



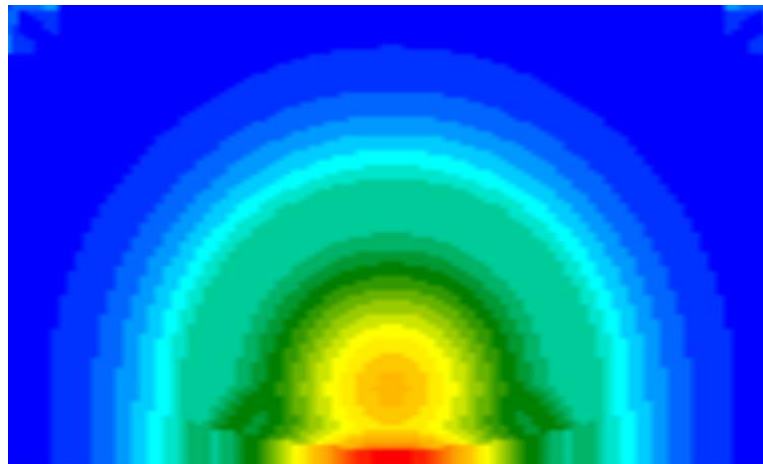
# NAVFAC

Naval Facilities Engineering Command

ENGINEERING SERVICE CENTER  
Port Hueneme, California 93043-4370

## Technical Report TR-NAVFAC ESC-CI-1101

### SHOCK 2.0 THEORY MANUAL



By

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June 2011

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| <b>REPORT DOCUMENTATION PAGE (SF 298)</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                             |                                           |                                   | <i>Form Approved<br/>OMB No. 0704-0811</i>                   |                                                  |
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| <b>13. SUPPLEMENTARY NOTES</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                             |                                           |                                   |                                                              |                                                  |
| <b>14. ABSTRACT</b><br><p>SHOCK is a computer program that implements the method used to generate Figures 2-52 through 2-100 for averaged reflected pressure and Figures 2-101 through 2-149 for reflected impulse in UFC 3-340-02 "Structures to Resist the Effects of Accidental Explosions". The methodology used in SHOCK was never fully documented or explained by the original authors or thereafter. Furthermore, lack of configuration management has resulted in numerous versions of the program without documentation of changes or differences.</p> <p>The Naval Facilities Engineering Service Center (NAVFAC ESC) has been tasked and funded by the Department of Defense Explosives Safety Board (DDESB) to document the semi-empirical method used in SHOCK, to identify and update anomalies or mistakes in the code and to create and validate a new version of the code.</p> <p>This report documents the history of the computer program, the updates and improvements that were carried out in the past and in the current effort, and explains the semi-empirical method in detail. The latest version of the program, SHOCK 2.0, is also validated by comparing against test data and ConWep. Results from SHOCK 2.0 for three points on a load wall are also compared with a numerical procedure that uses ConWep and Figures 2-193, 2-194(a), 2-194(b) in UFC 3-340-02 to calculate loads at various incidence angles. Details of these validations are presented in this report.</p> <p>The validation indicates that SHOCK 2.0, on average, does improve the results for reflected impulse and pressure. While the application has been improved, an in-depth study of the method and supporting literature indicates that the current method makes simplified assumptions and may be somewhat inaccurate. The program would be capable of computing pressure and impulse more accurately if recommended changes in Section 6.0 of this report are implemented.</p> |                             |                                           |                                   |                                                              |                                                  |
| <b>15. SUBJECT TERMS</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                             |                                           |                                   |                                                              |                                                  |
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## EXECUTIVE SUMMARY

SHOCK is a computer program that implements the method used to generate Figures 2-52 through 2-100 for averaged reflected pressure and Figures 2-101 through 2-149 for reflected impulse in UFC 3-340-02 “Structures to Resist the Effects of Accidental Explosions”. The methodology used in SHOCK was never fully documented or explained by the original authors or thereafter. Furthermore, lack of configuration management has resulted in numerous versions of the program without documentation of changes or differences.

The Naval Facilities Engineering Service Center (NAVFAC ESC) has been tasked and funded by the Department of Defense Explosives Safety Board (DDESB) to document the semi-empirical method used in SHOCK, to identify and update anomalies or mistakes in the code and to create and validate a new version of the code.

This report documents the history of the computer program, the updates and improvements that were carried out in the past and in the current effort, and explains the semi-empirical method in detail. The latest version of the program, SHOCK 2.0, is also validated by comparing against test data and ConWep. Results from SHOCK 2.0 for three points on a load wall are also compared with a numerical procedure that uses ConWep and Figures 2-193, 2-194(a), 2-194(b) in UFC 3-340-02 to calculate loads at various incidence angles. Details of these validations are presented in this report.

The validation indicates that SHOCK 2.0, on average, does improve the results for reflected impulse and pressure. While the application has been improved, an in-depth study of the method and supporting literature indicates that the current method makes simplified assumptions and may be somewhat inaccurate. The program would be capable of computing pressure and impulse more accurately if recommended changes in Section 6.0 of this report are implemented.

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## **ACRONYMS AND ABBREVIATIONS**

|            |                                              |
|------------|----------------------------------------------|
| A&W        | Ammann & Whitney                             |
| ASESB      | Armed Services Explosive Safety Board        |
| DDESB      | Department of Defense Explosive Safety Board |
| K-B        | Kingery-Bulmash                              |
| NAVFAC ESC | Naval Facilities Engineering Service Center  |
| NCEL       | Naval Civil Engineering Laboratory           |
| NSWC       | Naval Surface Weapons Center                 |
| SwRI       | Southwest Research Institute                 |

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## TABLE OF CONTENTS

|            |                                                                 |           |
|------------|-----------------------------------------------------------------|-----------|
| <b>1.0</b> | <b>Introduction.....</b>                                        | <b>1</b>  |
| <b>2.0</b> | <b>SHOCK Background.....</b>                                    | <b>1</b>  |
| <b>2.1</b> | <b>Original Average Impulse Method.....</b>                     | <b>1</b>  |
| <b>2.2</b> | <b>Original Method Deficiencies.....</b>                        | <b>2</b>  |
| <b>2.3</b> | <b>Computer Program IMPRES.....</b>                             | <b>3</b>  |
| <b>2.4</b> | <b>Computer Program SHOCK.....</b>                              | <b>3</b>  |
| <b>3.0</b> | <b>SHOCK 2.0 Update.....</b>                                    | <b>4</b>  |
| <b>4.0</b> | <b>Shock Theory/Method.....</b>                                 | <b>4</b>  |
| <b>4.1</b> | <b>Grid.....</b>                                                | <b>5</b>  |
| <b>4.2</b> | <b>Method Assumptions.....</b>                                  | <b>5</b>  |
| <b>4.3</b> | <b>Direct shock procedure.....</b>                              | <b>6</b>  |
| <b>4.4</b> | <b>Back Wall Reflection.....</b>                                | <b>7</b>  |
| <b>4.5</b> | <b>Adjacent Surface Reflection.....</b>                         | <b>9</b>  |
| <b>4.6</b> | <b>Total Reflected Impulse and Peak Reflected Pressure.....</b> | <b>16</b> |
| <b>5.0</b> | <b>Validation of SHOCK 2.0.....</b>                             | <b>16</b> |
| <b>5.1</b> | <b>Overview.....</b>                                            | <b>16</b> |
| <b>5.2</b> | <b>SHOCK 2.0 Results vs. Test Data.....</b>                     | <b>16</b> |
| <b>5.3</b> | <b>SHOCK 2.0 and ConWep Calculations.....</b>                   | <b>22</b> |
| <b>5.4</b> | <b>SHOCK 2.0 Calculations and Source Plots.....</b>             | <b>25</b> |
| <b>6.0</b> | <b>Conclusions/Recommendations.....</b>                         | <b>26</b> |
| <b>6.1</b> | <b>Conclusions.....</b>                                         | <b>26</b> |
| <b>6.2</b> | <b>Recommendations.....</b>                                     | <b>26</b> |
|            | <b>ACKNOWLEDGEMENT.....</b>                                     | <b>27</b> |

## LIST OF TABLES

|                                                          |    |
|----------------------------------------------------------|----|
| Table 5.1. Pressure and Impulse Results .....            | 20 |
| Table 5.2. SHOCK Results Normalized by Test Results..... | 21 |
| Table 5.3. Scaled Distance Comparison .....              | 24 |
| Table 5.4. Reflecting Surface Comparison .....           | 24 |
| Table 5.5. SHOCK 2.0 and Source Table Comparison .....   | 25 |

## LIST OF FIGURES

|                                                                                |    |
|--------------------------------------------------------------------------------|----|
| Figure 4.1. Cubicle load wall.....                                             | 5  |
| Figure 4.2. Direct Shock .....                                                 | 6  |
| Figure 4.3. Back wall reflection.....                                          | 8  |
| Figure 4.4. Regular vs. Mach Reflection .....                                  | 9  |
| Figure 4.5. Adjacent reflecting surface.....                                   | 10 |
| Figure 4.6. Adjacent reflecting surface, with Mach stem above load point ..... | 12 |
| Figure 4.7. Adjacent reflecting surface, with Mach stem below load point ..... | 14 |
| Figure 5.1. Structure layout in SHOCK 2.0.....                                 | 17 |
| Figure 5.2. Pressure plot from all tests .....                                 | 19 |
| Figure 5.3. Impulse plot from all tests .....                                  | 19 |
| Figure 5.4. Schematic for ConWep and SHOCK 2.0 problems .....                  | 23 |

## **1.0 INTRODUCTION**

The UFC 3-340-02 [1] procedure for computing confined explosion shock loads is not well defined. The process is dependent on the incident pressure plot in Figure 2-7, the reflected pressure coefficient plot in Figure 2-193, the scaled reflected impulse plot in Figures 2-194(a) and 2-194(b), and the scaled height of the triple point plot in Figure 2-13. The average reflected pressure in Figures 2-52 through 2-100 and the average reflected impulse in Figures 2-101 through 2-149 were produced with this process.

SHOCK is a computer program that implements the method used to generate the figures for averaged reflected pressure and reflected impulse in UFC 3-340-02 [1]. The methodology used in SHOCK was never fully documented or explained by the original authors or thereafter. Furthermore, lack of configuration management has resulted in numerous versions of the program without documentation of changes or differences.

