ARA PROJECT 001974

WATER SHOCK PREDICTION FOR EXPLOSIVE REMOVAL OF OFFSHORE STRUCTURES: UNDERWATER CALCULATOR (UWC) VERSION 2.0 UPDATE BASED UPON FIELD DATA

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Executive Summary

The UnderWater Calculator (UWC) is a spreadsheet-based tool that calculates the underwater shock, namely, peak pressure, impulse, and energy, caused by the use of explosives to remove offshore structures. The primary use of this tool is to calculate the range to a specified peak shock pressure and energy level, such as the temporary threshold shift (TTS) Level B. Version 1.0 was published in 2003, and was based on close-in, short time numerical simulations. These numerical simulations showed that less energy (30 to 70% reduction) is coupled to the water for the pile cases than would be coupled for open water explosions. Field data has indicated higher attenuation of peak pressure with range and an energy reduction of 90% or more when compared to open-water data.

The UWC, now referred to as Version 2.0, was updated to account for the newer 23-psi temporary threshold shift (TTS) Level B, and the models of peak value as a function of range are based on field data. The field data that were used include the *in situ* data from the Technical Assessment and Research (TAR) project titled, *"Effect of Depth Below Mudline of Charge Placement During Explosive Removal of Offshore Structures (EROS)"* (TAR Project #570), and earlier data reported by Connor.

Both forward and backward calculation spreadsheets are provided for UWC Version 2.0. The forward calculation provides the peak pressure, impulse and energy flux for a given slant range, explosive weight, and open-water or pile scenario. Conversely, the backward calculation provides the slant range for the Level B pressure and EFD for the different open-water and pile scenarios. The pile scenarios include main piles, well conductors, open caissons, and skirt piles.

Introduction

In 2003, Applied Research Associates Inc. (ARA) developed a method to determine the shock wave propagation into water caused by the explosive removal of offshore structures (EROS). This was accomplished by performing numerical simulations of various explosives, pile, clay, water systems and determining the amount of energy coupled to the water. The numerical simulations showed that less energy (30 to 70% reduction) is coupled to the water for the pile cases than would be coupled for open water explosions. From these results, the UnderWater Calculator (UWC) Version 1.0 spreadsheet was developed to predict peak pressure, impulse, and energy flux density for both the open-water and pile cases[1]. These results were based on early time (15 ms), in-close (25 m) numerical simulations which led to peak pressure attenuation with range factors similar to open water[2] ($R^{-1.13}$ to $R^{-1.22}$).

Close-in, half-scale test data (200-1000 psi) from the Connor report[3] supported this assumption with a measured attenuation of $R^{-1.21}$. However, pressure data at farther ranges and lower peak pressures (2-200 psi) from the TAR 570[4] test series and full-scale Connor tests[3] indicate a much higher attenuation of peak pressure with range (R^{-2} or more) and an energy reduction of 90% or more when compared to open-water data. The data with the higher attenuation indicates much closer ranges to the Level B pressure, now 23 psi for explosive weights of less than 2000 lbs., and Energy Flux Density (EFD), 182 dB re: 1 μPa^2-s 1/3-octave band.

The analytical support provided by ARA and reported here updated and improved the UWC in two areas. First, the temporary threshold shift (TTS) Level B was increased from 12 psi to 23 psi for explosive weights less than 2000 lbs. This change will lessen the calculated range to the TTS Level B. Second, the *in situ* data from the Technical Assessment and Research (TAR) project titled, *"Effect of Depth Below Mudline of Charge Placement During Explosive Removal of Offshore Structures (EROS)"* (TAR Project #570)[4] were analyzed, and new range-to-effect models for peak pressure, impulse and EFD were developed based on field data.

Update the Temporary Threshold Shift (TTS) Level B from 12 to 23 psi

The following items were accomplished:

- The new 23-psi Level B threshold for charge weights below 2000 lbs. was incorporated to the UWC
- Range to the 23-psi level was calculated for a range of inputs
- Comparisons were made between the 23-psi and 12-psi peak pressure
    - For example, for a 50-lb. explosive weight, the open-water range was reduced from 2846’ (12 psi) to 1608’ (23 psi). The EROS pile range using the TAR 570 main pile data was reduced from 314’ for 12 psi to 230’ for 23 psi for a 50-lb. explosive.
- The UWC coding was reviewed and improved
- Customary English units were incorporated for input with metric conversion provided
- Features not used were deleted and new ones added
- The pile scenarios include: main pile, well conductors, open caisson, and skirt piles
- Both forward and backward calculation Excel sheets are provided for UWC Version 2.0. The forward calculation provides the peak pressure, impulse and energy flux for a given slant range, explosive weight, and open-water or pile scenario. Conversely, the backward calculation provides the slant range for the Level B pressure and EFD for the different open-water and pile scenarios.

Analysis of Field Data and Development of New 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 TAR 570. The material plot, Figure 1, (explosive shown in red) is shown first and the pressure field is shown at 15.5 ms in Figure 2. The top of the mudline is at zero and the explosive is at 5 m (15') 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 hard layer below the 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. However, the difficulty is that the actual *in situ* soil conditions are generally not known. In particular, the energy losses in the soil have a significant impact on the attenuation in the water. Hence, there is a great need to base the models on field data.

The overall approach was to study the TAR 570 data and review the Connor data. The results of these analyses were used to develop new models of peak pressure, impulse and EFD as a function of explosive weight, range, and open-water and pile scenarios. The peak data vs. 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 the UWC.

The form of the relationships for peak pressure, impulse, and EFD is the same as used by Swisdak[2], Connor[3] and in the UWC Version 1.0[1]. 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.

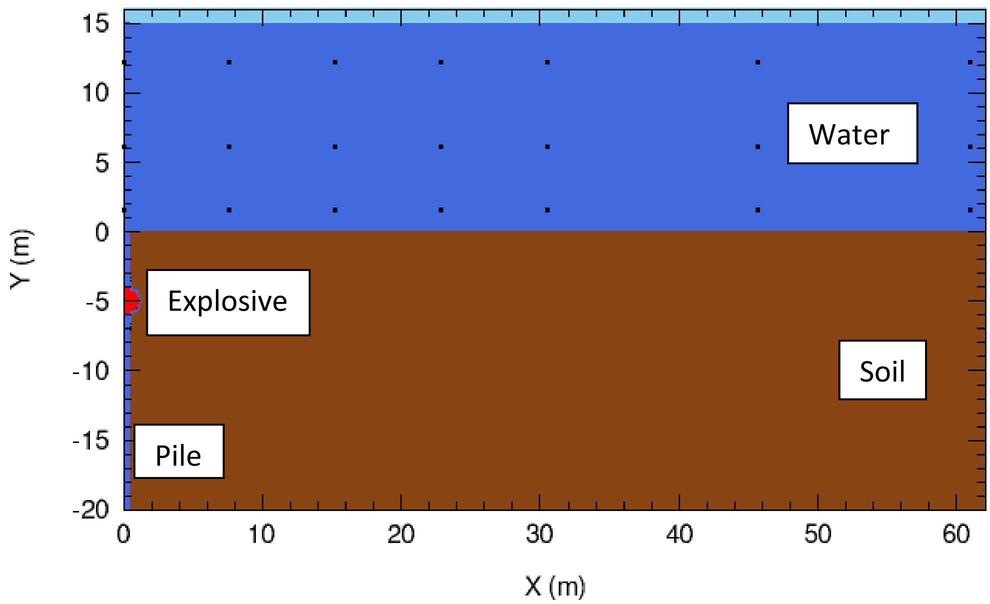

Figure 1. Material Plot for an EROS Numerical Simulation

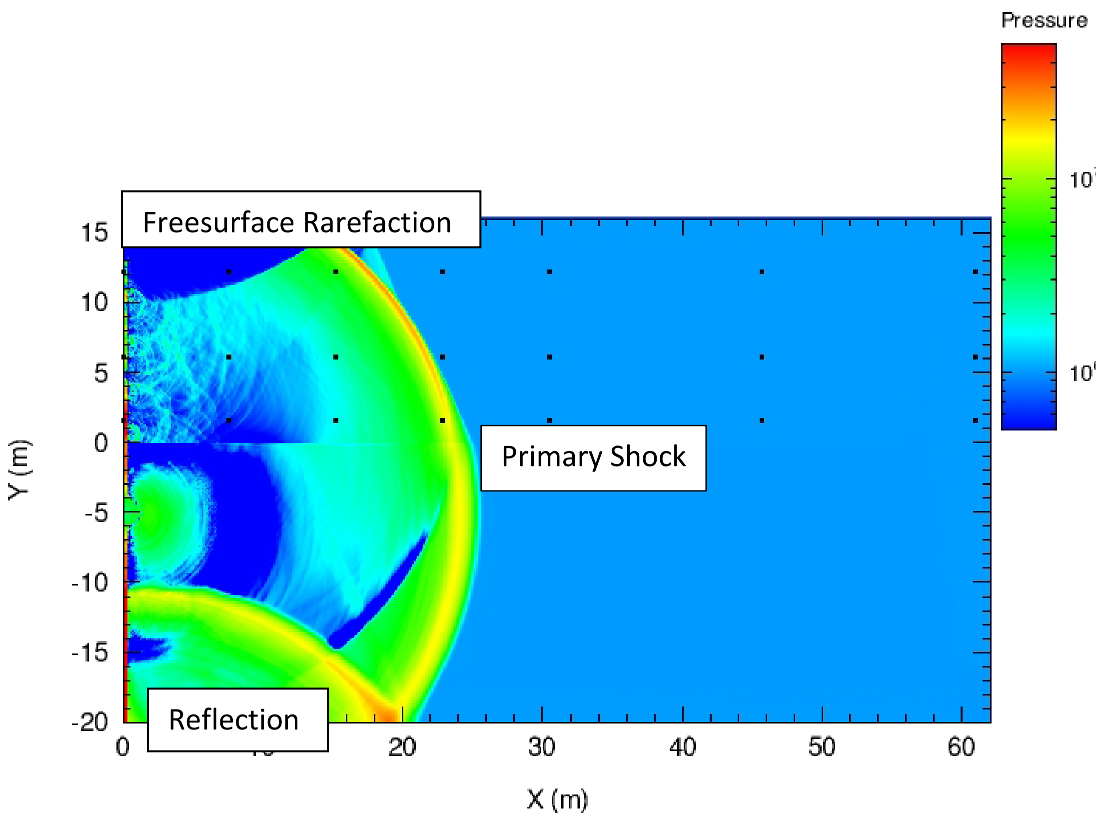

Figure 2. Pressure Plot at 15.5 ms for an EROS Numerical Simulation

The following was accomplished:

- Assembled the peak pressure, impulse, and EFD TAR 570 data
- Developed peak value vs. range plots for both the open-water and pile shots
- Correlated and regressed the peak values as a function of the range and explosive weight
- Developed the models from the experimental data and incorporated them into the UWC

The development of the models is described below. First, the models based on the field data from the 2009 TAR 570 report are described. The TAR 570 peak values used for the model development were the same as those given in the final report[4]. Second, the models from the 1992 Connor report are presented. These figures and relationships were directly copied from that report. The Connor data and relationships were included because: they provided a good comparison, the data is familiar to many, it is a valuable set of data, and one cannot have too much data.

Analysis of 2009 TAR 570 Field Data and Model Development

The peak data was obtained from Appendix D of the TAR 570 report for main piles, well conductors, and caissons. Each of these pile scenarios is described below.

Main Pile

To develop the coefficient for peak pressure, impulse, and EFD as a function of range, data is needed that spans the range of interest. For pressure, data is needed that varies from hundreds of psi down to a few tens of psi. By having this range, the trends and the quality of the data can be evaluated. After reviewing the main pile data, 80-lb bulk charge shots were used as the basis for this model. Other data from TAR 570 were compared to this model as will be presented below.

