AXPRO GROUP
Advanced Explosive
Processing Research Group
Explosive Research and Education Center

Colorado School of Mines, 1600 Illinois, Brown Building Room 142, Golden, CO 80401, Phone: 303 273 3222

Using High Speed Process Imaging Software to Compare A Single Shockwaves of Single and Parallel Detonators

Prepared for:
MNGN: 598 Experimental Techniques of Explosives Engineering

Prepared by:
Nicolo Redfern
Valerie Hickman

Colorado School of Mines
1600 Illinois Street
Brown Building, Room 129
Golden, Colorado 80401

Date: April 29, 2015

Table of Contents

Abstract:

This experiment implemented the use of shadowgraphs to analyze and compare detonations of a single shockwave resulting from a single detonator and two parallel detonators. The specific focal point of this research is to determine if the shockwave interaction has a Mach number greater than one. The single detonator is used as a baseline to compare the interaction of shockwaves between the two parallel detonators. Leroy Henderson's Triple Shock Entropy Theorem states that two shockwaves will produce a lower pressure, temperature, and Mach number values at the interaction face. Using advanced fluid dynamic calculations in conjunction with Phantom ™ software, we were able to verify this. Reviewing the analysis of the dual detonation, suggestion of a more precise mounting of the detonators should be utilized. The detonators should be mounted exactly parallel to maximize the interaction face. Lastly, a dual camera setup would also increase the reliability of the data, in which one camera would be placed overhead and another camera facing normal to the experiment.

Introduction:

Shadowgraph is a visual technique that utilizes a light source in conjunction with an optical system that is used to observe density variations in a medium. Robert Hooke first developed this method in 1672 using the sun to direct light on to white surfaces to generate shadows. Harold E. Edgerton improved this technique in 1958 by using a flash lamp in order to capture the shockwave from explosive reactions. His modified experimental procedure utilized a retroreflective screen, strobe illumination, and a standard old fashion view camera. The shadowgraph method has been improved over the years by modifying the cameras, lighting, and retroreflective screens.

For the purpose of this report, the application of the shadowgraph technique has been applied in capturing the detonation of an explosive reaction while simultaneously showing the density contrast of the shockwave projected on a retroreflective screen. After the shockwave has been projected onto the screen and captured using high speed imaging software, an analysis will be performed to compare the measureable differences between a single detonators shockwave and a shockwave of one detonator (the left detonator) coinciding next to another detonator in parallel (right detonator).

Objectives:

1. Calculate the shockwave velocity of a single detonator and two parallel detonators.
2. Calculate the pressure and temperature from the resulting single and parallel detonations.
3. Calculate the fragment velocity of the single detonator.
4. Calculate the Mach number from the resulting single and double detonations.
5. Compare the results from the single and two parallel detonators.

Materials:

1. 2 RP-2 Shape Charge Electric Bridge Wire Detonators
2. 1 RP-2 Electric Bridge Wire Detonator
3. Stand for Detonators
4. Wire For Hanging Detonators
5. High Speed Imaging Camera Model
6. Phantom High Speed Process Imaging Software

Procedure:

1. Open the Phantom™ software located on the desktop.
2. Locate and select the cine file "Shadowgraph EBWRP2 March4test1".
3. Under the Manage tab located on the top right of the software, click the preference button, see Figure 1.

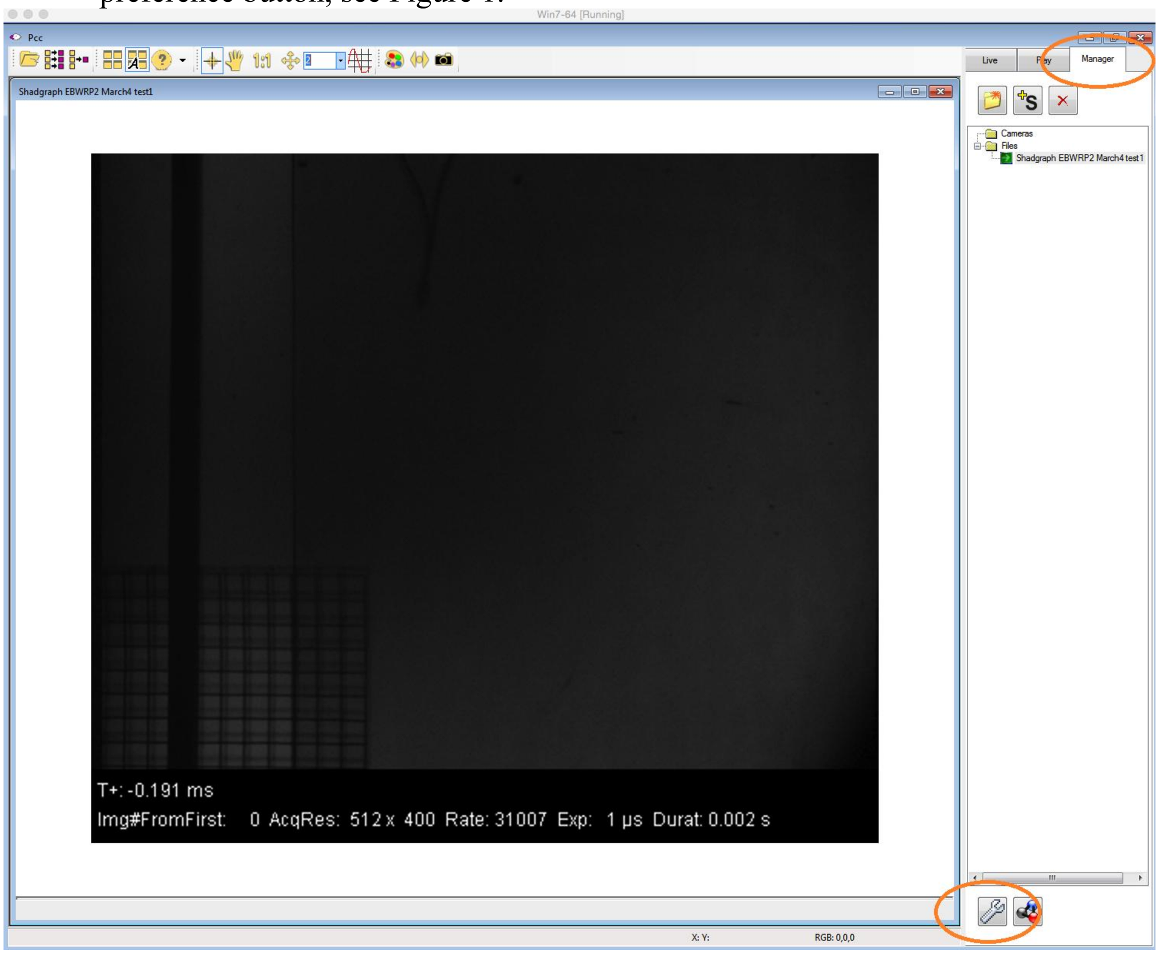


Figure 1 - Manager Tab and Preference Button Location

4. Next select the measurements tab, see Figure 2.
    a. Select auto advance to next image
    b. Select auto update

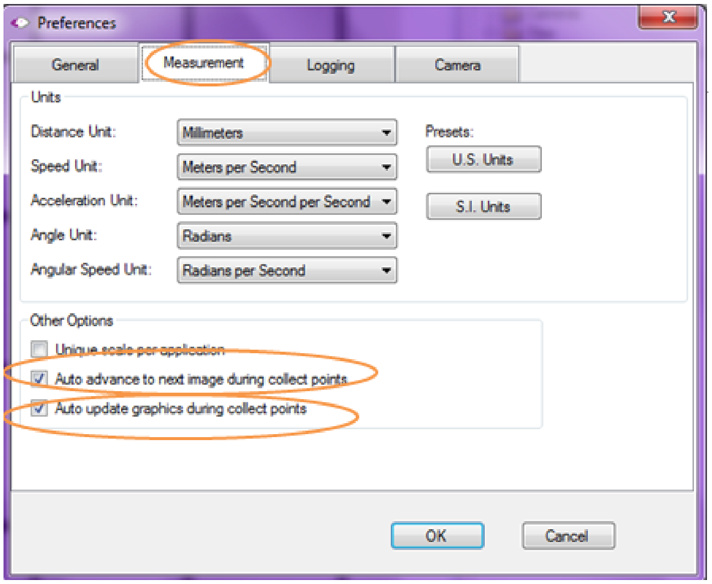


Figure 2 - Measurement Tab

5. Return to the Play tab located on the top right of the screen and scroll down to the Play Speed & Options tab.
6. Next select the photos per frame (fps) button, see Figure 3.
   a. Select 1 ppf.

