SURGE ANALYSIS AND THE WAVE PLAN METHOD

A Powerful, Accurate, and Stable Method for Water Hammer Studies

Srinivasa Lingireddy

Don J. Wood

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ISBN 978-1-7372753-0-5

Printed in the United States of America.

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To my beloved wife Anuradha, who left her fulfilling career and cozy suburban life to let me travel the world in pursuit of practical knowledge on water hammer problems. I am forever indebted to her for her unwavering support and sacrifices. To my children, who never protested moving to unfamiliar places at a young age, and for taking on the challenges of these transitions with stride. Thank you!

SL

To my children. I am forever grateful they chose to share and carry on my life's work.

DJW

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Foreword

It was more than 60 years ago as a Carnegie Mellon graduate student that I listened to my professor Dr. Thomas E. Stelson's lecture on the subject of pressure waves resulting from a valve closure. This was the inspiration for my doctoral thesis on pressure waves at junctions. From that time until now, my work, and that of my colleague Dr. Srinivasa Lingireddy, has been researching transients, developing analytical tools and making those tools ever more relevant and powerful as demanded by the industries of today.

The first analytical tools I developed were for NASA in the 1960s. As I envisioned the pressure waves transmitted through NASA's propellant systems, the analytical method that evolved was very natural and efficient, and this work on relatively simple systems provided the basis of what was later to be known as the Wave Plan Method.

The jump from simple systems to larger networks came soon after. I was involved in a bio-engineering project to determine the flow through capillaries during system shock. I was compelled to see if I could apply the effects of turbulent flow to these improvements in network modeling. This prompted the development of a Surge analysis tool based on the Wave Plan Method.

The Wave Plan Method is a simple, intuitive, and most importantly an accurate approach based on the principle that all pressure waves travel at sonic speeds, making it possible to predict when they will arrive at junctions and devices as they travel through pipes. This allows an analytical model to calculate the effects of the waves only at junctions and devices, with appropriate modifications for friction loss, as opposed to calculating their effects at multiple incremental points between junctions and devices. The simplicity of the method is really what makes the Wave Plan Method indispensable to the hydraulics industry. Large networks can be easily and efficiently analyzed. The other accepted method, the Method of Characteristics, is inefficient at handling large networks due to its requirement for incremental calculations between junctions and devices.

At the University of Kentucky, we made this analytical tool available to other researchers and institutions. Eventually it became clear that utilities and other industries had a great need for such a powerful and efficient tool to model transient conditions in their piping systems. The software that became the industry standard and the Wave Plan Method that powers it have been in continual use and development to this day.

It was at the University of Kentucky that Dr. Srinivasa Lingireddy and other esteemed professors joined me in the development of transient software. Dr. Lingireddy's pioneering work in genetic algorithms and component (protection device) modeling expanded greatly on the Wave Plan Method's capabilities. Ever since he joined in this endeavor, he has been a driving force behind the research and development of this method and the software packages that support it. His involvement over many years with industry outside academia, with engineers, operators, regulators, and even with manufacturing, has honed his knowledge and skills to the point where, in my opinion, there is no one in the world who equals his knowledge and expertise.

This book brings together decades of experience in modeling, engineering and software development. My own work, and the work of many others, is represented in these pages. But most of the work has been Dr. Lingireddy's. He has truly taken the helm of a life's work that began with a youthful intrigue. Dr. Lingireddy has helped me to make this method one that is utilized by thousands of engineers and operators in a multitude of countries around the world. He is truly the best choice for an author on this subject, and I am grateful that he has chosen to share his knowledge with industries and the world in this excellent book.

Don J. Wood

Preface

Let me begin this preface by thanking the University of Kentucky, the place I had called home for 16 years, for granting me a sabbatical in 2005. The extensive world travel during the sabbatical year made me realize how little I knew about the real-world water hammer challenges, without exaggeration! This was despite my more than a decade of academic experience on unsteady flows, several years of close interactions with many surge modelers, and a complete grasp on the source code of the most widely used surge analysis software.

