

THE OXYGEN BALANCE OF AN EXPLOSIVE REGULATES THE
POSITIVE-PHASE-DURATION AND INCIDENT-IMPULSE BY THE INTERACTION
OF UNREACTED DETONATION PRODUCTS WITH THE ATMOSPHERE
- PHD RESEARCH PROPOSAL

by

S. KEVIN MCNEILL

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Approved by

Paul Worsey, Advisor

Jason Barid

Catherine E. Johnson

Braden T. Lusk

Kyle A. Perry

Gillian Worsey

ABSTRACT

Recognizing the influence afterburn has on the detonation shockwave at small scaled distances is essential for modeling blast wave parameters at small scaled distances. The amount of afterburn is a function of the oxygen-balance of the explosive. Afterburn generates additional energy behind the shockwave, and in many cases more than the detonation, however, its precise influence on positive-phase-duration and incident-impulse at small scaled distances has remained unknown. Using high-frequency pressure sensors at small scaled distances, we will measure incident pressure and impulse, time-of-arrival, and positive-phase-duration of hemispherical explosive charges in the air over a range of oxygen-balances. This series of tests will show that positive-phase-duration and incident-impulse are a function of the oxygen-balance of the explosive. Simultaneous with the blast parameter measurements, we will measure the fireball temperature and diameter as a function of time using a spectograph and high-speed camera. This data will show a correlation between fireball temperature and diameter due to afterburn and the positive-phase-duration and incident-impulse. Finally, a series of validation experiments will be conducted on the same explosives in an inert atmosphere of helium. The inert atmosphere will prevent afterburn, negating the effect of the oxygen balance of the explosive. These tests should confirm the earlier testing by showing oxygen-balance no longer influences the positive-phase-duration and incident-impulse. With these results, we will develop revised Kingery Bulmash models to account for the oxygen-balance of the explosive at small scaled distances. This research will provide insight into the role explosive oxygen-balance plays in explosive performance at small scaled distances, result in an improved Kingery Bulmash model, and improve blast resistant design.

TABLE OF CONTENTS

	Page
ABSTRACT	iii
LIST OF ILLUSTRATIONS	viii
LIST OF TABLES	x
NOMENCLATURE	xi
 SECTION	
1. INTRODUCTION	1
1.1. STATEMENT OF THE PROBLEM	2
1.2. RESEARCH AND SCOPE OBJECTIVES	3
1.3. ORIGINALITY OF PHD RESEARCH	4
1.4. RESEARCH METHODOLOGY	4
1.5. EXPECTED CONTRIBUTIONS	5
1.6. ACADEMIC BACKGROUND PREPARATION OF CANDIDATE	5
2. REVIEW OF CRITICAL LITERATURE	10
2.1. OXYGEN BALANCE	10
2.2. HEAT OF DETONATION	13
2.3. HEAT OF AFTERBURN	16
2.4. INTRODUCTION TO SHOCKWAVES	16
2.4.1. Basic Shockwave Equations	16
2.4.2. Reactive Shockwaves	20
2.4.2.1. Oxygene Balance	22

2.4.2.2.	Heat of Explosion	22
2.4.2.3.	Heat of Afterburn.....	22
2.5.	AIR BLAST PARAMETERS	22
2.5.1.	Kingery and Pannill - 1964	23
2.5.2.	Kingery - 1966.....	23
2.5.3.	Kingery and Bulmash - 1984	23
2.5.4.	Polynomial Equations for Airblast Parameters at Small Scaled Dis- tances.....	24
2.5.5.	Measuring Air Blast	24
2.5.6.	Measuring Fireball Temperature	24
2.6.	BLAST RESISTANT DESIGN	25
3.	DETAILED RESEARCH PROPOSAL	26
3.1.	INTRODUCTION	26
3.1.1.	A Third-Level Heading.....	27
3.1.1.1.	A fourth-level heading with a very long and complicated title to once again verify the formatting	27
3.1.1.2.	Another fourth-level heading	28
3.1.2.	Another third-level heading but with a very long and complicated title to verify the formatting.....	29
3.2.	DISCUSSION USING A SECOND-LEVEL HEADING WHICH IS RE- ALLY LONG SO THAT IT PRODUCES A TWO-LINE TOC ENTRY.....	30
4.	RESEARCH PROGRESS	32
4.1.	INTRODUCTION	32
4.1.1.	A Third-Level Heading.....	33
4.1.1.1.	A fourth-level heading with a very long and complicated title to once again verify the formatting	33
4.1.1.2.	Another fourth-level heading	34

4.1.2.	Another third-level heading but with a very long and complicated title to verify the formatting.....	35
4.2.	DISCUSSION USING A SECOND-LEVEL HEADING WHICH IS REALLY LONG SO THAT IT PRODUCES A TWO-LINE TOC ENTRY.....	36
4.3.	CONTENT WITH FIGURES	37
4.3.1.	Floats with Figures	37
4.3.1.1.	Simple figure with label.....	38
4.3.1.2.	Figure with psfrag replacement.....	39
4.3.2.	A Bit More Discussion	40
4.4.	CONTENT WITH SAMPLE TABLES	41
4.4.1.	Floats with Tables	41
4.4.1.1.	Simple Table.....	42
4.4.1.2.	Three-Part Table Example	43
4.4.2.	One More Thing	44
4.5.	CONTENT WITH NATBIB CITATIONS	45
4.6.	CONTENT WITH NOMENCL ENTRIES	46
5.	RESEARCH SCHEDULE	48
5.1.	INTRODUCTION	48
5.1.1.	A Third-Level Heading.....	49
5.1.1.1.	A fourth-level heading with a very long and complicated title to once again verify the formatting	49
5.1.1.2.	Another fourth-level heading	50
5.1.2.	Another third-level heading but with a very long and complicated title to verify the formatting.....	51
5.2.	DISCUSSION USING A SECOND-LEVEL HEADING WHICH IS REALLY LONG SO THAT IT PRODUCES A TWO-LINE TOC ENTRY.....	52
5.3.	CONTENT WITH FIGURES	53
5.3.1.	Floats with Figures	53

5.3.1.1.	Simple figure with label	54
5.3.1.2.	Figure with psfrag replacement	55
5.3.2.	A Bit More Discussion	56
5.4.	CONTENT WITH SAMPLE TABLES	57
5.4.1.	Floats with Tables	57
5.4.1.1.	Simple Table	58
5.4.1.2.	Three-Part Table Example	59
5.4.2.	One More Thing	60
5.5.	CONTENT WITH NATBIB CITATIONS	61
5.6.	CONTENT WITH NOMENCL ENTRIES	62
6.	CONCLUSIONS	64
6.1.	INTRODUCTION	64
6.1.0.1.	Mass Balance	64
6.1.0.2.	Momentum Balance	65
6.1.0.3.	Energy Balance	67
6.1.1.	A Third-Level Heading	69
6.1.1.1.	A fourth-level heading with a very long and complicated title to once again verify the formatting	69
6.1.1.2.	Another fourth-level heading	70
6.1.2.	Another third-level heading but with a very long and complicated title to verify the formatting	71
6.2.	DISCUSSION USING A SECOND-LEVEL HEADING WHICH IS RE- ALLY LONG SO THAT IT PRODUCES A TWO-LINE TOC ENTRY	72
APPENDICES		
REFERENCES		74
VITA		76

LIST OF ILLUSTRATIONS

Figure	Page
1.1. Kingery Bulmash incident pressure, positive phase duration, and incident impulse plot showing the local maxima at a scaled distance of approximately $2.5 \frac{ft}{lb^{1/3}}$ [1]. Unlike the positive phase duration and the incident impulse, the incident pressure does not show a local maximum.	6
1.2. Average increase in the impulse due to the local maximum is approximately 15.36 times the log linear fit of the KB incident impulse data that was less than or equal to a scaled distance of $2.5 \frac{ft}{lb^{1/3}}$	7
1.3. The effects of explosive standoff distance on the cost of various structural and non-structural components (adapted from [2])......	8
1.4. Kingery Bulmash postive phase duration plot showing the local maximum at a scaled distance of approximately $2.5 \frac{ft}{lb^{1/3}}$ [1]......	9
2.1. Trinitrotoluene, TNT, $C_7H_5N_3O_6$	11
2.2. Nitroglycerine, NG, $C_3H_5N_3O_9$	13
2.3. Motion of a shockwave showing the discontinuous jump in pressure, temperature, and density.	17
2.4. Typical plots of (a) the $U - u$ plane, (b) the $P - v$ plane, and (c) the $P - u$ plane. These curves were developed experimentally using standard curve-fit techniques.	18
2.5. $P-v$ plane showing (a) an example of an inert material transitioning from state (0) pre-shock to state (1) post-shock (b) and an example of an explosive transitioning from the unreacted Hugoniot (0) pre-shock to the detonation products Hugoniot (1') post-shock. Note the unreacted explosive Hugoniot in (b) also transitions to state (1). Point (1) represents the explosive just prior to detonation. The line connecting the initial and final states is called the Raleigh line.	19
2.6. Shockwave with a reaction zone ranging from no reaction λ_0 to reaction complete λ_1	20
2.7. Family of Hugoniot curves related to successive quarters of reacted, λ , explosive.	21
4.1. The caption of the figure.	38
4.2. A figure caption which is extra long.	39

4.3. The figure caption made extra long so that the required spacing in the list of figures is evident.....	40
5.1. The caption of the figure.	54
5.2. A figure caption which is extra long.....	55
5.3. The figure caption made extra long so that the required spacing in the list of figures is evident.....	56

LIST OF TABLES

Table	Page
2.1. Oxygen Balance of Some Common Explosives	13
2.2. Kistiakowsky-Wilson Rules	14
2.3. Modified Kistiakowsky-Wilson Rules	15
2.4. Springall Roberts Rules	15
2.5. Kamlet Jacobs Rules	15
4.1. The capitalization of the table should match that of figures.	42
4.2. The caption of the three-part table.	43
5.1. The capitalization of the table should match that of figures.	58
5.2. The caption of the three-part table.	59

NOMENCLATURE

Roman

t time

t time

Greek

δ layer thickness

δ layer thickness

Subscripts

i inlet

i inlet

1. INTRODUCTION

The engineering standard for blast-resistant design is the Unified Facilities Criteria (UFC) 3-340-02 [3]. It is used extensively in the United States, United Kingdom, Australia, and Canada. The primary blast-parameters used for protective design in the UFC are the:

- incident-pressure,
- incident-impulse,
- reflected-pressure, and
- reflected-impulse.

The Kingery-Bulmash (KB) models are used to estimate these blast-parameters in the UFC. The models are presented as a series of charts (free-air spherical and surface hemispherical) and are based on higher-order polynomials [1]. Large scale testing of the explosive, trinitrotoluene (TNT), was used to develop the models. Because the models are curve fits of test data, they are only valid over the scaled distances of the corresponding tests, $Z = 0.134 - 100$, where,

$$Z = R/W^{1/3}$$

and R is the distance from the center of the charge to the point of interest and W is the charge weight (mass).

There are some interesting local maxima in the KB curves that occur in both the incident impulse and positive phase duration that are not present in any of the other KB curves, see Figure 1.1. The incident impulse is a function of peak pressure and time. Therefore it is logical to assume that the maximum in the impulse is correlated to if not caused by the maxima in the positive phase duration. Another interesting observation is

that none of the other KB curves (there are a total of 8 for a given charge configuration) show any local maxima including the reflected impulse and positive phase duration. The local maximum results in an increase in the incident-impulse at scaled distances above $1.0 \frac{ft}{\sqrt[3]{lb}}$. On average the incident impulse is increased by 15 times compared to a curve where no local maximum occurs, see Figure 1.2. The increase in incident impulse results in a larger design load on any nearby structures. Unfortunately, close-in blast loads represent a common threat for the protective design of buildings, bridges and critical infrastructure [4][5]. That increase also results in a corresponding increase in the construction cost of blast hardened facilities as indicated in Figure 1.3.

It is hypothesized in this research, that the of afterburn of the products of reaction of TNT produce the local maximum observed in the KB incident impulse and positive phase duration. The degree of afterburn is a function of the oxygen-balance of the explosive. Therefore, other explosives with different oxygen-balances would produce different incident impulses at small scaled distances than predicted by the KB equations.

1.1. STATEMENT OF THE PROBLEM

Detonations at small scaled-distances represent a common threat to the blast-resistant design of buildings, bridges and critical infrastructure due to proximity in urban areas and lack of protection in rural locations. The Kingery-Bulmash incident impulse curve used to predict the blasting loading shows significant non-linear behavior (local maximum) at small scaled distances. This non-linear behavior at small scaled distances is not well understood. In this research, the influence of explosive oxygen-balance on the non-linear behavior observed in the KB incident impulse curve will be examined. Three different explosives with increasing oxygen balance will be detonated and the following blast parameters will be measured:

- incident-overpressure

- incident-impulse
- time-of-arrival
- positive-phase-duration
- fireball diameter
- fireball temperature.

Finally, a set of validation experiments will be conducted in a neutral atmosphere (no oxygen present) using the same explosives and measuring the same blast parameters. Our objective is to determine the degree to which differences in explosive oxygen-balance causes the non-linear behavior observed. Additionally, a set of revised Kingery-Bulmash models will be developed that include the oxygen-balance as a parameter.

1.2. RESEARCH AND SCOPE OBJECTIVES

The primary objective of this research is to quantify the effect explosive oxygen balance has on blast parameters at small scaled distances. This will lead to the secondary objective, the development of an improved Kingery Bulmash model that accounts for the oxygen balance of the explosive. The elements of these objectives include the following:

- determine the near field positive-phase-duration, incident impulse, and other relevant blast parameters of explosives with a range of oxygen balances,
- evaluate fireball diameter and temperature for explosives with a range of oxygen-balances.
- validate the influence of oxygen balance by detonating the same range of explosives in inert atmospheres, and
- develop a modified Kingery Bulmash model that accounts for oxygen balance.

1.3. ORIGINALITY OF PHD RESEARCH

This research is novel in hypothesizing a cause for the local maximum observed in the near field Kingery Bulmash incident impulse model. Currently, there is no clear and concise explanation for the observed effect. This research would aid in the design of blast resistant structures by providing more accurate models.

1.4. RESEARCH METHODOLOGY

This research will empirically determine the positive-phase-duration and incident-impulse of the following explosives:

- trinitrotoluene (oxygen balance: -74%),
- PETN (oxygen balance: -10%)
- Dyno AP (oxygen balance: 0%).

Pressure transducers will measure the time of arrival, incident impulse, and other blast parameters. The explosives will be hemispherical in shape to minimize near-field shape effects. The explosive charge will be centered on a horizontal steel plate with incident pressure gauges positioned along a single axis. Regression analysis will be used to describe the relationship between scaled distance, oxygen balance, and blast parameter data.

Simultaneous with the blast-parameter measurements, the fireball diameter and fireball temperature will be measured with a high-speed camera and spectrometer respectively. Regression analysis will be used to determine a relationship between the oxygen balance and the fireball diameter and temperature.

A set of validation experiments will be conducted using the same explosives and incident pressure gauge configuration, but placed in an inert helium atmosphere. If the hypothesis is correct, the oxygen balance of the explosives should not influence the positive phase duration or the incident impulse.

Finally, the Kingery Bulmash model will be modified to account for the explosive oxygen balance. The new model will be a function of not just scaled distance but also the oxygen-balance of the explosive.

1.5. EXPECTED CONTRIBUTIONS

The expected contributions of this research are as follows:

- development of improved Kingery-Bulmash models that account for the explosive oxygen-balance at small scaled distances,
- empirical evidence of blast parameters in the near field, and
- improved blast loading calculations for blast resistant designs.

1.6. ACADEMIC BACKGROUND PREPARATION OF CANDIDATE

S. Kevin McNeill is currently a graduate student pursuing a Doctor of Philosophy in Explosive Engineering at Missouri University of Science and Technology (MST). He holds a Bachelors of Science in Mechanical Engineering from Louisiana State University and a Masters of Science in Explosive Engineering from MST. He is currently the Chief, of the Explosives Research and Development Division at the Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF). In this position, he has conducted numerous government studies involving the measurement of overpressure and other blast parameters for the National Counter Terrorism Center, U.S. Army Corps of Engineers, Department of Defense Explosives Safety Board, and the Joint Improvised Explosive Device Agency. In these studies, he has conducted test preparation, instrumentation selection, range layout, test controls, firing train selection, data analysis, and report writing.

