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Physics of High Energy Lasers (HEL)

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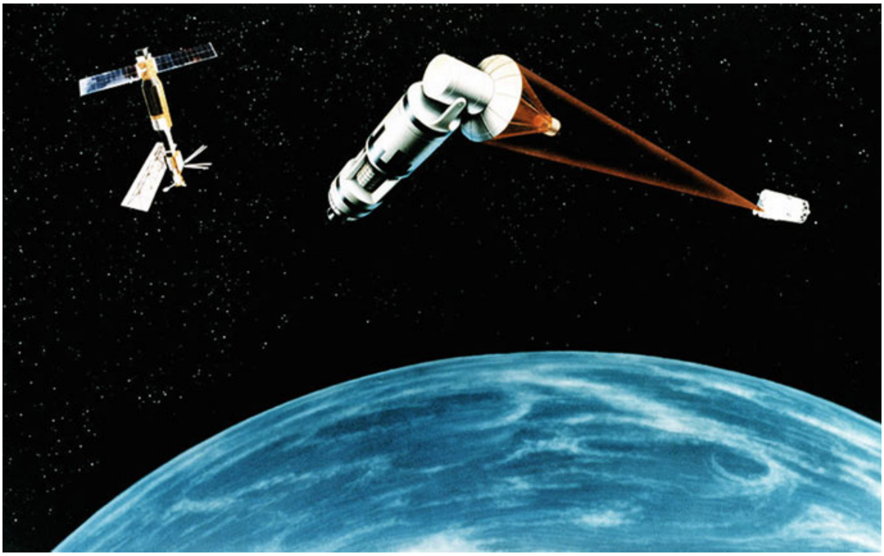

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This book is dedicated to my mother and father Marzieh and Akbar Zohuri.

Without their encouragement, this book would not have been written.

Preface

Directed energy weapons are nothing new to mankind; historically the origination of such weapons began centuries ago when the famous Greek mathematician, physicist, engineer, inventor, and astronomer; Archimedes of Syracuse used different mirrors to collect sunbeams and focused them on the Roman fleet in order to destroy enemy ships with fire. This is known as the Archimedes Heat Ray. Archimedes may have used mirrors acting collectively as a parabolic reflector to burn ships attacking Syracuse. The device was used to focus sunlight onto approaching ships, causing them to catch fire. Of course the myth or reality of the Archimedes Heat Ray still is questionable, but with the help of a group of students from Massachusetts Institute of Technology certain experiments were carried out with 127 one-foot (30 cm) square mirror tiles in October of 2005 that were focused on a mockup wooden ship at a range of about 100 feet (30 m). The flames broke out on a patch of the ship, but only after the sky had been cloudless and the ship had remained stationary for around 10 min. It was concluded the device was a feasible weapon under these conditions.

The battles of tomorrow will be fought with different weapons that have more lethal effects and faster delivery systems. One of mankind's greatest achievements in the twentieth century is the ability to destroy the entire human race several times over. At this time of intensive arms more money is invested in the next generation of weapons. It is in the best interest of every citizen to be aware and able to make an informed judgment on the best possible direction for the arms race. Offensive or defensive weapons are a cruel reality that nevertheless must be addressed.

The scientific work during the 1950s that led to the invention of the laser was followed closely by work in military research institutes and organizations all over the world and this opened a new door to the Archimedes Heat Ray. Lasers have found many military applications, not as new weapons, but rather as the supporting technology to enhance the performance of other weapons such as laser-guided bombs and so on. Our fascination and appreciation of modern weaponry is at an all-time high. It was not until the 1970s that the possibility of laser weapons again captured the imagination of military planners. High-energy and other directed energy weapons finally became a reality, and the possibility of using them in the battlefields of tomorrow has been investigated vigorously ever since.

The development of laser weaponry and other directed energy weapons technology conjures up the Heat Ray of Archimedes and Flash Gordon-like images of vaporizing enemies, demolishing buildings, and burning through metal. In this book introduces such weaponry to readers of different technical backgrounds as well as to introduce a certain technical approach to such research and to help better understanding of such weapons utilizing various technical and research resources.

The next 10 years will see the emergence of high-energy lasers as an operational capability in US service. These weapons will have the unique capability to attack targets at the speed of light and are likely to impair the effectiveness of many weapon types significantly, especially ballistic weapons. Constrained by propagation physics, these weapons will not provide all-weather capabilities, and will perform best in clear sky–dry air conditions.

The book in its laser technology section talks about the interaction between high-power laser beams and matters whereas other aspects of directed energy weapons, such as particle and high-power radar beams as a weapons of tomorrow can be found in the literature provided by other authors. Laser-beam interactions with materials, treat, from a physicist's point of view, the wide variety of processes that lasers can induce in materials. Physical phenomena ranging from optics to shock waves are discussed. The approach that is taken emphasizes the fundamental ideas both from a newcomer's or research worker's point of view to provide important background for material science, mathematics, optics, and the like, or a most critical up-to-date review of the field.