The sabbatical allowed me to meet with some of the finest practicing engineers, utility managers, and research and development specialists from Europe, Israel, United Arab Emirates, Oman, China, and India. I was also confronted with many unanswered questions. The existing books were not of much help as most of them focused on the complexities of the computational techniques and not on the real-world challenges. None had answers to questions such as: Would there be limits on opening and closing times for relief valves? Why placing a check valve in the middle of a long pipeline as a surge protection device is a bad idea, while theoretically it appears like a great idea? Can there be a delay in the activation of an air valve on down surge? etc. I was well-aware of the significant amounts of water loss through leakage even in the highly regulated distribution networks of the United States, but did not quite understand why such widespread leakages would develop in the first place? Why do we invest in efforts such as pressure management in controlling water loss through leakage instead of addressing the root causes of the leakage, i.e., broken pipe joints and cracked pipes? What causes the pipe joints to fail in these highly regulated water distribution networks that are required to maintain a minimum positive pressure of 20 psi (14m) under all demand conditions? Why are hundreds of “boil water” advisories issued every year even in technologically advanced countries like the US and Canada?

The sabbatical has inspired me to take the plunge and seek answers to the real-world water hammer problems. It prompted me to take up the challenge of solving at least one real-world problem involving a heavily battered water supply system. Countless number of hours spent with research and development specialists of the surge protection equipment helped me understand the intricate details of the diverse set of equipment and their relation to surge modeling. Close interaction with pump and check valve manufacturers, and pump station operators helped me appreciate the complex inter-relationships between various equipment within the pump station. On one occasion, I learned how a pump station check valve that has been operating trouble-free since its installation started generating severe slam pressures after a benign act of installing a large, compressed air tank at a location downstream of the check valve. The compressor air tank was required to protect the main pipeline from periodic burst events. Participation in several forensic studies allowed me to understand what matters the most in controlling pressure surges arising from the pump station equipment. Forensic investigations also allowed me to appreciate how certain seemingly irrelevant devices can cause destructive surge pressures at some faraway places within the pipeline systems. For example, in a well-conceived and well-constructed pipeline project comprising roughly 60 km of 2000 mm diameter pipeline and several one-way surge tanks, the periodic burst events close to the pump station were traced to an air valve roughly 40 km away from the pump station. Sadly, serious forensic investigations were initiated only after the fourth burst event that resulted in the death of a cyclist. The air valve in question was not part of the surge protection system and was intended only for routine filling and draining operations!

The strength of materials was not one of my strong areas and I had to relearn the subject after realizing that understanding the pressure rating of pipelines is fundamental to surge modeling. On the other hand, optimization was one of my strong areas and a thorough knowledge on pressure ratings helped me redesign certain pipeline projects, bringing substantial savings to either surge protection cost, pipeline cost, or both. Understanding the strength of materials is also important as pipes of different material react differently to surge pressures. For example, an intense positive pressure wave traversing a welded mild steel pipeline of certain rated pressure would burst the pipeline at the weakest point leaving rest of the pipeline practically intact. However, the same pressure wave traversing a glass reinforced plastic (GRP) pipeline of identical pressure rating can inflict hairline cracks at multiple locations, in addition to bursting the pipeline at its weakest point. This is despite the fact that GRP pipe is considered as one of the great modern inventions. The hairline cracks become trouble spots and future burst locations even when not so intense pressure waves traverse the pipeline later. In certain parts of the world, pipe burst events are considered acceptable when they occur during the commissioning stage of the project. Such a viewpoint might lead to perpetual leakages and burst events when GRP pipelines or pipelines with similar characteristics (for example, asbestos cement, reinforced concrete, and prestressed concrete) are used in the project.

In the developed countries, the loss of water through leakage is dominant only in the distribution networks. However, the loss of water through leakage is ubiquitous even in bulk water pipeline systems of the developing world. Frequent power outages coupled with inadequate surge protection or improper use of check valves (sometimes called zero velocity valves) as surge protection devices appear to have resulted in numerous distributed leakages in many bulk water supply pipelines. The efficiency of some of the highly battered bulk water pipeline systems is below 50%. Improper air management on these bulk water systems resulted in significant increase in power consumption which goes unnoticed due to lack of energy audits. A thorough understanding of the causes of widespread leakages on the bulk water pipelines should provide answers to persistent leakage problems in the distribution networks.