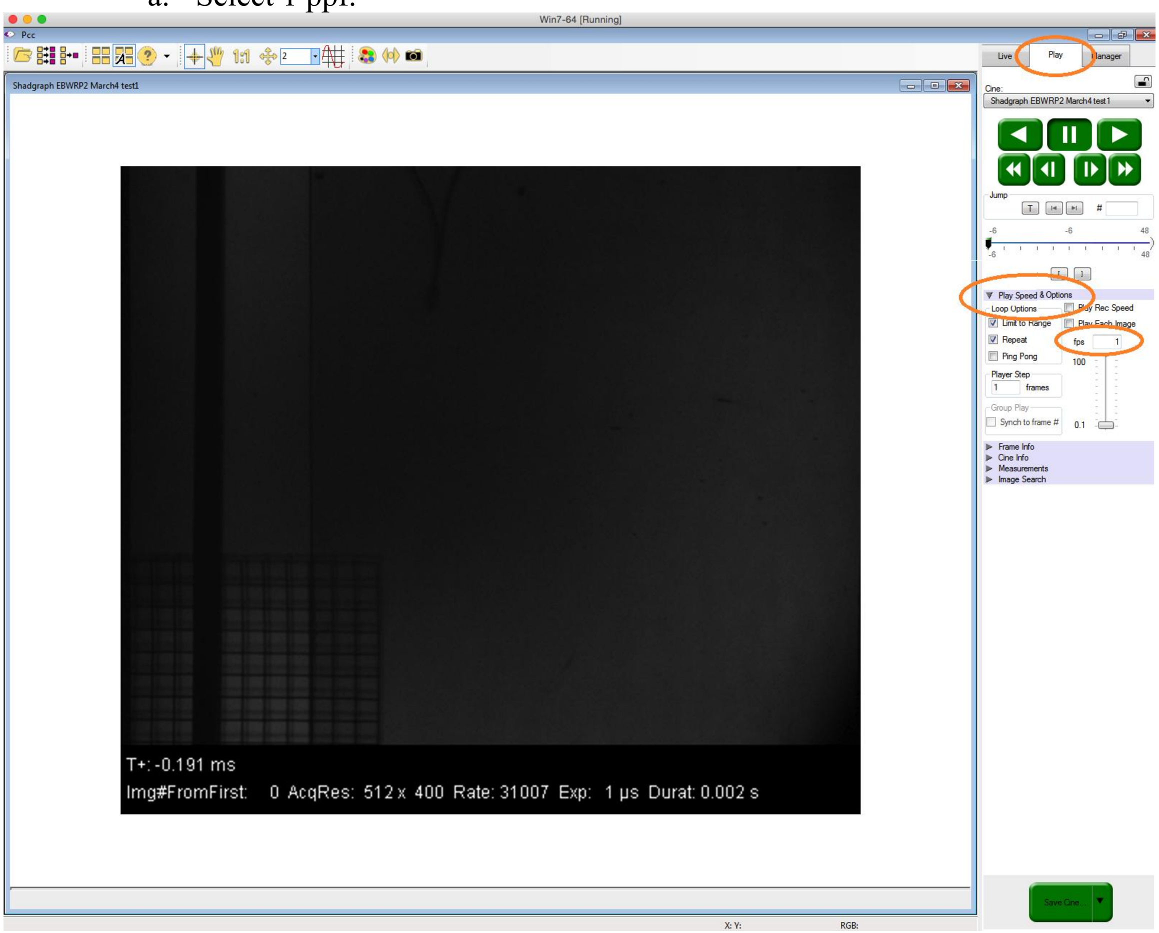


Figure 3 - Play Speed

7. Under the Measurement tab, click the Calibrate button, see Figure 4.
    a. Pick two points that represents a measured distance.

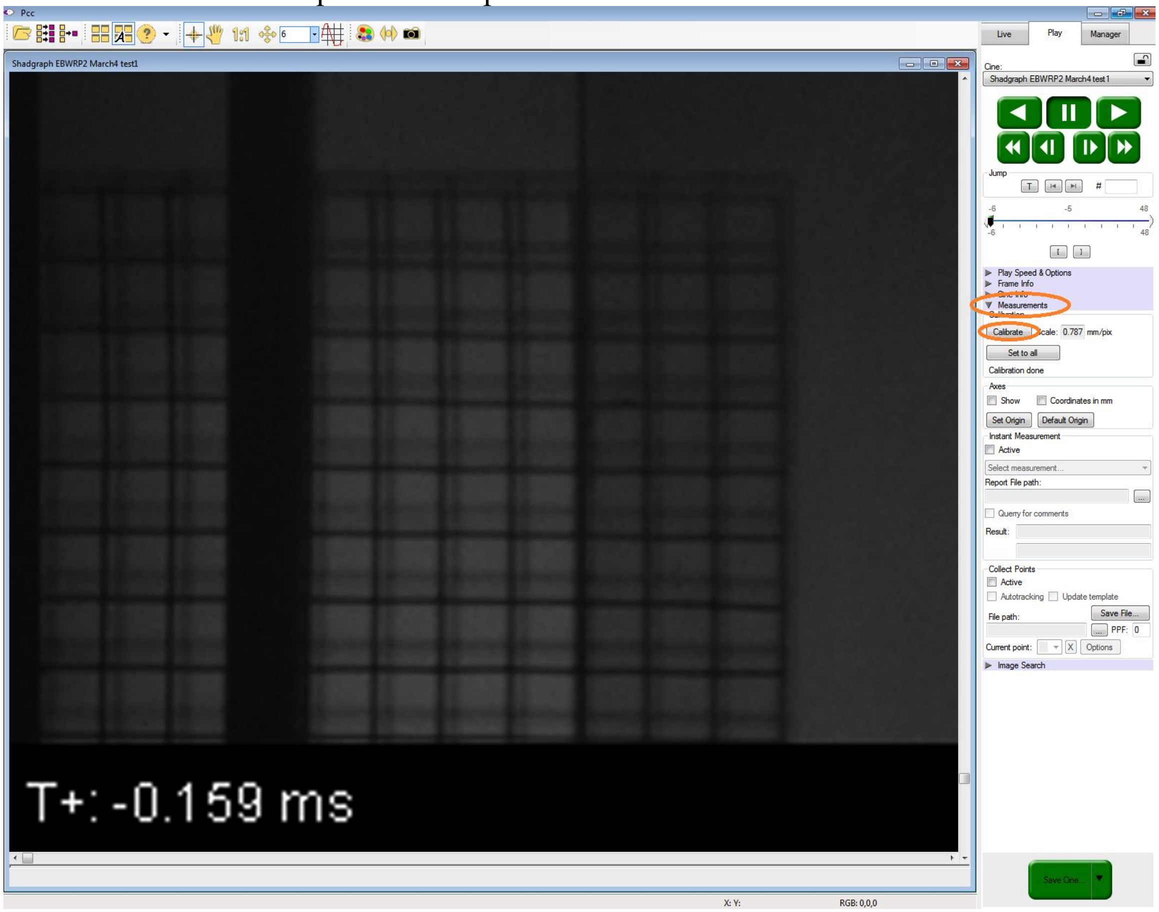


Figure 4 - Measurement Tab to Calibrate

8. Set the origin for measurement purposes.
    a. Select the two boxes under Axes ("Show" and "Coordinates in mm").
    b. Click on "Set Origin"
        i. Select the origin on the initial frame at the center of the detonator, see Figure 5 below.