Shot Conditions	
Pile Diameter	36”
Wall Thickness	1”
Explosive Weight	80 lbs.
Number of Tests	2
Explosive Distance BML (# tests)	15’ (one) 20’ (one)

The peak pressure vs. range plot for the main jackets piles for the 16’ BML shots is shown in Figure 3. Two explosive depths are presented: 15’ BML in blue, and 20’ BML in red. Also, fits are presented for the 15’ BML data, the 20’ BML data, and combined data. Overall, the explosive depth did not seem to affect the peak pressure very much. This is consistent with Connor’s finding: “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”. The key here is the term “precision of the data”. Field data usually has a fair degree of scatter. Also, for these two TAR 570 80-lb. shots, the distance below mudline was only different by 5’.

The combined fit had the highest correlation coefficient of 0.94 as compared to 0.934 for 15’ BML and 0.9144 for 20’ BML. The slightly higher correlation coefficient is due to the higher number of data points in the combined data. The combined fit coefficients were therefore used in the UWC. The UWC coefficients are $K=10^{4.623}$ or 41,976 and $\alpha=1.836$.

Peak pressure values from 50-lb. shots with 15’, 20’, and 30’ BLM were plotted for comparison with the 80-lb. data and fit relationship (Figure 4). The 50-lb. shot data are at large ranges (250’-370’) and low pressures (1 - 30 psi) which results in a large scatter. The scatter is due to natural variability and possibly by the difficulty of measuring such low pressures with 1000-psi pressure transducers. The 50-lb. test data indicated that there is a trend of lower peak pressure with increasing depth BLM of the explosive charge. While the scatter of the data makes it difficult to develop a robust relationship of peak pressure as a function of explosive depth BML and scaled range, the average peak pressure values plotted in Figure 4 for the 50-lb shots indicate the effect. The 15’ BLM had an average peak pressure of 24 psi; the 20’ BLM had an average value of 9 psi; the 30' BML had an average value of 5 psi. For comparison, the model fit of the 80-lb shot (green line in Figure 4) would give a peak pressure of 15 psi, which is about the average of the 15' and 20' BLM 50-lb. shot data.

To complete the UWC main pile model, the scaled impulse versus scaled range data is presented and fitted in Figure 5. Similarly, the peak scaled EFD data is shown and fitted in Figure 6.