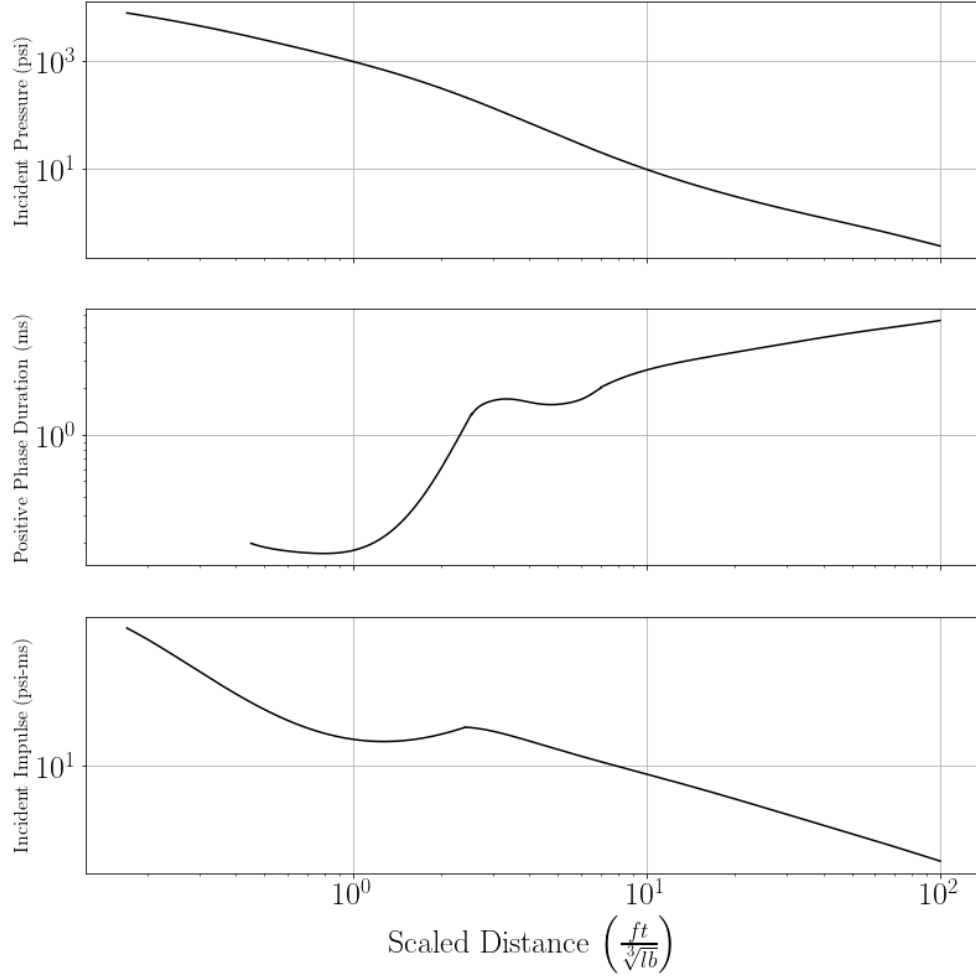


Figure 1.1. Kingery Bulmash incident pressure, positive phase duration, and incident impulse plot showing the local maxima at a scaled distance of approximately $2.5 \frac{ft}{lb^{1/3}}$ [1]. Unlike the positive phase duration and the incident impulse, the incident pressure does not show a local maximum.

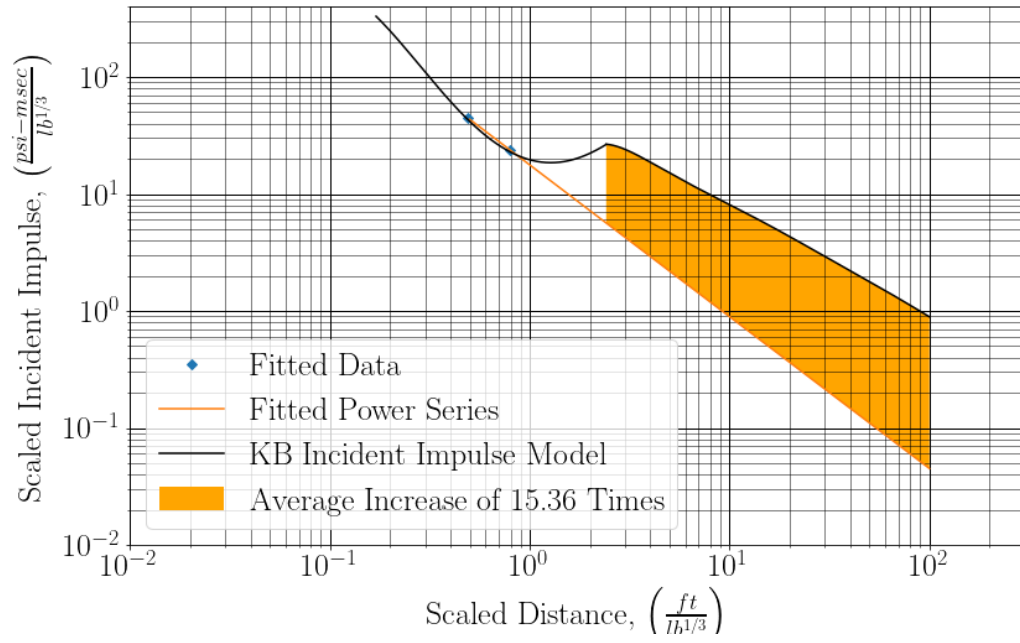


Figure 1.2. Average increase in the impulse due to the local maximum is approximately 15.36 times the log linear fit of the KB incident impulse data that was less than or equal to a scaled distance of $2.5 \frac{ft}{lb^{1/3}}$.

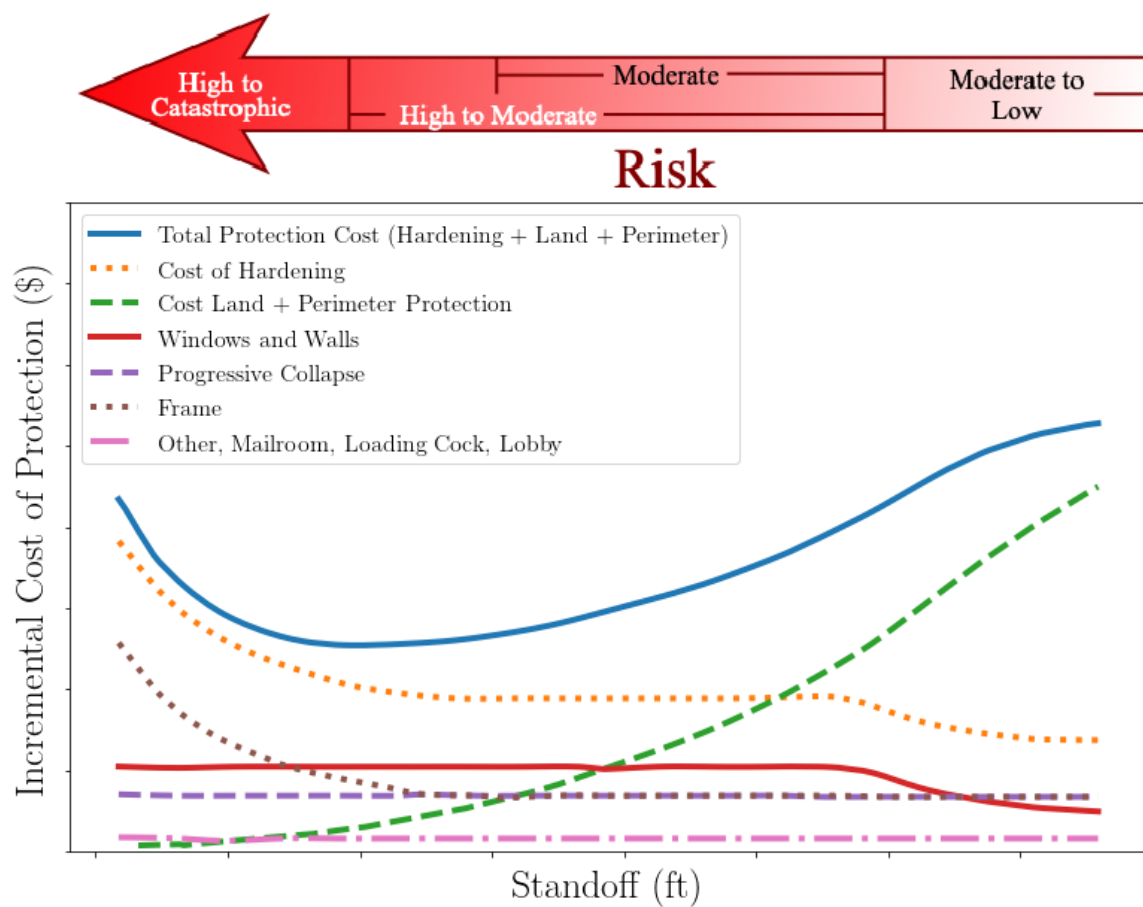


Figure 1.3. The effects of explosive standoff distance on the cost of various structural and non-structural components (adapted from [2]).

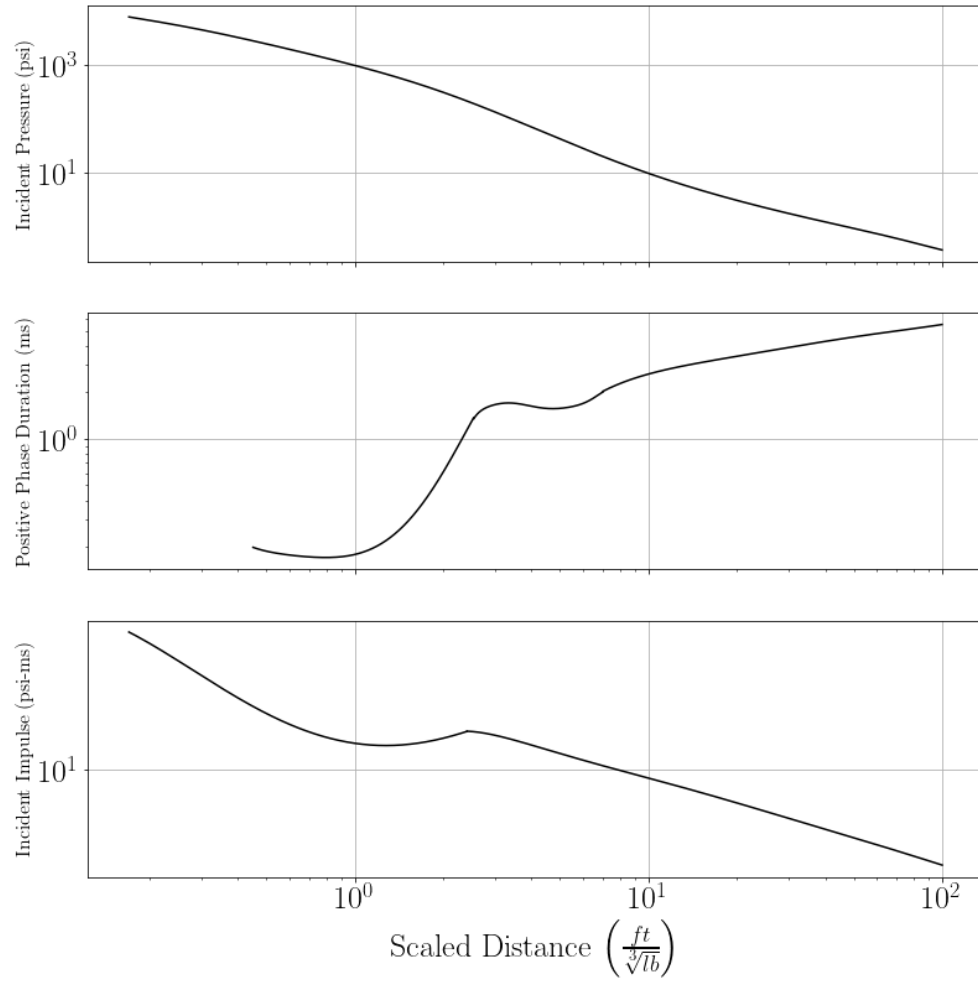


Figure 1.4. Kingery Bulmash positive phase duration plot showing the local maximum at a scaled distance of approximately $2.5 \frac{ft}{lb^{1/3}}$ [1].

2. REVIEW OF CRITICAL LITERATURE

The loading applied to structures due to an accidental or intentional blast are complex and based on a number of factors (peak pressure, peak impulse, positive phase duration etc.). There have been several models developed to predict these factors however, the most common are the Kingery Bulmash (KB) equations [1]. The KB equations are based upon the explosive trinitrotoluene (TNT). TNT is an explosive with a negative oxygen balance of approximately -74% . There have been a number of studies that have indicated the role oxygen balance may have on explosive performance. This literature review will examine some of these studies beginning with an introduction to oxygen balance.

2.1. OXYGEN BALANCE

Oxygen balance is the ratio of the amount of oxygen in an explosive molecule compared with the amount of oxygen required for complete oxidation of the explosive products. There are three possible oxygen balance outcomes:

- negative oxygen balance - there is insufficient oxygen for complete oxidation of the explosive products,
- oxygen balanced - there is exactly enough oxygen for complete oxidation of the explosive products,
- positive oxygen balance - there is excess oxygen for complete oxidation of the explosive products

There are two methods for calculating the oxygen balance. The first method involves calculating the stoichiometric reaction of the decomposition of the explosive. If we consider the detonation of TNT, see Figure 2.1, the reaction results in oxidized gaseous products. If

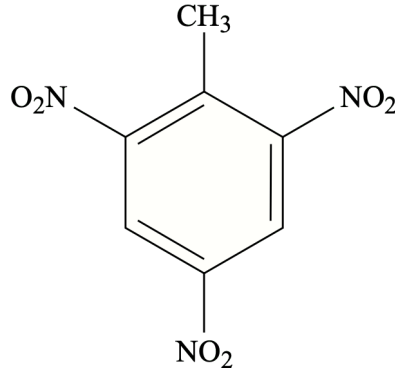
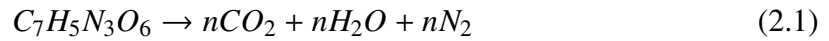
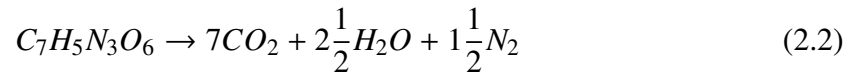


Figure 2.1. Trinitrotoluene, TNT, $C_7H_5N_3O_6$

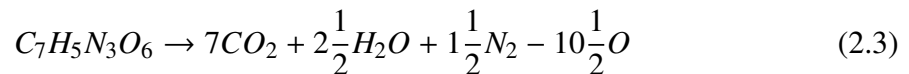
we assume the products fully react forming carbon dioxide, water, and nitrogen we have,



From the TNT molecule we know there are 7 moles of carbon, 5 moles of hydrogen, and 3 moles of nitrogen in the reactants,



There are 6 moles of oxygen in the TNT molecule. There are $16\frac{1}{2}$ moles of oxygen in the reactants. Therefore, to balance the equation we need to subtract $10\frac{1}{2}$ moles of oxygen from the reactants,



This clearly shows that there is insufficient oxygen in the TNT molecule to oxidize all the reactants into water and carbon dioxide. Oxygen balance is calculated by weight. The molecular weight (MW) of the TNT molecule is given by,

$$MW_{TNT} = 7MW_C + 5MW_H + 3MW_N + 6MW_O \quad (2.4)$$

$$MW_{TNT} = 7(12.0107) + 5(1.00794) + 3(14.00674) + 6(15.9994) \quad (2.5)$$

$$MW_{TNT} = 227.1312 \quad (2.6)$$

The molecular weight of the additional oxygen needed is,

$$MW_{oxygen} = -10\frac{1}{2}(15.9994) \quad (2.7)$$

$$MW_{oxygen} = -167.9937 \quad (2.8)$$

Therefore, the oxygen balance is,

$$OB\%_{TNT} = \frac{-167.9937}{227.1312} 100\% \quad (2.9)$$

$$OB\%_{TNT} = -73.96\% \quad (2.10)$$

The second method of calculating oxygen balance is shown in equation 2.11. This is only valid for explosives with the form $C_aH_bN_cO_d$.

$$OB\% = \frac{1599.940 \left(d - (2a) - \left(\frac{b}{2} \right) \right)}{MW} \quad (2.11)$$

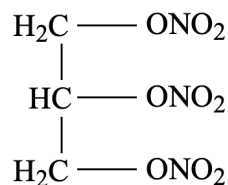
where MW is given by,

$$MW = a(12.0107) + b(1.00794) + c(14.00674) + d(15.9994) \quad (2.12)$$

For nitroglycerin, see Figure 2.2, we have,

$$a = 3, b = 5, c = 3, d = 9 \quad (2.13)$$

$$MW_{NG} = 3(12.0107) + 5(1.00794) + 3(14.00674) + 9(15.9994) \quad (2.14)$$

Figure 2.2. Nitroglycerine, NG, $\text{C}_3\text{H}_5\text{N}_3\text{O}_9$

$$MW_{NG} = 227.094 \quad (2.15)$$

Substituting we have,

$$OB\%_{NG} = \frac{1599.940 \left(9 - (2(3)) - \left(\frac{5}{2} \right) \right)}{227.094} \quad (2.16)$$

$$OB\%_{NG} = 3.52\% \quad (2.17)$$

This indicates that the decomposition of nitroglycerine has a slight positive oxygen balance. The oxygen balance of several common explosives is summarized in Table 2.1 for comparison.