Roughly a decade after diving into the real-world in 2007, my team and I have successfully rehabilitated a bulk water supply pipeline that was experiencing at least one pipe burst event each week (see Section 5.1.2 of this book) and proved that even highly battered pipeline systems can be brought back to life with suitable surge protection. In the last 15 years, I designed surge protection for more than hundred bulk water pipelines and scores of irrigation pipe distribution networks comprising several hundred kilometers of large diameter (>2000 mm) pipeline. A total of about 200 bladder surge tanks, scores of relief valves, and hundreds of non-slam air valves were used in protecting these pipeline systems. I worked with 20 mm diameter pipelines carrying cryogenic liquid as well as 5000 mm diameter bulk water cross-country pipelines. While most pipelines carried water at normal velocity limits of 2.5 m/s or less, I have also dealt with pipelines discharging water at an abnormally high 8 m/s velocity.

My world travel did not stop during this period. I used seminars and training courses as opportunities for two-way learning. Some of the most intriguing questions were from engineers of Inner Mongolia and Uganda during my lectures. This book is an effort at sharing the collective knowledge on the practical and intricate details pertaining to surge modeling. Based on the recent literature, the focus of the academic world continues to be on the surge analysis problems that are disconnected from the real-world challenges as illustrated in several sections of this book. This book is also an attempt at bridging that gap and motivating future researchers to find solutions to the persistent real-world challenges related to water hammer.

Srini Lingireddy

Acknowledgements

First, I would like to thank Dr. Don J. Wood for agreeing to coauthor this book. It is a great honor to be associated with the legend who revolutionized the pipe network modeling through his pioneering work in both steady state and unsteady state hydraulics. I learned not only the science of surge modeling but also the art of surge modeling from Dr. Wood, for which I am eternally grateful.

Book-writing is a long journey, and the information presented in this book is based on the cumulative knowledge of so many engineers and specialists who were a part of it. There were also several milestones along this journey, and I must thank everyone involved in those key moments. Mr. Naftali Zloczower, for introducing me to the modern air valves in the late 1990s, and for dragging me during my sabbatical to the breathtaking Kfar Haruv overlooking the Sea of Galilee for a 3-day seminar with several dozen practicing engineers from around the world. The exchange of ideas during that visit with a budding entrepreneur, Milind Murudkar, changed the trajectory of my professional career. Dr. Fanie Van Vuuren, the world-renowned expert on air valves for teaching the fundamentals of subject, and Pini Vardy for teaching all the practical aspects of air valves. Mike Hager, for sharing his knowledge and wisdom on bladder tanks. Yoav Tabenken, Ilan Ulman, Amir Livne, and the late Ezra Sabbagh, for sharing their immense knowledge on control valves. I must thank two other people who shaped my career leading to this book. Dr. K. Elango, who taught me how to conduct research and be an independent thinker, and more importantly for giving me the opportunity to work on many real-world water supply and distribution challenges right on the beautiful 640-acre campus of my alma mater, the IIT Madras. And Dr. Lindell Ormsbee, for being a wonderful teacher and mentor all through my tenure at the University of Kentucky. I could always count on him. Thank you, Dr. Ormsbee.

Vision tends to get blurry when you are done writing a few hundred pages of text, and you need eagle-eyed experts willing to spend their precious time looking for omissions and errors. I would like to thank Pani Ramalingam, Naftali Zloczower, Ferran Guillén, Sathish Kumar, Mokhtar Morsy, Eric Liebenauer, and Jana Faith for reviewing one or more chapters combing for mistakes and providing constructive comments. All remaining errors and omissions are solely my responsibility. I would also like to thank Hilla Sagi, Maya Fisher, Idit Bejerano Ben Schch, and Mike Hager for providing several of the images and illustrations, and Karthic Rangarajan and Sathish Kumar for coordinating with the publishers.

My special thanks to Mr. Eric Liebenauer, for a critical review and thorough editing of the entire manuscript. His extraordinary editing skills, coupled with his in-depth understanding of the surge modeling process helped to shape the manuscript into this book in a relatively short time. My special thanks are also to Jana Faith and Doug Wood for their continued support from the beginning of this book-writing project. Thank you.