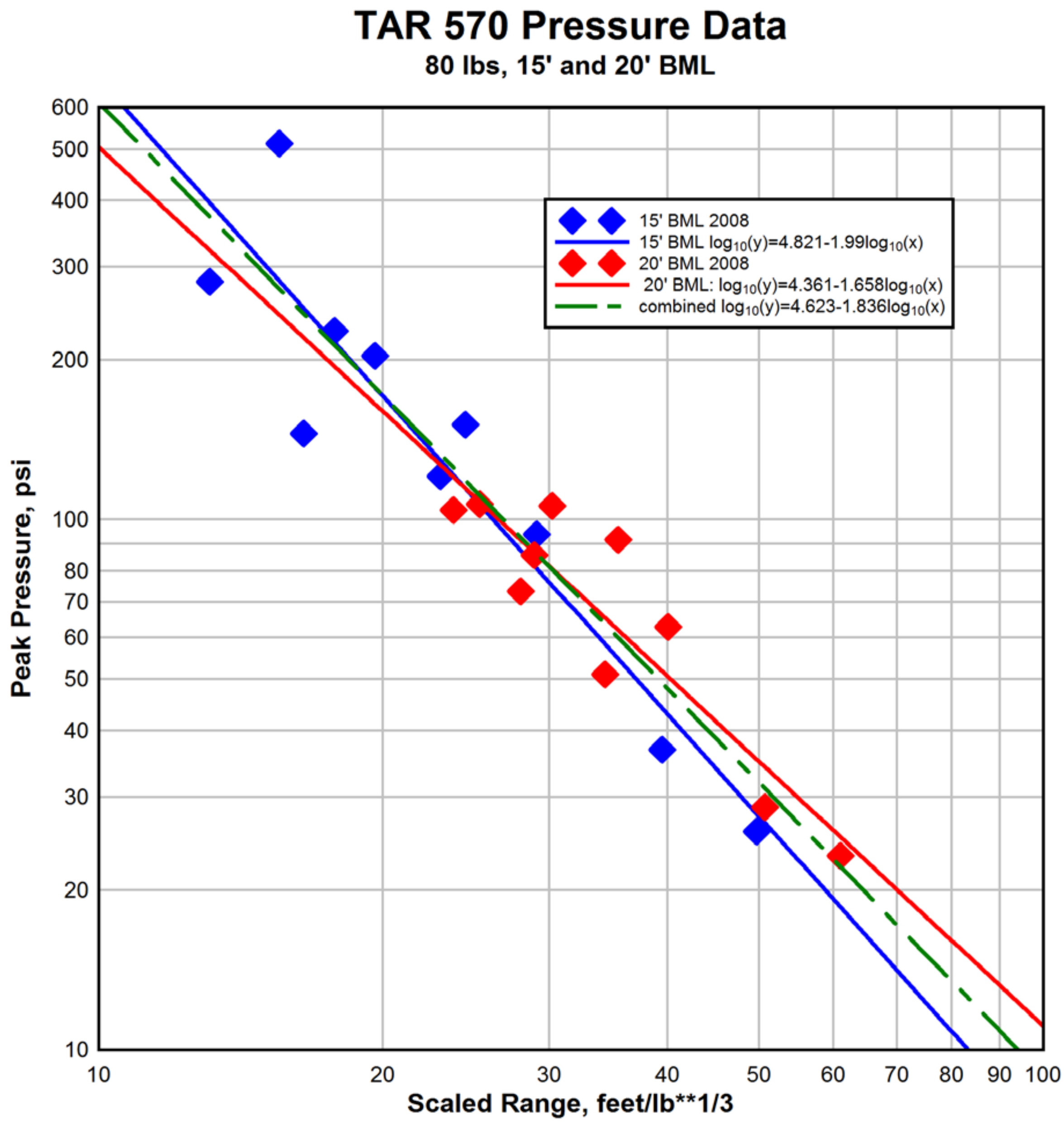

Figure 3. Peak Pressure versus Scaled Range for 80-lb. Main Pile Shots

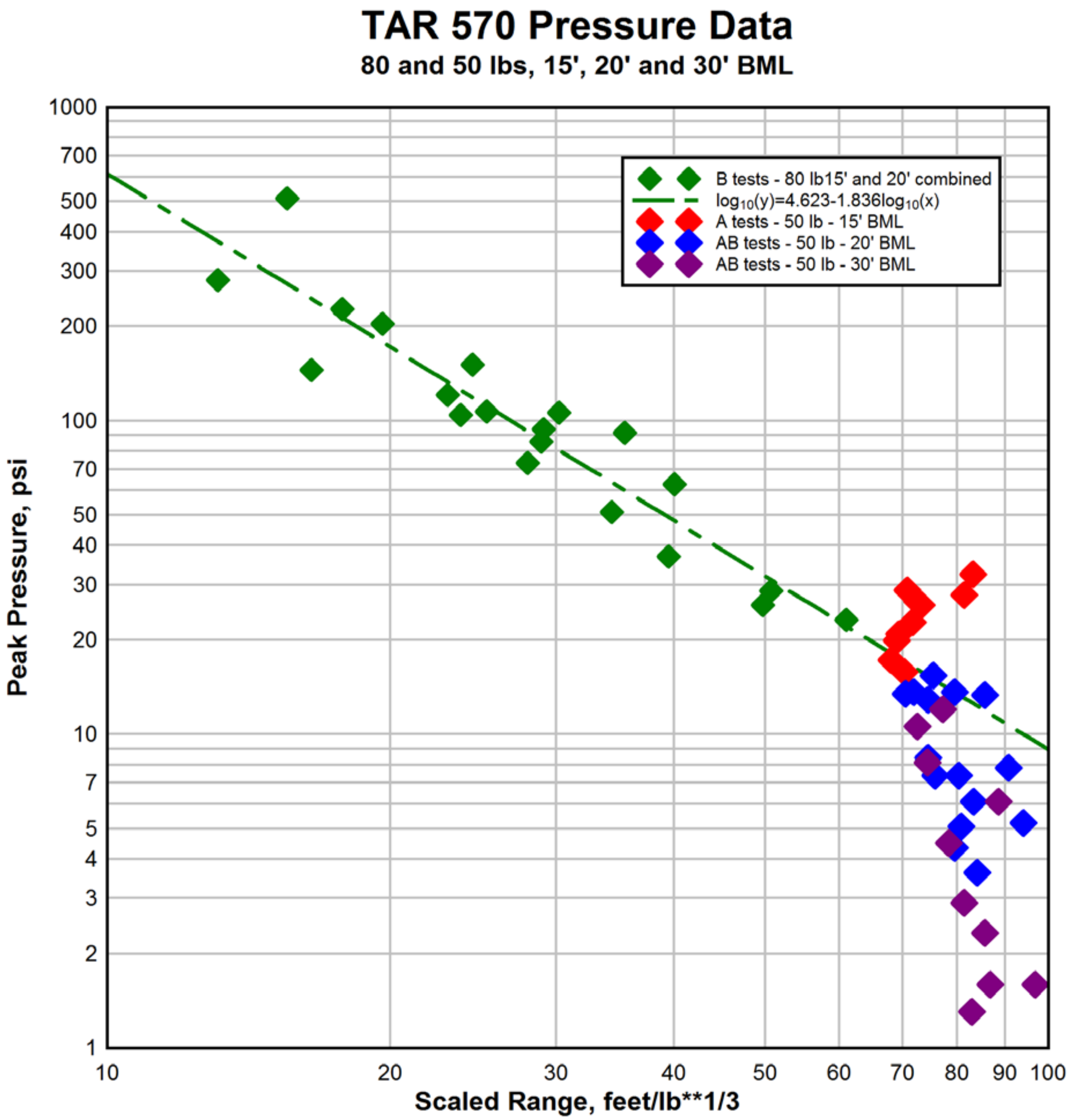

Figure 4. Peak Pressure versus Scaled Range for 50- and 80-lb. Main Pile Shots

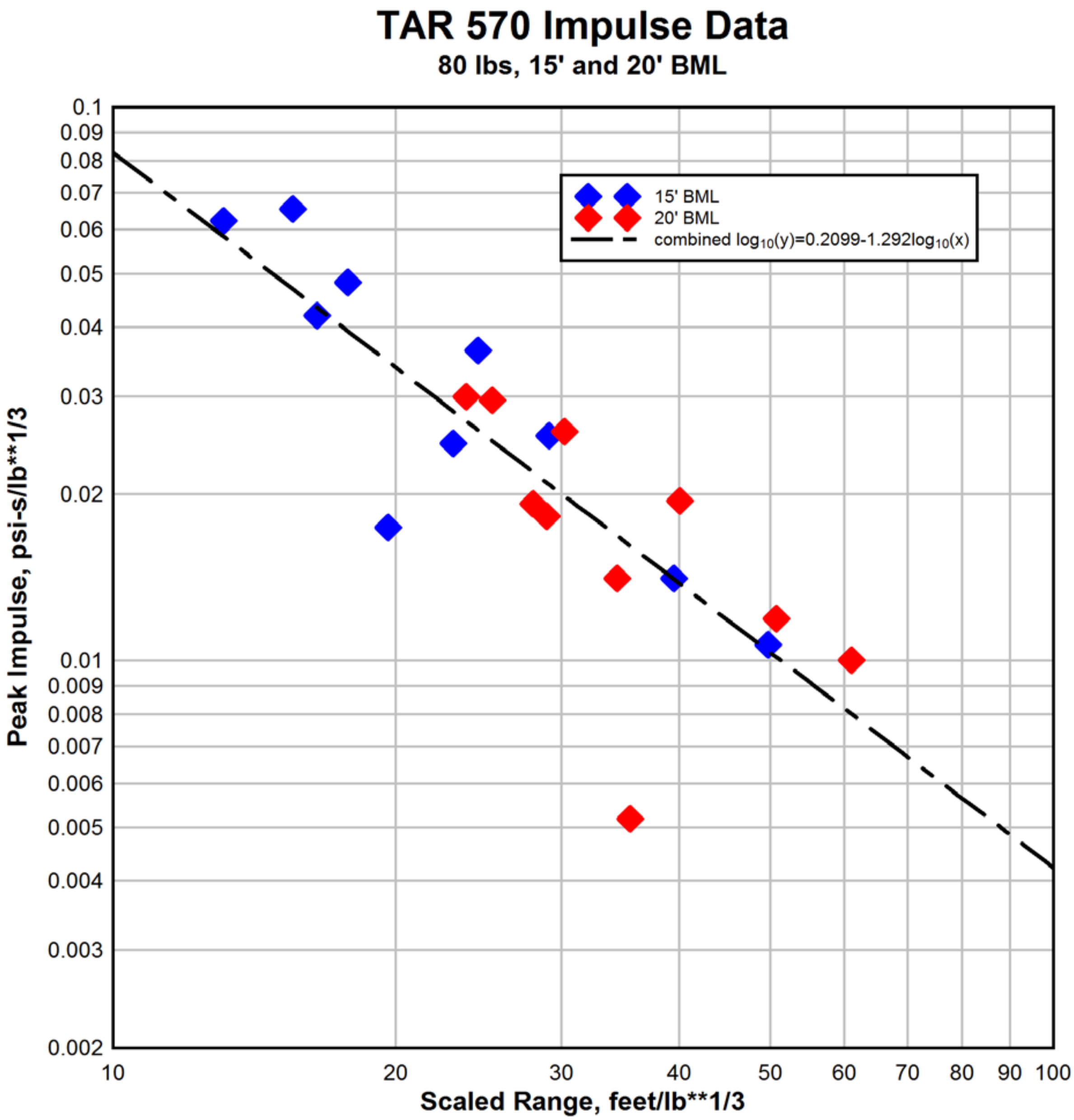

Figure 5. Peak Scaled Impulse versus Scaled Range for 80-lb. Main Pile Shots

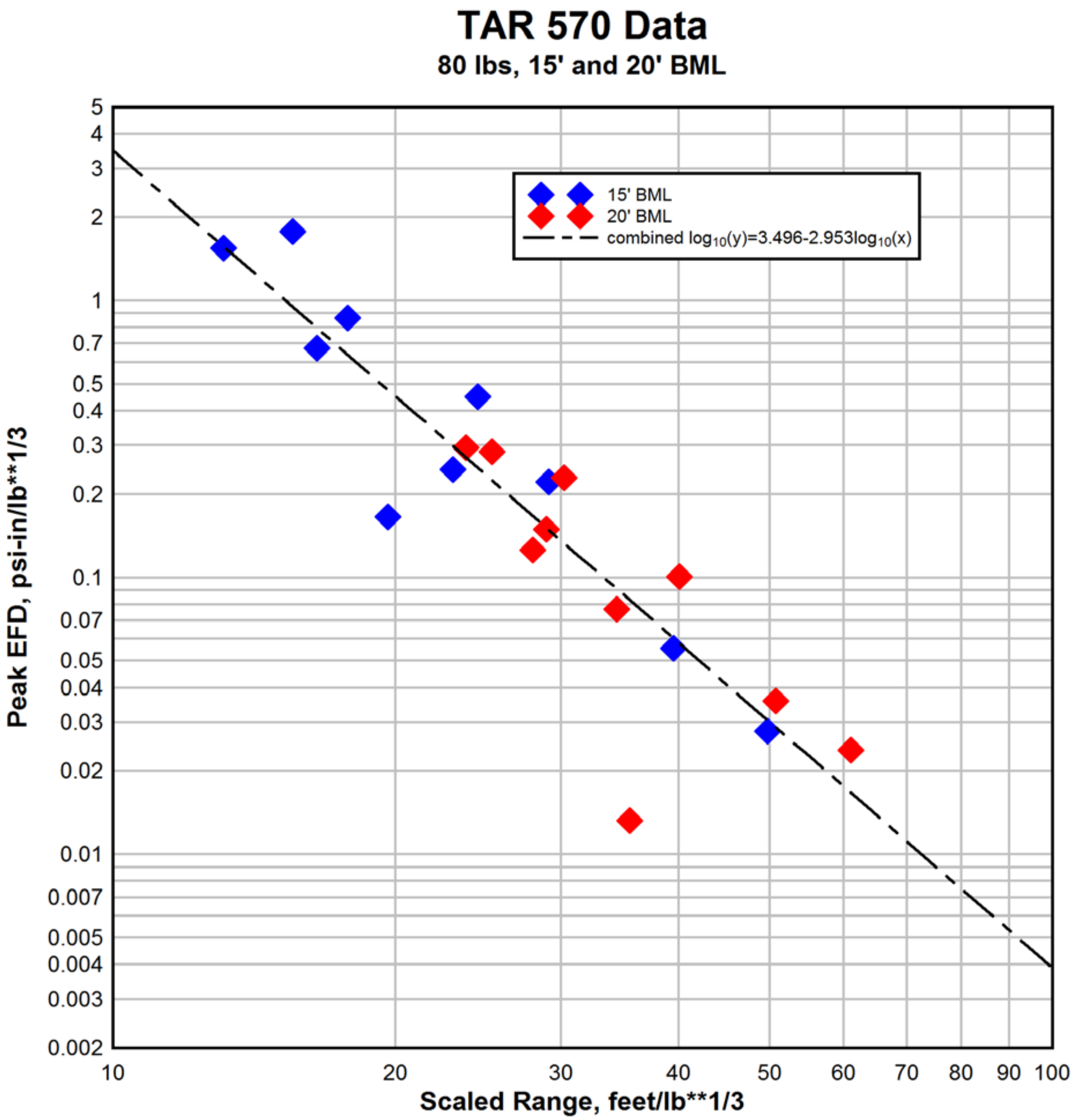

Figure 6. Peak Scaled EFD versus Scaled Range for 80-lb. Main Pile Shots

Well Conductor

Shot Conditions	
Pile Diameter	48”
Wall Thickness	1.25” or 1.5”
Explosive Weight	145 lbs.
Number of Tests	4
Explosive Distance BML (# tests)	25’ (two) 30’ (two)

The peak pressure vs. range plot for the well conductor shots for the 25’ and 30’ BML is shown in Figure 7. Similarly, Figure 8 and Figure 9 show the peak impulse and peak energy flux density relationships with scaled range. All three plots show a distinct dependence on the explosive depth BML. The 25’ BML data are higher than the 30’ BML data. Three models are provided: the 25’ BML average, the 30’ BML average, and lastly, the average of the 25’ and 30’ BML combined. The combined model fit was the one incorporated into the UWC Version 2.0. If needed, the other models can be used by inputting them into the “User” option in the UWC.