Explosive	Empirical Formula	Oxygen Balance
Ammonium Nitrate	NH_3HO_3	+19.99
Nitroglycerine	$\text{C}_3\text{H}_5\text{N}_3\text{O}_9$	+3.52
PETN	$\text{C}_5\text{H}_8\text{N}_4\text{O}_{12}$	-10.12
RDX	$\text{C}_3\text{H}_6\text{N}_6\text{O}_6$	-21.61
TNT	$\text{C}_7\text{H}_5\text{N}_3\text{O}_6$	-73.96

Table 2.1. Oxygen Balance of Some Common Explosives

2.2. HEAT OF DETONATION

Decomposition reactions of explosives release energy in the form of heat. Under adiabatic conditions the release of heat is called the heat of detonation, designated ΔH_d^0 . The heat of detonation is limited to the decomposition of the explosive and does not include any

additional heat generated as the products of reaction mix with air. The heat of detonation indicates the amount of work an explosive can generate as it expands. The heat of detonation can be calculated from the difference between the heats of formation of the reaction products and the explosive as shown in Equation 2.18.

$$\Delta H_r^0 = \sum \Delta H_f^0(\text{reaction products}) - \Delta H_f^0(\text{explosive}) \quad (2.18)$$

where H_f^0 is the heat of formation. The heat of formation is the change in enthalpy associated with the formation of one mole of a compound from its elements in their standard states. Where the standard state is 25°C (77°F) and 101.3 kPa (14.7 psi). By definition the standard heat of formation of an element is zero. For example, the standard heats of formation of H_2 , N_2 , O_2 (diatomic elements) is zero, as is the graphite form of solid carbon.

From 2.18 we can see that the heat of detonation is sensitive to the reaction products and therefore the reaction hierarchy. Typical examples of reaction hierarchies are the Kistiskowsky-Wilson Rules ($OB\% > -40$), Modified Kistiakowsky-Wilson Rules ($OB\% < -40$), Springall Roberts Rules, and Kamlet and Jacob Rules [6] [7]. These rules each generate different products of reaction, but overall are a good approximation and are easy to calculate. See Tables 2.2, 2.3, 2.4 and 2.5 for a summary of these rules.

Step No.	Reaction Point
1	Carbon atoms are converted to carbon dioxide, CO_2
2	If any oxygen remains then hydrogen is oxidized to water, H_2O
3	If any oxygen still remains then carbon monoxide is oxidized, CO
4	All the nitrogen is converted to nitrogen gas, N_2

Table 2.2. Kistiakowsky-Wilson Rules

For example, if we consider the detonation of TNT using the Springall Roberts Rules we have,

$$\text{Heat of formation of TNT: } \Delta H_f^0(TNT) = -929.34 \frac{\text{kJ}}{\text{mol}} \text{ Heat}$$

Step No.	Reaction Point
1	Hydrogen atoms are converted to water, H_2O
2	If any oxygen remains then carbon is converted to carbon monoxide, CO
3	If any oxygen still remains then carbon monoxide is converted to carbon dioxide, CO_2
4	All the nitrogen is converted to nitrogen gas, N_2

Table 2.3. Modified Kistiakowsky-Wilson Rules

Step No.	Reaction Point
1	Carbon atoms are converted to carbon monoxide, CO
2	If any oxygen remains then hydrogen is then oxidized to water, H_2O
3	If any oxygen still remains then carbon monoxide is oxidized to carbon dioxide, CO_2
4	All the nitrogen is converted to nitrogen gas, N_2
5	One third of the carbon monoxide formed is converted to carbon and carbon dioxide, C and CO_2
6	One sixth of the original amount of carbon monoxide is converted to form carbon and water, C and H_2O

Table 2.4. Springall Roberts Rules

Step No.	Reaction Point
1	All nitrogen is converted to nitrogen gas, N_2
2	Hydrogen atoms are oxidized to water, H_2O
3	If any oxygen still remains then carbon is oxidized to carbon dioxide, CO_2
4	All remaining carbon is converted to solid carbon, C

Table 2.5. Kamlet Jacobs Rules

When an explosive has a negative oxygen balance, like TNT, the unoxidized products of reaction are available to react with the oxygen in the air in a combustion reaction called afterburn. In many cases the afterburn reaction can release more energy than the heat of detonation. The next section will detail the calculation of the heat of afterburn.

2.3. HEAT OF AFTERBURN

2.4. INTRODUCTION TO SHOCKWAVES

A shockwave is a pressure disturbance moving through a medium faster than the speed of sound with a sharp increase in pressure, density, and temperature. The disturbance is typically caused by a mechanical event (supersonic bullet), electrical event (a lightening strike), or a chemical event (detonation of an explosive). When an explosive is detonated the shockwave is commonly referred to as a detonation wave or blast wave. A blast wave is sustained by the chemical energy of the detonation, however the wave is also losing energy as it propagates due to viscous effects. Without a continuous supply of chemical energy to propel the blast wave forward it will eventually dissipate to a sound wave.

2.4.1. Basic Shockwave Equations. The shockwave shown in Figure 2.3 was first described mathematically by Rankine and Hugoniot [8][9][10]. The now called Rankine-Hugoniot jump equations are based on the conservation of mass, momentum, and energy, see Figure 2.3. The equations are based on the following assumptions:

- 1D flow,
- discontinuous shock,
- transport effects (mass, energy, charge, momentum and angular momentum) out of the system are ignored,
- reaction rate is instantaneous and complete, and
- the shock is in steady-state condition before and after the shock.

The equations for a detonation wave with the coordinate system fixed to the shockwave are given by,

conservation of mass:

$$\rho_0(U - u_0) = \rho_1(U - u_1) \quad (2.19)$$

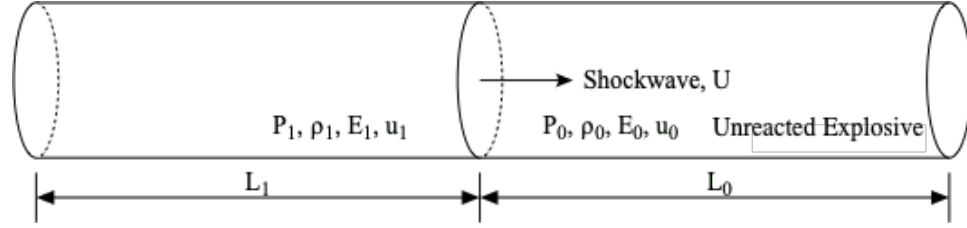


Figure 2.3. Motion of a shockwave showing the discontinuous jump in pressure, temperature, and density.

conservation of momentum:

$$P_0 + \rho_0 u_0^2 = P_1 + \rho_1 u_1^2 \quad (2.20)$$

conservation of energy:

$$e_0 + P_0 v_0 + \frac{1}{2} (U - u_0)^2 = e_1 + P_1 v_1 + \frac{1}{2} (U - u_1)^2 \quad (2.21)$$

Where ρ is the density, P is the pressure, u is the particle velocity, U is the shock velocity, e specific energy and the subscripts 0 and 1 refer to the reactant and product states, respectively. Unfortunately, these three equations are insufficient to solve for the five unknowns. Equations of state are needed to provide the additional equations. Three empirically-derived equations-of-state were developed between the following parameters [11][12]:

- shock velocity and particle velocity $U - u$ plane
- pressure and specific volume, $P - v$ plane
- pressure and particle velocity, $P - u$ plane

These relationships provide a fourth set of equations and are specific to the material (inert or explosive) undergoing a shock and are referred to collectively as Hugoniot equations, see Figure 2.4. These relationships represent the possible states of the material both pre

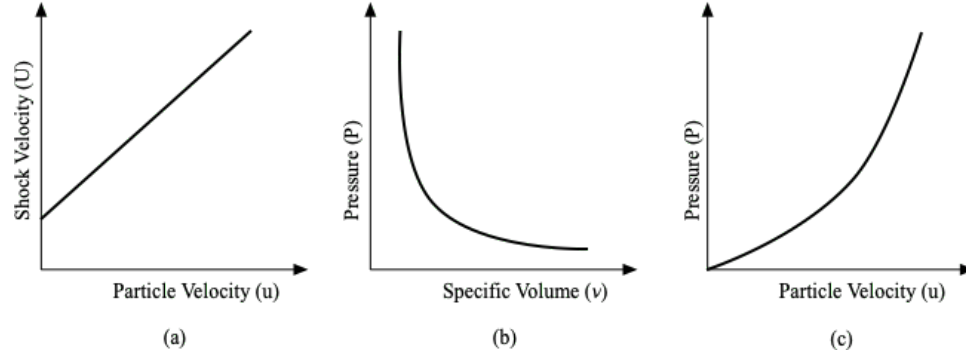


Figure 2.4. Typical plots of (a) the $U - u$ plane, (b) the $P - v$ plane, and (c) the $P - u$ plane. These curves were developed experimentally using standard curve-fit techniques.

and post-shock. For inert materials there is only a single Hugoniot curve but for explosives there is a reactants curve and a products curve, see Figure 2.5. These equations consider the products of reaction to be uniform i.e. no individual chemical species present.

In the $P-v$ plane, the line connecting the initial (0) and final (1) states in Figure 2.5 is a jump condition. This line is called the Raleigh line. Recalling the conservation of mass and momentum equations and that $v = 1/\rho$,

$$\frac{u_0}{v_0} = \frac{u_1}{v_1} = \frac{v_0}{v_1} = \frac{u_0}{u_1} \quad (2.22)$$

$$p = P_0 + \rho_0 u_0^2 = P_1 + \rho_1 u_1^2 \quad (2.23)$$

and assuming $u_0 = 0$ we can rewrite equation 2.22,

$$u_1 = \frac{u_0(v_1)}{v_0} \quad (2.24)$$

Substituting equation 2.24 into equation 2.23 and performing some algebra we have,

$$P_1 - P_0 = -\frac{U^2}{v_0^2} (v_1 - v_0) \quad (2.25)$$

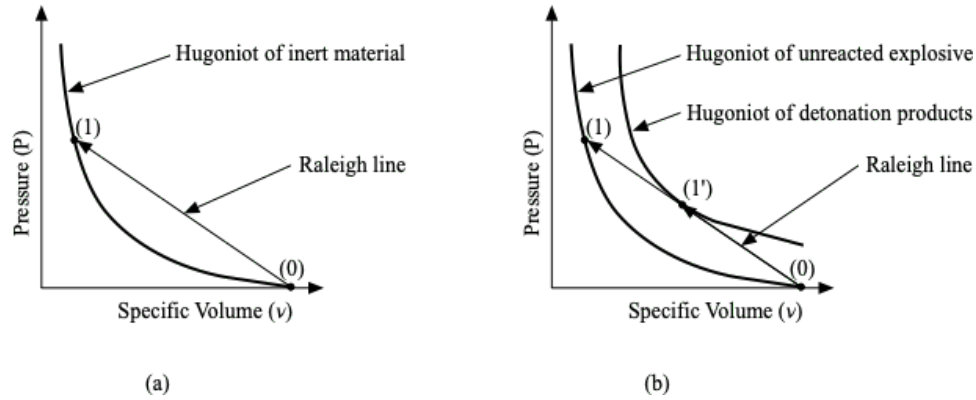


Figure 2.5. P - v plane showing (a) an example of an inert material transitioning from state (0) pre-shock to state (1) post-shock (b) and an example of an explosive transitioning from the unreacted Hugoniot (0) pre-shock to the detonation products Hugoniot (1') post-shock. Note the unreacted explosive Hugoniot in (b) also transitions to state (1). Point (1) represents the explosive just prior to detonation. The line connecting the initial and final states is called the Raleigh line.

Recalling that the equation for a line is given by,

$$y_1 - y_0 = m(x_1 - x_0) \quad (2.26)$$

where m is the slope of the line then the slope of the Raleigh line in the $P - v$ plane is,

$$m = -\frac{U^2}{v_0^2} \quad (2.27)$$

or,

$$U = -\rho_0 m^{1/2} \quad (2.28)$$

The empirically derived Hugoniot equations combined with the mass, momentum, and energy equations are successful in solving a range of shock related problems. Typical problems include:

- material impact problems

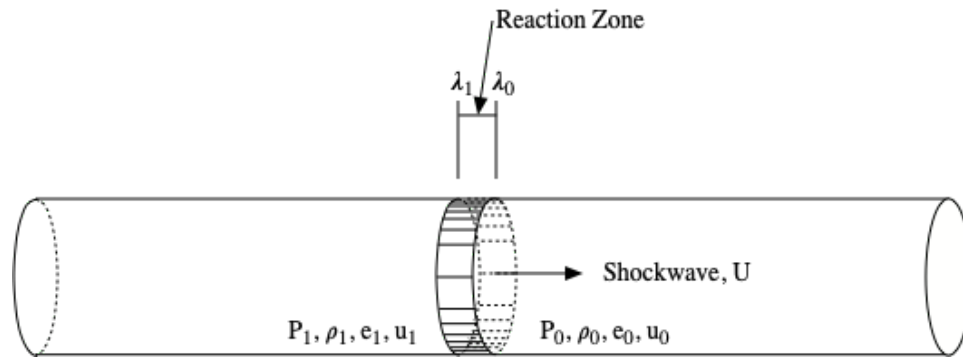


Figure 2.6. Shockwave with a reaction zone ranging from no reaction λ_0 to reaction complete λ_1 .

- shockwave behavior between materials with different impedances
- colliding shockwave behavior

2.4.2. Reactive Shockwaves. In the previous discussion, the reaction rate behind the shockwave was considered instantaneous. If we wish to consider a finite reaction rate we can use the Zeldovich-von Neumann-Doering (ZND) model[13][14]. The assumptions for the reactive shockwave are as follows:

- 1D flow,
- Discontinuous shock (transport effects neglected),
- Reaction rate is zero at the shock and finite behind the shock and the reaction is irreversible,
- Thermodynamics are at equilibrium except in the reaction zone.

In this model, the shockwave discontinuity is replaced with a shockwave and a finite reaction zone. The initial state in front of the shockwave remains unchanged however, the final state is now the end of the reaction zone, see Figure 2.6. The mass and momentum equations across the reactive shock are the same as for the basic shockwave, equations 2.19 and 2.20.