NAVFAC ESC has been tasked and funded by the DDESB to:

1. Document the method used in SHOCK
2. Identify and update anomalies or mistakes in the code
3. Create and validate a new version of the code

## **2.0 SHOCK BACKGROUND**

### **2.1 Original Average Impulse Method**

In the 1960s, the Armed Services Explosive Safety Board (ASESB) began an extensive test program to establish design standards for the engineering of explosive storage and explosive manufacturing facilities. The objective of the program was to provide protection against accidental explosions. In the 1960s, Picatinny Arsenal was under assignment to the ASESB and was engaged in the test program. Ammann & Whitney (A&W), under contract to Picatinny Arsenal, provided technical assistance to the Safety Design Criteria Program. Furthermore, A&W was tasked to carry out a study to establish the blast environment resulting from an explosive detonation in partially confined cubicle-type structures [2].

The results of the A&W study were documented in Reference [2] and include an approximate method for the calculation of the total impulse, for design purposes, developed in connection with the Safety Design Criteria Program. The method can be used to calculate the total reflected impulse acting at a grid of points on each surface of the cubicle. Subsequently, the results can be integrated to give the total impulse load acting on the surface and an average impulse can be determined by assuming the total load is uniformly distributed on the wall [2].

The method reported in [2] for calculating average impulse loads was developed using a semi-empirical procedure based on theoretical blast data [3] [4], and on results of response tests of reinforced concrete slabs [5]. The calculated average impulse loads were compared with average impulse loads obtained from results of tests of a scale-model steel cubicle [6]. It is reported in [2] that the measured and calculated average impulse loads were in good agreement and a portion of the comparison is presented in the report. The comparisons presented in the report are for the

back and side wall of a cubicle composed of a back-wall and two side-walls. The average of a comparison with 24 tests indicates that the average ratio of the calculated average impulse loads to those obtained from the back wall cubicle tests is equal to 1.05 with a standard deviation of 10.2 percent. On the other hand, the average of 19 tests for the side wall indicates that the average ratio of the calculated average impulse loads to those obtained from the cubicle tests is equal to 1.01 with a standard deviation of 11.5 percent. While the comparisons of these two cases are good, the remaining comparisons were not reported.

The semi-empirical procedure reported by A&W was programmed on a computer and used to generate the scaled average unit impulse load plots which were published in Reference [2] and subsequently in Figures 4-17 to 4-62 of the 1969 NAVFAC P-397 [7]. An appendix in Reference [2] documents the 15-step method developed by A&W and used to produce the average unit impulse load plots but no scientific explanation is provided to explain the steps, assumptions and approximations used.

## **2.2 Original Method Deficiencies**

In February 1981, the Navy Civil Engineering Laboratory (NCEL) submitted a work request [8] to the Naval Surface Weapons Center (NSWC), Dahlgren to recommend a procedure for predicting the design blast pressure-time loading on rectangular cell doors and windows. A review of the load prediction procedure in the NAVFAC P-397 Manual [7] was a task in the work request [8]. The procedure in Reference [7] is the same as that developed earlier by A&W and documented in the Picatinny Arsenal Report TR 3604 [2].

Francis B. Porzel and Richard A. Lorenz from the NSWC reviewed the average impulse load procedure in [2] and in a letter to the NCEL identified problems with the A&W method [9]. The main Issues identified by NSWC are summarized below:

- 1) **DIRECT SHOCK**<sup>1</sup>. The A&W procedure does not explicitly calculate the loading from the direct shock. The loads are determined by considering the shocks reflected from the floor and all other reflecting surfaces present.
- 2) **PRELIMINARY REFLECTION**<sup>2</sup>. The A&W procedure uses the reflected pressure coefficient of Figure 2-193 in Reference [1] to enhance the incident pressure on the preliminary reflecting surface. The increased pressure is correct at the preliminary reflecting surface but dissipates before arriving at the load wall. The pressure of the reflected shock waves from a preliminary reflecting surface must instead be treated as an incident wave propagating from the image charge on the opposite side of the reflecting surface.
- 3) **ANGLE OF INCIDENCE**. The angle of incidence for the shock on the load wall is calculated incorrectly.
- 4) **REFLECTION FACTORS**. The reflected pressure coefficient vs. angle of incidence curves, Figure 4-6 in [7], are used in the A&W method but are incomplete.
- 5) **MACH REFLECTIONS**. Mach reflection should be ignored in the procedure (Mach reflection is defined in Section 4.5).

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<sup>1</sup> In this report, the terms “direct shock” refers to the free-air shock, i.e., a shock which has not experienced any reflections from other surfaces before reaching the load wall.

<sup>2</sup> In this report, a 6-wall cubicle is composed of a “load wall” and five “preliminary reflecting surfaces”: four are adjacent to the load wall and one is opposite to the load wall.

An assessment by NAVFAC ESC of the A&W method in Reference [2] confirmed that the problems identified above by NSWC were valid. In addition to identifying the problems in the A&W method, Lorenz and Porzel recommended a revised procedure to calculate the internal blast load environment.

## **2.3 Computer Program IMPRES**

Subsequent to the NSWC letter to NCEL in 1981, A&W modified the original method for calculating the internal blast load environment. The improved method was programmed in the computer program IMPRES and was used to generate new average unit impulse load plots. The new plots were published in [10], [11] and ultimately in the current UFC 3-340-02 [1].

The authors of this report do not know if A&W reviewed the letter from NSWC prior to updating the load calculation method. The authors of this report suspect that the details about the theory and development of IMPRES may be detailed in Reference [12]. Unfortunately, this reference could not be found in a literature search and appears to have been lost. A request was made to A&W, the corporate author of the reference, to provide a copy of the report but they were also unable to find the subject report in their records.

Inspection of a 1988 version of IMPRES indicates that the method was updated and that Issues 1 and 4 in the previous section were fixed throughout the code. IMPRES uses two different methods to calculate the reflected pressures. One method is used for “regular reflections” and the other for “Mach reflections” (regular and Mach reflections are defined in Section 4.5). The angle of incidence Issue, identified in Issue 3 above, for the reflected waves from preliminary reflecting surfaces, has been fixed for “Mach reflections” in IMPRES but not for “regular reflections.” The suggested method in Issue 2 for calculating the reflected pressure is used in IMPRES in the “regular reflection regime”. IMPRES implements Mach reflections and Mach stems despite the recommendation in Issue 5 not to do so.

## **2.4 Computer Program SHOCK**

Engineers from NAVFAC ESC modified the 1988 version of IMPRES and created SHOCK. Several versions of SHOCK exist and are labeled SHOCK 1.0, SHOCK 1.2, SHOCK 1.3 and SHOCK 1.4. Only Version 1.0 was officially endorsed by the DDESB.

### **2.4.1 SHOCK 1.0**

SHOCK 1.0 is written in FORTRAN 77 and notes written by the engineers that updated the program indicate that the primary difference from IMPRES is improved input and output.

### **2.4.2 SHOCK 1.2**

The notes in SHOCK 1.2 indicate that the code was changed from FORTRAN77 to FORTRAN90 and that a grid bug has been corrected. Pressure vs. scaled distance data set was refined for better curve fit.

### 2.4.3 SHOCK 1.3

In Version 1.3 the code was upgraded to FORTRAN95.

### 2.4.4 SHOCK 1.4

In Version 1.4, an incorrect data point in the data set used for interpolating the incident pressure was corrected. Another incorrect data point in the data set used for interpolating the reflected pressure was also corrected. The Kingery-Bulmash (K-B) data set used in the code to interpolate the incident pressure from the scaled distance was replaced with a polynomial equation that is reported in [13]. The reflected impulse data set used in the code to interpolate the reflected impulse from the incidence angle was replaced with a sinusoidal function that identically reproduces Figure 2-194(a) in UFC 3-340-02 [1]. The sinusoidal function was obtained from a letter sent from NSWC to NAVFAC ESC in 1982 [14].

## 3.0 **SHOCK 2.0 UPDATE**

Versions 1.2, 1.3 and 1.4 were unofficial updates of SHOCK and were not tested or validated. All the updates made in these versions have been incorporated in a new update during this effort and it has been named SHOCK 2.0. Version 2.0 also includes additional bug fixes and improvements that were identified during the literature search for this report. The improvements include the following:

1. Fixed the incorrect angle of incidence used for the reflected pressure when a “regular reflection” occurs. This is Issue 3 in Section 1.2 of this report and which was partially fixed in IMPRES.
2. Increased the 32x32 grid of points on the load wall at which the pressure and impulse are calculated to a 96x96 grid
3. Added a back wall reflection algorithm to account for shock reflection from the wall opposite to the load wall

Section 4.0 of this report details the step-by-step method used in the SHOCK 2.0 program. Validation and verification of SHOCK 2.0 is presented in Section 5.0.

## 4.0 **SHOCK THEORY/METHOD**

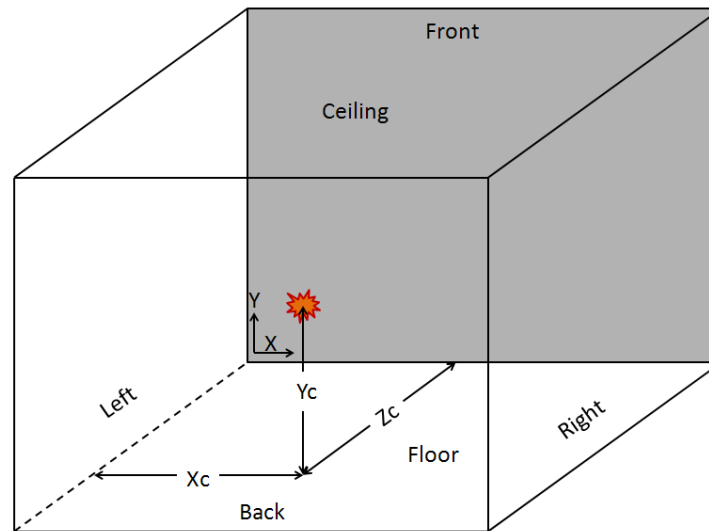
Detonation of a high explosive material produces a shock wave that expands outward from the explosive in the surrounding air. The energy output from detonation of the high explosive produces a large pressure behind the shock front. The strength of the shock wave decays as it expands in the surrounding air.