Srini Lingireddy

Introduction

Design of effective surge protection involves building an accurate model of the pipeline system, use of a reliable solution technique, and a modeler who understands all the intricacies of surge analysis. Advances in computing technology and human interface tools have reduced and streamlined model building efforts substantially. Powerful, accurate and numerically stable solution techniques such as the wave plan method (WPM) with decades of excellent track record eliminate the search for reliable modeling tools. There are many modelers who are well-versed in surge analysis through decades of experience. However, for those with little or no experience, the authors have not come across a book that details all the intricacies of surge modeling. Accordingly, the objective of this book is to explore these intricacies in detail, using the lessons learned through decades of surge protection design experience, including close interaction with pump station operators and field personnel, utility managers, fire protection specialists, research and development specialists of surge protection equipment, surge modeling consultants, and academics. The material is presented in seven chapters and several appendices. The chapters describe broader concepts in a logical way starting with the description of surge analysis tools, followed by causes and effects of surge events, methods of protecting the pipeline systems from extreme surge pressures, and assumptions and uncertainties encountered during surge analysis. The appendices provide corroborative material for several of the broader concepts described in various chapters and include many of the intricate details pertaining to the surge analysis. By bringing to light all the intricate details including the limitations of surge modeling and ways to overcome those limitations, the book is expected to instill greater confidence in undertaking surge analysis works. A summary of each chapter and appendix is provided in the following.

Chapter 1 describes the basic elements of surge analysis by introducing WPM, a powerful solution technique based on intuitive wave propagation mechanics. The mechanics of wave propagation are first illustrated using a simple reservoir-pipe-valve system which ignores friction losses; this example demonstrates the use of Joukowsky's equation, which is the foundation upon which all surge analysis techniques are built. Simple mathematical equations governing the reflection and transmission of pressure waves at junction nodes are introduced next. Discovery of these equations in the late 1950s formed the basis of the powerful WPM. The analysis of friction losses using friction elements is then discussed. WPM has proven to be the most powerful method and it derives that power from the use of friction elements that allow for the much sought-after nonlinear spatial computational grid. The concept of friction elements was then extended to describe the modeling of various components of pipeline systems. Appendix A is a companion section to Chapter 1 and provides an in-depth analysis on the role of friction in the discretization of the solution space.

Large and complex surge analysis problems need extraordinarily powerful solution techniques. Design of surge protection systems is an iterative process and may require numerous productive analytical runs, possibly several dozens to a few hundred, before arriving at an effective and efficient protection system. A computational tool that takes 8 hours to complete one surge analysis run, for example, would unnecessarily delay the design process, likely forcing practitioners to either miss real-world project deadlines or to limit their analytical runs, which could compromise the effectiveness or the efficiency of the surge protection system, or both. On the other hand, a computational tool that is even an order of magnitude faster would help to arrive at an effective and optimal design in a reasonable timeframe. WPM is that tool, and its computational efficiency scales with the size and complexity of the system under consideration. It is easy to appreciate the advantages of a powerful solution technique that may be up to several orders of magnitude faster than existing alternatives without compromising the accuracy of the results. **Chapter 2** describes the power of WPM when addressing large and complex surge analysis problems. The chapter describes the real-life challenges faced by water utilities, such as how to minimize the large number of water main breaks (currently around 180,000 per year in US and Canadian water distribution networks!), and ways to eliminate potential pathogen intrusion problems and the associated "boil water" advisories. Appendix B is a companion section to Chapter 2, providing an in-depth analysis of WPM and the competing Method of Characteristics (MOC), establishing the unequivocal superiority of WPM over MOC.

The objective of most surge analysis studies is to design an effective and optimal surge protection system. Some studies might be geared towards forensic investigation of pipeline or component failures. Regardless of the reason for surge analysis, a thorough understanding of the causes of pressure surges in pipeline systems is indispensable. **Chapter 3** illustrates a variety of scenarios that can generate pressure surges in pipeline systems. It is also important that modelers understand the most fundamental cause-and-effect relationship governing the occurrence of extreme surge pressures, which can be summarized by the statement, "rapid changes in velocities lead to rapid changes in pressures." Modelers must therefore consider all possible scenarios that could generate a rapid change in velocity, instead of relying on a compiled list of example scenarios. Accordingly, the material presented in this chapter directs the readers to visualize how each of the scenarios presented generates rapid changes in velocities, an understanding which is generalizable when identifying causes of transients that are not explicitly listed in this chapter. The companion sections of this Chapter 3 are Appendix C: Attenuation of Pressure, Appendix D: Wave Speed, Appendix G: Pumps and Turbines, and Appendix H: Check Valves.

When surge pressures exceed the pressure ratings of pipelines or other devices within a pipeline system, they can produce acute or chronic damage, or both. **Chapter 4** illustrates the types of damage extreme surge pressures cause in pipeline systems by describing real-world incidents. The chapter also provides a brief introduction to determining the pressure-withstanding capacities of pipelines constructed of different materials.