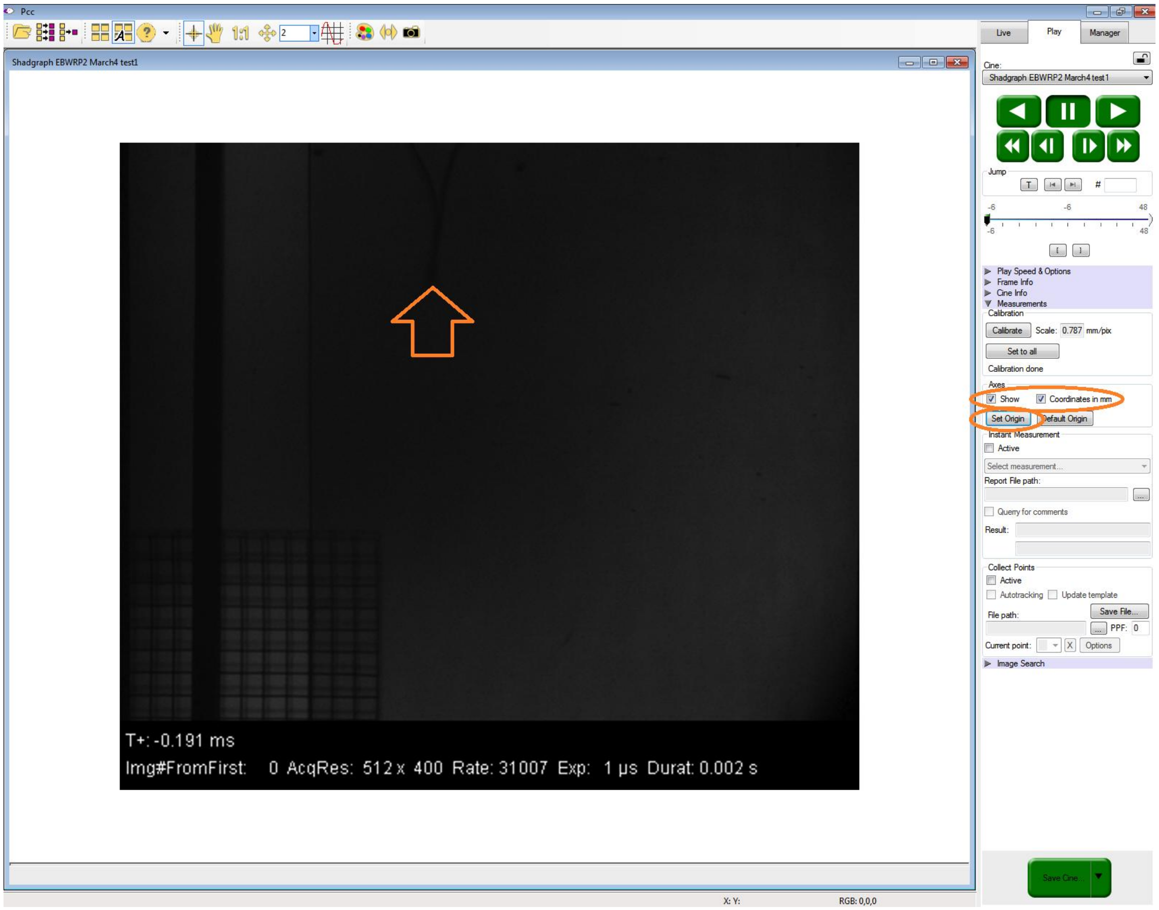


Figure 5 - Origin Options

9. Under the Measurement tab, under Instant Measurement, select the option (origin + 1 point), see Figure 6.

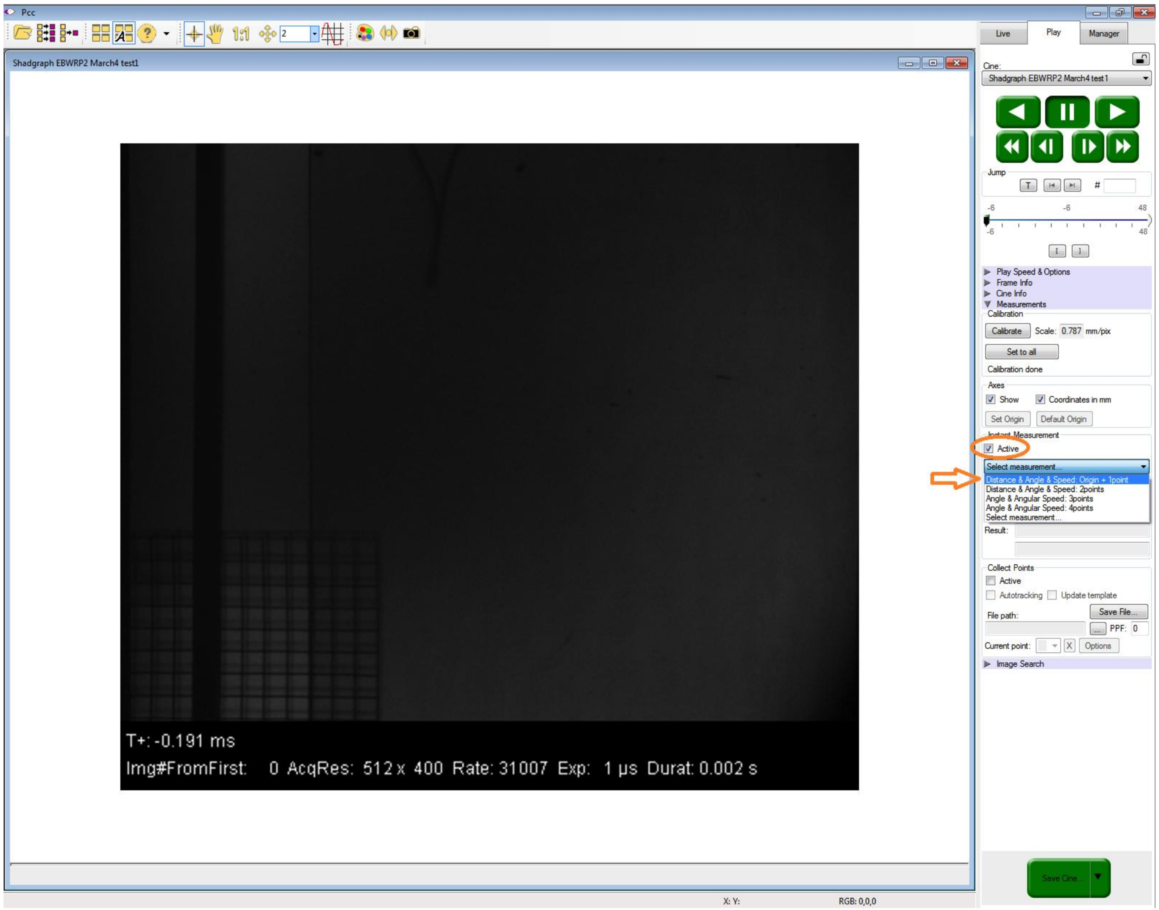


Figure 6 – Measurement Selection Options

10. Under the Measurement Tab, click on the "…" button. Create a file path to save the collected data. See Figure 7.

Figure 7 - Measurement Tab and Create a File Tab

11. Give the file a name and click open. See Figure 8.

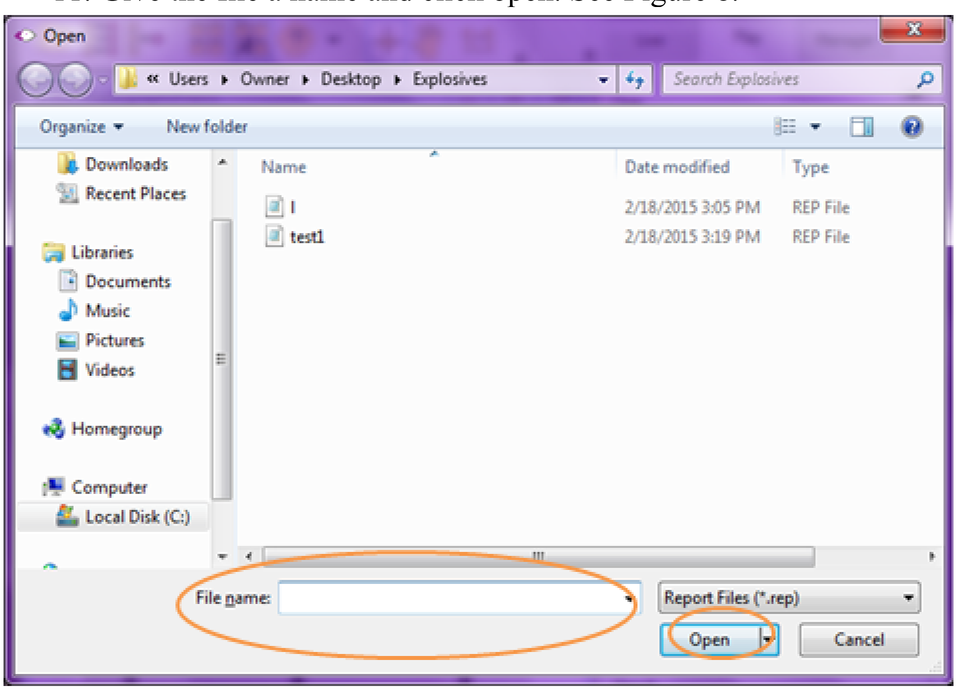


Figure 8 - File Name Window

12. Fill out the Measurement Report File information then click the “OK” button. See Figure 9.

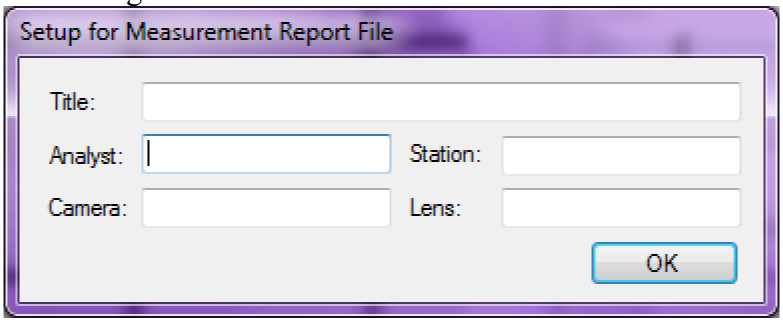


Figure 9 - Measurement Report File Window

13. Next click “Active” button. See Figure 7.
14. Next click the “Active” button under Collect Points. See Figure 9.
    a. Click the “…” button to choose a file path.
    b. Input the number of points per frame (PPF).

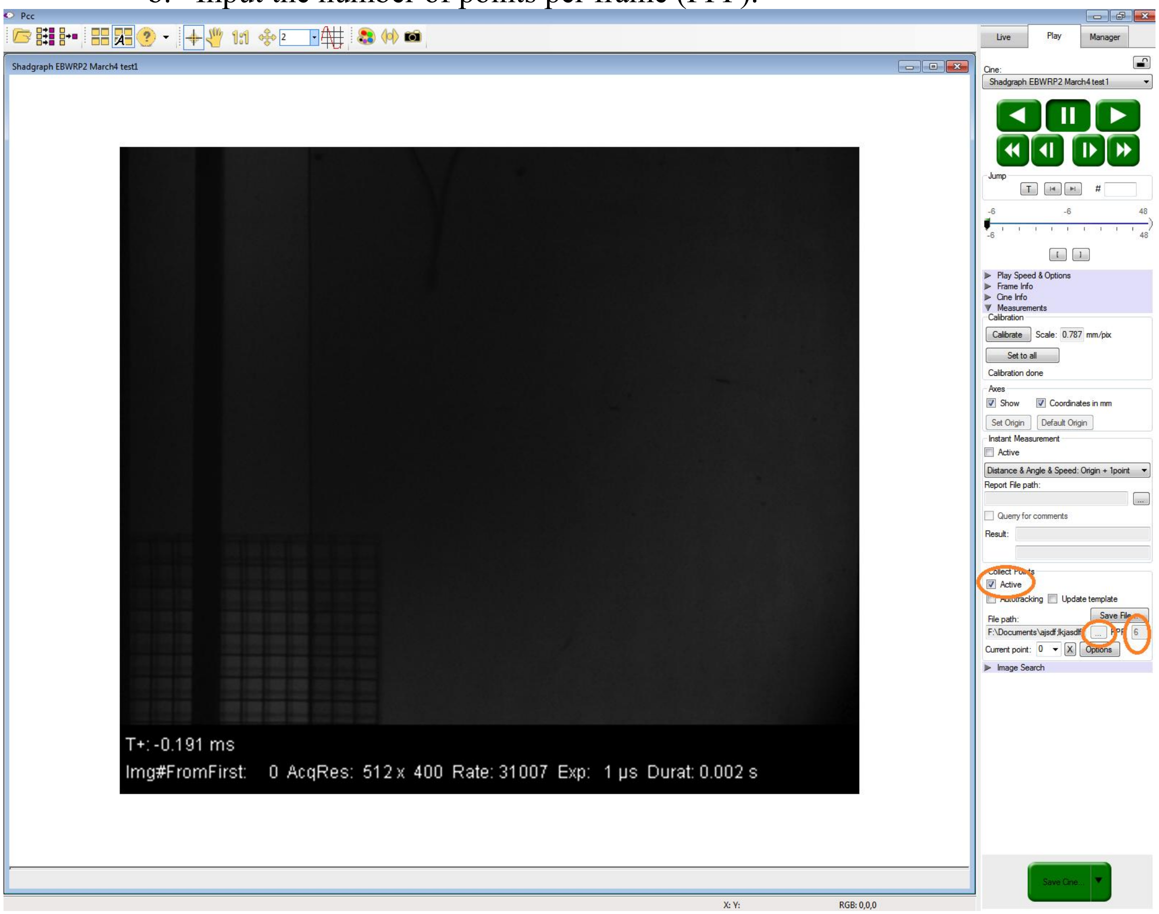


Figure 10 - Collection Point and PPF Input

15. Next select the amount of points specified in the PPF box on the shadowgraph to measure the shock velocity.
16. Choose the next frame and select the next points on the graph. See Figure 10.
    a. Make sure the points are selected in the same order.