In a cubicle structure, shock reflections from cubicle surfaces amplify the load environment. A semi-empirical procedure for calculating the load environment on each of the cubicle walls is described in detail in this section of the report.

A time dependent three-dimensional computer simulation is the best approach for calculating the loads on a cubicle wall with high accuracy. Interaction of intersecting shock waves, changes in

air density and shock properties as well as other three-dimensional phenomena are examples of the complexity of this problem. While these three-dimensional effects are difficult to predict, the impulse loading at a point on a wall can be expected to have a value near that calculated along a straight-line since it is related to momentum, which must be conserved [8]. The semi-empirical procedure used in SHOCK takes advantage of this simplification and provides a simple approach for calculating the impulse loading.

The step-by-step procedure provided in this section will detail how to calculate the loads on the grey surface represented in Figure 4.1 below. The process can be similarly applied to any of the other cubicle surfaces or for any other components such as doors or windows. This is the method used in SHOCK 2.0.



**Figure 4.1. Cubicle load wall**

#### 4.1 Grid

The first step in the computational process is to place a grid of points on the load wall. Depending on the aspect ratio of the load wall, a grid of 96x96, 120x84, 144x72, 168x60 or 192x48 points will be selected by SHOCK for the surface. A total of 1089 grid points will be distributed on the load wall if the 96x96 grid is selected. The grid points are equidistant from each other in the direction of each coordinate axis.

#### 4.2 Method Assumptions

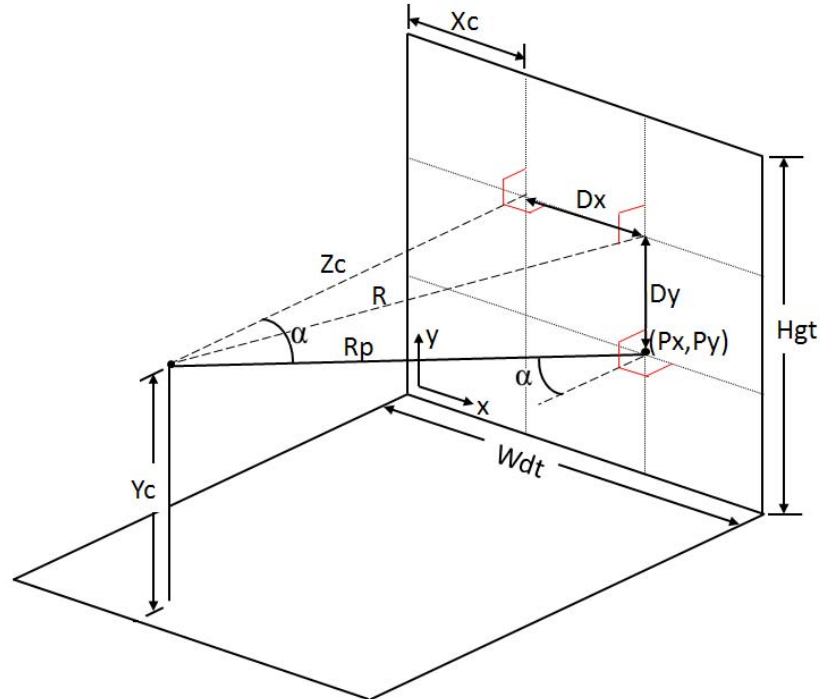
The majority of the assumptions derived below were obtained from Lorenz [9]:

1. Only direct and once reflected shocks are considered
2. Direct and reflected shock waves are not coupled and will be calculated separately as individual pulses
3. Each shock wave is assumed to be propagating through the ambient medium over its entire path
4. Impulse loads from the individual pulses can be superimposed (i.e. can be summed)

5. The current method cannot determine the time of arrival of the pulses and therefore the pressures are not superimposed and the largest pressure from all the pulses is designated as the peak pressure. This will generally underestimate the peak pressure if in actuality pulses have similar arrival times and reinforce each other.
6. Mach reflections are considered for adjacent reflecting surfaces. Mach reflections will occur if the distance from the charge to the load wall is greater than the height of the charge from reflecting surface
7. If Mach reflections are absent, the pressure of the reflected wave is approximated by a direct pulse originating from an image source
8. If Mach reflections are present, the Mach stem pressure is approximated by the reflected pressure at the reflecting surface directly below the load point (see Section 4.5.2.1)
9. If Mach reflections are present, the pressure of the reflected wave is approximated by the reflected pressure at the reflecting surface caused by an offset charge (see Section 4.5.2.2)
10. The pulses are assumed to be triangular. The peak pressure and total impulse are used to calculate the time duration

### 4.3 Direct shock procedure

Figure 4.2 illustrates an example grid on the load wall. The grid points at which the reflected impulse and pressure will be computed are at the intersection of the grid lines depicted in the figure. The example point used in the calculations is labeled  $(P_x, P_y)$ . The charge is located at a distance  $Y_c$  above the floor and a distance  $Z_c$  from the load wall.



**Figure 4.2. Direct Shock**

1. Calculate  $Dx$  and  $Dy$

$$\begin{aligned} Dx &= |Px - Xc| \\ Dy &= |Yc - Py| \end{aligned}$$

2. Calculate the incident wave path length  $Rp$  from charge to the load point

$$Rp = \sqrt{Zc^2 + Dx^2 + Dy^2}$$

3. Calculate the scaled standoff distance from charge to load point (if  $Z$  exceeds the range specified below, the value of  $Z$  will be overwritten with the limit of the range)

$$Z = \frac{Rp}{W^{1/3}}, 0.2 < Z < 100$$

4. Calculate the incidence angle

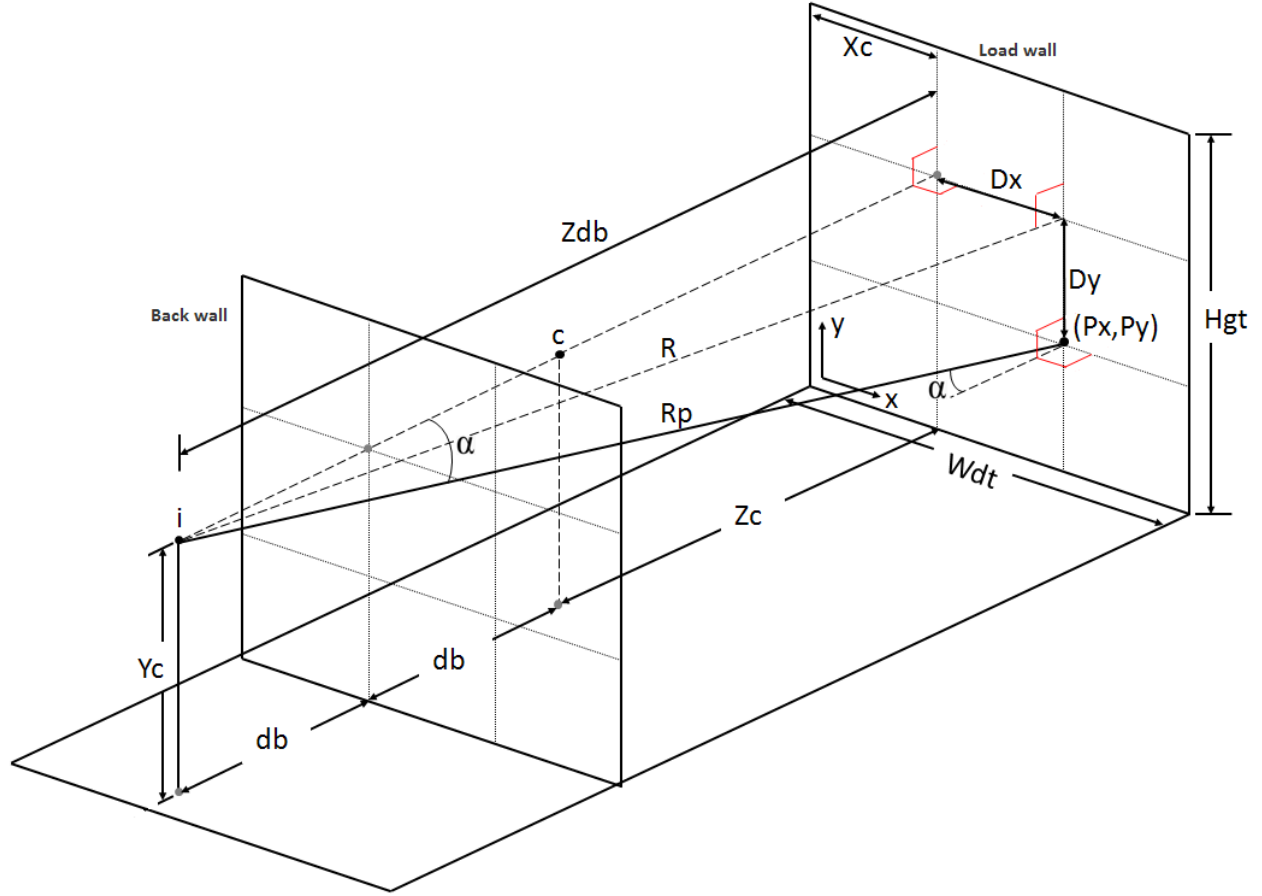
$$\alpha = \left| \cos^{-1} \left( \frac{Zc}{Rp} \right) \right|$$

5. Use  $Z$  and the K-B incident pressure equation in [13] to determine the incident pressure,  $Ps$ . This is equivalent to interpolating for  $Ps$  from Figure 2-7 in [1]
6. Use  $Ps$ ,  $\alpha$  and the reflected impulse equation in [14] to calculate the scaled reflected impulse,  $I_{r\alpha}$ . This is equivalent to interpolating for  $I_{r\alpha}$  from Figures 2-194(a) and 2-194(b) in [1]
7. Use  $Ps$ ,  $\alpha$  and Figure 2-193 in [1] to interpolate the reflected pressure coefficient,  $C_{r\alpha}$
8. Calculate the reflected pressure,  $P_{r\alpha}$

$$P_{r\alpha} = Ps * C_{r\alpha}$$

#### 4.4 Back Wall Reflection

Figure 4.3 below illustrates the load wall and the back wall. The shock reflected from the back wall is approximated as a direct shock originating from the image source. This approach is a conservative approximation of the back wall reflected shock.