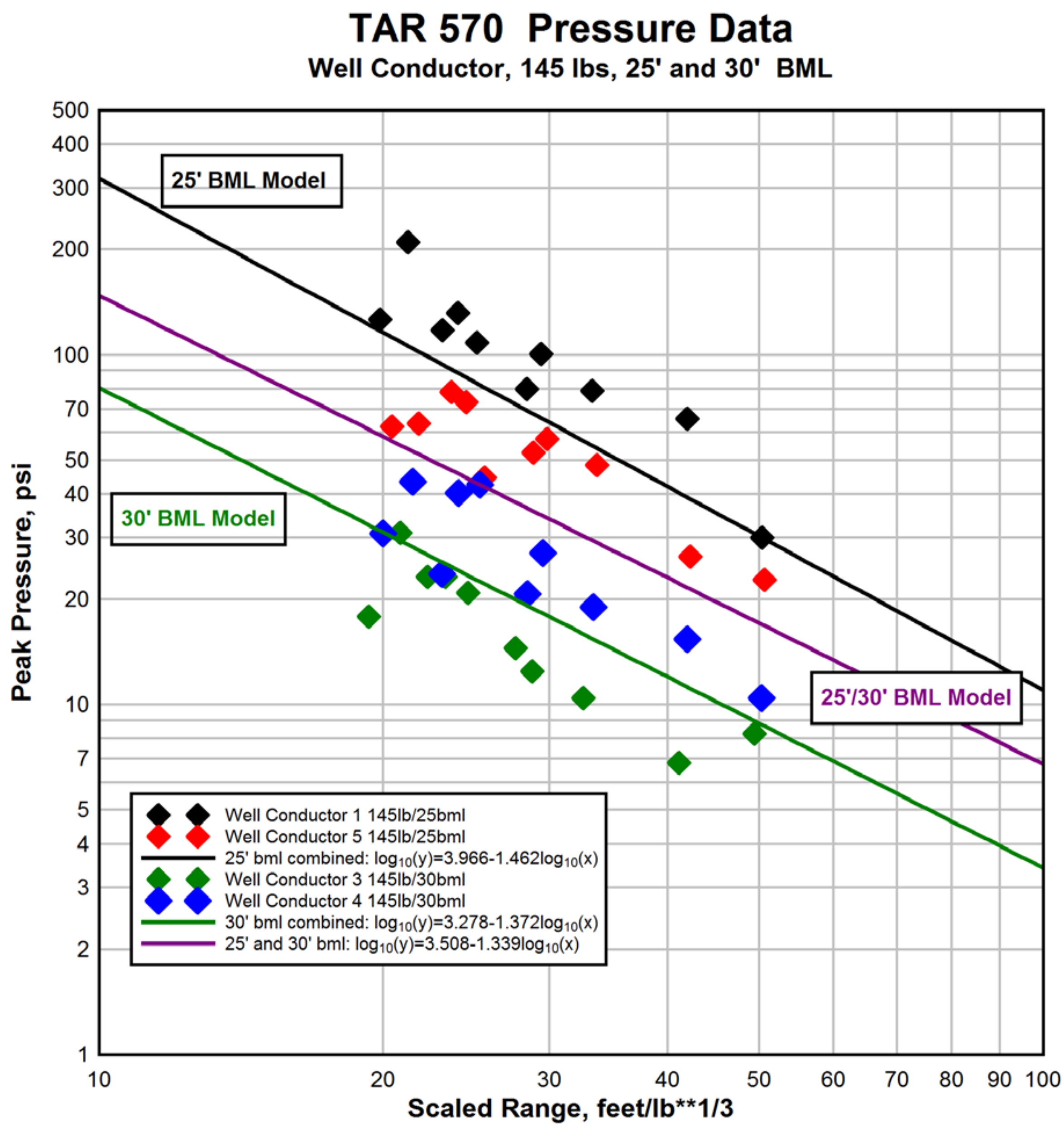

Figure 7. Peak Pressure versus Scaled Range for 145-lb. Well Conductor Shots

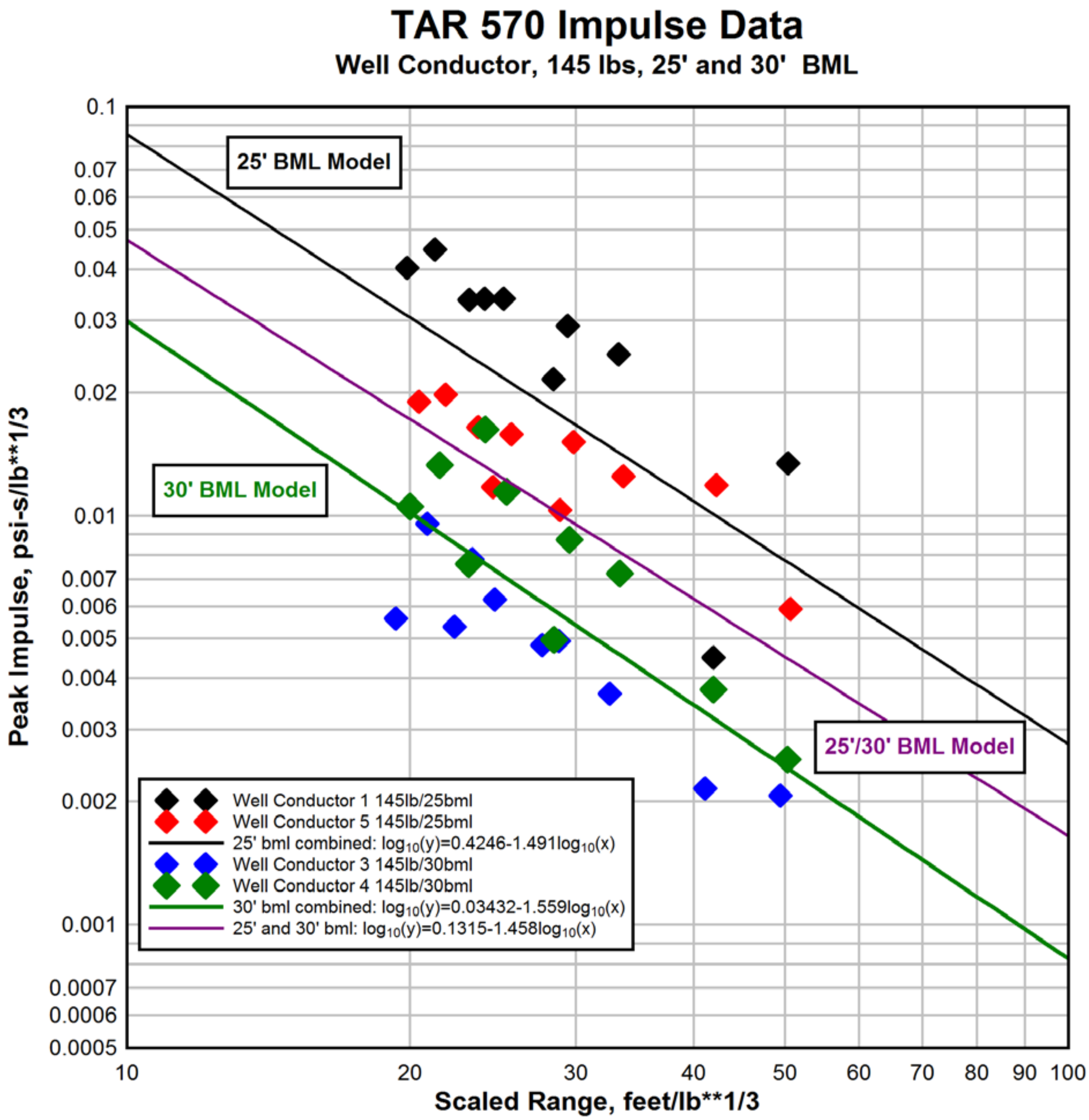

Figure 8. Peak Scaled Impulse versus Scaled Range for 145-lb. Well Conductor Shots

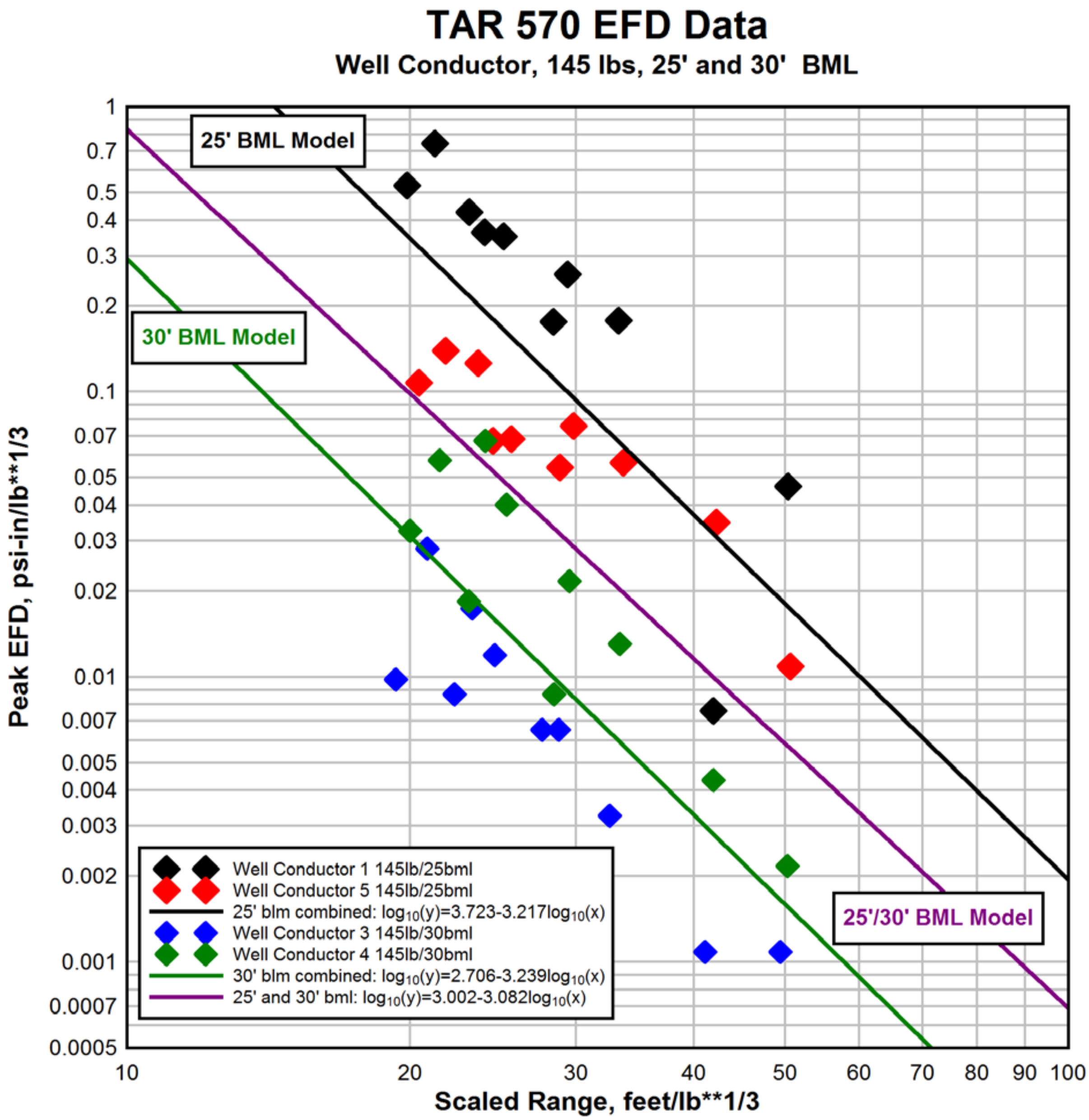

Figure 9. Peak Scaled EFD versus Scaled Range for 145-lb. Well Conductor Shots

Caisson

Shot Conditions	
Pile Diameter	36”
Wall Thickness	1”
Explosive Weight	25 and 75 lbs.
Number of Tests	2
Explosive Distance BML (# tests)	15’ (one) 20’ (one)

The peak pressure vs. range plot for the open caisson shot (20' BML and 75 lbs.) and conductor in a caisson shot (15' BML and 25 lbs.) is shown in Figure 10. Similarly, Figure 11 and Figure 12 show the peak impulse and peak energy flux density relationships with scaled range.