A directed energy weapon (DEW) such as a high-energy laser emits energy in an aimed direction without the means of a projectile. It transfers energy to a target for a desired effect. Some such weapons are real or in development; others are at present only in science fiction.

The energy can come in various forms:

- Electromagnetic radiation (typically lasers or masers)
- Particles with mass (particle beam weapons)
- Sound (sonic weaponry)
- Fire (flamethrowers)
- High-power laser weapons

Some lethal directed energy weapons are under active research and development, but most examples appear in science fiction, nonfunctional toys, film props, or animation.

In science fiction, these weapons are sometimes known as death rays or ray-guns and are usually portrayed as projecting energy at a person or object to kill or destroy. Many modern examples of science fiction have more specific names for directed energy weapons, due to research advances.

For those readers who need to dive deep into the technologies behind such research a short course in various topics of mathematics and physics has been offered in the appendices in order for them to brush up on these topics and be able to understand different solutions and mathematical modeling that are offered for the solution, for example, of the heat diffusion equation for different boundary and initial conditions. In the case of application of lasers as weapons, the book has attempted to serve both scientists interested in the physical phenomena of laser effects and engineers interested in practical applications of laser effects in industry. Thus, several sections are devoted to reviewing and dealing with the solution of the diffusion equation utilizing the aid of integral transform techniques. Among the several different approaches to solve the boundary value problems for heat conduction; the integral transform technique offers the most straightforward and elegant solution, provided that the transforms, the inversions, and the kernels are readily available.

Some appendices at the end of the book are devoted to systematic mathematics and physics of the heat conduction solution and its boundary value problems. As a result of the transforms, the inversions, complex variables, and their examples are presented and the kernels are tabulated, and the Laplace and Fourier transforms are also introduced. The appendix on introduction to ordinary and partial differentials is also presented to help the reader understand the solution techniques used to solve the heat conduction problem for various boundary values. Appendices on optics and the electromagnetic field also help better understanding of the behavior of the physics and mathematics of these weapons.

Note: In most of the appendices of different topics either the references mentioned at the end of each appendix have been used and quoted directly or indirectly or it is up to each reader to refer to them separately for more knowledge and information. I have also decided to shift these appendices around by eliminating some of their content that I believe is no longer necessary, as well as converting some content into part of the main chapters of different subjects of Volume II here and finally keeping the rest as appendices as originally planned.

Those left as an appendix of their own for those readers needing some refresher and review on the topics that are presented by these appendices are:

Appendix A: Short Course in Taylor Series
Appendix B: Short Course in Vector Analysis
Appendix C: Short Course in Ordinary and Partial Differential Equations
Appendix D: Short Course in Complex Variables
Appendix E: Short Course in Fourier and Laplace Transforms
Appendix F: Short Course in Electromagnetics
Appendix G: Short Course in Optics
Appendix H: Short Course in Heat Conduction Equation
Appendix I: Data and Plots of Thermal Parameters of Different Materials
Appendix H: Acronyms and Definitions

In this book, I have also taken under consideration to show the solutions and present the heat conduction complex problem and those boundary values that are very much related to problems of high- power laser interaction with materials. Most cases have looked at one-dimensional heat conduction with semi-infinite slab configuration with a heat resource as part of heat conduction equations making dealing with it a more difficult and complex problem. Wherever was needed the best possible references were given for further investigations by readers interested in doing their own research beyond what is given here.

Albuquerque, NM Bahman Zohuri

Acknowledgments

I am indebted to the many people who aided and encouraged me and the people who supported me beyond expectations. Some of them are not around to see the end result of their encouragement in the production of this book, yet I hope they can see this acknowledgment. I especially want to thank Nancy Reis of Sandia National Laboratory who both put the idea in me to start the book based on some work that I was contracted to do for them. My thanks go also to Joe Rogers of NASA, retired now, one of my best friends who helped with most of the computer codes that are presented in this book to bring them to their present status from their legacy stages and to be able to transfer them from a mainframe to a personal computer platform under the Windows operating system.

Another best friend, William Kemp of the Air Force Weapons Laboratory at Albuquerque, New Mexico is really a true friend and remains as one. Finally my many thanks to Jonathan W. Plant, Senior Editor—Mechanical, Aerospace, and Nuclear and Energy Engineering of Taylor & Francis/CRC Press who made all this happen. Finally, I am indebted to many people and the individuals and organizations that granted permission to reproduce copyright materials and published figures.

I am also indebted to Dr. John T. Schriemf and his time on the phone on so many occasions and advice about the different topics related to high-power laser interaction with matte, in particular allowing me to tap into his well-known Naval Research Laboratory (i.e., NRL Report 7728) under the title of "Response of Materials to Laser Radiation a Short Course," and allowing me to copy some of his well-written report to reflect on in this volume as presented in Chapter 1.

I also would like to thank Dr. Krzysztof Nowakowski for letting me use his efforts and research work and allowing me to utilize some sections of his research work. His work and his research under the title of "Laser Beam Interaction with Materials for Microscale Applications" was most helpful to me and Chapter 7 of the book.