**Figure 4.3. Back wall reflection**

1. Calculate  $Dx$ ,  $Dy$  and  $Zdb$

$$\begin{aligned} Dx &= |Px - Xc| \\ Dy &= |Yc - Py| \\ Zdb &= 2 * db + Zc \end{aligned}$$

2. Calculate the incident wave path length  $Rp$  from the charge image (denoted as  $i$  in the figure above) to the load point

$$Rp = \sqrt{Zdb^2 + Dx^2 + Dy^2}$$

3. Calculate the scaled standoff distance from the image to the load point

$$Z = \frac{Rp}{W^{1/3}}, 0.2 < Z < 100$$

4. Calculate the incidence angle

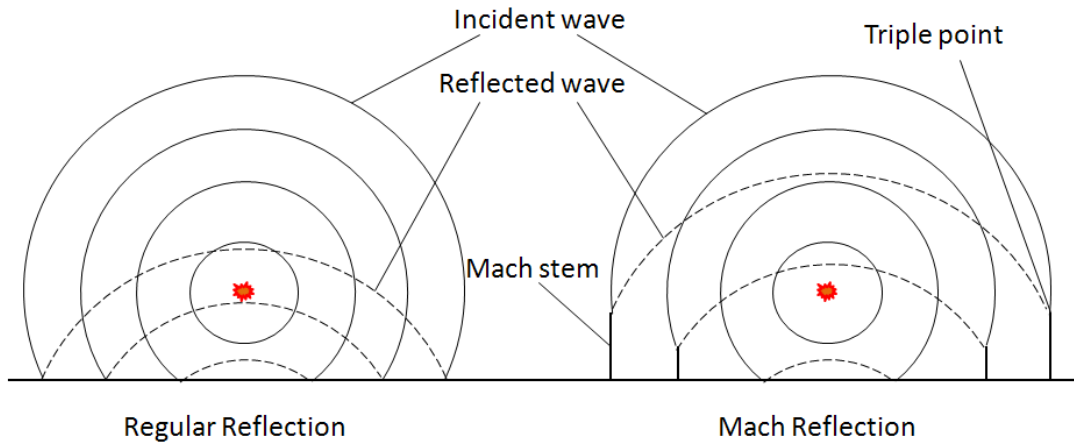
$$\alpha = \left| \cos^{-1} \left( \frac{Zdb}{Rp} \right) \right|$$

5. Use  $Z$  and the K-B incident pressure equation in [13] to determine the incident pressure,  $P_s$ . This is equivalent to interpolating for  $P_s$  from Figure 2-7 in [1]
9. Use  $P_s$ ,  $\alpha$  and the reflected impulse equation in [14] to calculate the scaled reflected impulse,  $I_{r\alpha}$ . This is equivalent to interpolating for  $I_{r\alpha}$  from Figures 2-194(a) and 2-194(b) in [1]
6. Use  $P_s$ ,  $\alpha$  and Figure 2-193 in [1] to interpolate the reflected pressure coefficient,  $C_{r\alpha}$
7. Calculate the reflected pressure,  $P_{r\alpha}$

$$P_{r\alpha} = P_s * C_{r\alpha}$$

#### 4.5 Adjacent Surface Reflection

For the adjacent reflecting surfaces, it must be determined if a Mach reflection will occur based on the height of burst and distance to the load wall. The difference between a regular reflection and Mach reflection is illustrated in Figure 4.4 below. A notable feature of a Mach reflection is the formation of a Mach stem which moves parallel to the reflecting surface. The point at which the Mach stem, incident wave and reflected wave meet is called the triple point.



**Figure 4.4. Regular vs. Mach Reflection**

SHOCK 2.0 uses different methods to determine the reflected impulse and pressure on the load wall from the reflected shock wave based on the following three scenarios:

1. Mach reflection does not occur
2. Mach reflection occurs and point of interest is above the height of the triple point
3. Mach reflection occurs and point of interest is below the height of the triple point

Mach stems form only at distances from the charge location which exceed some limiting or minimum distance. SHOCK 2.0 assumes a Mach reflection will not occur if the distance from the charge to the axis of the load point normal to the reflecting surface is smaller than the height of the charge from the reflecting surface.

In the example presented in this report, if  $Y_c > R$  a Mach stem will not form and the method described in Section 4.5.1 will be used to calculate the load environment. If  $R > Y_c$ , a Mach stem will form. The method in Section 4.5.2.1 will be used if the load point on the surface of interest is above the Mach stem height. The method in Section 4.5.2.2 will be used if the load point is below the Mach stem height. The example in this section is for only one of the adjacent reflecting surfaces but the process can be repeated to the remaining three adjacent reflecting surfaces.

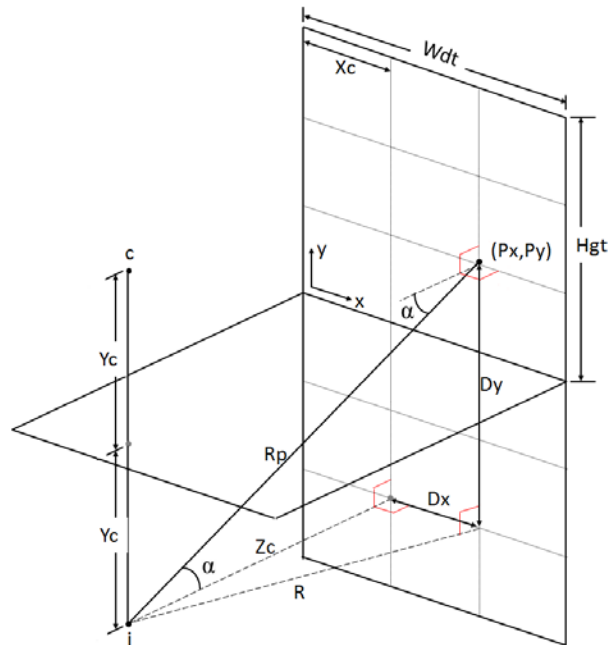
The scaled height of the Mach stem based on the scaled charge height and scaled distance to the point of interest should be determined using Figure 2-13 in [1]. SHOCK 2.0 uses the following equation instead of the figure:

$$H_{TP} = W^{1/3} \left( \frac{Z_c}{W^{1/3}} \right)^{5/2} * (0.0926 * W^{1/3} * Y_c)^{5/3}$$

The above equation does not agree with Figure 2-13 in [1] and should be replaced with a better curve fit.

#### 4.5.1 No Mach stem

Figure 4.5 below illustrates the load wall and one of the adjacent reflecting surfaces. The shock reflected from the adjacent wall is approximated by a direct shock originating from the image source. This approach is believed to be a conservative approximation of the reflected shock.



**Figure 4.5. Adjacent reflecting surface**

1. Calculate  $Dx$  and  $Dy$

$$\begin{aligned} Dx &= |Px - Xc|, \\ Dy &= Yc + Py \end{aligned}$$

2. Calculate the incident wave path length  $Rp$  from the charge image (denoted as  $i$  in the figure above) to the load point

$$Rp = \sqrt{Zc^2 + Dx^2 + Dy^2}$$

3. Calculate the scaled standoff distance from the image to the load point,  $Z$ .

$$Z = \frac{Rp}{w^{\frac{1}{3}}}, 0.2 < Z < 100$$

4. Calculate the incidence angle

$$\alpha = \left| \cos^{-1} \left( \frac{Zc}{Rp} \right) \right|$$

5. Use  $Z$  and the K-B incident pressure equation in [13] to determine the incident pressure,  $Ps$ . This is equivalent to interpolating for  $Ps$  from Figure 2-7 in [1]
6. Use  $Ps$ ,  $\alpha$  and the reflected impulse equation in [14] to calculate the scaled reflected impulse,  $I_{r\alpha}$ . This is equivalent to interpolating for  $I_{r\alpha}$  from Figures 2-194(a) and 2-194(b) in [1]
7. Use  $Ps$ ,  $\alpha$  and Figure 2-193 in [1] to interpolate the reflected pressure coefficient,  $C_{r\alpha}$
8. Calculate the reflected pressure,  $P_{r\alpha}$

$$P_{r\alpha} = Ps * C_{r\alpha}$$

#### 4.5.2 With Mach stem

##### 4.5.2.1 *Load Point is Below Triple Point*

Figure 4.6 below illustrates the load wall and one of the adjacent reflecting surfaces. The Mach stem pressure is approximated as the reflected pressure imposed on the reflecting surface at the point directly below the load point. The Mach stem pressure is subsequently used to calculate the reflected pressure and impulse at the load point. This approach produces unrealistic load distributions on the load wall and no physical explanation has been found to support it.

3D schematic diagram illustrating the geometry of a shock wave reflecting off a vertical wall. The diagram shows the incident wave (dashed blue line) and the reflected wave (solid blue line) meeting at a point on the wall. The wall is at  $x=0$ . The flow is in the  $x$ - $y$ - $z$  plane. Key parameters labeled include:  $X_c$  (horizontal distance from wall to point of reflection),  $Y_c$  (vertical distance from wall to point of reflection),  $H_{gt}$  (height of the domain),  $(P_x, P_y)$  (point on the wall),  $R_p$  (point of reflection),  $R$  (distance from origin to point of reflection),  $Z_c$  (vertical distance from origin to point of reflection),  $D_x$  (horizontal distance from point of reflection to point  $(P_x, P_y)$ ), and angles  $\alpha$  and  $\beta$ . The Mach stem is indicated as a vertical line at the point of reflection.

