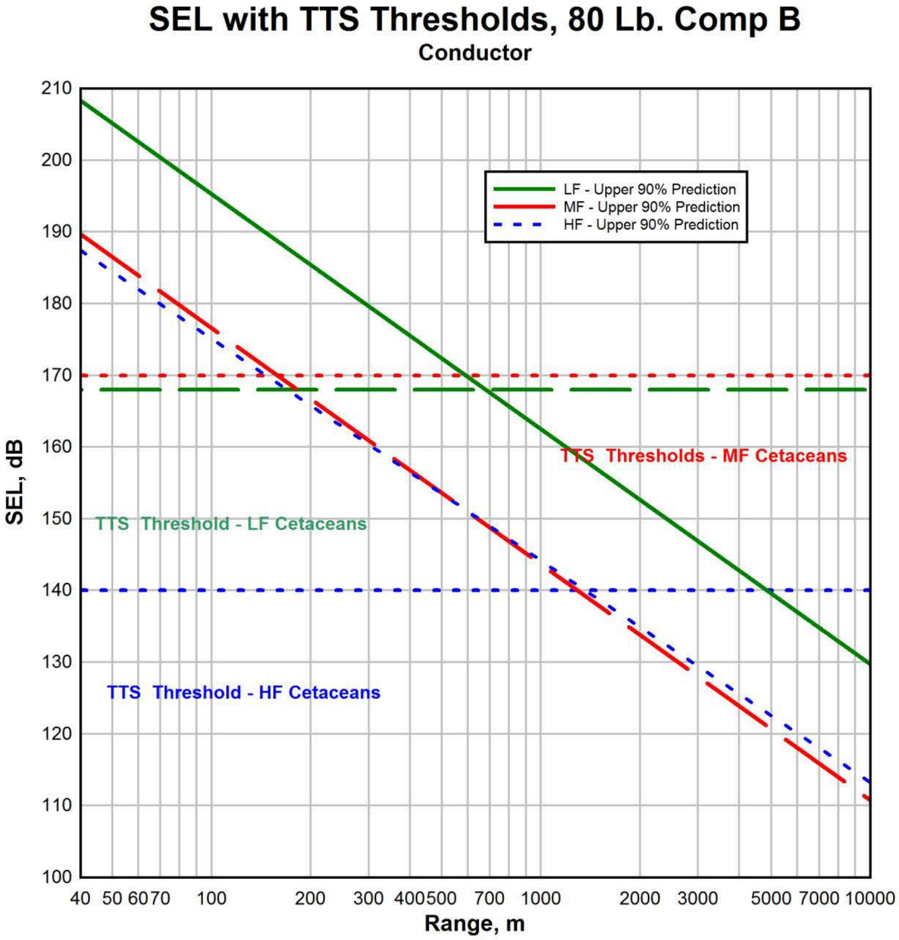


Figure 54. UWC3 SEL predictions for well conductors compared with the TTS thresholds.

8. Conclusions

The UnderWater Calculator 3 (UWC3) is a spreadsheet-based tool that calculates the underwater shock, namely, Sound Pressure Level (SPL), Impulse, and Sound Exposure Level (SEL), caused by the use of explosives for removal of offshore structures (EROS). The primary use of this tool is to calculate the isopleth (range) to specified criteria for permanent threshold shift (PTS), temporary threshold shift (TTS), behavioral effects, and injury for marine mammals.

The UWC3 threshold distance criteria are from the National Marine Fisheries Service. The PTS and TTS criteria are based in terms of both SPL and SEL, while behavioral effects are based upon SEL. The SEL criteria is specified by the low-, mid-, and high-frequency cetacean hearing groups. To determine the SEL as function of range and explosive mass, the pressure-time histories were processed using the provided auditory weighting functions for the three hearing groups. TAR429, TAR570, and PWAP had available the required pressure time histories to allow this analysis to be accomplished. In addition, to account for the wide variability in data, the relationships for the upper 90% percentile prediction were calculated and implemented as the calculated value in the UWC3 to reduce the chance of under-predicting the distances to thresholds.

The UWC3 is very flexible—updated shock environments, as specified by SPL, SEL, and impulse, can be entered, the criteria for PTS, TTS, and injury can be changed, other pile scenario can be added, and additional explosives can entered. Also, new and/or additional data can be incorporated into the UWC3 shock environment-distance relationships.

A significant area of improvement be to account for the variability of the data used to develop the shock parameter-distance relationships. In particular, the soil or sediment properties greatly affect the attenuation of the water shock with range. Knowing the soil air or gas content, or the compressional wave speed of the soil as a function of depth and range, may explain the data variability. These soil properties could then be incorporated into the data analysis procedures.

9. References

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