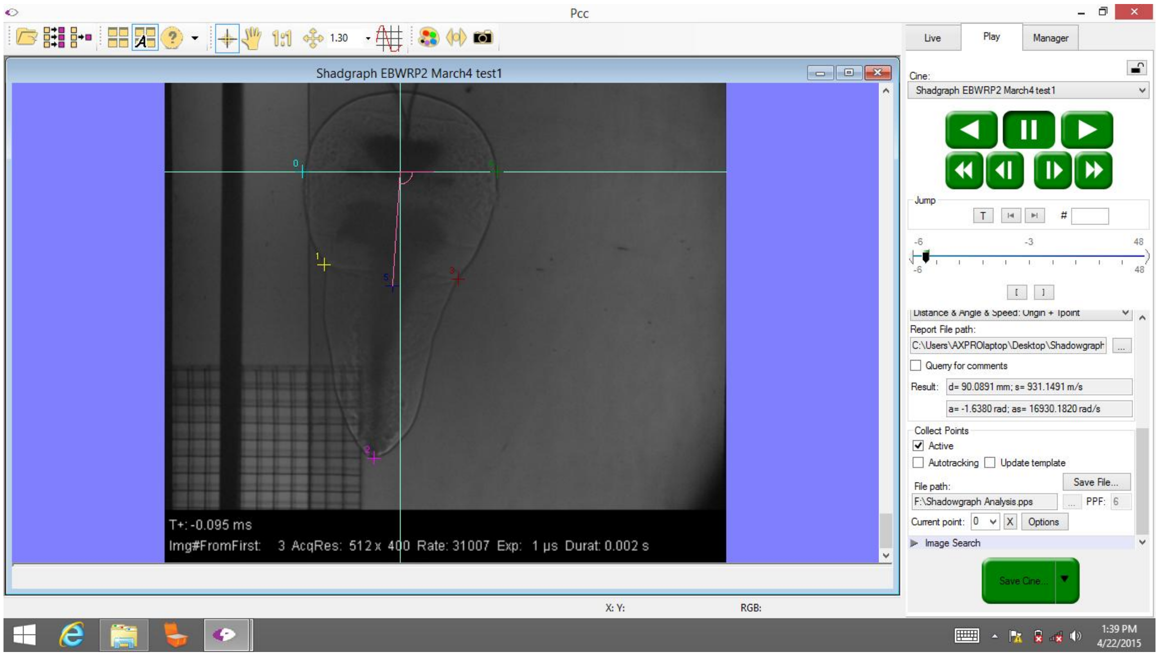
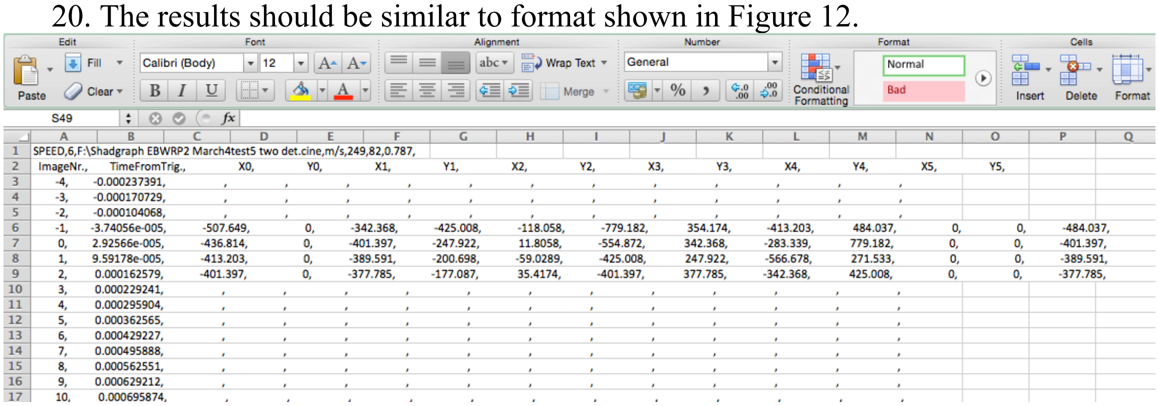


Figure 11 - Selecting Data Points Example

17. Repeat step 15 for four additional frames.
18. The data will save automatically to the file set up in the previous steps.
19. Rename the file extension to .xls to export the data into the an Excel spreadsheet.
20. The results should be similar to format shown in Figure 12.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	SPEED,6,F:\Shadgraph EBWRP2 March4test5 two det.cine,m/s,249,82,0.787,																
2	ImageNr.,	TimeFromTrig.,	X0,	Y0,	X1,	Y1,	X2,	Y2,	X3,	Y3,	X4,	Y4,	X5,	Y5,			
3	-4,	-0.000237391,	,	,	,	,	,	,	,	,	,	,	,	,			
4	-3,	-0.000170729,	,	,	,	,	,	,	,	,	,	,	,	,			
5	-2,	-0.000104068,	,	,	,	,	,	,	,	,	,	,	,	,			
6	-1,	-3.74056e-005,	-507.649,	0,	-342.368,	-425.008,	-118.058,	-779.182,	354.174,	-413.203,	484.037,	0,	0,	-484.037,			
7	0,	2.92566e-005,	-436.814,	0,	-401.397,	-247.922,	11.8058,	-554.872,	342.368,	-283.339,	779.182,	0,	0,	-401.397,			
8	1,	9.59178e-005,	-413.203,	0,	-389.591,	-200.698,	-59.0289,	-425.008,	247.922,	-566.678,	271.533,	0,	0,	-389.591,			
9	2,	0.000162579,	-401.397,	0,	-377.785,	-177.087,	35.4174,	-401.397,	377.785,	-342.368,	425.008,	0,	0,	-377.785,			
10	3,	0.000229241,	,	,	,	,	,	,	,	,	,	,	,	,			
11	4,	0.000295904,	,	,	,	,	,	,	,	,	,	,	,	,			
12	5,	0.000362565,	,	,	,	,	,	,	,	,	,	,	,	,			
13	6,	0.000429227,	,	,	,	,	,	,	,	,	,	,	,	,			
14	7,	0.000495888,	,	,	,	,	,	,	,	,	,	,	,	,			
15	8,	0.000562551,	,	,	,	,	,	,	,	,	,	,	,	,			
16	9,	0.000629212,	,	,	,	,	,	,	,	,	,	,	,	,			
17	10,	0.000695874,	,	,	,	,	,	,	,	,	,	,	,	,			

Figure 12 - Example of initial data format from PCC Software

Calculations:

Shockwave Velocity (Pythagorean Thm)

$$V := \frac{d}{t} \quad \text{(m/s)} \quad \textbf{(1)} \qquad d := \sqrt{x^2 + y^2} \quad \text{(m)} \quad \textbf{(2)}$$

Constants for air

$$k := 1.4 \qquad T_{room} := 293\ K \qquad R := 286.9\ \frac{J}{kg \cdot K} \qquad P_{atm} := 101.32\ kPa$$

Velocity from PCC Software

$$V := 462.84\ \frac{m}{s}$$

Speed of Sound at room temperature and atmospheric pressure

$$C := \sqrt{k \cdot R \cdot T_{room}} \quad \text{(m/s)} \quad \textbf{(2)}$$

Mach Number

$$Ma := \frac{V}{C} \quad \textbf{(3)} \qquad sin(\alpha) := \frac{C}{V} \quad \textbf{(4)}$$

Pressure Calculation

$$P := P_{atm} \cdot \left(1 + \frac{k-1}{2} \cdot Ma^2\right) \quad \text{(Pa)} \quad \textbf{(5)}$$

Temperature Calculation

$$T := T_{room} \cdot \left(1 + \frac{k-1}{2} \cdot Ma^2\right) \quad \text{(K)} \quad \textbf{(6)}$$

Analysis and Results:

The results from the single and parallel detonators show significant measureable differences in pressure, temperature, and the Mack number. The single detonator generally had higher calculated pressure, temperature, and Mach number values in comparison to the two parallel detonator interaction (Appendix, Tables 1 and 2). The highest values of the single detonator were calculated at point 2 and frame 3. The Mach number was calculated to be 6.64, almost 4 times as high as the two parallel detonator interaction, which was 1.62 (Appendix, Tables 3 and 4). The singular detonator was a shape charge. Shape charges are designed to create a jet at detonation, this is the phenomena at point 2. The graphs of the single detonator and of the two parallel detonator interaction were also different. Since the values of pressure, temperature, and the Mach number were high, especially at point 2, this caused the graphs to become skewed, providing difficulty in analyzing the relationship of the pressure, temperature, and Mach number between each frame and point (Appendix, Figures 1-4). The graphs for the two-detonator interaction were less skewed, since the values at point 2 were not as high compared to the single detonator.

The reason for the significant difference between the values for pressure, temperature, and Mach number values is contributed from the shockwave interaction difference between two detonators versus one detonator. The two parallel detonators have shockwave interference where the two shockwaves resulting from each detonator collide (Henderson), Figure 13.

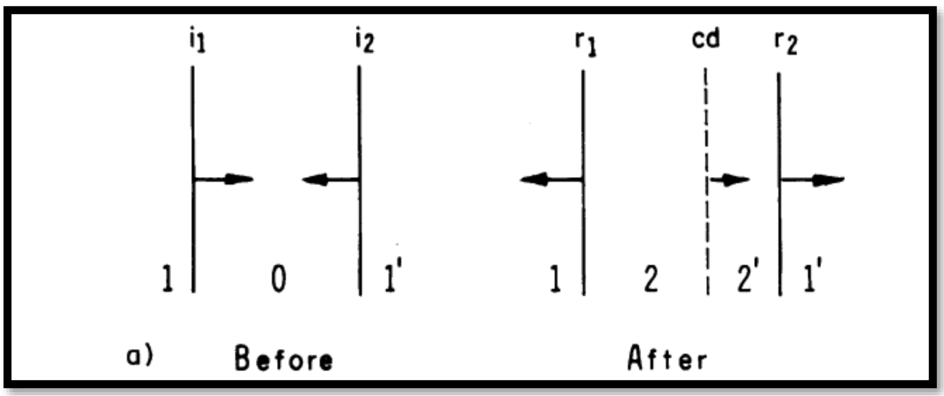


Figure 13: Collide Shockwaves of Two Parallel Shockwaves (Henderson)

According to the Triple Shock Entropy Theorem, the entropy increase across a sequence of two shock waves is smaller than that of a single shockwave (Henderson). Additionally, the theorem continues to state that the pressure is also smaller than that of a single detonator as well. This theorem validates the results that were calculated in Tables 1-4, where the pressure and Mach number were calculated to be smaller of the two parallel detonators than that of the single detonator. Lastly, since there is a less entropy with the interaction of two shockwaves, the increase the temperature is also smaller compared to that of a single detonator (Henderson).