7. Calculate the Mach stem pressure, which is approximated as the reflected pressure acting on the reflecting surface at the point directly below the load point,  $P_{r\beta}$

$$P_{r\beta} = P_s * C_{r\beta}$$

8. Calculate the Mach stem angle of incidence,  $\alpha$

$$\alpha = \left| \tan^{-1} \left( \frac{Dx}{Zc} \right) \right|$$

9. Calculate the reflected pressure and reflected scaled impulse at the load point using the incident Mach stem pressure,  $P_{r\beta}$ , and the Mach stem angle of incidence,  $\alpha$ . See steps 10 and 11 below
10. Use  $P_{r\beta}$ ,  $\alpha$  and the reflected impulse equation in [14] to calculate the scaled reflected impulse,  $I_{r\alpha}$ . This is equivalent to interpolating for  $I_{r\alpha}$  from Figures 2-194(a) and 2-194(b) in [1]
11. Use  $P_{r\beta}$ ,  $\alpha$  and Figure 2-193 in [1] to interpolate the reflected pressure coefficient,  $C_{r\alpha}$
12. Calculate the reflected pressure at the load point,  $P_{r\alpha}$

$$P_{r\alpha} = P_{r\beta} * C_{r\alpha}$$

#### 4.5.2.2 Load Point is Above Triple Point

Figure 4.7 below illustrates the load wall and one of the adjacent reflecting surfaces. The reflected wave pressure that is incident at the load point is approximated as the reflected pressure imposed on the reflecting surface at the point directly below the load point from a charge location that has been offset. The angle of incidence of the reflected wave is determined from the image source to the load point. Similar to the logic in Section 4.5.2.1, this approach produces unrealistic load distributions on the load wall and no physical explanation has been found to support it.



$$Rp2 = \sqrt{Rz^2 + Hp^2}$$

7. Initially  $Rp2 < Rp1$ . Incrementally adjust  $Rz$  and repeat steps 4 to 6 until  $Rp2 = Rp1$ .
8.  $Rp2$  marks a new charge location that is offset further away from the load wall, see figure above. The reflected wave pressure imposed on the reflecting surface from this new charge location is used as the incident pressure at the load point. The reason for this step in SHOCK 2.0 is not understood but the offset serves to reduce the reflected wave pressure by increasing standoff from the load wall. This method is not recommended by the authors of this paper.
9. Calculate  $Rp$

$$Rp = \sqrt{Rz^2 + Yc^2}$$

10. Calculate the scaled standoff distance from the revised charge location to the load point,  $Z$ .

$$Z = \frac{Rp}{w^{\frac{1}{3}}}, 0.2 < Z < 100$$

11. Calculate the incidence angle with the ground

$$\beta = \left| \cos^{-1} \left( \frac{Yc}{Rp} \right) \right|$$

12. Use  $Z$  and the K-B incident pressure equation in [13] to determine the incident pressure at the point on the reflecting surface directly below the load point,  $Ps$ . This is equivalent to interpolating for  $Ps$  from Figure 2-7 in [1]
13. Use  $Ps$ ,  $\beta$  and Figure 2-193 in [1] to interpolate the reflected pressure coefficient,  $C_{r\beta}$
14. Calculate the reflected wave pressure, which is the floor reflected pressure at the point below the load point,  $P_{r\beta}$

$$P_{r\beta} = Ps * C_{r\beta}$$

15. Calculate the angle of incidence using the path from charge image, at original location, to the load point,  $\alpha$

$$\alpha = \left| \cos^{-1} \left( \frac{Zc}{Rp} \right) \right|$$

16. Calculate the reflected pressure and reflected scaled impulse at the load point using the incident reflected wave pressure,  $P_{r\beta}$ , and the Mach stem angle of incidence,  $\alpha$
17. Use  $P_{r\beta}$ ,  $\alpha$  and the reflected impulse equation in [14] to calculate the scaled reflected impulse,  $I_{r\alpha}$ . This is equivalent to interpolating for  $I_{r\alpha}$  from Figures 2-194(a) and 2-194(b) in [1]
18. Use  $P_{r\beta}$ ,  $\alpha$  and Figure 2-193 in [1] to interpolate the reflected pressure coefficient,  $C_{r\alpha}$
19. Calculate the reflected pressure at the load point,  $P_{r\alpha}$

$$P_{r\alpha} = P_{r\beta} * C_{r\alpha}$$

#### **4.6 Total Reflected Impulse and Peak Reflected Pressure**

The steps described in Sections 4.3-4.5 must be repeated for every grid point on the load wall. The total reflected impulse at each grid point is determined by adding the reflected impulses calculated for each of the reflected shocks. The peak reflected pressure is the largest reflected pressure calculated at each grid point.

The averaged total impulse and peak pressure are subsequently computed by averaging the total impulses and peak pressures that were calculated at all the grid points.

### **5.0 VALIDATION OF SHOCK 2.0**

#### **5.1 Overview**

Three separate analyses were used to validate SHOCK 2.0: comparison with measured test results, comparison with the program ConWep—which is widely recognized as a reliable source for blast analyses—and comparison with the data used to create SHOCK 1.0. Each of these tests will be further explained briefly below.

#### **5.2 SHOCK 2.0 Results vs. Test Data**

In 1991 the Southwest Research Institute (SwRI) published a report [15] which included a series of tests measuring the effects of an explosion within a test structure. In the SwRI report, the test data is compared to calculated values using SHOCK 1.0. Nine of these tests and the accompanying results are used in this report to compare with the calculated values using SHOCK 2.0. SHOCK 2.0 calculations were carried out twice, once with the wall opposite to the load surface treated as non-reflecting and once treated as reflecting. This was done because SHOCK 1.0 did not take into account the reflections from the opposite wall whereas SHOCK 2.0 has this capability. SHOCK 2.0 calculations without reflections from the wall opposite to the load surface allow for direct comparison with SHOCK 1.0 results. On the other hand, comparison of the results with the opposite wall reflection enabled to the test data demonstrates the accuracy of this improved capability.

### 5.2.1 SwRI Tests

The following information was obtained from Section 4.0, Section 6.1.1, and Appendix B of the SwRI report [15].

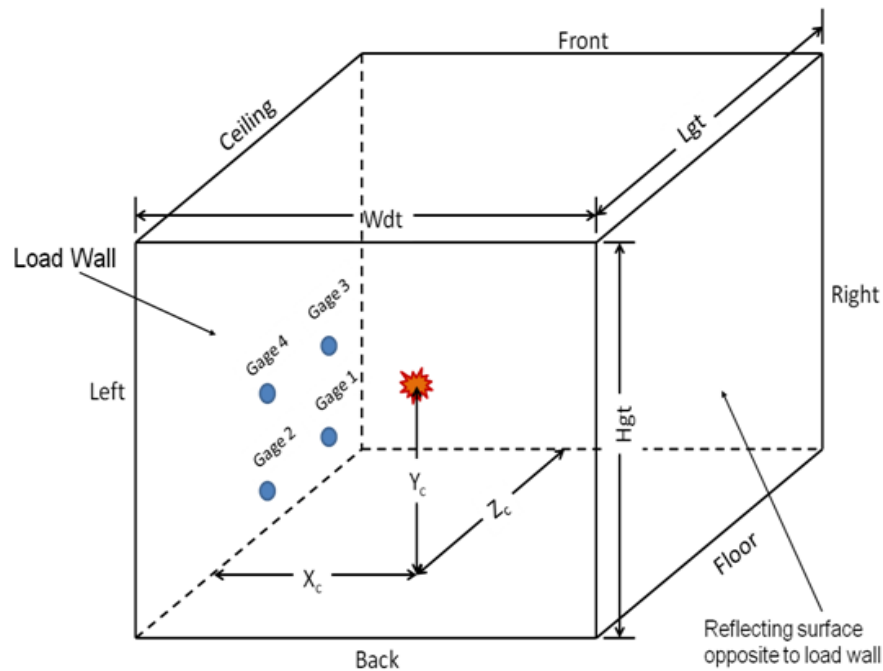
The tests used in this analysis all took place in a quarter scale concrete box test structure. This structure was designed so that the front wall could be interchanged and so that the back wall could be removed partially or entirely. Four pressure gages were placed in the left wall, located on the lower right quadrant when looking at the wall from the interior of the structure. The variables pertinent to SHOCK 2.0 for the nine tests used for comparison in this report are: the charge weight, charge distance from the front wall, and whether the back wall was present (reflecting) or not (non-reflecting).

Appendix B of [15] contains plots for each test and pressure gage and a table summarizing the test data. The contents of the appendix were used to obtain the test data and SHOCK 1.0 results for the pressure and impulse at each gage.

### 5.2.2 SHOCK 2.0 Calculations

The input data for SHOCK 2.0 was obtained from the SwRI report Sections 4.1, 4.2, 4.3.1, 4.3.2, 4.4.1, Figures 4-1 and 6-1a [15], and an email from report author Patricia Bowles [16], May 10, 2011. Test Numbers 1.3, 1.4, 1.8, 1.9, 2.1, 2.9, 2.10, 2.11, and 2.16 were used for this analysis. SHOCK 2.0 calculations were made for each pressure gage of every test; once with the opposite wall treated as non-reflecting and once as reflecting.

Figure 5.1 shows the basic layout of the structure in SHOCK 2.0 and the charge location.



**Figure 5.1. Structure layout in SHOCK 2.0**

### 5.2.3 Results Comparison

In comparing the results it must first be acknowledged that SHOCK 2.0 was developed primarily to compute the averaged impulse on the load surface for design purposes. The original semi-empirical method was validated only against test data for averaged impulse. SHOCK 2.0 also computes the averaged peak pressure as well as the total impulse and peak pressure at specific point coordinates on the load wall. Calculations at specific points appear to provide accurate load distributions on the loading wall except near the edges.

The test data used for validation of SHOCK 2.0 in this report is reported at four gage locations and therefore comparison could only be made using point loads in SHOCK. It can be seen from Figure 5.2 that Gage 1 and 2, which are located near the edge of the wall, do not agree well for peak pressure.