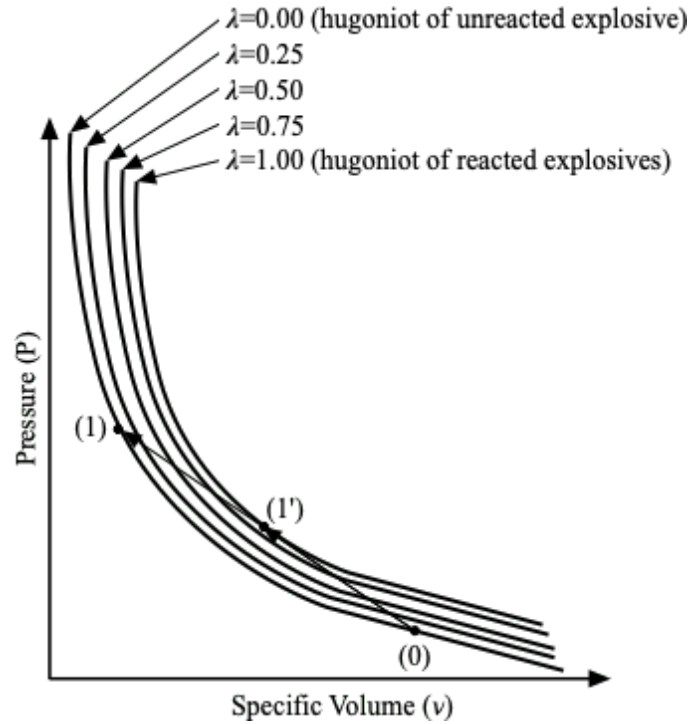


Figure 2.7. Family of Hugoniot curves related to successive quarters of reacted, λ , explosive.

The energy equation however, depends on the degree of chemical reaction λ . Where λ varies from 0 (no reaction) to 1 (reaction complete). The energy from chemical reaction appears in the internal energy term e in the conservation of energy equation,

$$e_1\lambda_1 - e_0\lambda_0 = \frac{P_1u_1 - P_0 - u_0}{\rho_0(U - u_0)} - \frac{1}{2}(u_1^2 - u_0^2) \quad (2.29)$$

If an equation of state is known (same requirement as the basic shockwave equation) and a reaction rate equation is known we can calculate the thermodynamic properties inside the reaction zone as a function of time or distance. If we consider the P - v plane again, we would have multiple Hugoniot curves as the reaction goes to completion, see Figure 2.7. However, even simple reaction rate equations that produce plausible results require numeric analysis.

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2.4.2.3. Heat of Afterburn. Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetur odio sem sed wisi.

2.5. AIR BLAST PARAMETERS

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2.5.3. Kingery and Bulmash - 1984. Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetur odio sem sed wisi.

2.5.4. Polynomial Equations for Airblast Parameters at Small Scaled Distances.

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2.5.5. Measuring Air Blast. Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetur odio sem sed wisi.

2.5.6. Measuring Fireball Temperature. Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetur odio sem sed wisi.

2.6. BLAST RESISTANT DESIGN

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3. DETAILED RESEARCH PROPOSAL

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3.1. INTRODUCTION

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3.1.2. Another third-level heading but with a very long and complicated title to verify the formatting. Aliquam lectus. Vivamus leo. Quisque ornare tellus ullamcorper nulla. Mauris porttitor pharetra tortor. Sed fringilla justo sed mauris. Mauris tellus. Sed non leo. Nullam elementum, magna in cursus sodales, augue est scelerisque sapien, venenatis congue nulla arcu et pede. Ut suscipit enim vel sapien. Donec congue. Maecenas urna mi, suscipit in, placerat ut, vestibulum ut, massa. Fusce ultrices nulla et nisl. Etiam ac leo a risus tristique nonummy. Donec dignissim tincidunt nulla. Vestibulum rhoncus molestie odio. Sed lobortis, justo et pretium lobortis, mauris turpis condimentum augue, nec ultricies nibh arcu pretium enim. Nunc purus neque, placerat id, imperdiet sed, pellentesque nec, nisl. Vestibulum imperdiet neque non sem accumsan laoreet. In hac habitasse platea dictumst. Etiam condimentum facilisis libero. Suspendisse in elit quis nisl aliquam dapibus.

Pellentesque auctor sapien. Sed egestas sapien nec lectus. Pellentesque vel dui vel neque bibendum viverra. Aliquam porttitor nisl nec pede. Proin mattis libero vel turpis. Donec rutrum mauris et libero. Proin euismod porta felis. Nam lobortis, metus quis elementum commodo, nunc lectus elementum mauris, eget vulputate ligula tellus eu neque. Vivamus eu dolor. Nulla in ipsum. Praesent eros nulla, congue vitae, euismod ut, commodo a, wisi. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Aenean nonummy magna non leo. Sed felis erat, ullamcorper in, dictum non, ultricies ut, lectus. Proin vel arcu a odio lobortis euismod. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Proin ut est. Aliquam odio. Pellentesque massa turpis, cursus eu, euismod nec, tempor congue, nulla. Duis viverra gravida mauris. Cras tincidunt. Curabitur eros ligula, varius ut, pulvinar in, cursus faucibus, augue.

3.2. DISCUSSION USING A SECOND-LEVEL HEADING WHICH IS REALLY LONG SO THAT IT PRODUCES A TWO-LINE TOC ENTRY

Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetur odio sem sed wisi. Sed feugiat. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Ut pellentesque augue sed urna. Vestibulum diam eros, fringilla et, consectetur eu, nonummy id, sapien. Nullam at lectus. In sagittis ultrices mauris. Curabitur malesuada erat sit amet massa. Fusce blandit. Aliquam erat volutpat. Aliquam euismod. Aenean vel lectus. Nunc imperdiet justo nec dolor. Etiam euismod. Fusce facilisis lacinia dui. Suspendisse potenti. In mi erat, cursus id, nonummy sed, ullamcorper eget, sapien. Praesent pretium, magna in eleifend egestas, pede pede

pretium lorem, quis consecetur tortor sapien facilisis magna. Mauris quis magna varius
nulla scelerisque imperdiet. Aliquam non quam. Aliquam porttitor quam a lacus. Praesent
vel arcu ut tortor cursus volutpat. In vitae pede quis diam bibendum placerat. Fusce
elementum convallis neque. Sed dolor orci, scelerisque ac, dapibus nec, ultricies ut, mi.
Duis nec dui quis leo sagittis commodo.

4. RESEARCH PROGRESS

Suspendisse vel felis. Ut lorem lorem, interdum eu, tincidunt sit amet, laoreet vitae, arcu. Aenean faucibus pede eu ante. Praesent enim elit, rutrum at, molestie non, nonummy vel, nisl. Ut lectus eros, malesuada sit amet, fermentum eu, sodales cursus, magna. Donec eu purus. Quisque vehicula, urna sed ultricies auctor, pede lorem egestas dui, et convallis elit erat sed nulla. Donec luctus. Curabitur et nunc. Aliquam dolor odio, commodo pretium, ultricies non, pharetra in, velit. Integer arcu est, nonummy in, fermentum faucibus, egestas vel, odio.

4.1. INTRODUCTION

Sed commodo posuere pede. Mauris ut est. Ut quis purus. Sed ac odio. Sed vehicula hendrerit sem. Duis non odio. Morbi ut dui. Sed accumsan risus eget odio. In hac habitasse platea dictumst. Pellentesque non elit. Fusce sed justo eu urna porta tincidunt. Mauris felis odio, sollicitudin sed, volutpat a, ornare ac, erat. Morbi quis dolor. Donec pellentesque, erat ac sagittis semper, nunc dui lobortis purus, quis congue purus metus ultricies tellus. Proin et quam. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Praesent sapien turpis, fermentum vel, eleifend faucibus, vehicula eu, lacus. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Donec odio elit, dictum in, hendrerit sit amet, egestas sed, leo. Praesent feugiat sapien aliquet odio. Integer vitae justo. Aliquam vestibulum fringilla lorem. Sed neque lectus, consectetur at, consectetur sed, eleifend ac, lectus. Nulla facilisi. Pellentesque eget lectus. Proin eu metus. Sed porttitor. In hac habitasse platea dictumst. Suspendisse eu lectus. Ut mi mi, lacinia sit amet, placerat et, mollis vitae, dui. Sed ante tellus, tristique ut, iaculis eu, malesuada ac, dui. Mauris nibh leo, facilisis non, adipiscing quis, ultrices a, dui. Morbi luctus, wisi viverra faucibus pretium, nibh est placerat

odio, nec commodo wisi enim eget quam. Quisque libero justo, consectetur a, feugiat vitae, porttitor eu, libero. Suspendisse sed mauris vitae elit sollicitudin malesuada. Maecenas ultricies eros sit amet ante. Ut venenatis velit. Maecenas sed mi eget dui varius euismod. Phasellus aliquet volutpat odio. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Pellentesque sit amet pede ac sem eleifend consectetur. Nullam elementum, urna vel imperdiet sodales, elit ipsum pharetra ligula, ac pretium ante justo a nulla. Curabitur tristique arcu eu metus. Vestibulum lectus. Proin mauris. Proin eu nunc eu urna hendrerit faucibus. Aliquam auctor, pede consequat laoreet varius, eros tellus scelerisque quam, pellentesque hendrerit ipsum dolor sed augue. Nulla nec lacus.

4.1.1. A Third-Level Heading. Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetur odio sem sed wisi.

4.1.1.1. A fourth-level heading with a very long and complicated title to once again verify the formatting. Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetur odio sem sed wisi. Sed feugiat. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Ut pellentesque augue sed urna. Vestibulum diam eros, fringilla et, consectetur eu, nonummy id, sapien. Nullam at lectus. In sagittis ultrices mauris. Curabitur malesuada erat sit amet massa. Fusce

blandit. Aliquam erat volutpat. Aliquam euismod. Aenean vel lectus. Nunc imperdiet justo nec dolor. Etiam euismod. Fusce facilisis lacinia dui. Suspendisse potenti. In mi erat, cursus id, nonummy sed, ullamcorper eget, sapien. Praesent pretium, magna in eleifend egestas, pede pede pretium lorem, quis consectetur tortor sapien facilisis magna. Mauris quis magna varius nulla scelerisque imperdiet. Aliquam non quam. Aliquam porttitor quam a lacus. Praesent vel arcu ut tortor cursus volutpat. In vitae pede quis diam bibendum placerat. Fusce elementum convallis neque. Sed dolor orci, scelerisque ac, dapibus nec, ultricies ut, mi. Duis nec dui quis leo sagittis commodo.

4.1.1.2. Another fourth-level heading. Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetur odio sem sed wisi. Sed feugiat. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Ut pellentesque augue sed urna. Vestibulum diam eros, fringilla et, consectetur eu, nonummy id, sapien. Nullam at lectus. In sagittis ultrices mauris. Curabitur malesuada erat sit amet massa. Fusce blandit. Aliquam erat volutpat. Aliquam euismod. Aenean vel lectus. Nunc imperdiet justo nec dolor. Etiam euismod. Fusce facilisis lacinia dui. Suspendisse potenti. In mi erat, cursus id, nonummy sed, ullamcorper eget, sapien. Praesent pretium, magna in eleifend egestas, pede pede pretium lorem, quis consectetur tortor sapien facilisis magna. Mauris quis magna varius nulla scelerisque imperdiet. Aliquam non quam. Aliquam porttitor quam a lacus. Praesent vel arcu ut tortor cursus volutpat. In vitae pede quis diam bibendum placerat. Fusce elementum convallis neque. Sed dolor orci, scelerisque ac, dapibus nec, ultricies ut, mi. Duis nec dui quis leo sagittis commodo.

A fifth-level heading also with a very long and complicated title to verify the formatting. Nulla ac nisl. Nullam urna nulla, ullamcorper in, interdum sit amet, gravida ut, risus. Aenean ac enim. In luctus. Phasellus eu quam vitae turpis viverra pellentesque. Duis feugiat felis ut enim. Phasellus pharetra, sem id porttitor sodales, magna nunc aliquet nibh, nec blandit nisl mauris at pede. Suspendisse risus risus, lobortis eget, semper at, imperdiet sit amet, quam. Quisque scelerisque dapibus nibh. Nam enim. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Nunc ut metus. Ut metus justo, auctor at, ultrices eu, sagittis ut, purus. Aliquam aliquam.

Another fifth-level heading. Etiam pede massa, dapibus vitae, rhoncus in, placerat posuere, odio. Vestibulum luctus commodo lacus. Morbi lacus dui, tempor sed, euismod eget, condimentum at, tortor. Phasellus aliquet odio ac lacus tempor faucibus. Praesent sed sem. Praesent iaculis. Cras rhoncus tellus sed justo ullamcorper sagittis. Donec quis orci. Sed ut tortor quis tellus euismod tincidunt. Suspendisse congue nisl eu elit. Aliquam tortor diam, tempus id, tristique eget, sodales vel, nulla. Praesent tellus mi, condimentum sed, viverra at, consectetur quis, lectus. In auctor vehicula orci. Sed pede sapien, euismod in, suscipit in, pharetra placerat, metus. Vivamus commodo dui non odio. Donec et felis.

4.1.2. Another third-level heading but with a very long and complicated title to verify the formatting. Aliquam lectus. Vivamus leo. Quisque ornare tellus ullamcorper nulla. Mauris porttitor pharetra tortor. Sed fringilla justo sed mauris. Mauris tellus. Sed non leo. Nullam elementum, magna in cursus sodales, augue est scelerisque sapien, venenatis congue nulla arcu et pede. Ut suscipit enim vel sapien. Donec congue. Maecenas urna mi, suscipit in, placerat ut, vestibulum ut, massa. Fusce ultrices nulla et nisl. Etiam ac leo a risus tristique nonummy. Donec dignissim tincidunt nulla. Vestibulum rhoncus molestie odio. Sed lobortis, justo et pretium lobortis, mauris turpis condimentum augue, nec ultricies nibh arcu pretium enim. Nunc purus neque, placerat id, imperdiet sed, pellentesque nec, nisl. Vestibulum imperdiet neque non sem accumsan laoreet. In hac habitasse platea dictumst. Etiam condimentum facilisis libero. Suspendisse in elit quis nisl aliquam dapibus.

Pellentesque auctor sapien. Sed egestas sapien nec lectus. Pellentesque vel dui vel neque bibendum viverra. Aliquam porttitor nisl nec pede. Proin mattis libero vel turpis. Donec rutrum mauris et libero. Proin euismod porta felis. Nam lobortis, metus quis elementum commodo, nunc lectus elementum mauris, eget vulputate ligula tellus eu neque. Vivamus eu dolor. Nulla in ipsum. Praesent eros nulla, congue vitae, euismod ut, commodo a, wisi. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Aenean nonummy magna non leo. Sed felis erat, ullamcorper in, dictum non, ultricies ut, lectus. Proin vel arcu a odio lobortis euismod. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Proin ut est. Aliquam odio. Pellentesque massa turpis, cursus eu, euismod nec, tempor congue, nulla. Duis viverra gravida mauris. Cras tincidunt. Curabitur eros ligula, varius ut, pulvinar in, cursus faucibus, augue.

4.2. DISCUSSION USING A SECOND-LEVEL HEADING WHICH IS REALLY LONG SO THAT IT PRODUCES A TWO-LINE TOC ENTRY

Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetur odio sem sed wisi. Sed feugiat. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Ut pellentesque augue sed urna. Vestibulum diam eros, fringilla et, consectetur eu, nonummy id, sapien. Nullam at lectus. In sagittis ultrices mauris. Curabitur malesuada erat sit amet massa. Fusce blandit. Aliquam erat volutpat. Aliquam euismod. Aenean vel lectus. Nunc imperdiet justo nec dolor. Etiam euismod. Fusce facilisis lacinia dui. Suspendisse potenti. In mi erat, cursus id, nonummy sed, ullamcorper eget, sapien. Praesent pretium, magna in eleifend egestas, pede pede

pretium lorem, quis consecetur tortor sapien facilisis magna. Mauris quis magna varius nulla scelerisque imperdiet. Aliquam non quam. Aliquam porttitor quam a lacus. Praesent vel arcu ut tortor cursus volutpat. In vitae pede quis diam bibendum placerat. Fusce elementum convallis neque. Sed dolor orci, scelerisque ac, dapibus nec, ultricies ut, mi. Duis nec dui quis leo sagittis commodo.