Chapter 5 illustrates various methods of protecting pipeline systems from extreme surge pressures. This includes summarizing the types of currently available surge protection devices, details of their working principles, and their relative advantages and disadvantages. Air valves as surge protection devices are described in Chapter 6. Chapter 5 shows how understanding and relying on the principle that "rapid changes in velocities result in rapid changes in pressures" assists with the selection of appropriate surge protection methods and devices. Inappropriately selected or sized surge protection devices can introduce secondary surge pressures that could be more severe than the primary surge pressures they are designed to mitigate. More information is contained within this chapter's companion section, Appendix E: Air-water interface.

There has been significant progress in the last two decades in the design of air valves used in pipeline systems. While air valves are indispensable to most pipeline systems for filling and draining operations (including removal of residual air), these valves are often not designed or sized as surge protection devices. However, certain specially designed air valves, called non-slam air valves, have been used successfully to protect pipeline systems from extreme negative pressures while minimizing the slam pressures associated with rejoining water columns during air venting cycle. The cost of surge protection can be drastically reduced when air valves are incorporated as part of the surge protection design, where appropriate. When air valves are used as part of surge protection, they introduce air into the pipeline during unsteady state, and the presence of air violates the fundamental closed-conduit flow assumption that underpins both WPM and MOC. Therefore, it is important to understand the assumptions associated with air valve modeling so informed decisions can be made on the suitability of air valves as part of surge protection system. **Chapter 6** describes the different types of air valves, including those used for surge protection, and how they are modeled by a popular WPM-based surge analysis tool. More information is available in this chapter's companion sections, Appendix E: Air-Water Interface and Appendix F: Air Valves and Common Misconceptions. Chapter 7: Assumptions and Uncertainties, contains a detailed review of a real-world scenario in which non-slam air valves are shown to be an essential component of an effective and efficient surge protection design by examining the increased cost and practical limitations of alternative designs.

All non-trivial modeling tasks must account for certain assumptions and uncertainties, and surge analysis is no exception. A few modelers are aware of all the assumptions and uncertainties, capable of interpreting the model results accordingly, and thus can build sufficient factors of safety into their surge protection designs. **Chapter 7** summarizes the assumptions associated with the available modeling techniques (WPM and MOC) and describes the assumptions made when modeling various components of the pipeline system. This chapter also describes the various sources of uncertainty involved when characterizing pipeline components, including the lack of manufacturer-provided specifications and the resultant use of generalized as opposed to component-specific data sets. Though the long list of assumptions and uncertainties might be somewhat discouraging to novice modelers, the authors are of the opinion that empowering modelers with the complete set of facts is the best teaching method, since these assumptions and uncertainties, if not properly accounted for, can invalidate the resultant surge protection design, regardless of which tool is used for modeling. Chapter 7 also describes the importance of sensitivity analysis to gain further confidence in model results and recommends adding factors of safety to the surge protection design where the uncertainties cannot otherwise be accounted for. The need for a powerful solution technique is self-evident when several dozens of productive model runs (driven by the need for extensive sensitivity analysis) are required to quantify the potential impact of these uncertainties on system surge pressures and thus arrive at an effective and optimal surge protection design.

When pressure waves are generated by any transient-initiating event, they travel through all hydraulically connected regions of the pipeline at sonic speeds. The wave mechanics described in Chapter 1 helps to visualize wave propagation as the waves traverse the entire pipeline system, being partially reflected and partially transmitted at junction nodes, components and other boundary conditions. These fast-moving pressure waves are also attenuated by the pipeline's frictional resistance. Whereas MOC-based numerical methods require division of long pipelines into uniform grids satisfying certain criteria, WPM can employ a nonuniform spatial grid to accurately account for the friction loss while maintaining the numerical stability. **Appendix A** describes the role of friction in the discretization of the solution space which is quantified through extensive numerical experiments. These experiments establish the ability of WPM to accurately assess the effects of friction in long pipelines, validating the use of the nonuniform spatial grid. These numerical experiments also illustrate the limits on the maximum grid spacing when selecting the non-uniform spatial grid.

Appendix B describes the basics of MOC and further elaborates on the information provided in Appendix A to establish the superiority of WPM over MOC. Specifically, the performance of first- and second order MOC are compared with the performance of WPM when addressing friction in longer pipe sections. Extensive numerical experiments originally presented in a doctoral thesis are provided to demonstrate the superiority of WPM over MOC.