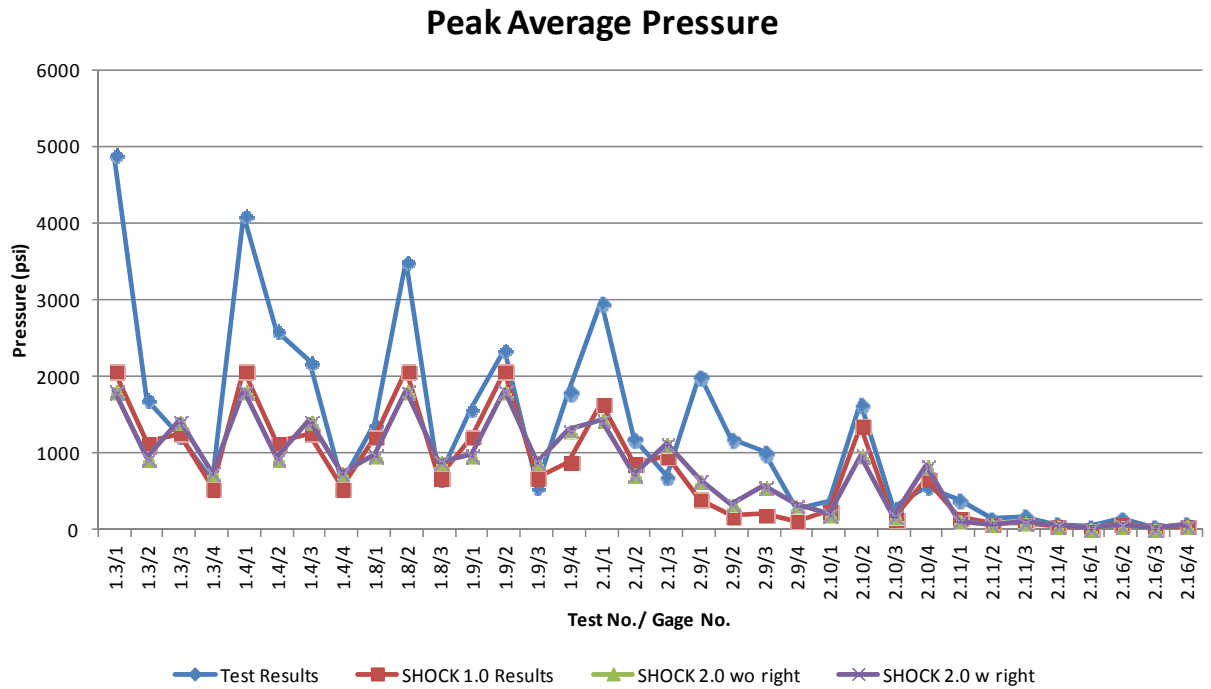
The output derived from pressure Gage 4 in Test Numbers 1.8 and 2.1 were omitted as the actual test results were omitted from the report [15]—most likely due to the gage being faulty or destroyed.

The plot in Figure 5.2 shows the pressure found from all four methods—testing, SHOCK 1.0, SHOCK 2.0 without the right wall reflecting, and SHOCK 2.0 with the right wall reflecting. The plot in Figure 5.3 shows the impulse found from the same four methods.

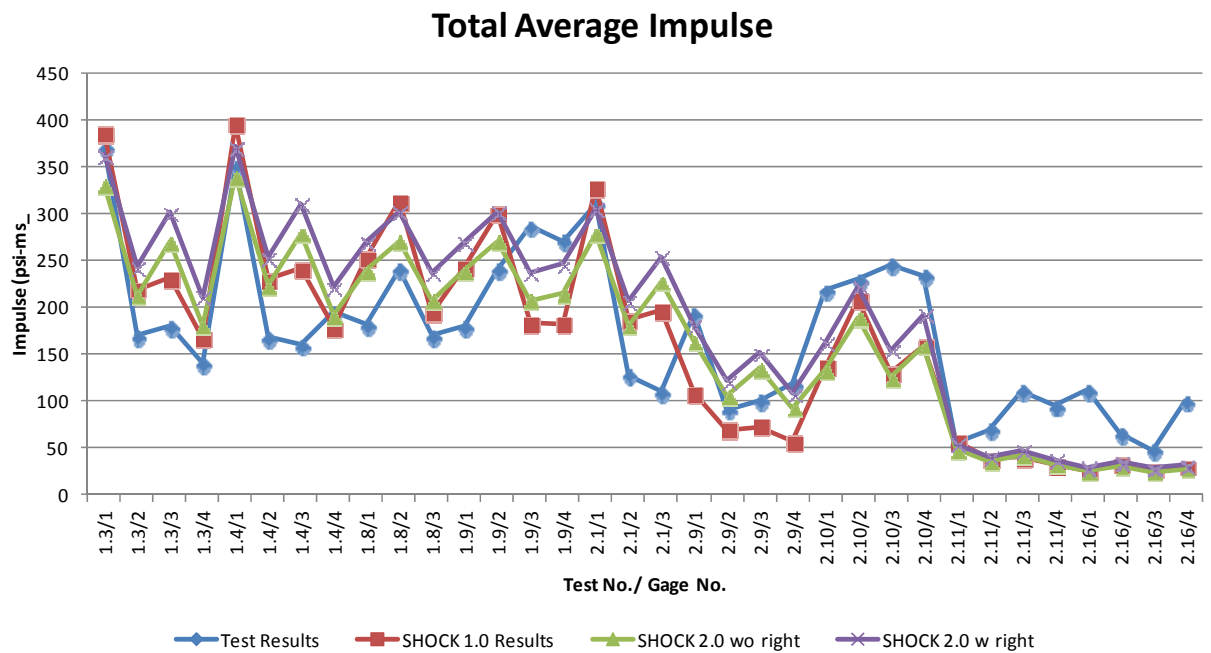
Table 5.1 summarizes the results. The results measured from the actual tests are listed first, followed by the calculated results from SHOCK 1.0 as reported by SwRI [15], the calculated results from SHOCK 2.0 with the right wall—or opposite wall from the specified point load—specified as non-reflecting, and the calculated results from SHOCK 2.0 with the same wall reflecting.

Table 5.2 summarizes the comparison of the results, with the three computed results normalized by the test results. At the bottom of each column, the set of data have been averaged and the standard deviation calculated.

In Table 5.1, 5.2 and Figures 5.2 and 5.3, “wo right” designates a calculation without the opposite (right wall) reflecting surface and “w right” designates a calculations with the opposite reflecting surface enabled.



**Figure 5.2. Pressure plot from all tests**



**Figure 5.3. Impulse plot form all tests**

**Table 5.1. Pressure and Impulse Results**

| Test No.<br>/ Gage<br>No. | Test Results      |                     | SHOCK1.0 Results  |                     | SHOCK2.0 wo right |                     | SHOCK2.0 w right  |                     |
|---------------------------|-------------------|---------------------|-------------------|---------------------|-------------------|---------------------|-------------------|---------------------|
|                           | Pressure<br>(psi) | Impulse<br>(psi-ms) | Pressure<br>(psi) | Impulse<br>(psi-ms) | Pressure<br>(psi) | Impulse<br>(psi-ms) | Pressure<br>(psi) | Impulse<br>(psi-ms) |
| 1.3/1                     | 4900              | 370                 | 2082              | 385                 | 1811              | 331                 | 1811              | 362                 |
| 1.3/2                     | 1700              | 170                 | 1141              | 219                 | 945               | 213                 | 945               | 243                 |
| 1.3/3                     | 1220              | 180                 | 1255              | 231                 | 1427              | 270                 | 1427              | 301                 |
| 1.3/4                     | 630               | 140                 | 553               | 167                 | 748               | 181                 | 748               | 211                 |
| 1.4/1                     | 4100              | 350                 | 2082              | 395                 | 1811              | 339                 | 1811              | 371                 |
| 1.4/2                     | 2600              | 168                 | 1141              | 230                 | 945               | 223                 | 945               | 253                 |
| 1.4/3                     | 2200              | 160                 | 1255              | 241                 | 1427              | 278                 | 1427              | 310                 |
| 1.4/4                     | 620               | 195                 | 553               | 178                 | 748               | 191                 | 748               | 221                 |
| 1.8/1                     | 1388              | 181                 | 1219              | 253                 | 981               | 239                 | 981               | 270                 |
| 1.8/2                     | 3500              | 240                 | 2079              | 313                 | 1811              | 270                 | 1811              | 302                 |
| 1.8/3                     | 677               | 170                 | 690               | 194                 | 891               | 207                 | 891               | 237                 |
| 1.9/1                     | 1590              | 180                 | 1219              | 243                 | 981               | 239                 | 981               | 270                 |
| 1.9/2                     | 2350              | 240                 | 2072              | 300                 | 1811              | 270                 | 1811              | 302                 |
| 1.9/3                     | 570               | 286                 | 690               | 183                 | 891               | 207                 | 891               | 237                 |
| 1.9/4                     | 1800              | 270                 | 891               | 182                 | 1308              | 215                 | 1308              | 246                 |
| 2.1/1                     | 2980              | 310                 | 1657              | 328                 | 1437              | 279                 | 1437              | 306                 |
| 2.1/2                     | 1196              | 127                 | 871               | 186                 | 731               | 180                 | 731               | 206                 |
| 2.1/3                     | 704               | 110                 | 957               | 196                 | 1120              | 227                 | 1120              | 254                 |
| 2.9/1                     | 2018              | 193                 | 399               | 108                 | 655               | 164                 | 655               | 180                 |
| 2.9/2                     | 1198              | 91                  | 185               | 70                  | 335               | 106                 | 335               | 122                 |
| 2.9/3                     | 1025              | 101                 | 210               | 73                  | 574               | 135                 | 574               | 152                 |
| 2.9/4                     | 264               | 118                 | 118               | 57                  | 330               | 93                  | 330               | 108                 |
| 2.10/1                    | 368               | 218                 | 246               | 136                 | 212               | 133                 | 212               | 163                 |
| 2.10/2                    | 1655              | 230                 | 1360              | 208                 | 970               | 189                 | 970               | 223                 |
| 2.10/3                    | 292               | 245                 | 150               | 130                 | 174               | 125                 | 174               | 154                 |
| 2.10/4                    | 565               | 234                 | 666               | 159                 | 840               | 159                 | 840               | 192                 |
| 2.11/1                    | 402               | 55                  | 165               | 56                  | 121               | 49                  | 121               | 54                  |
| 2.11/2                    | 145               | 69                  | 87                | 39                  | 71                | 36                  | 71                | 41                  |
| 2.11/3                    | 176               | 111                 | 96                | 40                  | 107               | 43                  | 107               | 48                  |
| 2.11/4                    | 75                | 95                  | 56                | 32                  | 69                | 33                  | 69                | 37                  |
| 2.16/1                    | 41                | 112                 | 28                | 26                  | 28                | 25                  | 28                | 29                  |
| 2.16/2                    | 153               | 65                  | 82                | 33                  | 68                | 30                  | 68                | 35                  |
| 2.16/3                    | 38                | 48                  | 20                | 26                  | 23                | 25                  | 23                | 29                  |
| 2.16/4                    | 74                | 100                 | 54                | 30                  | 68                | 27                  | 68                | 32                  |