4.3. CONTENT WITH FIGURES

Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consecetur odio sem sed wisi.

4.3.1. Floats with Figures. Etiam euismod. Fusce facilisis lacinia dui. Suspendisse potenti. In mi erat, cursus id, nonummy sed, ullamcorper eget, sapien. Praesent pretium, magna in eleifend egestas, pede pede pretium lorem, quis consecetur tortor sapien facilisis magna. Mauris quis magna varius nulla scelerisque imperdiet. Aliquam non quam. Aliquam porttitor quam a lacus. Praesent vel arcu ut tortor cursus volutpat. In vitae pede quis diam bibendum placerat. Fusce elementum convallis neque. Sed dolor orci, scelerisque ac, dapibus nec, ultricies ut, mi. Duis nec dui quis leo sagittis commodo. Aliquam lectus. Vivamus leo. Quisque ornare tellus ullamcorper nulla. Mauris porttitor pharetra tortor. Sed fringilla justo sed mauris. Mauris tellus. Sed non leo. Nullam elementum, magna in cursus sodales, augue est scelerisque sapien, venenatis congue nulla arcu et pede. Ut suscipit enim vel sapien. Donec congue. Maecenas urna mi, suscipit in, placerat ut, vestibulum ut, massa. Fusce ultrices nulla et nisl.

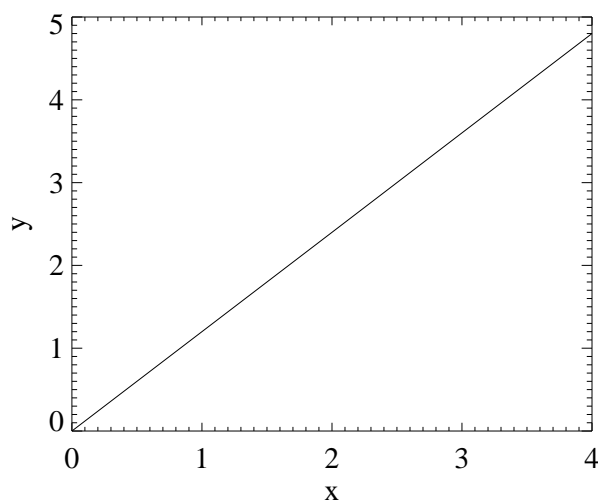


Figure 4.1. The caption of the figure.

4.3.1.1. Simple figure with label. Sed feugiat. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Ut pellentesque augue sed urna. Vestibulum diam eros, fringilla et, consectetur eu, nonummy id, sapien. Nullam at lectus. In sagittis ultrices mauris. Curabitur malesuada erat sit amet massa. Fusce blandit. Aliquam erat volutpat. Aliquam euismod. Aenean vel lectus. Nunc imperdiet justo nec dolor.

Add a simple figure, Figure 4.1, to illustrate an entry in the list of figures. Etiam euismod. Fusce facilisis lacinia dui. Suspendisse potenti. In mi erat, cursus id, nonummy sed, ullamcorper eget, sapien. Praesent pretium, magna in eleifend egestas, pede pede pretium lorem, quis consectetur tortor sapien facilisis magna. Mauris quis magna varius nulla scelerisque imperdiet. Aliquam non quam. Aliquam porttitor quam a lacus. Praesent vel arcu ut tortor cursus volutpat. In vitae pede quis diam bibendum placerat. Fusce elementum convallis neque. Sed dolor orci, scelerisque ac, dapibus nec, ultricies ut, mi. Duis nec dui quis leo sagittis commodo.

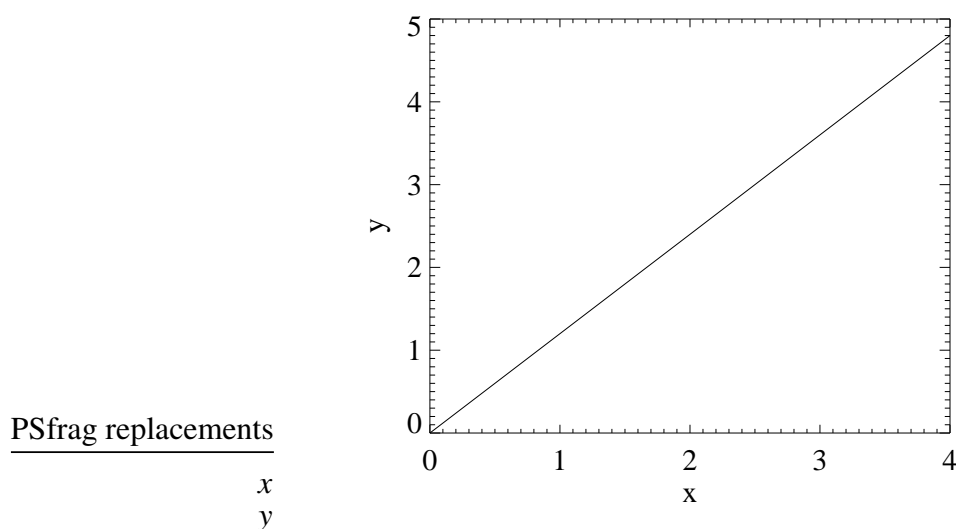


Figure 4.2. A figure caption which is extra long. This long caption not only demonstrates that the required spacing in the list of figures is correct, but also the general practice of making the list of figures (or tables) entry the first sentence of the caption.

4.3.1.2. Figure with psfrag replacement. Aliquam lectus. Vivamus leo. Quisque ornare tellus ullamcorper nulla. Mauris porttitor pharetra tortor. Sed fringilla justo sed mauris. Mauris tellus. Sed non leo. Nullam elementum, magna in cursus sodales, augue est scelerisque sapien, venenatis congue nulla arcu et pede. Ut suscipit enim vel sapien. Donec congue. Maecenas urna mi, suscipit in, placerat ut, vestibulum ut, massa. Fusce ultrices nulla et nisl.. Figure 4.2 illustrates the use of the psfrag package to place \LaTeX math in a graphic. Etiam ac leo a risus tristique nonummy. Donec dignissim tincidunt nulla. Vestibulum rhoncus molestie odio. Sed lobortis, justo et pretium lobortis, mauris turpis condimentum augue, nec ultricies nibh arcu pretium enim. Nunc purus neque, placerat id, imperdiet sed, pellentesque nec, nisl. Vestibulum imperdiet neque non sem accumsan laoreet. In hac habitasse platea dictumst. Etiam condimentum facilisis libero. Suspendisse in elit quis nisl aliquam dapibus. Pellentesque auctor sapien. Sed egestas sapien nec lectus. Pellentesque vel dui vel neque bibendum viverra. Aliquam porttitor nisl nec pede. Proin mattis libero vel turpis. Donec rutrum mauris et libero. Proin euismod porta felis. Nam

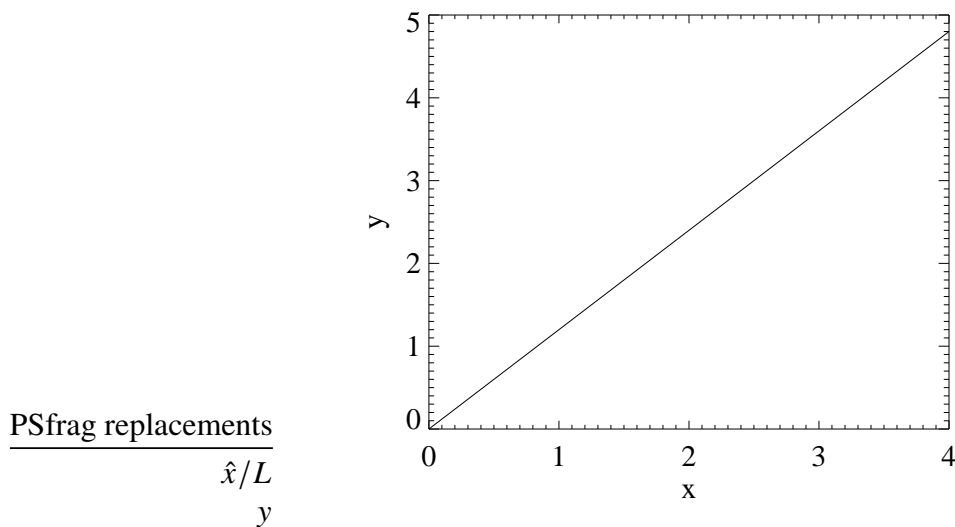


Figure 4.3. The figure caption made extra long so that the required spacing in the list of figures is evident.

lobortis, metus quis elementum commodo, nunc lectus elementum mauris, eget vulputate ligula tellus eu neque. Vivamus eu dolor.. The filler content is followed by a second figure, Figure 4.3. Nulla in ipsum. Praesent eros nulla, congue vitae, euismod ut, commodo a, wisi. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Aenean nonummy magna non leo. Sed felis erat, ullamcorper in, dictum non, ultricies ut, lectus. Proin vel arcu a odio lobortis euismod. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Proin ut est. Aliquam odio. Pellentesque massa turpis, cursus eu, euismod nec, tempor congue, nulla. Duis viverra gravida mauris. Cras tincidunt. Curabitur eros ligula, varius ut, pulvinar in, cursus faucibus, augue.

4.3.2. A Bit More Discussion. Nulla mattis luctus nulla. Duis commodo velit at leo. Aliquam vulputate magna et leo. Nam vestibulum ullamcorper leo. Vestibulum condimentum rutrum mauris. Donec id mauris. Morbi molestie justo et pede. Vivamus eget turpis sed nisl cursus tempor. Curabitur mollis sapien condimentum nunc. In wisi nisl, malesuada at, dignissim sit amet, lobortis in, odio. Aenean consequat arcu a ante.

Pellentesque porta elit sit amet orci. Etiam at turpis nec elit ultricies imperdiet. Nulla facilisi. In hac habitasse platea dictumst. Suspendisse viverra aliquam risus. Nullam pede justo, molestie nonummy, scelerisque eu, facilisis vel, arcu. Curabitur tellus magna, porttitor a, commodo a, commodo in, tortor. Donec interdum. Praesent scelerisque. Maecenas posuere sodales odio. Vivamus metus lacus, varius quis, imperdiet quis, rhoncus a, turpis. Etiam ligula arcu, elementum a, venenatis quis, sollicitudin sed, metus. Donec nunc pede, tincidunt in, venenatis vitae, faucibus vel, nibh. Pellentesque wisi. Nullam malesuada. Morbi ut tellus ut pede tincidunt porta. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Etiam congue neque id dolor. Donec et nisl at wisi luctus bibendum. Nam interdum tellus ac libero. Sed sem justo, laoreet vitae, fringilla at, adipiscing ut, nibh. Maecenas non sem quis tortor eleifend fermentum. Etiam id tortor ac mauris porta vulputate. Integer porta neque vitae massa. Maecenas tempus libero a libero posuere dictum. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Aenean quis mauris sed elit commodo placerat. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Vivamus rhoncus tincidunt libero. Etiam elementum pretium justo. Vivamus est. Morbi a tellus eget pede tristique commodo. Nulla nisl. Vestibulum sed nisl eu sapien cursus rutrum. Nulla non mauris vitae wisi posuere convallis. Sed eu nulla nec eros scelerisque pharetra. Nullam varius. Etiam dignissim elementum metus. Vestibulum faucibus, metus sit amet mattis rhoncus, sapien dui laoreet odio, nec ultricies nibh augue a enim. Fusce in ligula. Quisque at magna et nulla commodo consequat. Proin accumsan imperdiet sem. Nunc porta. Donec feugiat mi at justo. Phasellus facilisis ipsum quis ante. In ac elit eget ipsum pharetra faucibus. Maecenas viverra nulla in massa.

4.4. CONTENT WITH SAMPLE TABLES

4.4.1. Floats with Tables. Nulla mattis luctus nulla. Duis commodo velit at leo. Aliquam vulputate magna et leo. Nam vestibulum ullamcorper leo. Vestibulum condimentum rutrum mauris. Donec id mauris. Morbi molestie justo et pede. Vivamus eget turpis

Table 4.1. The capitalization of the table should match that of figures.

Example	Time	Cost
1	12.5	\$1,000
2	24	\$2,000

sed nisl cursus tempor. Curabitur mollis sapien condimentum nunc. In wisi nisl, malesuada at, dignissim sit amet, lobortis in, odio. Aenean consequat arcu a ante. Pellentesque porta elit sit amet orci. Etiam at turpis nec elit ultricies imperdiet. Nulla facilisi. In hac habitasse platea dictumst. Suspendisse viverra aliquam risus. Nullam pede justo, molestie nonummy, scelerisque eu, facilisis vel, arcu.

4.4.1.1. Simple Table. Finally the tables, Table 4.1 illustrates the syntax of a basic table. Nulla mattis luctus nulla. Duis commodo velit at leo. Aliquam vulputate magna et leo. Nam vestibulum ullamcorper leo. Vestibulum condimentum rutrum mauris. Donec id mauris. Morbi molestie justo et pede. Vivamus eget turpis sed nisl cursus tempor. Curabitur mollis sapien condimentum nunc. In wisi nisl, malesuada at, dignissim sit amet, lobortis in, odio. Aenean consequat arcu a ante. Pellentesque porta elit sit amet orci. Etiam at turpis nec elit ultricies imperdiet. Nulla facilisi. In hac habitasse platea dictumst. Suspendisse viverra aliquam risus. Nullam pede justo, molestie nonummy, scelerisque eu, facilisis vel, arcu. Curabitur tellus magna, porttitor a, commodo a, commodo in, tortor. Donec interdum. Praesent scelerisque. Maecenas posuere sodales odio. Vivamus metus lacus, varius quis, imperdiet quis, rhoncus a, turpis. Etiam ligula arcu, elementum a, venenatis quis, sollicitudin sed, metus. Donec nunc pede, tincidunt in, venenatis vitae, faucibus vel, nibh. Pellentesque wisi. Nullam malesuada. Morbi ut tellus ut pede tincidunt porta. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Etiam congue neque id dolor. Donec et nisl at wisi luctus bibendum. Nam interdum tellus ac libero. Sed sem justo, laoreet vitae, fringilla at, adipiscing ut, nibh. Maecenas non sem quis tortor eleifend fermentum. Etiam id

Table 4.2. The caption of the three-part table.

Example	Time ¹	Cost
1	12.5	\$1,000
2	24	\$2,000

¹ The first note.

tortor ac mauris porta vulputate. Integer porta neque vitae massa. Maecenas tempus libero a libero posuere dictum. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Aenean quis mauris sed elit commodo placerat. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Vivamus rhoncus tincidunt libero. Etiam elementum pretium justo. Vivamus est. Morbi a tellus eget pede tristique commodo. Nulla nisl. Vestibulum sed nisl eu sapien cursus rutrum.

4.4.1.2. Three-Part Table Example. Table 4.2, which illustrates the syntax of a three-part table which includes table notes in addition to a caption and table body. Nulla non mauris vitae wisi posuere convallis. Sed eu nulla nec eros scelerisque pharetra. Nullam varius. Etiam dignissim elementum metus. Vestibulum faucibus, metus sit amet mattis rhoncus, sapien dui laoreet odio, nec ultricies nibh augue a enim. Fusce in ligula. Quisque at magna et nulla commodo consequat. Proin accumsan imperdiet sem. Nunc porta. Donec feugiat mi at justo. Phasellus facilisis ipsum quis ante. In ac elit eget ipsum pharetra faucibus. Maecenas viverra nulla in massa. Nulla ac nisl. Nullam urna nulla, ullamcorper in, interdum sit amet, gravida ut, risus. Aenean ac enim. In luctus. Phasellus eu quam vitae turpis viverra pellentesque. Duis feugiat felis ut enim. Phasellus pharetra, sem id porttitor sodales, magna nunc aliquet nibh, nec blandit nisl mauris at pede. Suspendisse risus risus, lobortis eget, semper at, imperdiet sit amet, quam. Quisque scelerisque dapibus nibh. Nam enim. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Nunc ut metus. Ut metus justo, auctor at, ultrices eu, sagittis ut, purus. Aliquam aliquam. Etiam pede massa, dapibus vitae, rhoncus in, placerat posuere, odio. Vestibulum luctus commodo lacus. Morbi lacus dui, tempor sed, euismod eget, condimentum at, tortor. Phasellus aliquet

odio ac lacus tempor faucibus. Praesent sed sem. Praesent iaculis. Cras rhoncus tellus sed justo ullamcorper sagittis. Donec quis orci. Sed ut tortor quis tellus euismod tincidunt. Suspendisse congue nisl eu elit. Aliquam tortor diam, tempus id, tristique eget, sodales vel, nulla. Praesent tellus mi, condimentum sed, viverra at, consectetur quis, lectus. In auctor vehicula orci. Sed pede sapien, euismod in, suscipit in, pharetra placerat, metus. Vivamus commodo dui non odio. Donec et felis.