Error Analysis:

There were four associated areas within the data analysis. The first error is contributed within the assumptions that were used to calculate pressure and temperature. Standard temperature and pressure conditions were assumed when in actuality, a barometer should have been used as a reference in calculating the actual values for temperature and pressure. Therefore, the speed of sound used in the calculations is not the true value. The speed of sound affects the Mach number calculations, consequently, the reported Mach number are not a true representation of the correct values.

The second error is contributed to the user error of the Phantom ™ software. Calibration of grid had significant error depending on how the mouse was placed on the software. Also, selecting the points varied among each frame and depending on how well the user could track the points, the location of the points varied among each frame.

The detonators used to compare the results are different, where the single detonator is and RP-2 electric bridge wire detonator, and the parallel detonators are RP-2 electrical bridge wire shape charge detonators. Therefore, the results being compared are not from the same detonator, which makes it difficult to draw conclusions on the shockwave interaction.

Also, there were two assumptions that were made throughout the calculations and analysis. The first assumption was that the resulting explosive reactions were isentropic and adiabatic. The isentropic assumption means there is no heat transfer between the fluid and the environment. The adiabatic assumption states there is no change in entropy during the analysis. We can then relate pressure temperature and density during our analysis. In reality, detonations are neither isentropic nor adiabatic; energy is transferred in the form of heat. Two constants were used in the calculations, k = 1.4 and R = 286.9 J/kg*K, these are a product of our assumptions.

These four contributing errors lead to significant amount of error within the results and analysis, but did not detract from the main objectives of this report. A table listing the assumptions made within the analysis is included below, Table 1.

Table 1: Assumptions Made in Analysis and Calculations

Parameters	Symbol	Assumptions		Error
		Assumed	Actual	
Room Temperature (K)	T_O	293	294.66	0.57
Pressure (kPa)	P_O	101.3	82.06	18.99
Density (kg/m^3)	ρ	1.293	1.0345	19.99
Humidity (%)		0	25	-
Elevation (m)		0	1737.8	-
Gas Constant (J/kg*K)	R	286.9	286.9	0
Adiabatic Index	k	1.4	1.4	0

Conclusions:

The objective of this report is to show the interaction of a single shockwave from two parallel detonators compared to a single detonator. The resulting calculations for a single shockwave resulting from both a single detonator and two parallel detonators proved to follow suit with the Triple Shock Entropy Theorem presented by Leroy Henderson. The theorem explained that the interaction of 2 shockwaves has a decrease in entropy, which yield lower pressure, temperature, and Mach number values in comparison to a single detonator, which had higher entropy values. It is important to acknowledge the error in the assumptions listed in

Table 1 because the assumptions made do not reflect the true conditions (temperature and pressure) of the laboratory settings. Even though there was significant error within the assumptions and use of the Phantom ™ software, the results proved to be consistent with known published shockwave theory. In the future, a barometer should be present in the lab testing room to have an accurate measure of the temperature and pressure. Additionally, the same detonators should be tested in order to ensure that the same detonator properties. Lastly, there is always going to be user error when using the Phantom ™ software, therefore it is in best practice to have the same user utilizing the software for consistency purposes.

Appendix:

Tables:

Table 1: Results for Mach Number For Each Frame and Point For Single Detonator

Frame #	Point 0	Mach Number	Point 1	Mach	Point 2	Mach	Point 3	Mach	Point 4	Mach	Point5	Mach
1	0	0	0	0	0	0	0	0	0	0	0	0
2	507.65	1.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	436.81	1.27	1204.75	3.51	2276.67	6.64	444.41	1.30	725.36	2.11	912.86	2.66
4	413.20	1.20	583.92	1.70	1089.69	3.18	618.54	1.80	500.25	1.46	779.00	2.27
5	401.40	1.17	562.08	1.64	800.78	2.33	509.84	1.49	475.23	1.39	403.31	1.18

Table 2: Pressure and Temperature of Shockwave For a Single Detonator

Frame #	Pressure 0 (Pa)	Pressure 1 (Pa)	Pressure 2 (Pa)	Pressure 3 (Pa)	Pressure 4 (Pa)	Pressure 5 (Pa)	Temperature 0 (C)	Temperature 1 (C)	Temperature 2 (C)	Temperature 3 (C)	Temperature 4 (C)	Temperature 5 (C)
1	101325.00	101325.00	101325.00	101325.00	101325.00	101325.00	20.00	20.00	20.00	20.00	20.00	20.00
2	145936.98	101325.00	101325.00	101325.00	101325.00	101325.00	28.76	20.00	20.00	20.00	20.00	20.00
3	134355.68	352583.04	998597.73	135513.86	192406.05	245581.75	26.49	69.35	196.23	26.71	37.89	48.33
4	130881.39	160348.95	306880.33	167555.38	144645.32	206376.97	25.80	31.59	60.37	33.01	28.51	40.63
5	129216.55	156017.00	212333.44	146322.99	140421.64	129483.24	25.48	30.74	41.80	28.84	27.68	25.53

Table 3: Results for Mach Number For Each Frame and Point For Parallel Detonators

Frame #	Point 0	Mach Number	Point 1	Mach	Point 2	Mach	Point 3	Mach	Point 4	Mach	Point5	Mach
1	0	0	0	0	0	0	0	0	0	0	0	0
2	507.65	1.48	545.75	1.59	788.08	2.30	544.22	1.59	484.04	1.41	484.04	1.41
3	436.81	1.27	471.79	1.38	555.00	1.62	444.41	1.30	779.18	2.27	401.40	1.17
4	413.20	1.20	438.25	1.28	429.09	1.25	618.54	1.80	271.53	0.79	389.59	1.14
5	401.40	1.17	417.23	1.22	402.96	1.17	509.84	1.49	425.01	1.24	377.79	1.10

Table 4: Pressure and Temperature of Shockwave For Parallel Detonators

Frame #	Pressure 0 (Pa)	Pressure 1 (Pa)	Pressure 2 (Pa)	Pressure 3 (Pa)	Pressure 4 (Pa)	Pressure 5 (Pa)	Temperature 0 (C)	Temperature 1 (C)	Temperature 2 (C)	Temperature 3 (C)	Temperature 4 (C)	Temperature 5 (C)
1	101,325.00	101,325.00	101,325.00	101,325.00	101,325.00	101,325.00	20.00	20.00	20.00	20.00	20.00	20.00
2	145,936.98	152,885.68	208,837.65	152,596.29	141,883.47	141,883.47	28.76	30.13	41.12	30.07	27.97	27.97
3	134,355.68	139,856.87	154,647.02	135,513.86	206,424.89	129,216.55	26.49	27.57	30.47	26.71	40.64	25.48
4	130,881.39	134,572.83	133,197.52	167,555.38	114,088.50	127,599.97	25.80	26.53	26.26	33.01	22.51	25.16
5	129,216.55	131,460.37	129,433.70	146,322.99	132,594.33	126,031.65	25.48	25.92	25.52	28.84	26.14	24.85

Graphs:

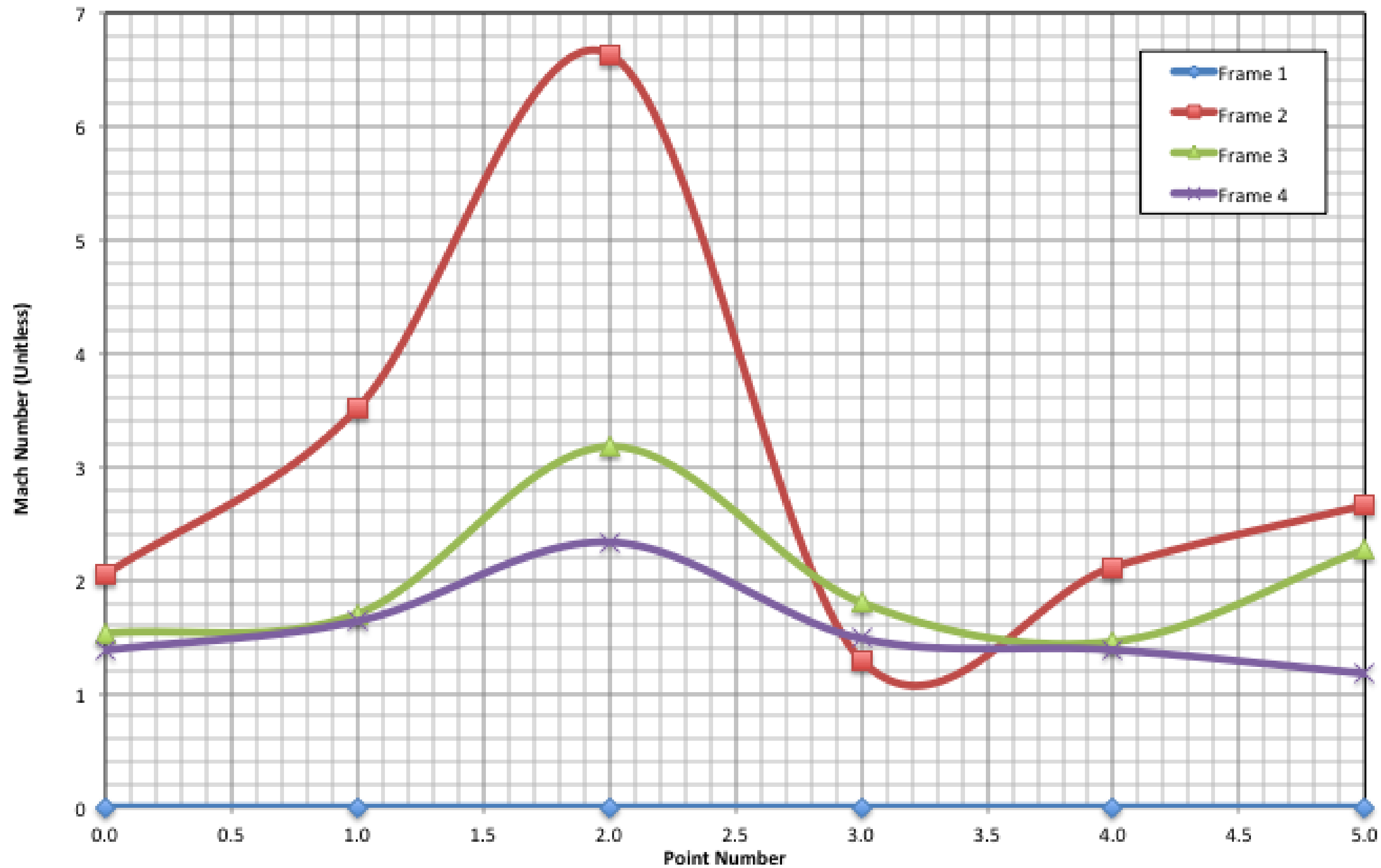


Figure 1: Mach Number Per Each Point Related to Frame For Single Detonator

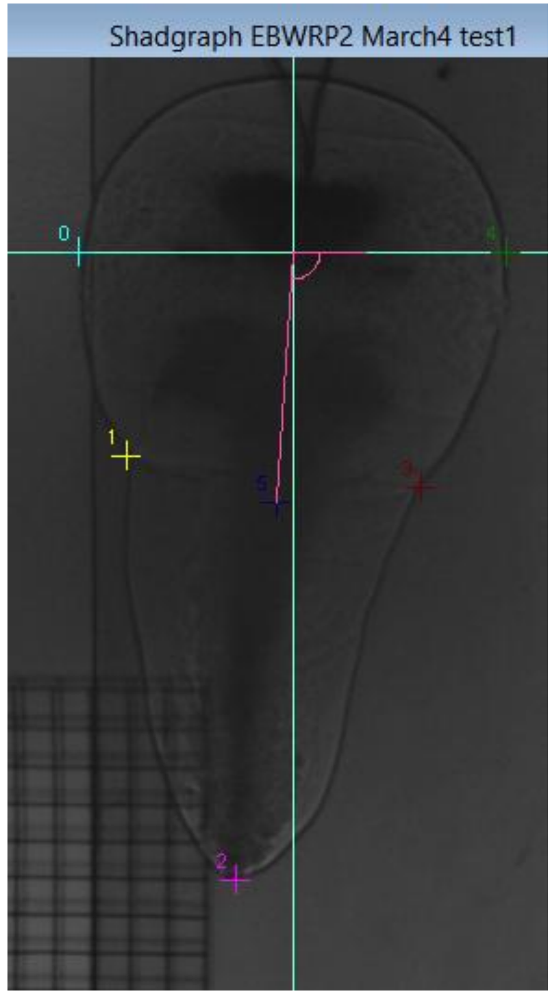


Figure 1A: Corresponding Shockwave For Figure 1

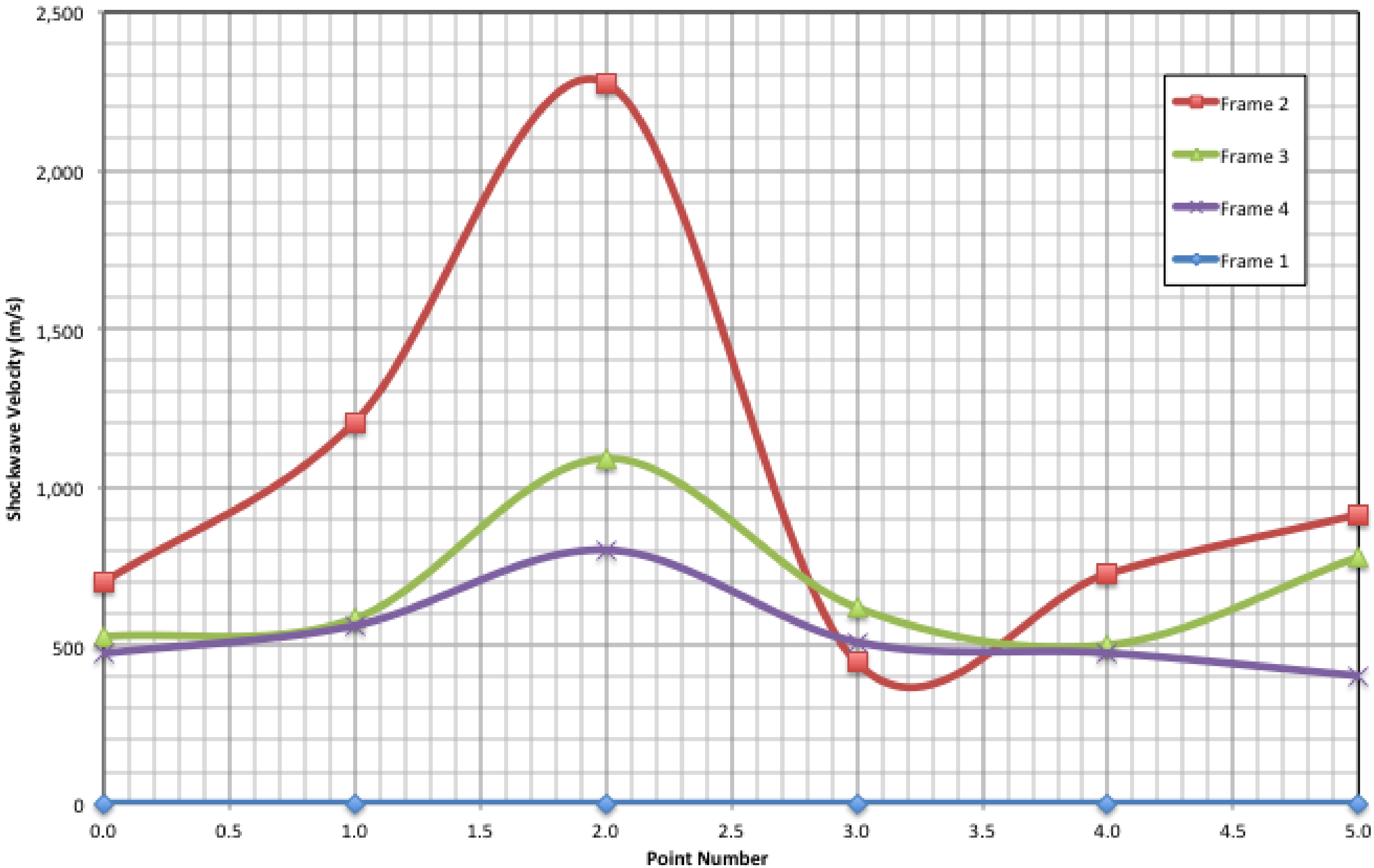


Figure 2: Shockwave Velocity Per Each Point Related to Frame For Single Detonator