**Table 5.2. SHOCK Results Normalized by Test Results**

| Test No. /<br>Gage No. | SHOCK1.0 Results |         | SHOCK2.0 wo right |         | SHOCK2.0 w right |         |
|------------------------|------------------|---------|-------------------|---------|------------------|---------|
|                        | Pressure         | Impulse | Pressure          | Impulse | Pressure         | Impulse |
| 1.3/1                  | 0.425            | 1.041   | 0.370             | 0.893   | 0.370            | 0.979   |
| 1.3/2                  | 0.671            | 1.288   | 0.556             | 1.250   | 0.556            | 1.427   |
| 1.3/3                  | 1.029            | 1.283   | 1.170             | 1.497   | 1.170            | 1.672   |
| 1.3/4                  | 0.878            | 1.193   | 1.187             | 1.291   | 1.187            | 1.505   |
| 1.4/1                  | 0.508            | 1.129   | 0.442             | 0.970   | 0.442            | 1.060   |
| 1.4/2                  | 0.439            | 1.369   | 0.363             | 1.326   | 0.363            | 1.505   |
| 1.4/3                  | 0.570            | 1.506   | 0.649             | 1.740   | 0.649            | 1.936   |
| 1.4/4                  | 0.892            | 0.913   | 1.206             | 0.980   | 1.206            | 1.133   |
| 1.8/1                  | 0.878            | 1.398   | 0.706             | 1.323   | 0.706            | 1.490   |
| 1.8/2                  | 0.594            | 1.304   | 0.517             | 1.125   | 0.517            | 1.257   |
| 1.8/3                  | 1.019            | 1.141   | 1.316             | 1.218   | 1.316            | 1.394   |
| 1.9/1                  | 0.767            | 1.350   | 0.617             | 1.330   | 0.617            | 1.498   |
| 1.9/2                  | 0.882            | 1.250   | 0.771             | 1.125   | 0.771            | 1.257   |
| 1.9/3                  | 1.211            | 0.640   | 1.564             | 0.724   | 1.564            | 0.828   |
| 1.9/4                  | 0.495            | 0.674   | 0.727             | 0.794   | 0.727            | 0.911   |
| 2.1/1                  | 0.556            | 1.058   | 0.482             | 0.899   | 0.482            | 0.986   |
| 2.1/2                  | 0.728            | 1.465   | 0.611             | 1.420   | 0.611            | 1.622   |
| 2.1/3                  | 1.359            | 1.782   | 1.591             | 2.065   | 1.591            | 2.308   |
| 2.9/1                  | 0.198            | 0.560   | 0.324             | 0.850   | 0.324            | 0.934   |
| 2.9/2                  | 0.154            | 0.767   | 0.279             | 1.170   | 0.279            | 1.343   |
| 2.9/3                  | 0.205            | 0.721   | 0.560             | 1.340   | 0.560            | 1.501   |
| 2.9/4                  | 0.447            | 0.481   | 1.250             | 0.786   | 1.250            | 0.917   |
| 2.10/1                 | 0.668            | 0.624   | 0.576             | 0.612   | 0.576            | 0.746   |
| 2.10/2                 | 0.822            | 0.904   | 0.586             | 0.821   | 0.586            | 0.967   |
| 2.10/3                 | 0.514            | 0.531   | 0.595             | 0.510   | 0.595            | 0.629   |
| 2.10/4                 | 1.179            | 0.679   | 1.486             | 0.678   | 1.486            | 0.821   |
| 2.11/1                 | 0.410            | 1.025   | 0.300             | 0.889   | 0.300            | 0.982   |
| 2.11/2                 | 0.600            | 0.558   | 0.490             | 0.523   | 0.490            | 0.593   |
| 2.11/3                 | 0.547            | 0.361   | 0.610             | 0.384   | 0.610            | 0.430   |
| 2.11/4                 | 0.747            | 0.334   | 0.924             | 0.343   | 0.924            | 0.394   |
| 2.16/1                 | 0.685            | 0.229   | 0.678             | 0.223   | 0.678            | 0.262   |
| 2.16/2                 | 0.538            | 0.511   | 0.443             | 0.466   | 0.443            | 0.542   |
| 2.16/3                 | 0.543            | 0.542   | 0.614             | 0.510   | 0.614            | 0.598   |
| 2.16/4                 | 0.732            | 0.296   | 0.912             | 0.274   | 0.919            | 0.322   |
| Average                | 0.673            | 0.909   | 0.749             | 0.951   | 0.749            | 1.081   |
| Std Dev                | 0.281            | 0.409   | 0.375             | 0.432   | 0.375            | 0.479   |

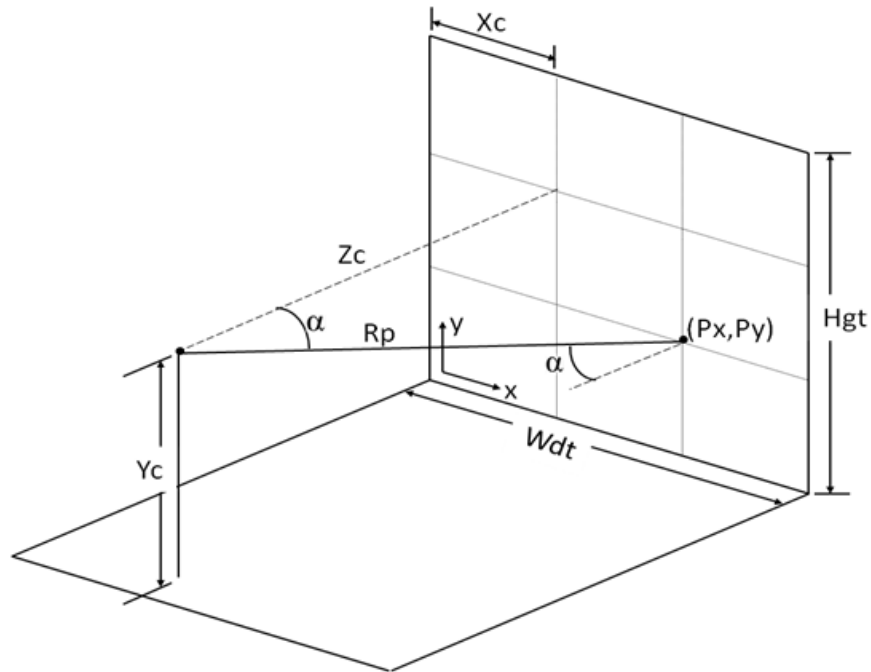
As expected, the impulse calculations are more accurate than the pressure calculations. The SHOCK 2.0 results on average, as shown in the bottom of Table 5.2, are closer to the measured results than SHOCK1.0. The averaged SHOCK 2.0 impulse loading without the opposite wall reflection at the bottom of Table 5.2 are slightly closer to the test results than the averaged impulse loading with the opposite wall reflection, 95.1 % accurate versus 108.1% accurate. However, the loads without the opposite wall reflection are under-predicted. Therefore, SHOCK 2.0 with opposite wall reflection enabled is the recommended method and is the default option in the program.

Figure 5.2 demonstrates that near corners and edges (i.e. Gages 1 and 2) the peak pressure computed by SHOCK 2.0 does not compare well with the test data. The current method implemented in SHOCK 2.0 does not consider time of arrival of the incident and reflected shocks. SHOCK 2.0 uses the largest peak pressure from any of the shocks as the peak pressure. In the vicinity of corners or edges, the time of arrival of the incident and reflected pulses are expected to be close enough for the pulses to reinforce each other. Near the edges the pressures could almost double, and near the corners they could almost triple, explaining the large differences in Figure 5.2 at those locations. This could be corrected if the program kept track of the time of arrival of the first shock and of the reflections, as well as the time decay of the pressure to allow for superposition when the reflections arrive from the other walls. This has not been implemented here, but could be implemented in a following version.

### **5.3 SHOCK 2.0 and ConWep Calculations**

ConWep is an explosion effects program that is widely used and its calculations are regarded as a reliable means for analyzing the effects of explosions. Comparison of SHOCK 2.0 to ConWep can be used to demonstrate the soundness of the SHOCK 2.0 results. ConWep considers only normal reflected waves and does not take into account reflecting waves from adjacent surfaces. SHOCK 2.0 can account for reflecting surfaces and incidence angles for waves that are not normal to the load wall. A comparison between SHOCK 2.0 and ConWep can be made if all reflecting surfaces are disabled in SHOCK 2.0 and by choosing a point load calculation for a point on the load wall that will have an incidence angle,  $\alpha$ , of zero, see Figure 5.4.

The ConWep 2.1.0.8 aboveground airblast function was used for this analysis. Six problems were devised to compare the two programs. Three problems are described in Section 5.3.1 and three other problems are described in Section 5.3.2.



**Figure 5.4. Schematic for ConWep and SHOCK 2.0 problems**

### 5.3.1 Scaled Distance problems

ConWep and SHOCK 2.0 use the K-B equations in Reference [13] to calculate the incident pressure at a scaled distance from the source charge. ConWep also uses the K-B equations for normal reflections to compute the reflected impulse and the reflected pressure. These equations are valid for scaled distances between 0.134 and 100. On the other hand, SHOCK 2.0 uses Figures 2-193 in [1] and the reflected impulse equation in [14] to compute the reflected impulse and the reflected pressure as a function of the incident pressure and angle of incidence.

Three tests were created to confirm that SHOCK 2.0 can predict the incident pressure, reflected impulse and pressure accurately in the range of K-B equations. The three problems used for comparison are for scaled distance ( $Z$ ) of 0.2, 10 and 95.