4.4.2. One More Thing. Etiam suscipit aliquam arcu. Aliquam sit amet est ac purus bibendum congue. Sed in eros. Morbi non orci. Pellentesque mattis lacinia elit. Fusce molestie velit in ligula. Nullam et orci vitae nibh vulputate auctor. Aliquam eget purus. Nulla auctor wisi sed ipsum. Morbi porttitor tellus ac enim. Fusce ornare. Proin ipsum enim, tincidunt in, ornare venenatis, molestie a, augue. Donec vel pede in lacus sagittis porta. Sed hendrerit ipsum quis nisl. Suspendisse quis massa ac nibh pretium cursus. Sed sodales. Nam eu neque quis pede dignissim ornare. Maecenas eu purus ac urna tincidunt congue. Donec et nisl id sapien blandit mattis. Aenean dictum odio sit amet risus. Morbi purus. Nulla a est sit amet purus venenatis iaculis. Vivamus viverra purus vel magna. Donec in justo sed odio malesuada dapibus. Nunc ultrices aliquam nunc. Vivamus facilisis pellentesque velit. Nulla nunc velit, vulputate dapibus, vulputate id, mattis ac, justo. Nam mattis elit dapibus purus. Quisque enim risus, congue non, elementum ut, mattis quis, sem. Quisque elit. Maecenas non massa. Vestibulum pharetra nulla at lorem. Duis quis quam id lacus dapibus interdum. Nulla lorem. Donec ut ante quis dolor bibendum condimentum. Etiam egestas tortor vitae lacus. Praesent cursus. Mauris bibendum pede at elit. Morbi et felis a lectus interdum facilisis. Sed suscipit gravida turpis. Nulla at lectus. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Praesent nonummy luctus nibh. Proin turpis nunc, congue eu, egestas ut, fringilla at, tellus. In hac habitasse platea dictumst. Vivamus eu tellus sed tellus consequat suscipit. Nam orci orci, malesuada id, gravida nec, ultricies vitae, erat. Donec risus turpis, luctus sit amet, interdum quis, porta sed, ipsum. Suspendisse condimentum, tortor at egestas posuere, neque metus tempor orci,

et tincidunt urna nunc a purus. Sed facilisis blandit tellus. Nunc risus sem, suscipit nec, eleifend quis, cursus quis, libero. Curabitur et dolor. Sed vitae sem. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Maecenas ante. Duis ullamcorper enim. Donec tristique enim eu leo. Nullam molestie elit eu dolor. Nullam bibendum, turpis vitae tristique gravida, quam sapien tempor lectus, quis pretium tellus purus ac quam. Nulla facilisi.

4.5. CONTENT WITH NATBIB CITATIONS

This had been discussed previously by [?] and ?]. Etiam suscipit aliquam arcu. Aliquam sit amet est ac purus bibendum congue. Sed in eros. Morbi non orci. Pellentesque mattis lacinia elit. Fusce molestie velit in ligula. Nullam et orci vitae nibh vulputate auctor. Aliquam eget purus. Nulla auctor wisi sed ipsum. Morbi porttitor tellus ac enim. Fusce ornare. Proin ipsum enim, tincidunt in, ornare venenatis, molestie a, augue. Donec vel pede in lacus sagittis porta. Sed hendrerit ipsum quis nisl. Suspendisse quis massa ac nibh pretium cursus. Sed sodales. Nam eu neque quis pede dignissim ornare. Maecenas eu purus ac urna tincidunt congue. Donec et nisl id sapien blandit mattis. Aenean dictum odio sit amet risus. Morbi purus. Nulla a est sit amet purus venenatis iaculis. Vivamus viverra purus vel magna. Donec in justo sed odio malesuada dapibus. Nunc ultrices aliquam nunc. Vivamus facilisis pellentesque velit. Nulla nunc velit, vulputate dapibus, vulputate id, mattis ac, justo. Nam mattis elit dapibus purus. Quisque enim risus, congue non, elementum ut, mattis quis, sem. Quisque elit. Maecenas non massa. Vestibulum pharetra nulla at lorem. Duis quis quam id lacus dapibus interdum. Nulla lorem. Donec ut ante quis dolor bibendum condimentum. Etiam egestas tortor vitae lacus. Praesent cursus. Mauris bibendum pede at elit. Morbi et felis a lectus interdum facilisis. Sed suscipit gravida turpis. Nulla at lectus. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Praesent nonummy luctus nibh. Proin turpis nunc, congue eu, egestas ut, fringilla at, tellus. In hac habitasse platea dictumst. Vivamus eu tellus sed tellus consequat

suscipit. Nam orci orci, malesuada id, gravida nec, ultricies vitae, erat. Donec risus turpis, luctus sit amet, interdum quis, porta sed, ipsum. Suspendisse condimentum, tortor at egestas posuere, neque metus tempor orci, et tincidunt urna nunc a purus. Sed facilis blandit tellus. Nunc risus sem, suscipit nec, eleifend quis, cursus quis, libero. Curabitur et dolor. Sed vitae sem. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Maecenas ante. Duis ullamcorper enim. Donec tristique enim eu leo. Nullam molestie elit eu dolor. Nullam bibendum, turpis vitae tristique gravida, quam sapien tempor lectus, quis pretium tellus purus ac quam. Nulla facilisi.

4.6. CONTENT WITH NOMENCL ENTRIES

Finally, we add a simple equation to illustrate the use of the nomencl package for automatic generation of a list of symbols.

$$\delta_i = \sqrt{t/\text{Pe}} \quad (4.1)$$

where δ is the layer thickness as defined previously. Duis aliquet dui in est. Donec eget est. Nunc lectus odio, varius at, fermentum in, accumsan non, enim. Aliquam erat volutpat. Proin sit amet nulla ut eros consectetur cursus. Phasellus dapibus aliquam justo. Nunc laoreet. Donec consequat placerat magna. Duis pretium tincidunt justo. Sed sollicitudin vestibulum quam. Nam quis ligula. Vivamus at metus. Etiam imperdiet imperdiet pede. Aenean turpis. Fusce augue velit, scelerisque sollicitudin, dictum vitae, tempor et, pede. Donec wisi sapien, feugiat in, fermentum ut, sollicitudin adipiscing, metus. Donec vel nibh ut felis consectetur laoreet. Donec pede. Sed id quam id wisi laoreet suscipit. Nulla lectus dolor, aliquam ac, fringilla eget, mollis ut, orci. In pellentesque justo in ligula. Maecenas turpis. Donec eleifend leo at felis tincidunt consequat. Aenean turpis metus, malesuada sed, condimentum sit amet, auctor a, wisi. Pellentesque sapien elit, bibendum ac, posuere et, congue eu, felis. Vestibulum mattis libero quis metus scelerisque ultrices.

Sed purus. Donec molestie, magna ut luctus ultrices, tellus arcu nonummy velit, sit amet pulvinar elit justo et mauris. In pede. Maecenas euismod elit eu erat. Aliquam augue wisi, facilisis congue, suscipit in, adipiscing et, ante. In justo. Cras lobortis neque ac ipsum. Nunc fermentum massa at ante. Donec orci tortor, egestas sit amet, ultrices eget, venenatis eget, mi. Maecenas vehicula leo semper est. Mauris vel metus. Aliquam erat volutpat. In rhoncus sapien ac tellus. Pellentesque ligula. Cras dapibus, augue quis scelerisque ultricies, felis dolor placerat sem, id porta velit odio eu elit. Aenean interdum nibh sed wisi. Praesent sollicitudin vulputate dui. Praesent iaculis viverra augue. Quisque in libero. Aenean gravida lorem vitae sem ullamcorper cursus. Nunc adipiscing rutrum ante. Nunc ipsum massa, faucibus sit amet, viverra vel, elementum semper, orci. Cras eros sem, vulputate et, tincidunt id, ultrices eget, magna. Nulla varius ornare odio. Donec accumsan mauris sit amet augue. Sed ligula lacus, laoreet non, aliquam sit amet, iaculis tempor, lorem. Suspendisse eros. Nam porta, leo sed congue tempor, felis est ultrices eros, id mattis velit felis non metus. Curabitur vitae elit non mauris varius pretium. Aenean lacus sem, tincidunt ut, consequat quis, porta vitae, turpis. Nullam laoreet fermentum urna. Proin iaculis lectus. Sed mattis, erat sit amet gravida malesuada, elit augue egestas diam, tempus scelerisque nunc nisl vitae libero. Sed consequat feugiat massa. Nunc porta, eros in eleifend varius, erat leo rutrum dui, non convallis lectus orci ut nibh. Sed lorem massa, nonummy quis, egestas id, condimentum at, nisl. Maecenas at nibh. Aliquam et augue at nunc pellentesque ullamcorper. Duis nisl nibh, laoreet suscipit, convallis ut, rutrum id, enim. Phasellus odio. Nulla nulla elit, molestie non, scelerisque at, vestibulum eu, nulla. Ut odio nisl, facilisis id, mollis et, scelerisque nec, enim. Aenean sem leo, pellentesque sit amet, scelerisque sit amet, vehicula pellentesque, sapien.

5. RESEARCH SCHEDULE

Suspendisse vel felis. Ut lorem lorem, interdum eu, tincidunt sit amet, laoreet vitae, arcu. Aenean faucibus pede eu ante. Praesent enim elit, rutrum at, molestie non, nonummy vel, nisl. Ut lectus eros, malesuada sit amet, fermentum eu, sodales cursus, magna. Donec eu purus. Quisque vehicula, urna sed ultricies auctor, pede lorem egestas dui, et convallis elit erat sed nulla. Donec luctus. Curabitur et nunc. Aliquam dolor odio, commodo pretium, ultricies non, pharetra in, velit. Integer arcu est, nonummy in, fermentum faucibus, egestas vel, odio.

5.1. INTRODUCTION

Sed commodo posuere pede. Mauris ut est. Ut quis purus. Sed ac odio. Sed vehicula hendrerit sem. Duis non odio. Morbi ut dui. Sed accumsan risus eget odio. In hac habitasse platea dictumst. Pellentesque non elit. Fusce sed justo eu urna porta tincidunt. Mauris felis odio, sollicitudin sed, volutpat a, ornare ac, erat. Morbi quis dolor. Donec pellentesque, erat ac sagittis semper, nunc dui lobortis purus, quis congue purus metus ultricies tellus. Proin et quam. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Praesent sapien turpis, fermentum vel, eleifend faucibus, vehicula eu, lacus. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Donec odio elit, dictum in, hendrerit sit amet, egestas sed, leo. Praesent feugiat sapien aliquet odio. Integer vitae justo. Aliquam vestibulum fringilla lorem. Sed neque lectus, consectetur at, consectetur sed, eleifend ac, lectus. Nulla facilisi. Pellentesque eget lectus. Proin eu metus. Sed porttitor. In hac habitasse platea dictumst. Suspendisse eu lectus. Ut mi mi, lacinia sit amet, placerat et, mollis vitae, dui. Sed ante tellus, tristique ut, iaculis eu, malesuada ac, dui. Mauris nibh leo, facilisis non, adipiscing quis, ultrices a, dui. Morbi luctus, wisi viverra faucibus pretium, nibh est placerat

odio, nec commodo wisi enim eget quam. Quisque libero justo, consectetur a, feugiat vitae, porttitor eu, libero. Suspendisse sed mauris vitae elit sollicitudin malesuada. Maecenas ultricies eros sit amet ante. Ut venenatis velit. Maecenas sed mi eget dui varius euismod. Phasellus aliquet volutpat odio. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Pellentesque sit amet pede ac sem eleifend consectetur. Nullam elementum, urna vel imperdiet sodales, elit ipsum pharetra ligula, ac pretium ante justo a nulla. Curabitur tristique arcu eu metus. Vestibulum lectus. Proin mauris. Proin eu nunc eu urna hendrerit faucibus. Aliquam auctor, pede consequat laoreet varius, eros tellus scelerisque quam, pellentesque hendrerit ipsum dolor sed augue. Nulla nec lacus.

5.1.1. A Third-Level Heading. Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetur odio sem sed wisi.

5.1.1.1. A fourth-level heading with a very long and complicated title to once again verify the formatting. Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetur odio sem sed wisi. Sed feugiat. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Ut pellentesque augue sed urna. Vestibulum diam eros, fringilla et, consectetur eu, nonummy id, sapien. Nullam at lectus. In sagittis ultrices mauris. Curabitur malesuada erat sit amet massa. Fusce

blandit. Aliquam erat volutpat. Aliquam euismod. Aenean vel lectus. Nunc imperdiet justo nec dolor. Etiam euismod. Fusce facilisis lacinia dui. Suspendisse potenti. In mi erat, cursus id, nonummy sed, ullamcorper eget, sapien. Praesent pretium, magna in eleifend egestas, pede pede pretium lorem, quis consectetur tortor sapien facilisis magna. Mauris quis magna varius nulla scelerisque imperdiet. Aliquam non quam. Aliquam porttitor quam a lacus. Praesent vel arcu ut tortor cursus volutpat. In vitae pede quis diam bibendum placerat. Fusce elementum convallis neque. Sed dolor orci, scelerisque ac, dapibus nec, ultricies ut, mi. Duis nec dui quis leo sagittis commodo.

5.1.1.2. Another fourth-level heading. Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetur odio sem sed wisi. Sed feugiat. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Ut pellentesque augue sed urna. Vestibulum diam eros, fringilla et, consectetur eu, nonummy id, sapien. Nullam at lectus. In sagittis ultrices mauris. Curabitur malesuada erat sit amet massa. Fusce blandit. Aliquam erat volutpat. Aliquam euismod. Aenean vel lectus. Nunc imperdiet justo nec dolor. Etiam euismod. Fusce facilisis lacinia dui. Suspendisse potenti. In mi erat, cursus id, nonummy sed, ullamcorper eget, sapien. Praesent pretium, magna in eleifend egestas, pede pede pretium lorem, quis consectetur tortor sapien facilisis magna. Mauris quis magna varius nulla scelerisque imperdiet. Aliquam non quam. Aliquam porttitor quam a lacus. Praesent vel arcu ut tortor cursus volutpat. In vitae pede quis diam bibendum placerat. Fusce elementum convallis neque. Sed dolor orci, scelerisque ac, dapibus nec, ultricies ut, mi. Duis nec dui quis leo sagittis commodo.

A fifth-level heading also with a very long and complicated title to verify the formatting. Nulla ac nisl. Nullam urna nulla, ullamcorper in, interdum sit amet, gravida ut, risus. Aenean ac enim. In luctus. Phasellus eu quam vitae turpis viverra pellentesque. Duis feugiat felis ut enim. Phasellus pharetra, sem id porttitor sodales, magna nunc aliquet nibh, nec blandit nisl mauris at pede. Suspendisse risus risus, lobortis eget, semper at, imperdiet sit amet, quam. Quisque scelerisque dapibus nibh. Nam enim. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Nunc ut metus. Ut metus justo, auctor at, ultrices eu, sagittis ut, purus. Aliquam aliquam.