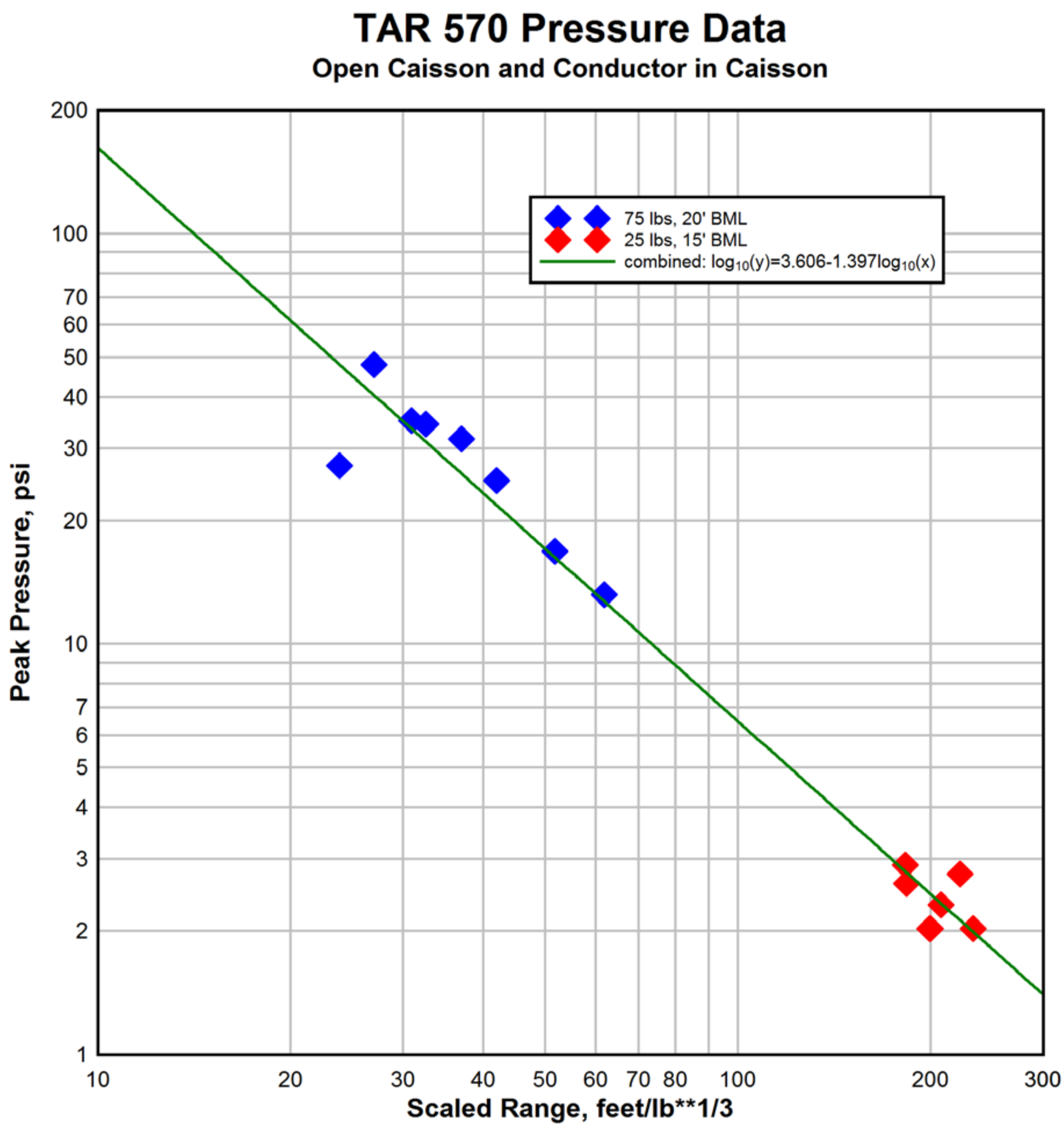

Figure 10. Peak Pressure versus Scaled Range for Caisson Shots

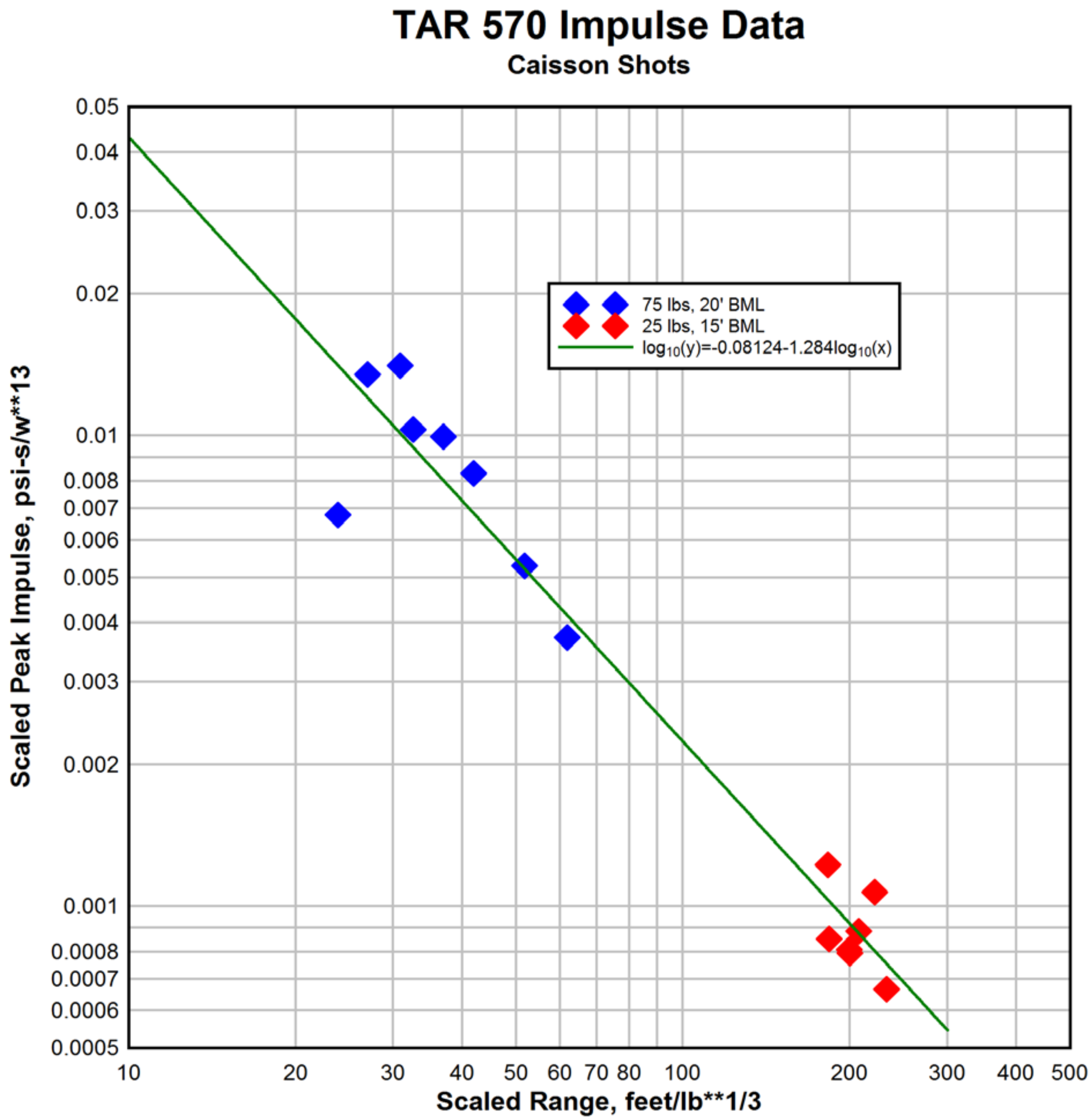

Figure 11. Peak Scaled Impulse versus Scaled Range for Caisson Shots

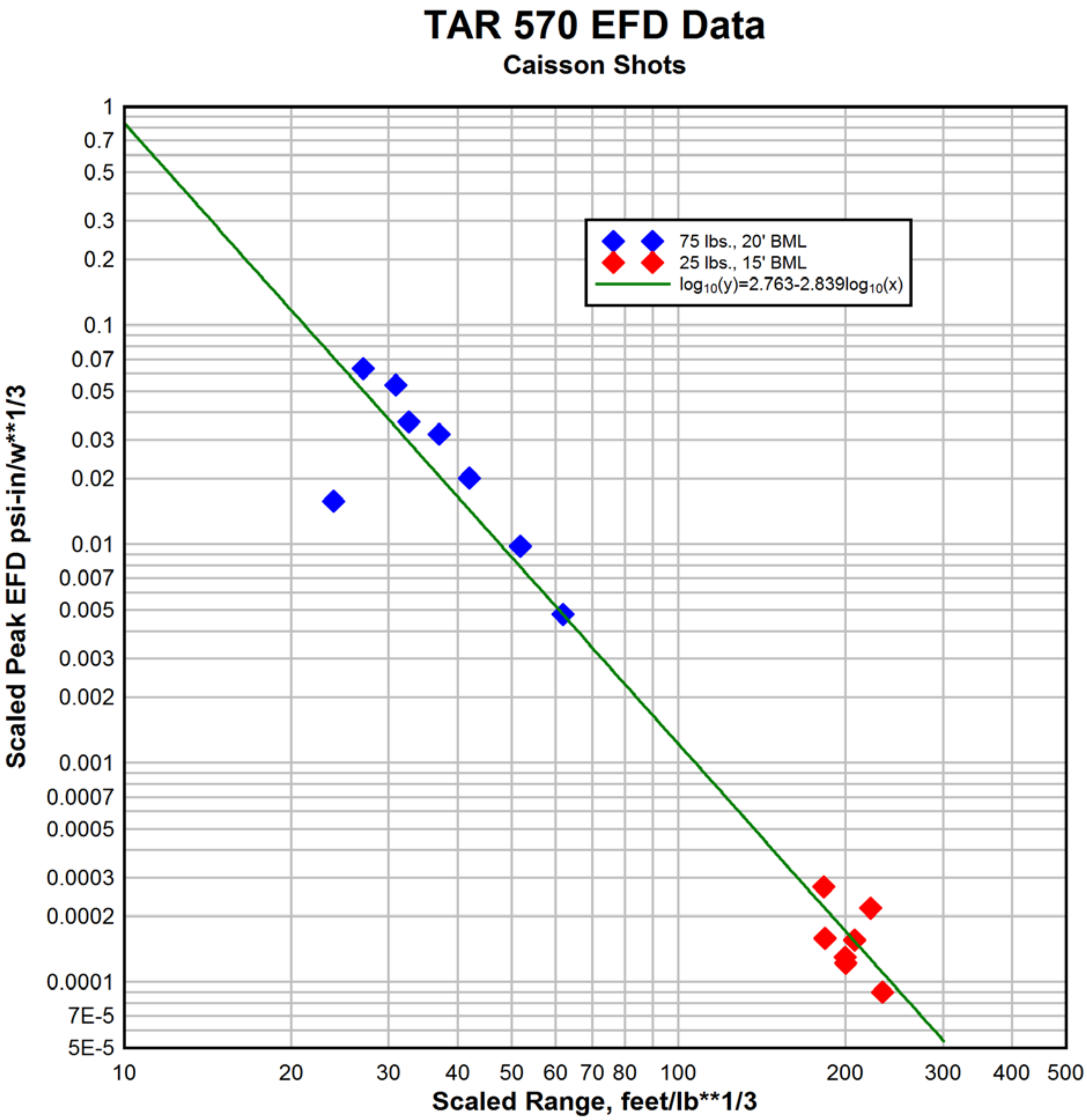

Figure 12. Peak Scaled EFD versus Scaled Range for Caisson Shots

Connor Models

The Connor report provided data for main piles, well conductors, and skirt piles. Each of these pile scenarios is described below. The plots of peak pressure, impulse, and EFD versus scaled range are presented below. The Connor derived relationships (coefficients K and α), which were incorporated into UWC Version 2.0, are also presented in these figures.

Main Pile

Shot Conditions	
Pile Diameter	30”
Wall Thickness	1”
Explosive Weight	38 lbs.
Number of Tests	12
Explosive Distance BML (# tests)	16’ (ten) 8’ (one) 26’ (one)

The peak pressure vs. range plot for the main jackets piles for the 16’ BML shots is shown in Figure 13. Similarly, Figure 14 and Figure 15 show the peak impulse and peak energy flux density relationships with scaled range.