There has been a considerable attention in recent literature to a phenomenon currently being referred to as "unsteady friction," which has been proposed to account for the faster-than-expected attenuation of pressure waves in certain laboratory-scale pipeline experiments. Unfortunately, no one has yet presented a reliable unsteady friction model that can be generalized to pipelines of different characteristics, even at the experimental scale. **Appendix C** explores multiple possible reasons for the attenuation of pressure waves, allowing readers to make informed decisions regarding the necessity of accounting for unsteady friction when working with more complex, real-world pipeline systems.

A pressure wave generated in a pipeline system travels at sonic speed (called wave speed or celerity), the exact value of which depends on the characteristics of the transported fluid and the pipe structure bounding the fluid. Wave speed plays a dominant role in unsteady flow calculations. **Appendix D** describes the various factors influencing wave speeds in pipeline systems. Uncertainties surrounding the estimation of wave speeds for old, buried pipelines are discussed. This appendix also demonstrates the often-counter-intuitive effects of abrupt changes in wave speeds within pipelines of non-uniform diameters and/or materials (for example, a short, high-density polyethylene pipe with a low wave speed placed in the middle of a long, mild steel pipe with a higher wave speed).

Appendix E describes the air-water interface as it relates to surge analysis of pipeline systems. While there may be some pipeline systems that are completely free of air intrusion, the majority of pipelines must deal with the effects of air intrusion in some form. Air can be present in both the dissolved state and the suspended state. While the presence of large amounts of suspended (bulk) air violates the fundamental closed-conduit flow assumption underpinning both WPM and MOC, the presence of small quantities of suspended air can affect liquid density, bulk modulus, etc. Changes in the liquid density and bulk modulus affect wave speed and, in turn, the unsteady flow results. This appendix begins by describing the solubility of air in water, which affects the disappearance and reappearance of air bubbles and air pockets that can occur at different locations within the pipeline throughout unsteady state. Several other related topics such as vapor pressure, suspended vs. dissolved air, factors influencing the transport of air in pipelines, the polytropic process, corrosion, etc., are discussed as well. This appendix also describes several important factors that can generate either adverse or favorable effects arising from the presence of an air-water interface in isolated portions (such as dead ends) of pipeline systems.

Appendix F illustrates common misconceptions associated with air valves in pipeline systems. Many of these misconceptions result from the lack of unified standards on the design and use of air valves, and more importantly, the use of air valves for surge protection.

Appendix G describes the inertial characteristics of pumps and turbines. It describes the origins of "industry standard" nondimensional pump characteristics in the well-known Suter curves format, beginning with the collection of experimental data at Caltech in the early 1930s. The appendix discusses the transformation of this data, first presented in Karman-Knapp circle diagrams, through Donsky's compilation of the same data into a format suitable for use with computational tools. The appendix also illustrates the operating ranges of both pumps and turbines within Suter curve diagrams. The dependability of the "industry standard" nondimensional characteristics generated using three laboratory-scale pumps of nearly century old designs for today's pumps of diverse capacities is discussed.

Appendix H describes the operation of various types of check valves used in pipeline systems. It illustrates the complexity of check valve operation, and explains the difficulties associated with obtaining deterministic, time-dependent check valve closing characteristics. The appendix also demonstrates the workable solution of employing manufacturer-provided dynamic characteristic curves relating potential reverse velocity just before the final closing of the check valve to the flow deceleration at the check valve's location, which can be used to validate check valve modeling assumptions.

Conversion Factors:

1 ft = 0.3048m, 1m = 3.2808 ft = 39.37 in
1 mile = 1.609 km, 1 km = 0.6214 miles
1 lbm = 0.4536 kg, 1 kg = 2.2046 lbm = 0.06852 slug
1 oz = 28.3495 g, 1 g = 0.03527 oz
1 lbf = 4.448 N, 1 N = 0.2248 lbf
1 psi = 6.895 kPa = 0.06895 bar, 1 bar = 14.5038 psi
1 ft^3/s = 0.0283 m^3/s, 1000 l/s, 1 m^3/s = 35.3147 ft^3/s = 15852 gpm
Temperature: T_C (°C) = (T_F (°F) – 32) * (5/9), T_F (°F) = (T_C (°C) * (9/5)) + 32

APPENDIX I

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APPENDIX J
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