Another fifth-level heading. Etiam pede massa, dapibus vitae, rhoncus in, placerat posuere, odio. Vestibulum luctus commodo lacus. Morbi lacus dui, tempor sed, euismod eget, condimentum at, tortor. Phasellus aliquet odio ac lacus tempor faucibus. Praesent sed sem. Praesent iaculis. Cras rhoncus tellus sed justo ullamcorper sagittis. Donec quis orci. Sed ut tortor quis tellus euismod tincidunt. Suspendisse congue nisl eu elit. Aliquam tortor diam, tempus id, tristique eget, sodales vel, nulla. Praesent tellus mi, condimentum sed, viverra at, consectetur quis, lectus. In auctor vehicula orci. Sed pede sapien, euismod in, suscipit in, pharetra placerat, metus. Vivamus commodo dui non odio. Donec et felis.

5.1.2. Another third-level heading but with a very long and complicated title to verify the formatting. Aliquam lectus. Vivamus leo. Quisque ornare tellus ullamcorper nulla. Mauris porttitor pharetra tortor. Sed fringilla justo sed mauris. Mauris tellus. Sed non leo. Nullam elementum, magna in cursus sodales, augue est scelerisque sapien, venenatis congue nulla arcu et pede. Ut suscipit enim vel sapien. Donec congue. Maecenas urna mi, suscipit in, placerat ut, vestibulum ut, massa. Fusce ultrices nulla et nisl. Etiam ac leo a risus tristique nonummy. Donec dignissim tincidunt nulla. Vestibulum rhoncus molestie odio. Sed lobortis, justo et pretium lobortis, mauris turpis condimentum augue, nec ultricies nibh arcu pretium enim. Nunc purus neque, placerat id, imperdiet sed, pellentesque nec, nisl. Vestibulum imperdiet neque non sem accumsan laoreet. In hac habitasse platea dictumst. Etiam condimentum facilisis libero. Suspendisse in elit quis nisl aliquam dapibus.

Pellentesque auctor sapien. Sed egestas sapien nec lectus. Pellentesque vel dui vel neque bibendum viverra. Aliquam porttitor nisl nec pede. Proin mattis libero vel turpis. Donec rutrum mauris et libero. Proin euismod porta felis. Nam lobortis, metus quis elementum commodo, nunc lectus elementum mauris, eget vulputate ligula tellus eu neque. Vivamus eu dolor. Nulla in ipsum. Praesent eros nulla, congue vitae, euismod ut, commodo a, wisi. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Aenean nonummy magna non leo. Sed felis erat, ullamcorper in, dictum non, ultricies ut, lectus. Proin vel arcu a odio lobortis euismod. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Proin ut est. Aliquam odio. Pellentesque massa turpis, cursus eu, euismod nec, tempor congue, nulla. Duis viverra gravida mauris. Cras tincidunt. Curabitur eros ligula, varius ut, pulvinar in, cursus faucibus, augue.

5.2. DISCUSSION USING A SECOND-LEVEL HEADING WHICH IS REALLY LONG SO THAT IT PRODUCES A TWO-LINE TOC ENTRY

Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetur odio sem sed wisi. Sed feugiat. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Ut pellentesque augue sed urna. Vestibulum diam eros, fringilla et, consectetur eu, nonummy id, sapien. Nullam at lectus. In sagittis ultrices mauris. Curabitur malesuada erat sit amet massa. Fusce blandit. Aliquam erat volutpat. Aliquam euismod. Aenean vel lectus. Nunc imperdiet justo nec dolor. Etiam euismod. Fusce facilisis lacinia dui. Suspendisse potenti. In mi erat, cursus id, nonummy sed, ullamcorper eget, sapien. Praesent pretium, magna in eleifend egestas, pede pede

pretium lorem, quis consectetur tortor sapien facilisis magna. Mauris quis magna varius nulla scelerisque imperdiet. Aliquam non quam. Aliquam porttitor quam a lacus. Praesent vel arcu ut tortor cursus volutpat. In vitae pede quis diam bibendum placerat. Fusce elementum convallis neque. Sed dolor orci, scelerisque ac, dapibus nec, ultricies ut, mi. Duis nec dui quis leo sagittis commodo.

5.3. CONTENT WITH FIGURES

Suspendisse vitae elit. Aliquam arcu neque, ornare in, ullamcorper quis, commodo eu, libero. Fusce sagittis erat at erat tristique mollis. Maecenas sapien libero, molestie et, lobortis in, sodales eget, dui. Morbi ultrices rutrum lorem. Nam elementum ullamcorper leo. Morbi dui. Aliquam sagittis. Nunc placerat. Pellentesque tristique sodales est. Maecenas imperdiet lacinia velit. Cras non urna. Morbi eros pede, suscipit ac, varius vel, egestas non, eros. Praesent malesuada, diam id pretium elementum, eros sem dictum tortor, vel consectetur odio sem sed wisi.

5.3.1. Floats with Figures. Etiam euismod. Fusce facilisis lacinia dui. Suspendisse potenti. In mi erat, cursus id, nonummy sed, ullamcorper eget, sapien. Praesent pretium, magna in eleifend egestas, pede pede pretium lorem, quis consectetur tortor sapien facilisis magna. Mauris quis magna varius nulla scelerisque imperdiet. Aliquam non quam. Aliquam porttitor quam a lacus. Praesent vel arcu ut tortor cursus volutpat. In vitae pede quis diam bibendum placerat. Fusce elementum convallis neque. Sed dolor orci, scelerisque ac, dapibus nec, ultricies ut, mi. Duis nec dui quis leo sagittis commodo. Aliquam lectus. Vivamus leo. Quisque ornare tellus ullamcorper nulla. Mauris porttitor pharetra tortor. Sed fringilla justo sed mauris. Mauris tellus. Sed non leo. Nullam elementum, magna in cursus sodales, augue est scelerisque sapien, venenatis congue nulla arcu et pede. Ut suscipit enim vel sapien. Donec congue. Maecenas urna mi, suscipit in, placerat ut, vestibulum ut, massa. Fusce ultrices nulla et nisl.

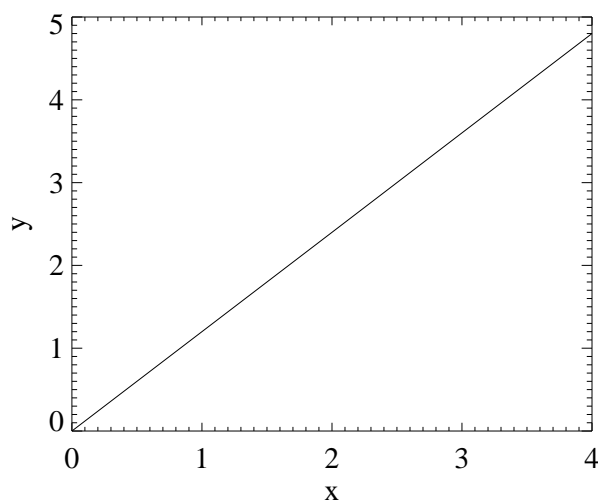


Figure 5.1. The caption of the figure.

5.3.1.1. Simple figure with label. Sed feugiat. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Ut pellentesque augue sed urna. Vestibulum diam eros, fringilla et, consectetur eu, nonummy id, sapien. Nullam at lectus. In sagittis ultrices mauris. Curabitur malesuada erat sit amet massa. Fusce blandit. Aliquam erat volutpat. Aliquam euismod. Aenean vel lectus. Nunc imperdiet justo nec dolor.

Add a simple figure, Figure ??, to illustrate an entry in the list of figures. Etiam euismod. Fusce facilisis lacinia dui. Suspendisse potenti. In mi erat, cursus id, nonummy sed, ullamcorper eget, sapien. Praesent pretium, magna in eleifend egestas, pede pede pretium lorem, quis consectetur tortor sapien facilisis magna. Mauris quis magna varius nulla scelerisque imperdiet. Aliquam non quam. Aliquam porttitor quam a lacus. Praesent vel arcu ut tortor cursus volutpat. In vitae pede quis diam bibendum placerat. Fusce elementum convallis neque. Sed dolor orci, scelerisque ac, dapibus nec, ultricies ut, mi. Duis nec dui quis leo sagittis commodo.

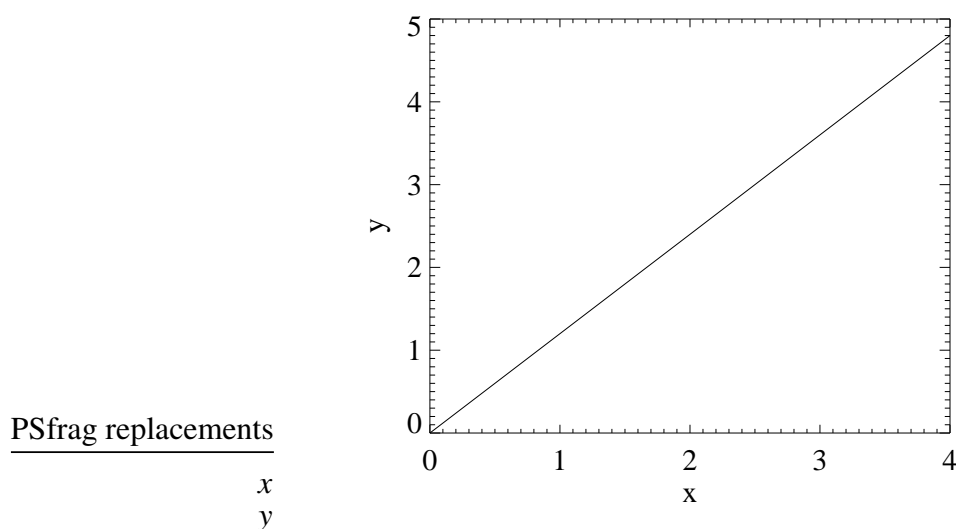


Figure 5.2. A figure caption which is extra long. This long caption not only demonstrates that the required spacing in the list of figures is correct, but also the general practice of making the list of figures (or tables) entry the first sentence of the caption.

5.3.1.2. Figure with psfrag replacement. Aliquam lectus. Vivamus leo. Quisque ornare tellus ullamcorper nulla. Mauris porttitor pharetra tortor. Sed fringilla justo sed mauris. Mauris tellus. Sed non leo. Nullam elementum, magna in cursus sodales, augue est scelerisque sapien, venenatis congue nulla arcu et pede. Ut suscipit enim vel sapien. Donec congue. Maecenas urna mi, suscipit in, placerat ut, vestibulum ut, massa. Fusce ultrices nulla et nisl.. Figure 5.2 illustrates the use of the psfrag package to place \LaTeX math in a graphic. Etiam ac leo a risus tristique nonummy. Donec dignissim tincidunt nulla. Vestibulum rhoncus molestie odio. Sed lobortis, justo et pretium lobortis, mauris turpis condimentum augue, nec ultricies nibh arcu pretium enim. Nunc purus neque, placerat id, imperdiet sed, pellentesque nec, nisl. Vestibulum imperdiet neque non sem accumsan laoreet. In hac habitasse platea dictumst. Etiam condimentum facilisis libero. Suspendisse in elit quis nisl aliquam dapibus. Pellentesque auctor sapien. Sed egestas sapien nec lectus. Pellentesque vel dui vel neque bibendum viverra. Aliquam porttitor nisl nec pede. Proin mattis libero vel turpis. Donec rutrum mauris et libero. Proin euismod porta felis. Nam

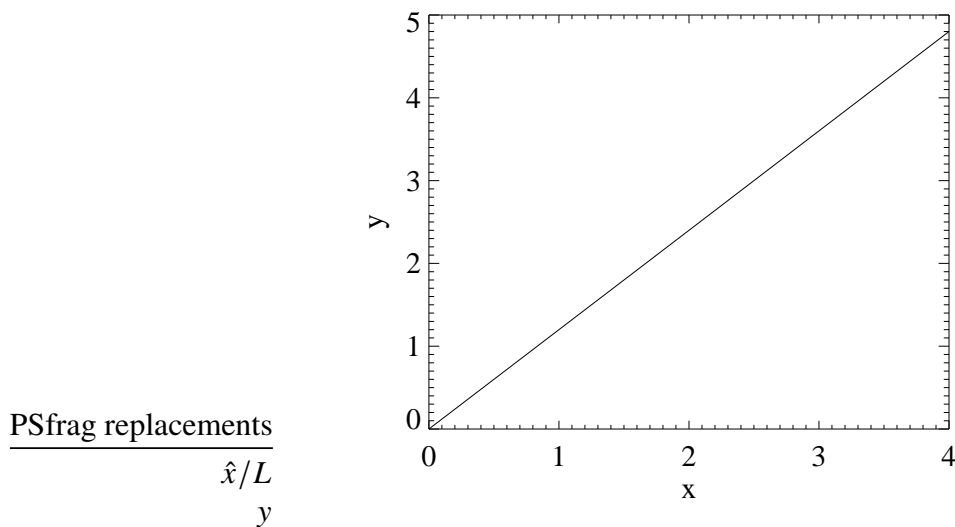


Figure 5.3. The figure caption made extra long so that the required spacing in the list of figures is evident.

lobortis, metus quis elementum commodo, nunc lectus elementum mauris, eget vulputate ligula tellus eu neque. Vivamus eu dolor.. The filler content is followed by a second figure, Figure 5.3. Nulla in ipsum. Praesent eros nulla, congue vitae, euismod ut, commodo a, wisi. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Aenean nonummy magna non leo. Sed felis erat, ullamcorper in, dictum non, ultricies ut, lectus. Proin vel arcu a odio lobortis euismod. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Proin ut est. Aliquam odio. Pellentesque massa turpis, cursus eu, euismod nec, tempor congue, nulla. Duis viverra gravida mauris. Cras tincidunt. Curabitur eros ligula, varius ut, pulvinar in, cursus faucibus, augue.

5.3.2. A Bit More Discussion. Nulla mattis luctus nulla. Duis commodo velit at leo. Aliquam vulputate magna et leo. Nam vestibulum ullamcorper leo. Vestibulum condimentum rutrum mauris. Donec id mauris. Morbi molestie justo et pede. Vivamus eget turpis sed nisl cursus tempor. Curabitur mollis sapien condimentum nunc. In wisi nisl, malesuada at, dignissim sit amet, lobortis in, odio. Aenean consequat arcu a ante.

Pellentesque porta elit sit amet orci. Etiam at turpis nec elit ultricies imperdiet. Nulla facilisi. In hac habitasse platea dictumst. Suspendisse viverra aliquam risus. Nullam pede justo, molestie nonummy, scelerisque eu, facilisis vel, arcu. Curabitur tellus magna, porttitor a, commodo a, commodo in, tortor. Donec interdum. Praesent scelerisque. Maecenas posuere sodales odio. Vivamus metus lacus, varius quis, imperdiet quis, rhoncus a, turpis. Etiam ligula arcu, elementum a, venenatis quis, sollicitudin sed, metus. Donec nunc pede, tincidunt in, venenatis vitae, faucibus vel, nibh. Pellentesque wisi. Nullam malesuada. Morbi ut tellus ut pede tincidunt porta. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Etiam congue neque id dolor. Donec et nisl at wisi luctus bibendum. Nam interdum tellus ac libero. Sed sem justo, laoreet vitae, fringilla at, adipiscing ut, nibh. Maecenas non sem quis tortor eleifend fermentum. Etiam id tortor ac mauris porta vulputate. Integer porta neque vitae massa. Maecenas tempus libero a libero posuere dictum. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Aenean quis mauris sed elit commodo placerat. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Vivamus rhoncus tincidunt libero. Etiam elementum pretium justo. Vivamus est. Morbi a tellus eget pede tristique commodo. Nulla nisl. Vestibulum sed nisl eu sapien cursus rutrum. Nulla non mauris vitae wisi posuere convallis. Sed eu nulla nec eros scelerisque pharetra. Nullam varius. Etiam dignissim elementum metus. Vestibulum faucibus, metus sit amet mattis rhoncus, sapien dui laoreet odio, nec ultricies nibh augue a enim. Fusce in ligula. Quisque at magna et nulla commodo consequat. Proin accumsan imperdiet sem. Nunc porta. Donec feugiat mi at justo. Phasellus facilisis ipsum quis ante. In ac elit eget ipsum pharetra faucibus. Maecenas viverra nulla in massa.