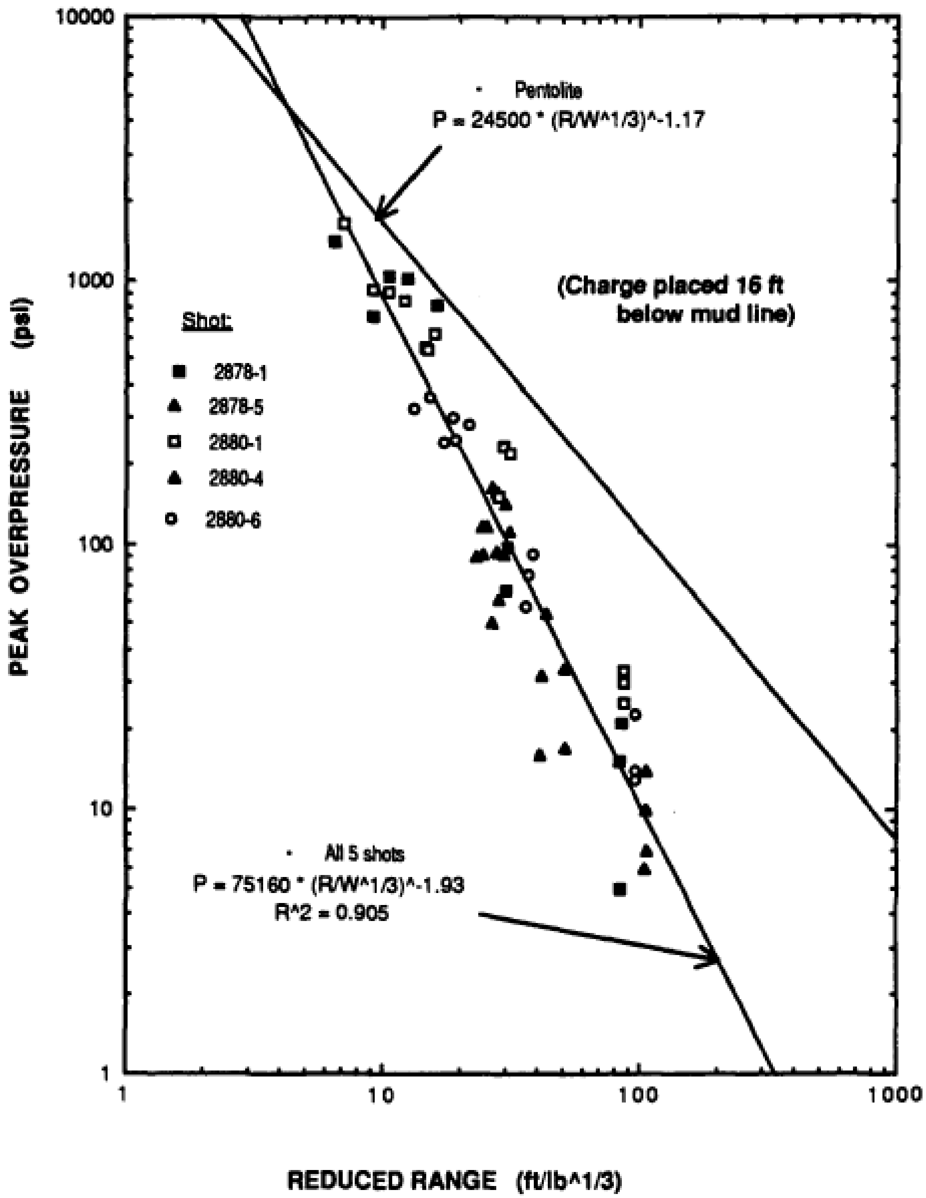

Figure 13. Direct Shock Overpressure from Main Jacket Piles

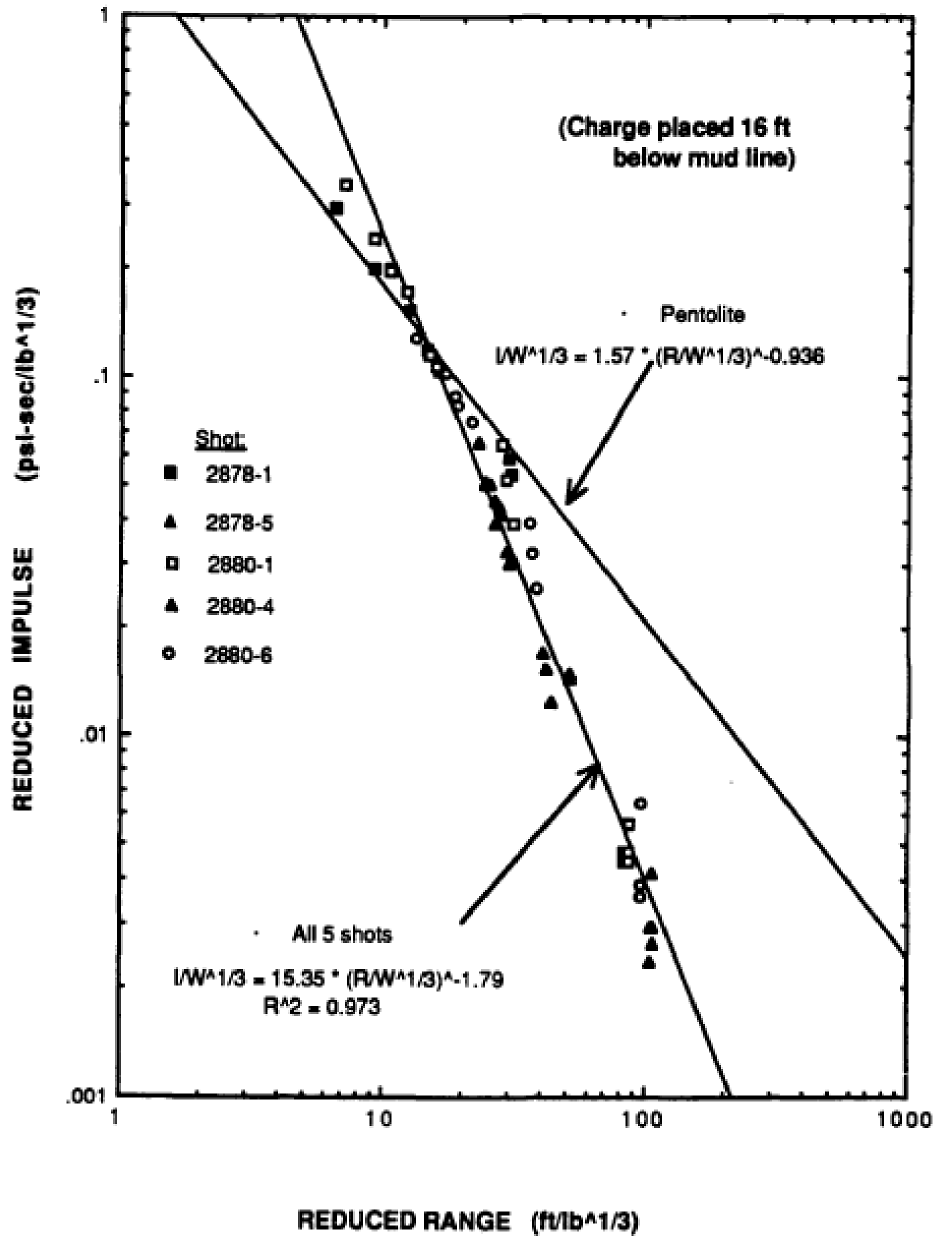

Figure 14. Direct Shock Impulse from Main Jacket Piles

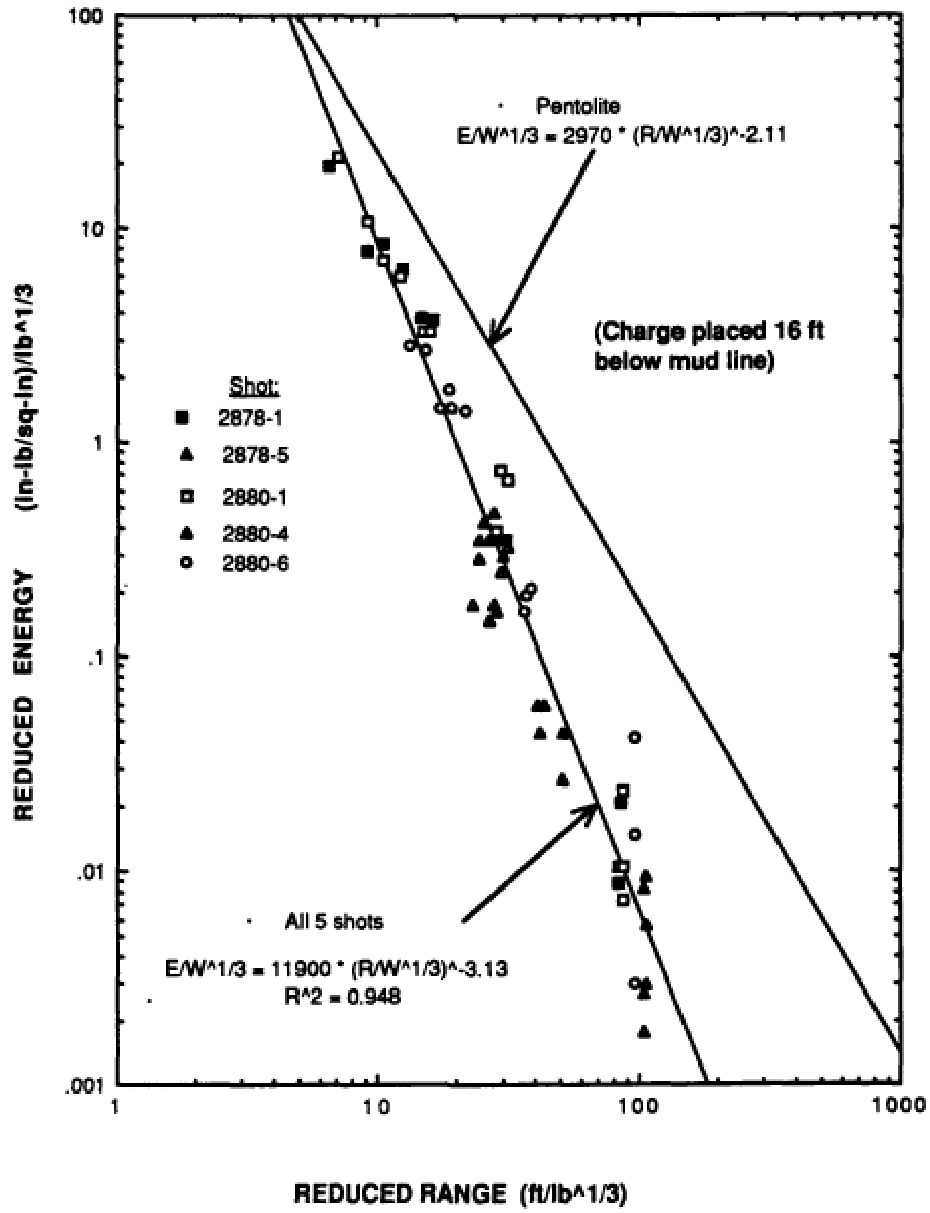

Figure 15. Direct Shock Energy from Main Jacket Piles

Well Conductor

Shot Conditions	
Pile Diameter	20”, 11” conductor, grout in between
Wall Thickness	1”
Explosive Weight (# tests)	25 lbs. (three) 50 lbs. (one)
Number of Tests	4
Explosive Distance BML (# tests)	20’ (three)

The peak pressure vs. range plot for the well conductor shots is shown in Figure 16Figure 13. Similarly, Figure 17 and Figure 18 show the peak impulse and peak energy flux density relationships with scaled range.