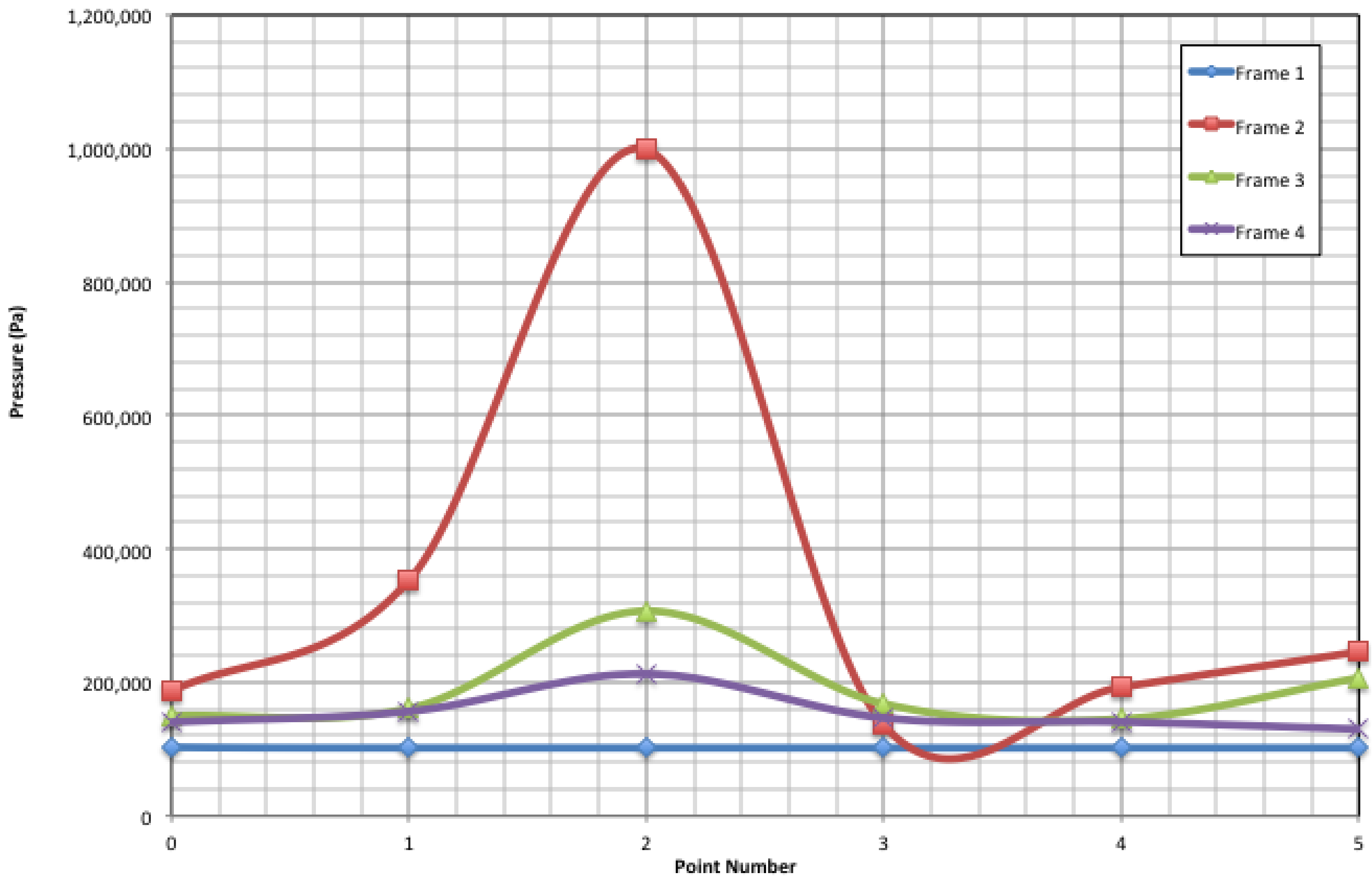


Figure 3: Generated Presure From Shockwave Velocity For Single Detonator

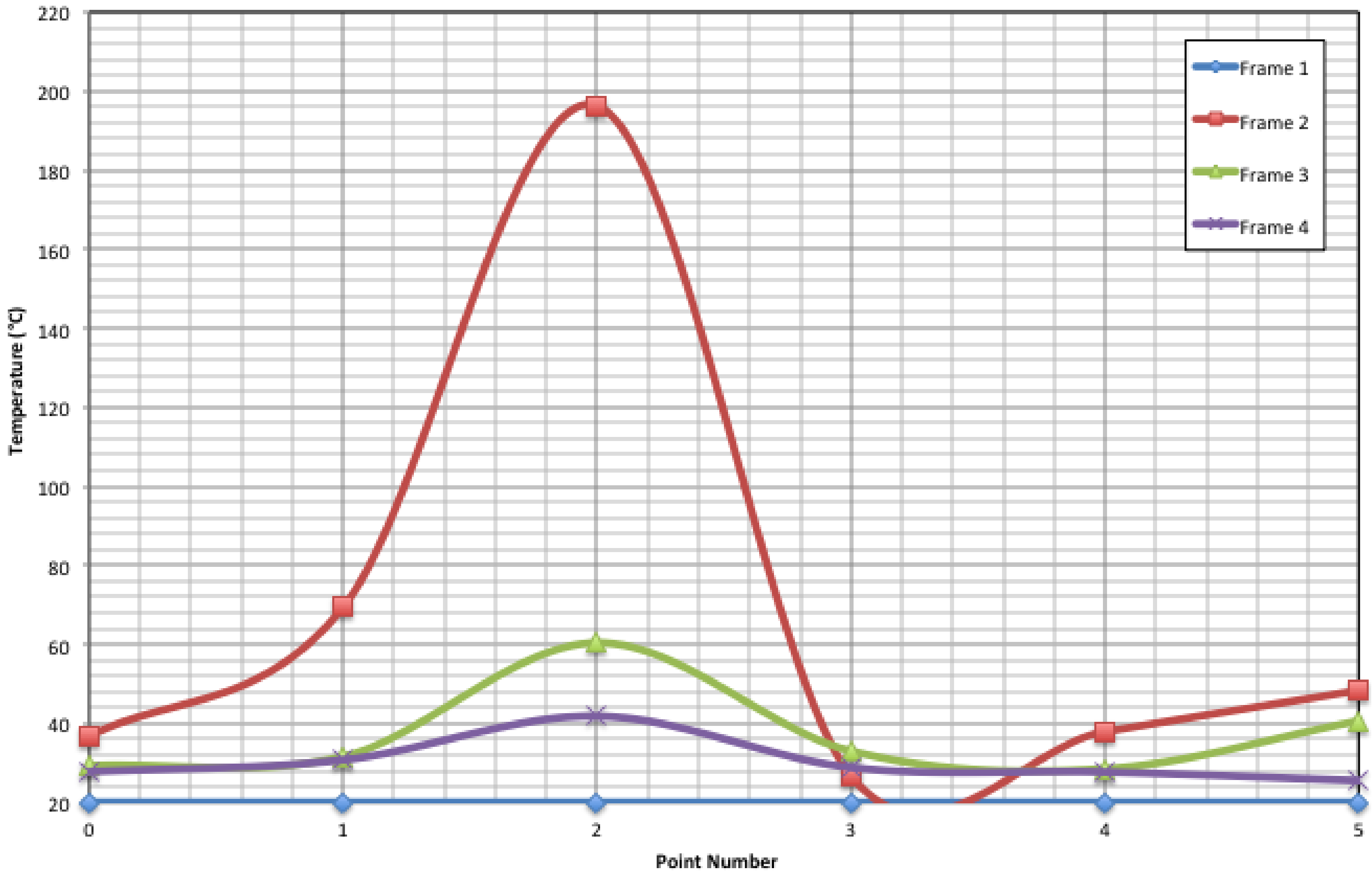


Figure 4: Generated Temperature From Shockwave Velocity For Single Detonator

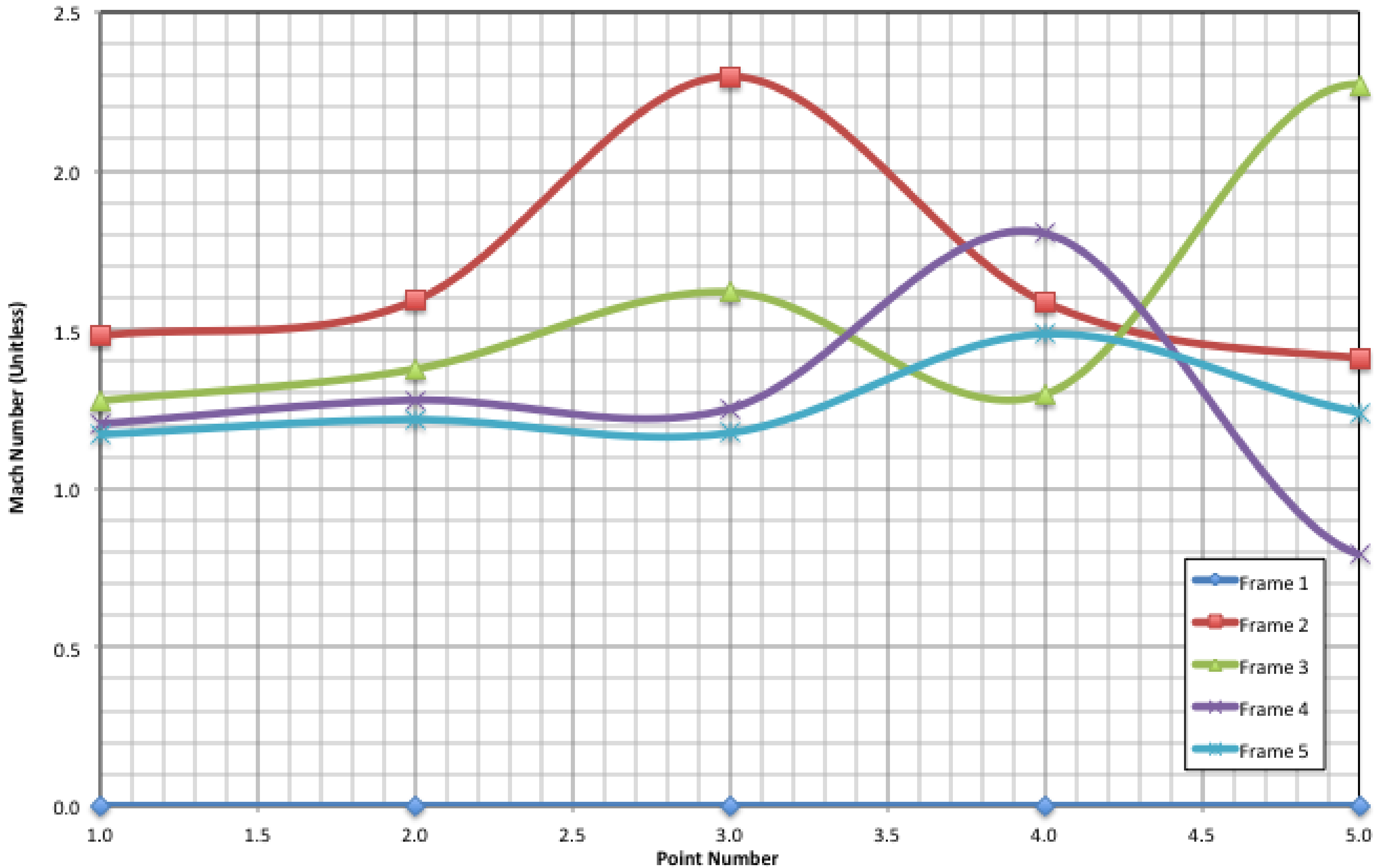


Figure 5: Mach Number Per Each Point Related to Frame For Parallel Detonators

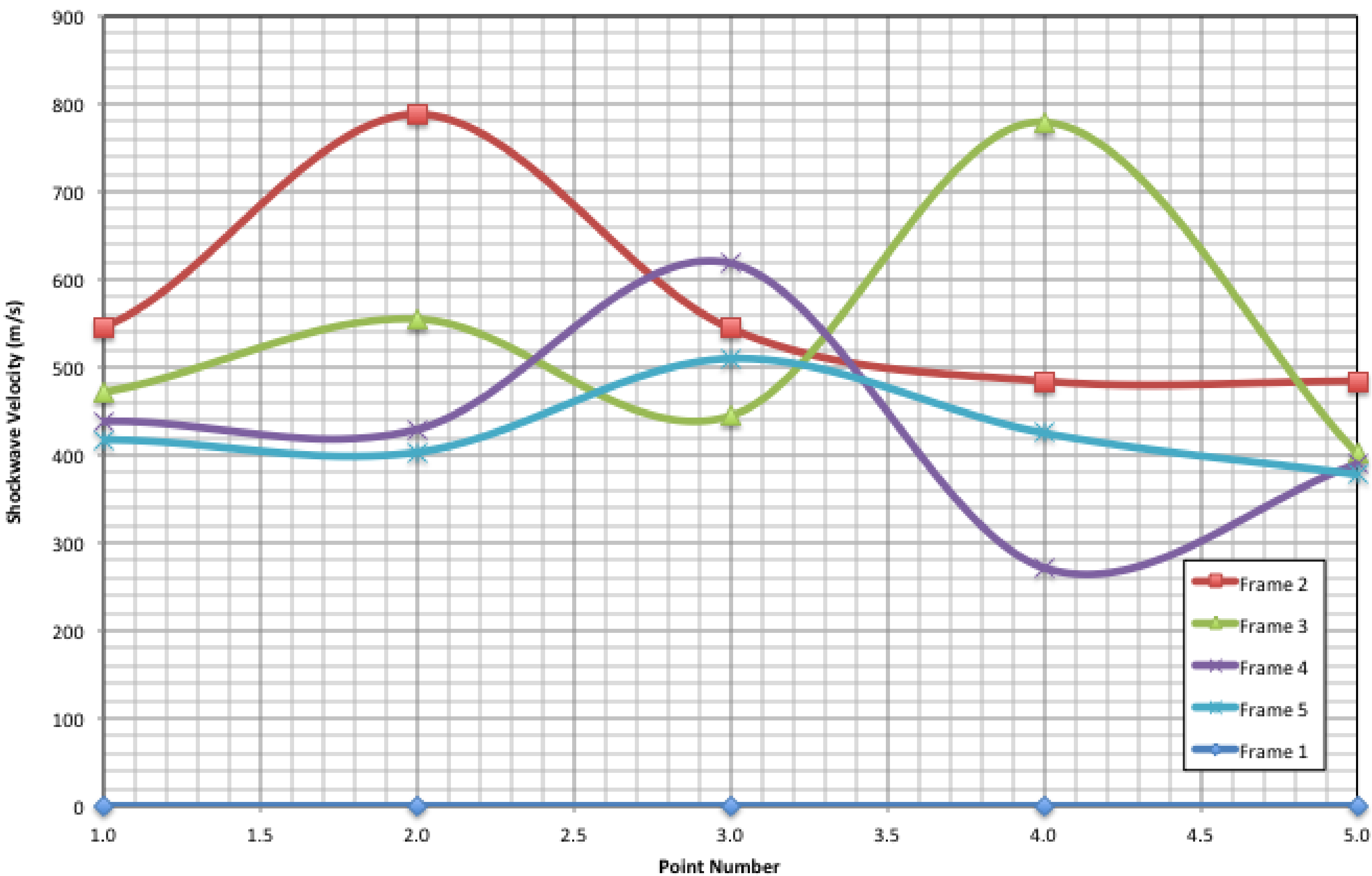


Figure 6: Shockwave Velocity Per Each Point Related to Frame For Parallel Detonators

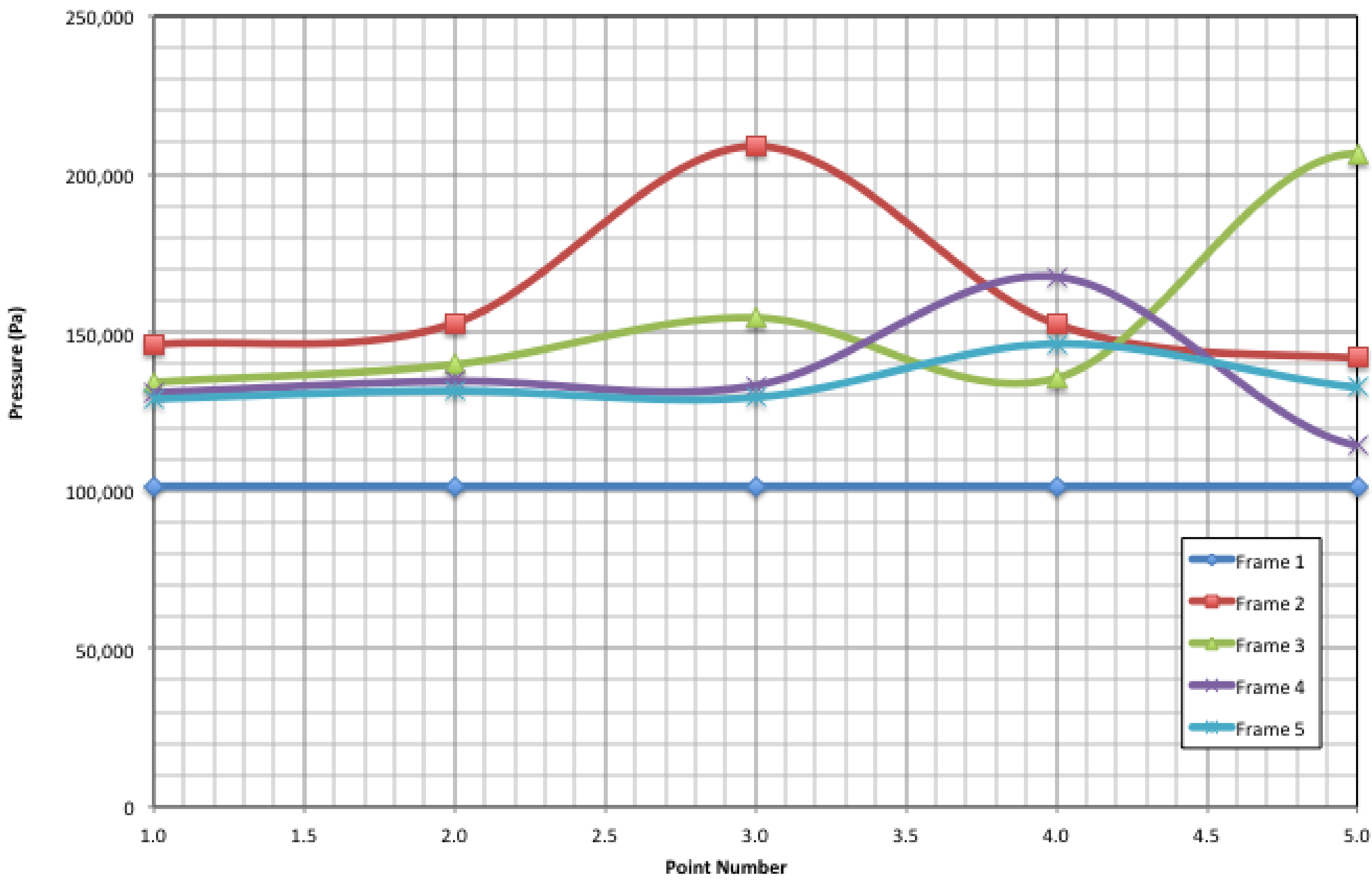