5.4. CONTENT WITH SAMPLE TABLES

5.4.1. Floats with Tables. Nulla mattis luctus nulla. Duis commodo velit at leo. Aliquam vulputate magna et leo. Nam vestibulum ullamcorper leo. Vestibulum condimentum rutrum mauris. Donec id mauris. Morbi molestie justo et pede. Vivamus eget turpis

Table 5.1. The capitalization of the table should match that of figures.

Example	Time	Cost
1	12.5	\$1,000
2	24	\$2,000

sed nisl cursus tempor. Curabitur mollis sapien condimentum nunc. In wisi nisl, malesuada at, dignissim sit amet, lobortis in, odio. Aenean consequat arcu a ante. Pellentesque porta elit sit amet orci. Etiam at turpis nec elit ultricies imperdiet. Nulla facilisi. In hac habitasse platea dictumst. Suspendisse viverra aliquam risus. Nullam pede justo, molestie nonummy, scelerisque eu, facilisis vel, arcu.

5.4.1.1. Simple Table. Finally the tables, Table 5.1 illustrates the syntax of a basic table. Nulla mattis luctus nulla. Duis commodo velit at leo. Aliquam vulputate magna et leo. Nam vestibulum ullamcorper leo. Vestibulum condimentum rutrum mauris. Donec id mauris. Morbi molestie justo et pede. Vivamus eget turpis sed nisl cursus tempor. Curabitur mollis sapien condimentum nunc. In wisi nisl, malesuada at, dignissim sit amet, lobortis in, odio. Aenean consequat arcu a ante. Pellentesque porta elit sit amet orci. Etiam at turpis nec elit ultricies imperdiet. Nulla facilisi. In hac habitasse platea dictumst. Suspendisse viverra aliquam risus. Nullam pede justo, molestie nonummy, scelerisque eu, facilisis vel, arcu. Curabitur tellus magna, porttitor a, commodo a, commodo in, tortor. Donec interdum. Praesent scelerisque. Maecenas posuere sodales odio. Vivamus metus lacus, varius quis, imperdiet quis, rhoncus a, turpis. Etiam ligula arcu, elementum a, venenatis quis, sollicitudin sed, metus. Donec nunc pede, tincidunt in, venenatis vitae, faucibus vel, nibh. Pellentesque wisi. Nullam malesuada. Morbi ut tellus ut pede tincidunt porta. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Etiam congue neque id dolor. Donec et nisl at wisi luctus bibendum. Nam interdum tellus ac libero. Sed sem justo, laoreet vitae, fringilla at, adipiscing ut, nibh. Maecenas non sem quis tortor eleifend fermentum. Etiam id

Table 5.2. The caption of the three-part table.

Example	Time ¹	Cost
1	12.5	\$1,000
2	24	\$2,000

¹ The first note.

tortor ac mauris porta vulputate. Integer porta neque vitae massa. Maecenas tempus libero a libero posuere dictum. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Aenean quis mauris sed elit commodo placerat. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos hymenaeos. Vivamus rhoncus tincidunt libero. Etiam elementum pretium justo. Vivamus est. Morbi a tellus eget pede tristique commodo. Nulla nisl. Vestibulum sed nisl eu sapien cursus rutrum.

5.4.1.2. Three-Part Table Example. Table 5.2, which illustrates the syntax of a three-part table which includes table notes in addition to a caption and table body. Nulla non mauris vitae wisi posuere convallis. Sed eu nulla nec eros scelerisque pharetra. Nullam varius. Etiam dignissim elementum metus. Vestibulum faucibus, metus sit amet mattis rhoncus, sapien dui laoreet odio, nec ultricies nibh augue a enim. Fusce in ligula. Quisque at magna et nulla commodo consequat. Proin accumsan imperdiet sem. Nunc porta. Donec feugiat mi at justo. Phasellus facilisis ipsum quis ante. In ac elit eget ipsum pharetra faucibus. Maecenas viverra nulla in massa. Nulla ac nisl. Nullam urna nulla, ullamcorper in, interdum sit amet, gravida ut, risus. Aenean ac enim. In luctus. Phasellus eu quam vitae turpis viverra pellentesque. Duis feugiat felis ut enim. Phasellus pharetra, sem id porttitor sodales, magna nunc aliquet nibh, nec blandit nisl mauris at pede. Suspendisse risus risus, lobortis eget, semper at, imperdiet sit amet, quam. Quisque scelerisque dapibus nibh. Nam enim. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Nunc ut metus. Ut metus justo, auctor at, ultrices eu, sagittis ut, purus. Aliquam aliquam. Etiam pede massa, dapibus vitae, rhoncus in, placerat posuere, odio. Vestibulum luctus commodo lacus. Morbi lacus dui, tempor sed, euismod eget, condimentum at, tortor. Phasellus aliquet

odio ac lacus tempor faucibus. Praesent sed sem. Praesent iaculis. Cras rhoncus tellus sed justo ullamcorper sagittis. Donec quis orci. Sed ut tortor quis tellus euismod tincidunt. Suspendisse congue nisl eu elit. Aliquam tortor diam, tempus id, tristique eget, sodales vel, nulla. Praesent tellus mi, condimentum sed, viverra at, consectetur quis, lectus. In auctor vehicula orci. Sed pede sapien, euismod in, suscipit in, pharetra placerat, metus. Vivamus commodo dui non odio. Donec et felis.

5.4.2. One More Thing. Etiam suscipit aliquam arcu. Aliquam sit amet est ac purus bibendum congue. Sed in eros. Morbi non orci. Pellentesque mattis lacinia elit. Fusce molestie velit in ligula. Nullam et orci vitae nibh vulputate auctor. Aliquam eget purus. Nulla auctor wisi sed ipsum. Morbi porttitor tellus ac enim. Fusce ornare. Proin ipsum enim, tincidunt in, ornare venenatis, molestie a, augue. Donec vel pede in lacus sagittis porta. Sed hendrerit ipsum quis nisl. Suspendisse quis massa ac nibh pretium cursus. Sed sodales. Nam eu neque quis pede dignissim ornare. Maecenas eu purus ac urna tincidunt congue. Donec et nisl id sapien blandit mattis. Aenean dictum odio sit amet risus. Morbi purus. Nulla a est sit amet purus venenatis iaculis. Vivamus viverra purus vel magna. Donec in justo sed odio malesuada dapibus. Nunc ultrices aliquam nunc. Vivamus facilisis pellentesque velit. Nulla nunc velit, vulputate dapibus, vulputate id, mattis ac, justo. Nam mattis elit dapibus purus. Quisque enim risus, congue non, elementum ut, mattis quis, sem. Quisque elit. Maecenas non massa. Vestibulum pharetra nulla at lorem. Duis quis quam id lacus dapibus interdum. Nulla lorem. Donec ut ante quis dolor bibendum condimentum. Etiam egestas tortor vitae lacus. Praesent cursus. Mauris bibendum pede at elit. Morbi et felis a lectus interdum facilisis. Sed suscipit gravida turpis. Nulla at lectus. Vestibulum ante ipsum primis in faucibus orci luctus et ultrices posuere cubilia Curae; Praesent nonummy luctus nibh. Proin turpis nunc, congue eu, egestas ut, fringilla at, tellus. In hac habitasse platea dictumst. Vivamus eu tellus sed tellus consequat suscipit. Nam orci orci, malesuada id, gravida nec, ultricies vitae, erat. Donec risus turpis, luctus sit amet, interdum quis, porta sed, ipsum. Suspendisse condimentum, tortor at egestas posuere, neque metus tempor orci,

et tincidunt urna nunc a purus. Sed facilisis blandit tellus. Nunc risus sem, suscipit nec, eleifend quis, cursus quis, libero. Curabitur et dolor. Sed vitae sem. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Maecenas ante. Duis ullamcorper enim. Donec tristique enim eu leo. Nullam molestie elit eu dolor. Nullam bibendum, turpis vitae tristique gravida, quam sapien tempor lectus, quis pretium tellus purus ac quam. Nulla facilisi.

5.5. CONTENT WITH NATBIB CITATIONS

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5.6. CONTENT WITH NOMENCL ENTRIES

Finally, we add a simple equation to illustrate the use of the nomencl package for automatic generation of a list of symbols.

$$\delta_i = \sqrt{t/\text{Pe}} \quad (5.1)$$

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6. CONCLUSIONS

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6.1. INTRODUCTION

6.1.0.1. Mass Balance. The conservation of mass simply states that mass entering (m_0) the shockwave must equal the mass leaving (m_1) the shockwave.

$$m_0 = m_1 \quad (6.1)$$

We know from the definition of density (ρ) that,

$$\rho = \frac{m}{V} \quad (6.2)$$

where m is the mass and V is the volume. We can then substitute 6.2 into 6.1 to get,

$$\rho_0 V_0 = \rho_1 V_1 \quad (6.3)$$

We can see from Figure 2.3 that the volumes of the cylinder in front of and behind the shock are given by,

$$V = AL \quad (6.4)$$

where A is the cross sectional area of the cylinder and L is the length of the cylinder. We are going to assume the cross sectional areas in front of and behind the shock are a constant. The length of the cylinder is defined as the distance a particle travels away from the shock relative to the shock speed in time t . Therefore the relative particle speed is given by,

$$u_{rel} = U - u \quad (6.5)$$

where U is the absolute shock speed and u is the absolute particle speed. Then our length L is,

$$L = u_{rel}t \quad (6.6)$$

or substituting 6.5 into 6.6

$$L = (U - u)t \quad (6.7)$$

Now substituting 6.4 and 6.7 into 6.3 we have,

$$\rho_0 A (U - u_0) t = \rho_1 A (U - u_1) t \quad (6.8)$$

and simplifying we have conservation of mass across the shockwave,

$$\rho_0 (U - u_0) = \rho_1 (U - u_1) \quad (6.9)$$

6.1.0.2. Momentum Balance. The conservation of momentum implies that the momentum in front of the shock must equal the momentum after the shock. The basic equation for momentum is given by,

$$p = mu \quad (6.10)$$

where m is the mass and u is the velocity of the mass. We know from Newton's second law of motion that force, F , is the product of the mass and acceleration, a . Since acceleration is the change in velocity divided by time we can connect the concepts of momentum and

force with,

$$\Delta F = \frac{m(\Delta u)}{t} = \frac{(mu_1 - mu_0)}{t} = \frac{p_1 - p_0}{t} = \frac{\Delta p}{t} \quad (6.11)$$

or the change in force is equal to the rate of change in momentum. From 6.8 we can substitute for the mass with $m = \rho A(U - u)t$,

$$\Delta F = \frac{(\rho_1 A(U - u_1)tu_1 - \rho_0 A(U - u_0)tu_0)}{t} \quad (6.12)$$

Simplifying we have,

$$\frac{\Delta F}{A} = \rho_1 u_1 (U - u_1) - \rho_0 u_0 (U - u_0) \quad (6.13)$$

We know that the pressure is force divided the area therefore we can substitute $P = F/A$,

$$P_1 - P_0 = \rho_1 u_1 (U - u_1) - \rho_0 u_0 (U - u_0) \quad (6.14)$$

Using 6.9 and solving for ρ_1 and substituting into 6.14 we have,

$$\rho_1 = \rho_0 \frac{(U - u_0)}{(U - u_1)} \quad (6.15)$$

$$P_1 - P_0 = \rho_0 \frac{(U - u_0)}{(U - u_1)} u_1 (U - u_1) - \rho_0 u_0 (U - u_0) \quad (6.16)$$

$$P_1 - P_0 = \rho_0 u_1 U - \rho_0 u_1 u_0 - \rho_0 u_0 U + \rho_0 u_0^2 \quad (6.17)$$

$$P_1 - P_0 = \rho_0 (u_1 U - u_1 u_0 - u_0 U + u_0^2) \quad (6.18)$$

and from factoring we get the standard momentum equation,

$$P_1 - P_0 = \rho_0 (u_1 - u_0)(U - u_0) \quad (6.19)$$

6.1.0.3. Energy Balance. The First law of thermodynamics states the total energy of a system is the sum of the internal energy (E), kinetic energy (KE), and potential energy (PE) less any heat (Q) added to the system and any work (W) done by the system:

$$\Delta E + \Delta KE + \Delta PE = \Delta Q + \Delta W \quad (6.20)$$

If we assume there is no change in potential energy and no heat added to the system then 6.20 becomes,

$$\Delta E + \Delta KE = \Delta W \quad (6.21)$$

The internal energy, E , can be expressed as the mass m times the specific internal energy e ,

$$U = me = \rho ALe \quad (6.22)$$

where the density, ρ , multiplied by volume or area, A , times the length, L , can then replace the mass, m . The change in internal energy can then be rewritten as,

$$\Delta E = \rho_1 AL_1 e_1 - \rho_0 AL_0 e_0 \quad (6.23)$$

The general equation for kinetic energy is given by:

$$KE = \frac{1}{2}mu^2 \quad (6.24)$$

where m is the mass and u is the velocity. The change in kinetic energy is then,

$$\Delta KE = \frac{1}{2}m_1u_1^2 - \frac{1}{2}m_0u_0^2 \quad (6.25)$$

Substituting the mass, m , with the density multiplied by the area times length we have,

$$\Delta KE = \frac{1}{2}\rho_1 AL_1 u_1^2 - \frac{1}{2}\rho_0 AL_0 u_0^2 \quad (6.26)$$

The left-hand-side of 6.21 then becomes,

$$\rho_1 AL_1 e_1 - \rho_0 AL_0 e_0 + \frac{1}{2}\rho_1 AL_1 u_1^2 - \frac{1}{2}\rho_0 AL_0 u_0^2 = W \quad (6.27)$$

The rate of thermodynamic work done on or by a system is referred to as pressure-volume work and is defined as,

$$\frac{W}{t} = \frac{P_1 V_1 - P_0 V_0}{t} \quad (6.28)$$

The work volume divided by the time can be replaced with the area A multiplied by the velocity, $\frac{V}{t} = Au$. Substituting back into 6.28,

$$\frac{W}{t} = P_1 Au_1 - P_0 Au_0 \quad (6.29)$$

Therefore the rate of work done is equal to the rate of change of the internal and kinetic energy,

$$P_1 Au_1 - P_0 Au_0 = \frac{\rho_1 AL_1 e_1 - \rho_0 AL_0 e_0}{t} + \frac{\frac{1}{2}\rho_1 AL_1 u_1^2 - \frac{1}{2}\rho_0 AL_0 u_0^2}{t} \quad (6.30)$$

Dividing through by A we have,

$$P_1 u_1 - P_0 u_0 = \frac{\rho_1 L_1 e_1 - \rho_0 L_0 e_0}{t} + \frac{\frac{1}{2}\rho_1 L_1 u_1^2 - \frac{1}{2}\rho_0 L_0 u_0^2}{t} \quad (6.31)$$

Recalling 6.7 and substituting in 6.31 we have the time t canceling out,

$$P_1 u_1 - P_0 u_0 = \rho_1 (U - u_1) e_1 - \rho_0 (U - u_0) e_0 + \frac{1}{2}\rho_1 (U - u_1) u_1^2 - \frac{1}{2}\rho_0 (U - u_0) u_0^2 \quad (6.32)$$

Consolidating the $(U - u)$ terms and factoring out the ρ we can rewrite as,

$$P_1 u_1 - P_0 u_0 = \rho_1 (U - u_1) \left(e_1 + \frac{1}{2} u_1^2 \right) - \rho_0 (U - u_0) \left(e_0 + \frac{1}{2} u_0^2 \right) \quad (6.33)$$

Recalling from 6.9 the conservation of mass we can divide both sides by $\rho(U - u)$,

$$\frac{P_1 u_1 - P_0 u_0}{\rho_0 (U - u_0)} = \left(e_1 + \frac{1}{2} u_1^2 \right) - \left(e_0 + \frac{1}{2} u_0^2 \right) \quad (6.34)$$

Rearranging we have conservation of energy equation,

$$e_1 - e_0 = \frac{P_1 u_1 - P_0 u_0}{\rho_0 (U - u_0)} - \frac{1}{2} (u_1^2 - u_0^2) \quad (6.35)$$

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6.2. DISCUSSION USING A SECOND-LEVEL HEADING WHICH IS REALLY LONG SO THAT IT PRODUCES A TWO-LINE TOC ENTRY

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VITA

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