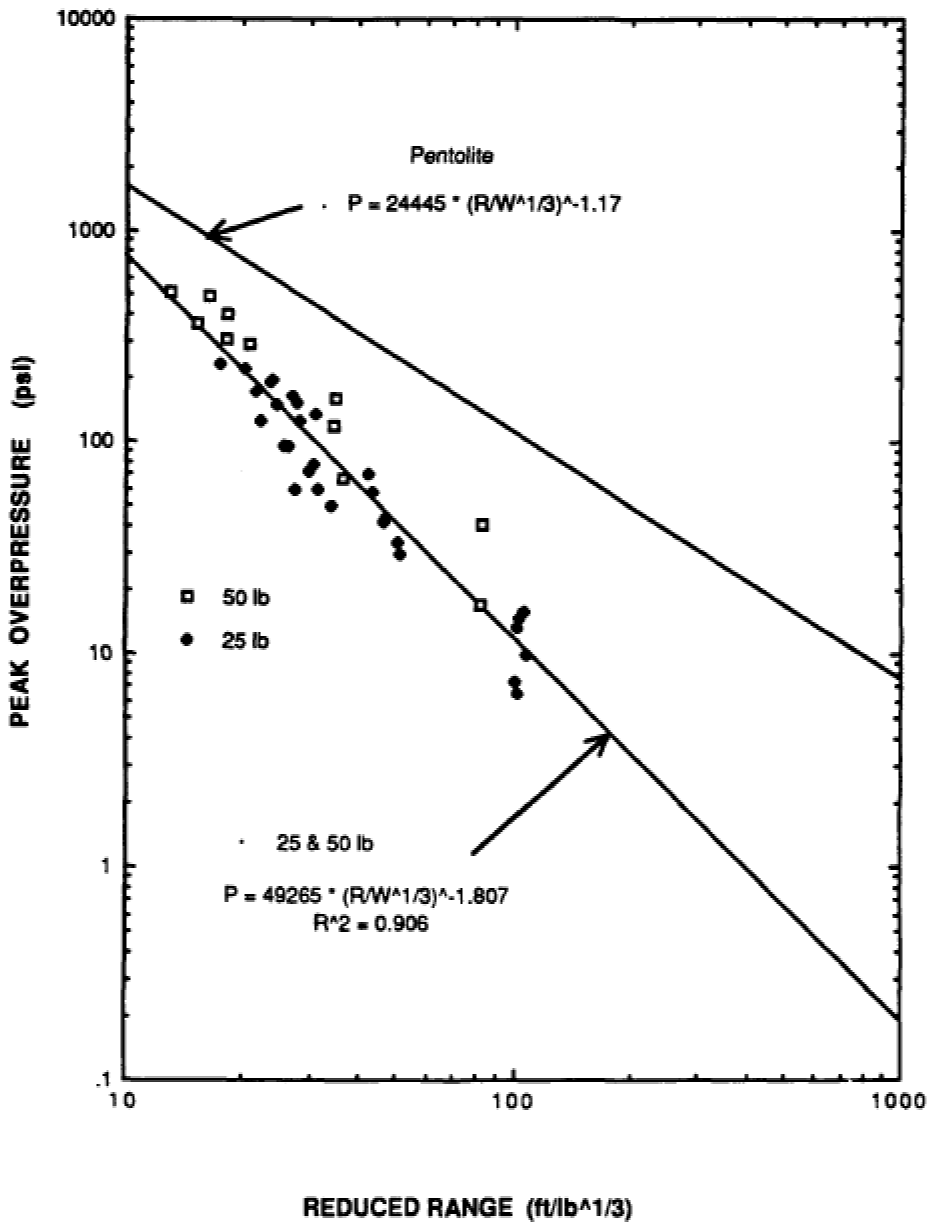

Figure 16. Direct Shock Overpressure from Well Conductors

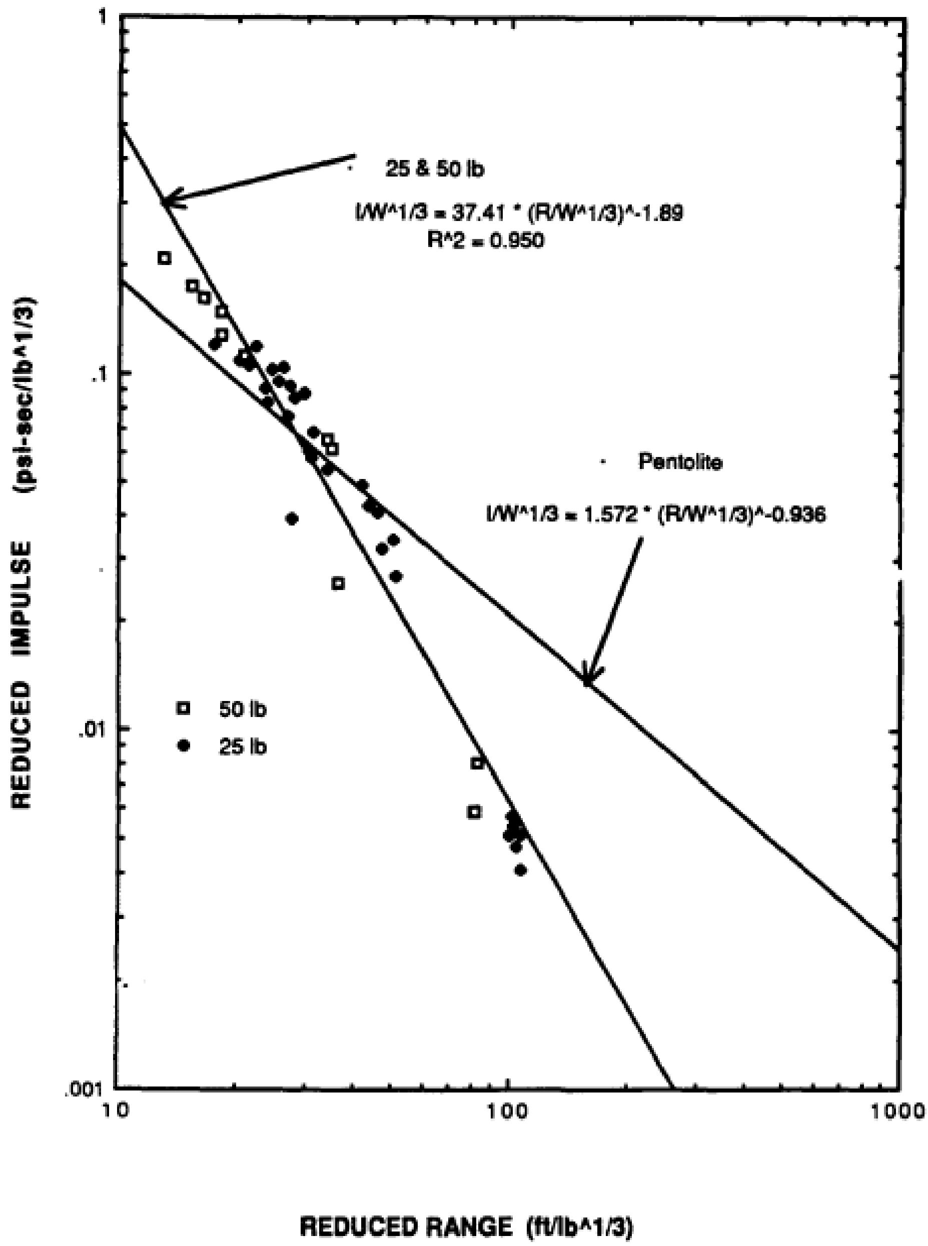

Figure 17. Direct Shock Impulse from Well Conductors

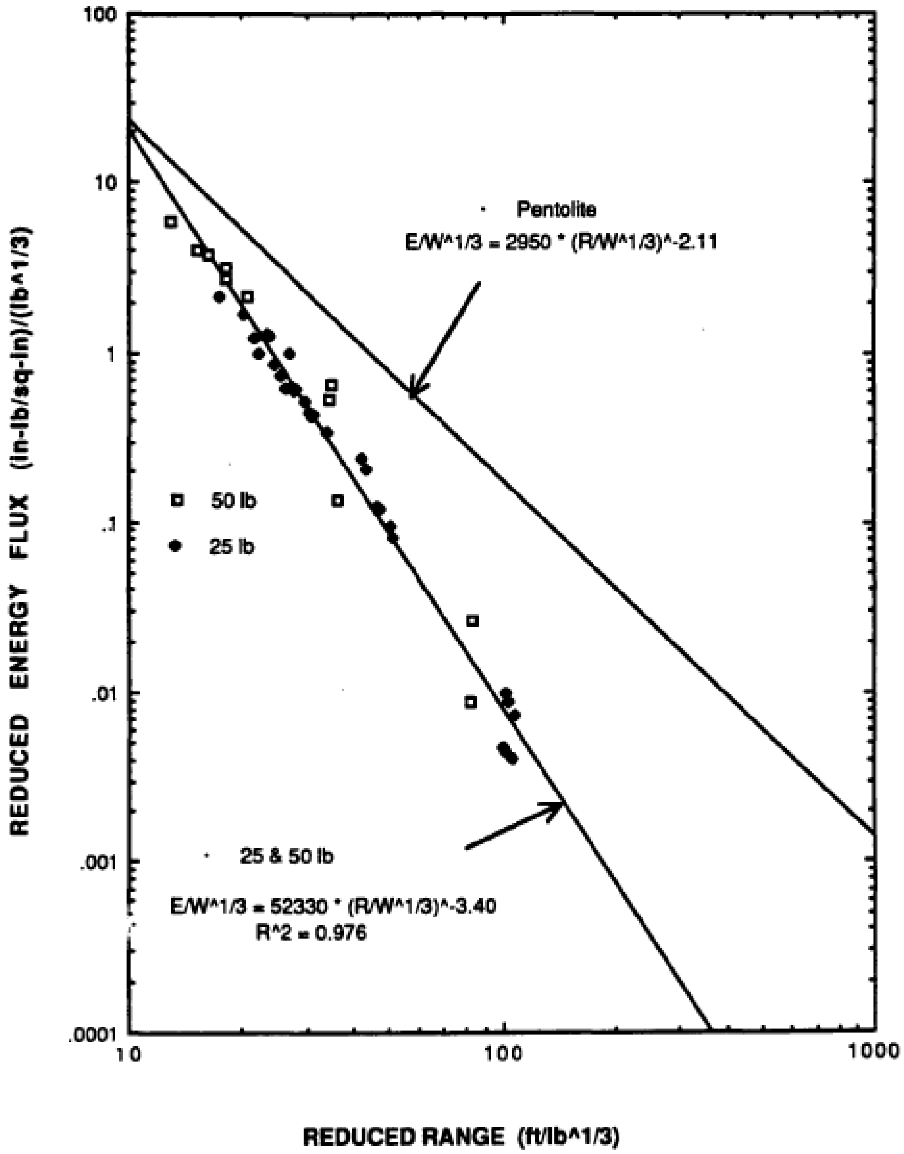

Figure 18. Direct Shock Energy from Well Conductors

Skirt Pile

Shot Conditions	
Pile Diameter	30”
Wall Thickness	1”
Explosive Weight	38 lbs.
Number of Tests	6
Explosive Distance BML (# tests)	16’ (three) 26’ (three)

The peak pressure vs. range plot for the skirt piles is shown in Figure 19. Similarly, Figure 20 and Figure 21 show the peak impulse and peak energy flux density relationships with scaled range.