#### 5.3.1.1 *ConWep*

The three problems use the ConWep Aboveground Airblast function. A spherical free-air burst of TNT bare high explosives was used to compute the normally reflected pressure and the reflected impulse for the scaled distances indicated above.

#### 5.3.1.2 *SHOCK 2.0*

A room with dimensions of 100x100x100 ft dimensions was defined with all reflecting surfaces disabled. This is equivalent to calculating the reflected impulse and the reflected pressure on a designated load wall without any enhancing reflecting effects from any other surfaces. Details of the threat scenario and results of the three comparison problems are shown below in Table 5.3. Figure 5.1 defines the parameters  $Zc$  and  $Yc$ .

**Table 5.3. Scaled Distance Comparison**

| Case | W<br>(lbs) | $Z_c$<br>(ft) | $z$<br>(ft/lb <sup>1/3</sup> ) | ConWep            |                     | SHOCK2.0      |                   |                     | SHK2.0/CnWp |         |
|------|------------|---------------|--------------------------------|-------------------|---------------------|---------------|-------------------|---------------------|-------------|---------|
|      |            |               |                                | Pressure<br>(psi) | Impulse<br>(psi-ms) | $Y_c$<br>(ft) | Pressure<br>(psi) | Impulse<br>(psi-ms) | Pressure    | Impulse |
| 1    | 500        | 1.76          | 0.2217                         | 60400             | 24850               | 50            | 61011             | 24753               | 1.01        | 0.996   |
| 2    | 500        | 80.0          | 10.08                          | 15.980            | 94.210              | 50            | 16.600            | 94.200              | 0.976       | 1.00    |
| 3    | 1.00       | 95.0          | 95.00                          | 0.5457            | 1.0890              | 50            | 0.5000            | 1.1000              | 0.916       | 1.01    |

### 5.3.1.3 Results Comparison

SHOCK 2.0 is nearly identical to ConWep at calculating the reflected impulse. The reflected pressure prediction is accurate for small scaled distance and less accurate as the scaled distance increases. The reason for this divergence in the reflected pressure prediction may be due to poor resolution in the data set used in SHOCK 2.0 to interpolate the reflected pressure coefficient value from Figure 2-193 in [1].

### 5.3.2 Reflecting Surface Effect

ConWep does not include calculations for reflected waves from adjacent surfaces while SHOCK 2.0 does. Reflecting surfaces reflect the incident wave and enhance the load environment. Three problems were created to demonstrate that for the same scaled distance from the charge, the impulse and pressure loads at a point of interest are larger in SHOCK 2.0 than in ConWep if a reflecting surface is added.

Similar to Section 5.3.1 above, the ConWep Aboveground Airblast function was used to compute the reflected impulse and the reflected pressure at a given scaled distance,  $Z$ . This ConWep calculation does not consider reflecting surfaces.

For the same scaled distance,  $Z$ , three SHOCK 2.0 runs were carried out with an adjacent reflecting surface to the load wall enabled. Figure 5.4 demonstrates the load wall used in SHOCK 2.0 and the floor reflecting surface. In the first problem, the charge is placed 5 ft above the floor. It is 50 ft above the floor in the second problem and 95 feet above the floor in the third problem. In all three cases, the point of interest on the load wall is placed directly across the charge in order to predict the normal reflected impulse and pressure. This allows direct comparison with ConWep which always computes the normal reflected impulse and pressure.

The results of these three problems are summarized in Table 5.4 below.

**Table 5.4. Reflecting Surface Comparison**

| Case | W<br>(lbs) | $Z_c$<br>(ft) | $z$<br>(ft/lb <sup>1/3</sup> ) | ConWep            |                     | SHOCK2.0      |                   |                     | SHK2.0/CnWp |         |
|------|------------|---------------|--------------------------------|-------------------|---------------------|---------------|-------------------|---------------------|-------------|---------|
|      |            |               |                                | Pressure<br>(psi) | Impulse<br>(psi-ms) | $Y_c$<br>(ft) | Pressure<br>(psi) | Impulse<br>(psi-ms) | Pressure    | Impulse |
| 1    | 500        | 80.0          | 10.08                          | 15.980            | 94.210              | 5.0           | 17.900            | 194.90              | 1.12        | 2.07    |
| 2    | 500        | 80.0          | 10.08                          | 15.980            | 94.210              | 50            | 22.500            | 174.20              | 1.41        | 1.85    |
| 3    | 500        | 80.0          | 10.08                          | 15.980            | 94.210              | 95            | 15.600            | 119.00              | 0.976       | 1.26    |

The SHOCK 2.0 impulse loading is larger than ConWep in all three cases since the reflecting surface contributes an additional impulse from the reflected wave. As the charge is placed further from the floor, i.e. Cases 2 and 3 in Table 5.4, the effect of the reflecting surface diminishes and the SHOCK 2.0 calculated impulse approaches the ConWep result.

A Mach stem is expected to form in Cases 1 and 2 because  $Zc > Yc$  (see Section 4.5), and therefore the pressure computed by SHOCK 2.0 is substantially larger than the reflected pressure computed by ConWep as can be seen in Table 5.4. The SHOCK 2.0 pressure in Case 3 of Table 5.4 is the same as Case 2 in Table 5.3 because the charge is far from the floor and the pressure calculation is computed from the charge image.

#### 5.4 SHOCK 2.0 Calculations and Source Plots

The method used in SHOCK 2.0 to calculate the blast pressure and impulse is based on Figures 2-7, 2-193, 2-194(a) and 2-194(b) in the UFC 3-340-02 [1]. In order to verify that SHOCK 2.0 implements the semi-empirical method correctly three problems were created and solved manually using ConWep and the figures cited above. The results were compared to SHOCK 2.0 and are documented in Table 5.5.

The manual method entailed the use of ConWep to calculate the incident pressure. From the geometry of the problem, the incident angle is computed. Once the incident pressure and angle are known, Figure 2-193 and 2-194(a) and 2-194(b) of [1] are used to compute the reflected pressure and the reflected impulse. Three incidence angles were tested with this method: 10, 40 and 70 degrees.

The same problems were simulated using SHOCK 2.0 and all the surfaces were treated as non-reflecting.

In Table 5.5,  $\alpha$  is the angle of incidence (see Figure 5.4),  $P_s$  is the incidence pressure computed from ConWep,  $C_{ra}$  is the reflected pressure coefficient estimated from Figure 2-193,  $P_{ra}$  is the reflected pressure coefficient,  $I_{ra}$  is the reflected impulse estimated from Figures 2-194(a) and 2-194(b).  $P_r$  and  $I_r$  are the reflected pressure and reflected impulse computed from SHOCK 2.0. The charge weight and distance to target in all three problems were 500 lbs and 7.152 ft, respectively.

**Table 5.5. SHOCK 2.0 and Source Table Comparison**

| Case | User-def<br>$\alpha$<br>(deg) | ConWep<br>$P_s$<br>(psi) | SHOCK          |                   | Figures 2-193 & 2-194(a) |                   |                      | SHK2.0/CnWp |         |
|------|-------------------------------|--------------------------|----------------|-------------------|--------------------------|-------------------|----------------------|-------------|---------|
|      |                               |                          | $P_r$<br>(psi) | $I_r$<br>(psi-ms) | $C_{ra}$                 | $P_{ra}$<br>(psi) | $I_{ra}$<br>(psi-ms) | Pressure    | Impulse |
| 1    | 10                            | 1000                     | 8217.5         | 259.5             | 8.235                    | 8235.3            | 240                  | 0.998       | 1.08    |
| 2    | 40                            | 1000                     | 6107.0         | 165.0             | 6.176                    | 6176.5            | 150                  | 0.989       | 1.10    |
| 3    | 70                            | 1000                     | 1306.6         | 48.80             | 1.235                    | 1235.3            | 46.0                 | 1.06        | 1.06    |

The comparison shows a high degree of correlation. The values from the plots were read by hand, which is a probable source for error in some of the values. The maximum difference between the SHOCK 2.0 and the manual method is 10%, the minimum difference is 0.2%. Considering the potential for error in the values obtained from the plots and the small percent difference between SHOCK 2.0 these comparisons indicate that SHOCK 2.0 implements the semi-empirical method described in this report correctly.

## **6.0 CONCLUSIONS/RECOMMENDATIONS**

### **6.1 Conclusions**

This report documents the history and development of the SHOCK computer program. Program updates made during this effort and in the past are also explained in detail. The theory and details of the semi-empirical method implemented in SHOCK were not previously fully documented or explained. This report explains the theory and provides step-by-step explanation of the method. Three types of validations were carried out on the most recent version of the code. The validation against test results and SHOCK 1.0 indicates that peak pressure and impulse for individual load points are improved. Comparisons with ConWep and with manually computed results indicate that SHOCK 2.0 implements the semi-empirical method correctly and functions as intended.

### **6.2 Recommendations**

The recommendations made by Lorenz and Porzel in [9] should be fully implemented in SHOCK 2.0. This will allow for more accurate peak pressure and impulse calculations for the load wall average and for individual load points. The accuracy of load distribution on any load surface would significantly improve.

Based on the procedure describe by NSWC in [9], the recommended future changes for SHOCK are summarized below:

1. Remove the Mach reflections. The load contribution from any reflected wave must be computed based on the path length and incidence angle originating from the image source. This is the same approach used in Sections 4.4 and 4.5.1. The Mach reflection method and the enhanced reflected wave pressure of Sections 4.5.2 and 4.5.3 should not be used. The unusually high Mach reflection pressures which can be momentarily generated at certain angles of incidence are unstable and do not represent a significant increase in deliverable impulse loading. The enhancement in the loading near wall boundaries and in corners should be sufficiently represented by the superposition of the incident and the reflected shocks.
2. Compute time of arrival for the direct and reflected shock waves.
3. Superimpose the pressures from each wave based on time of arrival and time duration of each wave to compute a better estimate of peak pressure.
4. Improve interpolation routines for Figure 2-193 in [1] or replace with an equation.

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Phillip C. Wager

Mr. Wager upgraded the SHOCK code from FORTRAN77 to FORTRAN90, improved input/output routines, fixed programming bugs and made improvements to the interpolation subroutines.

L. Javier Malvar

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