Figure 7: Generated Pressure From Shockwave Velocity For Parallel Detonators

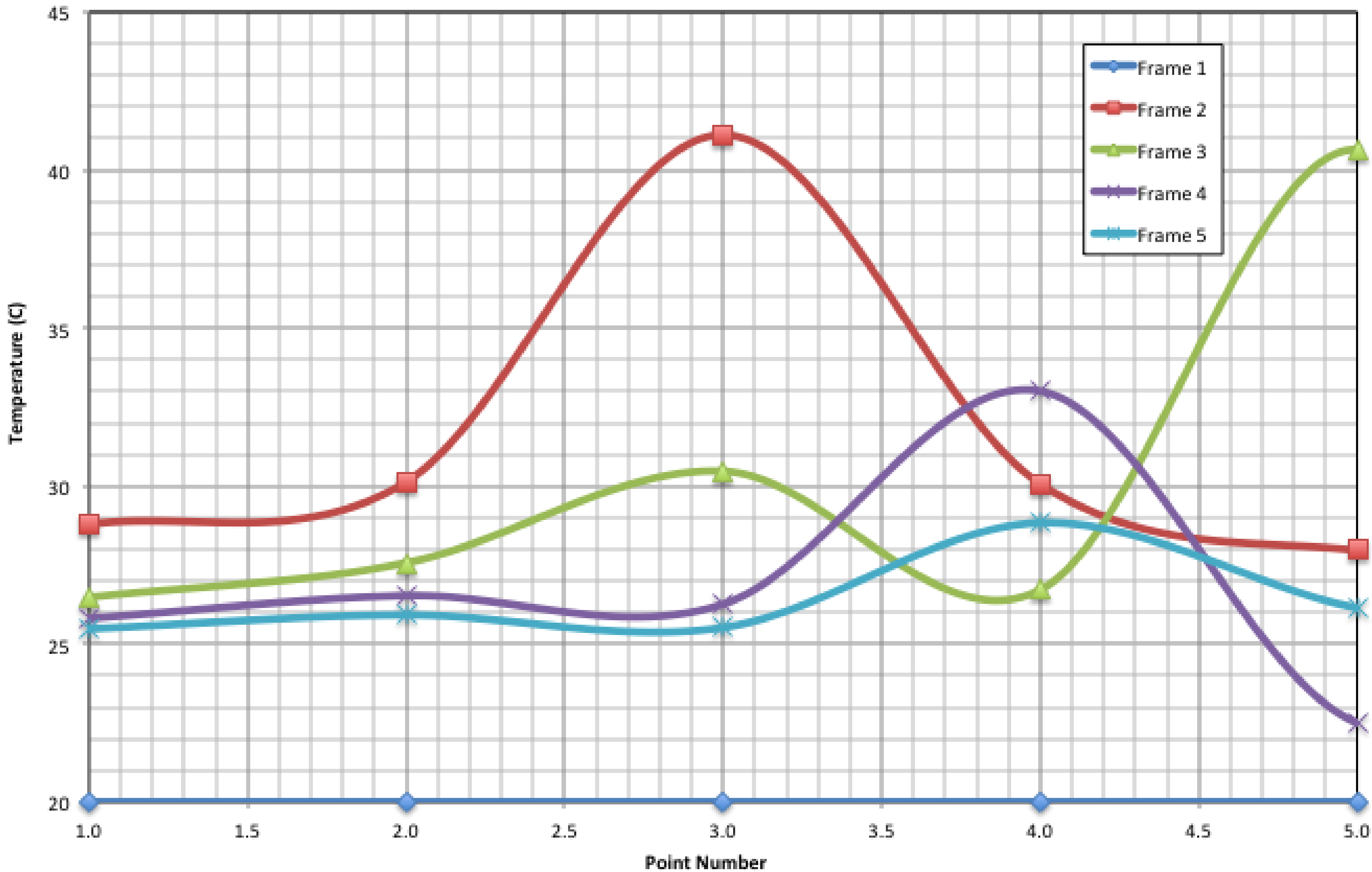


Figure 8: Generated Temperature From Shockwave Velocity For Parallel Detonators

References:

[1] R.C. Hibbeler, "Compressible Flow," in *Fluid Mechanincs,* 1st ed. New York, USA: Pearson, 2015.

[2] Phantom™ Software, Vision Research

[3] Henderson, Leroy, F. "General Laws for Propagation of Shock Waves through Matter." *Handbook of Shockwaves* . Vol. 1. Academic Press . 38. Web.