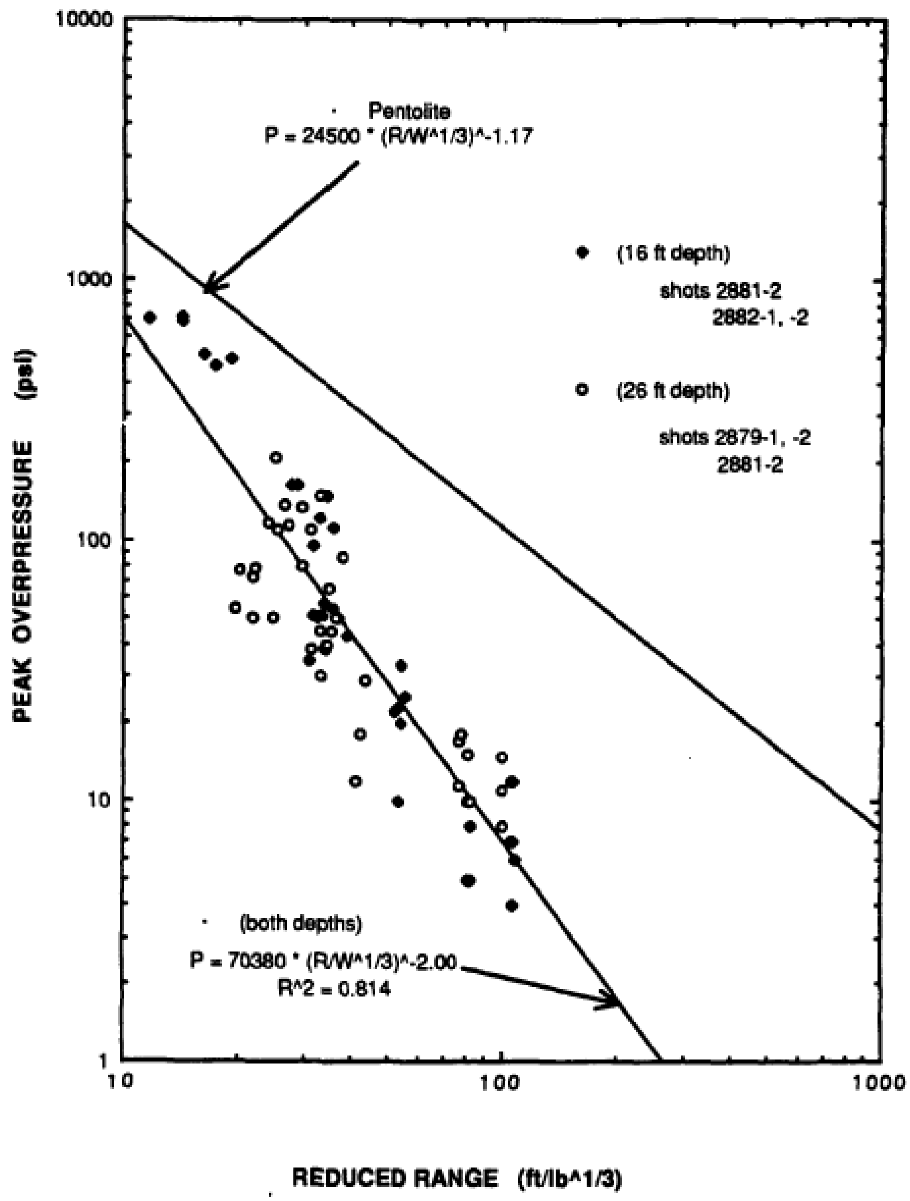

Figure 19. Direct Shock Overpressure from Skirt Piles

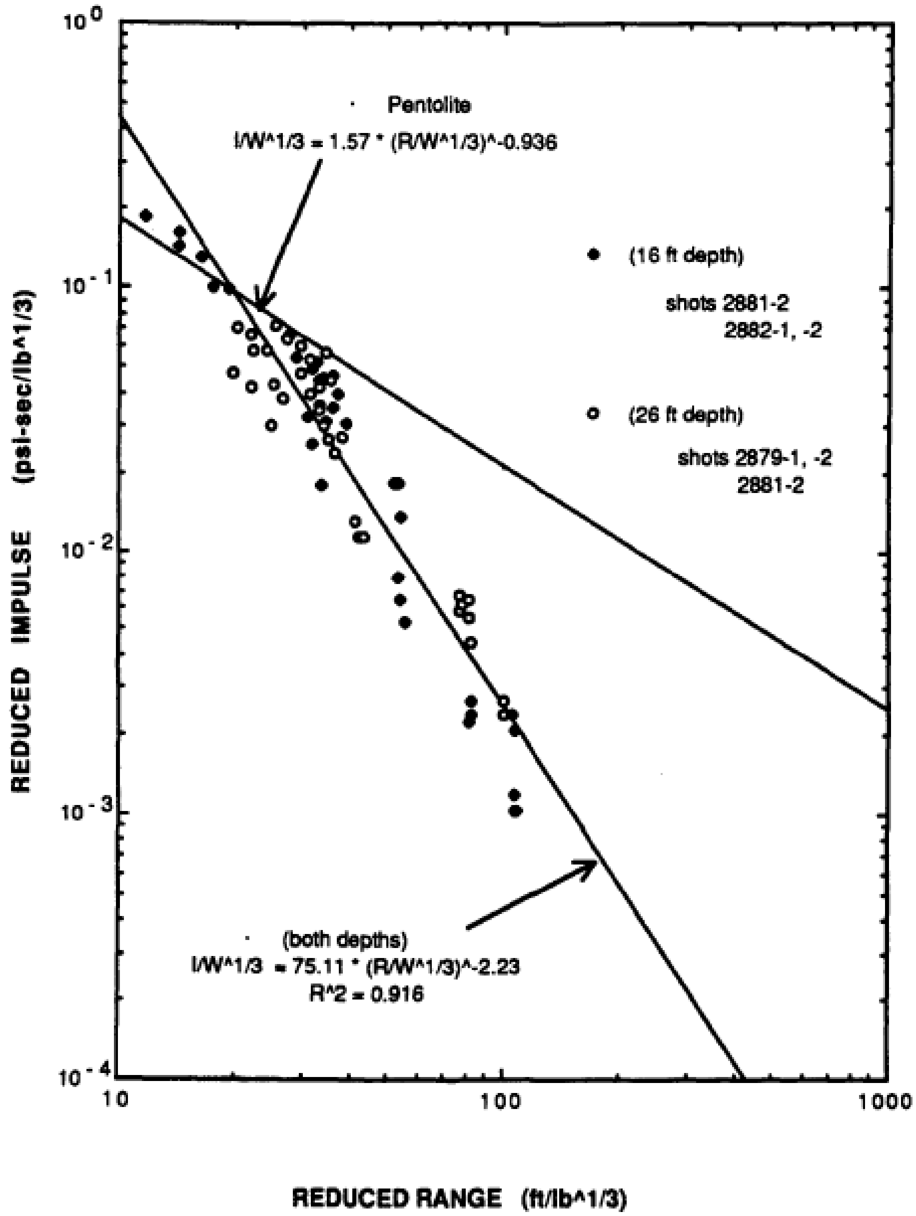

Figure 20. Direct Shock Impulse from Skirt Piles

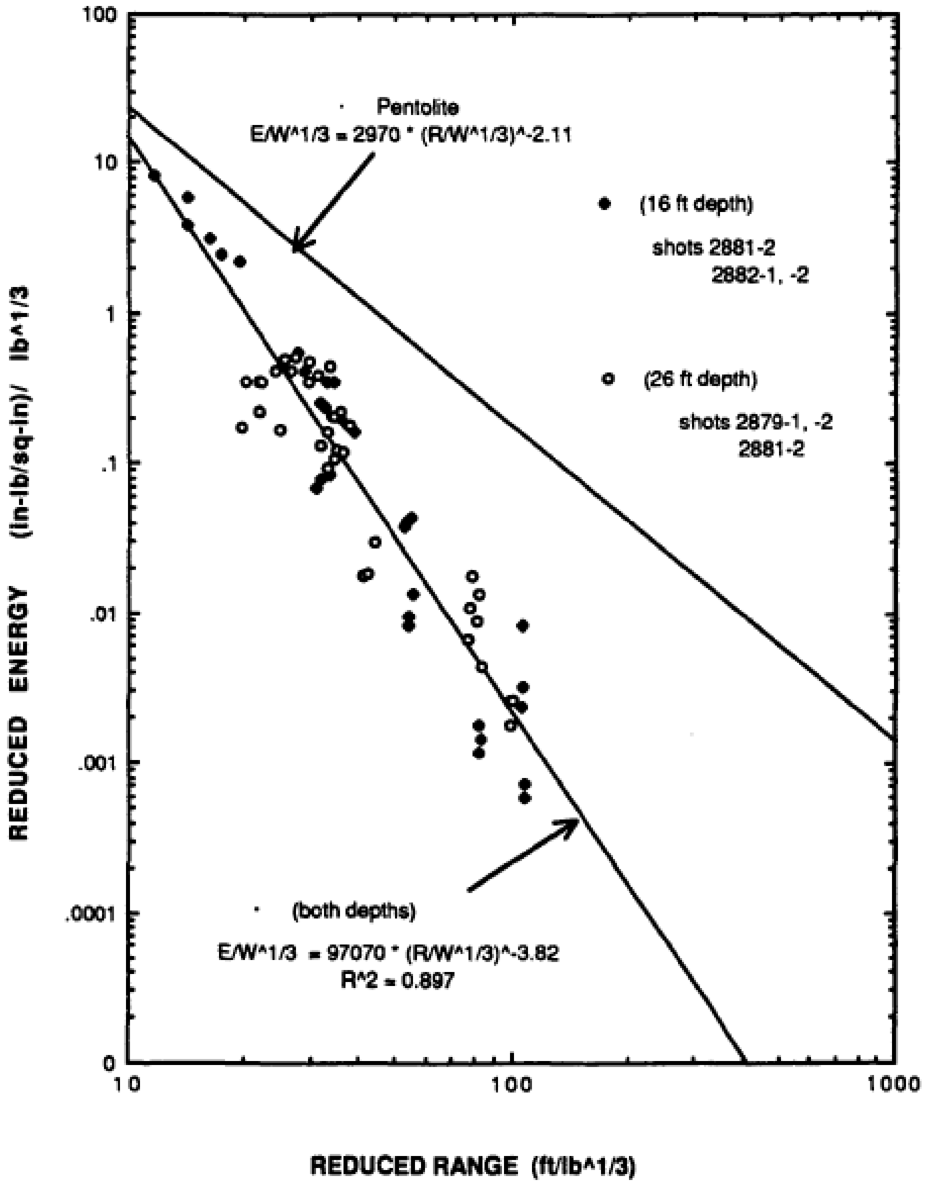

Figure 21. Direct Shock Energy from Skirt Piles

Version 2.0 UnderWater Calculator (UWC)

Both forward and backward calculation Excel sheets are provided for UWC Version 2.0. The forward calculation provides the peak pressure, impulse and energy flux for a given slant range, explosive weight, and open-water or pile scenario (Figure 22). Conversely, the backward calculation provides the slant range for the Level B pressure and EFD for the different open-water and pile scenarios (Figure 23). The relationships between peak pressure, impulse, and EFD and scaled range are those that were previously presented above. On both sheets, the level for peak pressure and EFD are variables that can be changed by the user. These variables are set to 23 psi for peak pressure and 182 dB for EFD (Figure 24).

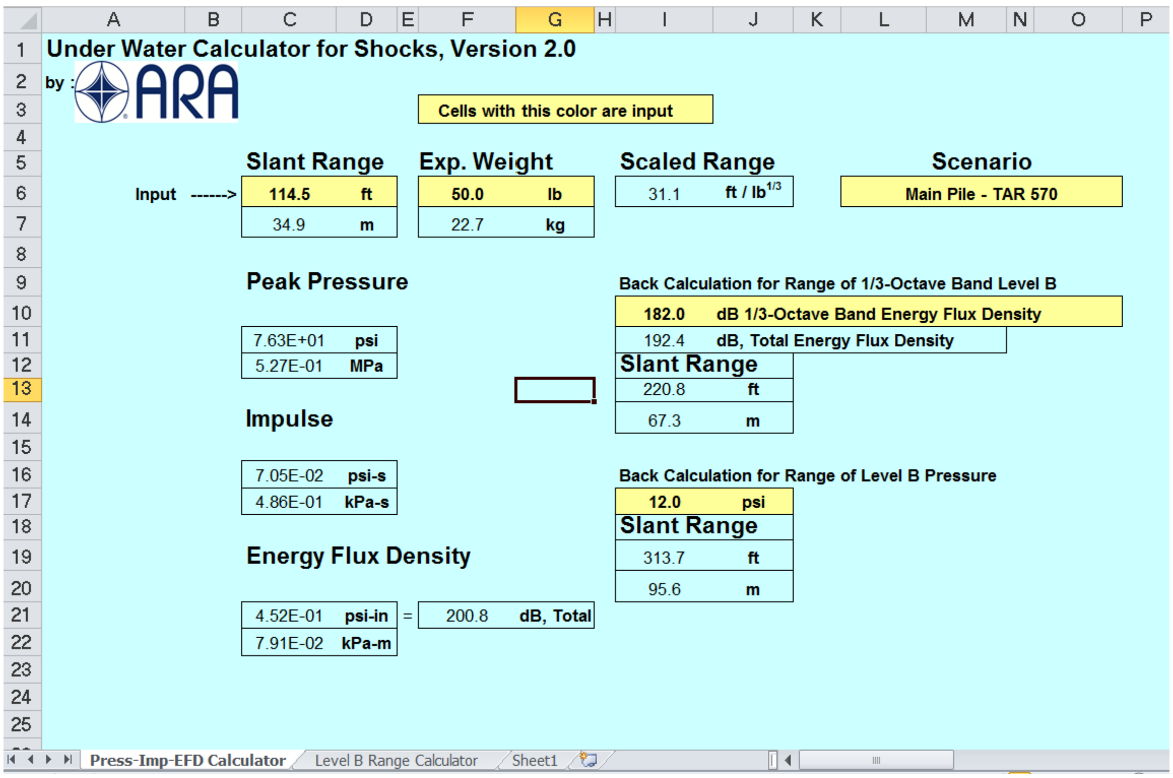

Figure 22. Forward Calculation: Press-Imp-EFD Calculator Tab

	A	B	C	D	E	F	G	H	I	J
1										
2		Cells with this color are input								
3			50.0	lbs, Explosive Weight						
4			182.0	dB, 1/3-Octave Band Energy Flux Density					Back Calculation for Range	
5			192.4	dB, Total Energy Flux Density						
6			23.0	Psi					Back Calculation for Range	
7										
8		**Note**: Coefficient and seawater parameters come	Coefficients for Scenarios							
9		from the corresponding table on the previous sheet.	Pm		Impulse		EFD			
10		Scenario Type	K	a	K	a	K	a	Level B Pressure, ft	Level B EFD, ft
11		Open Water Exp[1]	23514	1.14	1.482	0.91	2659	2.04	1608.1	1272.99
12		Main Pile - TAR 570 [2]	41976	1.836	1.622	1.292	3130.7	2.953	220.1	220.80
13		Well Conductor - TAR 570 [2]	3221	1.339	1.3536	1.458	1004.6	3.082	147.6	128.65
14		Open Caisson - TAR 570 [2]	4036	1.397	0.82939	1.284	579.4	2.839	148.9	143.65
15		Main Pile - Connor [3]	75160	1.93	15.35	1.79	11900	3.13	243.9	268.38
16		Well Conductor (air term) - Connor [3]	49265	1.807	37.41	1.89	52330	3.4	256.8	295.14
17		Skirt Pile - Connor [3]	70380	2	75.11	2.23	97070	3.82	203.8	214.27
18		USER								
19										
20		rho (kg/m^3)	1025							
21		c (m/s)	1500	Water Properties						
22		Z	1537500							
23										
24										

Press-Imp-EFD Calculator | Level B Range Calculator | Sheet1

Figure 23. Backward Calculation: Level B Calculator Tab.

Criterion	Criterion Definition	Threshold
Level A (mortality)	Onset of severe lung injury (mass of dolphin calf)	31 psi-msec
Level A (injury)	50% animals would experience ear drum rupture	205 dB re: 1 μPa^2-s
Level A (injury)	Onset of slight lung injury (mass of dolphin calf)	13 psi-msec
Level B	TTS and associated behavioral disruption (dual criteria)	12 psi peak (> 2000 lb*) 23 psi peak (< 2000 lb)
Level B	TTS and associated behavioral disruption (dual criteria)	182 dB re: 1 μPa^2-s, 1/3 octave band
Level B	Sub-TTS behavioral disruption (for multiple detonations only)	177 dB re: 1 μPa^2-s, 1/3 octave band

Figure 24. Acoustic Criteria from NMF[5]

Summary and Conclusions

The UnderWater Calculator (UWC) is a spreadsheet-based tool that calculates the underwater shock, namely, peak pressure, impulse, and energy, caused by the use of explosives to remove offshore structures. The primary use of this tool is to calculate the range to a specified peak shock pressure and energy level, such as the temporary threshold shift (TTS) Level B. Version 1.0 was published in 2003, and was based on close-in, short time numerical simulations. These numerical simulations showed that less energy (30 to 70% reduction) is coupled to the water for the pile cases than would be coupled for open water explosions. Field data has indicated higher attenuation of peak pressure with range and an energy reduction of 90% or more when compared to open-water data.

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