Above all, I offer very special thanks to my mother and father while they were alive, and my wife and children. They provided constant interest and encouragement, without which this book would not have been written.

Their patience with my many absences from home and long hours in front of the computer during preparation of the manuscript is especially appreciated.

Contents

About the Author

Bahman Zohuri is currently with Galaxy Advanced Engineering, a consulting company that he started himself in 1991 when he left both the semiconductor and defense industries after many years of working as a chief scientist. After graduating from the University of Illinois in the fields of physics and applied mathematics, he joined Westinghouse Electric Corporation where he performed thermal hydraulic analysis and natural circulation for the inherent shutdown heat removal system (ISHRS) in the core of a liquid metal fast breeder reactor (LMFBR) as a secondary fully inherent shut system for secondary loop heat exchange. All these designs were used for nuclear safety and reliability engineering for a self-actuated shutdown system. He designed the mercury heat pipe and electromagnetic pumps for large pool concepts of LMFBR for the heat rejection purpose for this reactor around 1978 where he received a patent for it. He later was transferred to the defense division of Westinghouse where he was responsible for the dynamic analysis and method of launching and handling of the MX missile out of the canister. The results are applied to MX launch seal performance and muzzle blast phenomena analysis (i.e., missile vibration and hydrodynamic shock formation). He was also involved in analytical calculation and computation in the study of the nonlinear ion wave in rarefying plasma. The results are applied to the propagation of the "soliton wave" and the resulting charge collector traces, in the rarefactions characteristic of the corona of a laser-irradiated target pellet. As part of his graduate research work at Argonne National Laboratory Zohuri performed computation and programming of the multiexchange integral in surface physics and solid-state physics. He holds different patents in areas such as diffusion processes and design of a diffusion furnace while he was senior process engineer working for different semiconductor industries such as Intel, Varian, and National Semiconductor. Later on he joined Lockheed Missile and Aerospace Corporation as Senior Chief Scientist and was responsible for in R&D and the study of vulnerability, survivability, and both radiation and laser hardening of different payload components (i.e., IR sensor) for the defense support program (DSP), boost surveillance and tracking satellite (BSTS), and space surveillance and tracking satellite (SSTS) against laser or nuclear threat. While there he also studied and performed the analysis of characteristics of laser beam and nuclear radiation interaction with materials, transient radiation effects in electronics (TREE), electromagnetic pulse (EMP), system-generated electromagnetic pulse (SGEMP), single-event upset (SEU), blast and thermomechanical, hardness assurance, maintenance, and device technology.

He spent several years consulting for his company Galaxy Advanced Engineering with Sandia National Laboratories (SNL), where he supported development of operational hazard assessments for the Air Force Safety Center (AFSC) in concert with other interested parties. The intended use of the results was their eventual inclusion in Air Force instructions (AFIs) specifically issued for directed energy weapons (DEW) operational safety. He completed the first version of a comprehensive library of detailed laser tools for the airborne laser (ABL), advanced tactical laser (ATL), tactical high-energy laser (THEL), and the mobile/tactical high-energy laser (M-THEL), among others.

He also was responsible for SDI computer programs involved in battle management C^3 and artificial intelligence (AI), and autonomous systems. He is the author of several publications and holds various patents such as "Laser Activated Radioactive Decay and Results of Thru-Bulkhead Initiation."

Chapter 1
Directed Energy Weapons

Will the United States develop laser and beam weaponry for a strong nuclear defense to replace the policy of mutually assured destruction. Has the Soviet Union violated treaties by using “yellow rain” in Afghanistan and Indochina? What future lies in store for the clean neutron bomb? What kinds of super missiles are being tested for the future? What new biological and chemical weapons has the United States been cooking up?

1.1 Introduction

The idea of using an omnipotent “death ray ” on the battlefield is not a new concept. Ancient literature credits the Greek mathematician Archimedes as the first to conceive the idea of using light as a defensive weapon. Hippocrates, commander of the Greek force, applied Archimedes’ concept by focusing the energy of sunlight through a series of mirrors to produce a beam that set fire to the sails of the Roman fleet under Consul Marcus Claudius Marcellus during the siege of Syracuse in 212 BC. [1]

Laser weapon projects have been shrouded by very tight security. In spite of this, it is possible to follow the general lines, at least, of the high-energy laser (HEL) weapon research field through the open literature.

Our fascination and appreciation of modern weaponry is at an all-time high. With the wonders and horrors of the Persian Gulf war and event of 9/11 fresh in our minds, the development of laser weapon technology conjures up Flash Gordon-like images of vaporizing enemies, demolishing building, and burning through metals [2].

Armed forces in many countries are already using a great number of laser devices, and the inexorable pace of progress in developing special laser weapons indicates that they will ultimately revolutionize the modern battlefield. Practically invisible when fired, silent, capable of pinpoint accuracy, and traveling at the speed

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of light, laser weapons would seem to offer unparalleled advantages over conventional weapons.

This paper examines the effects of lasers—one of the first exotic directed energy weapons (DEWs) to capture public attention—and our focus in particular is on airborne laser (ABL).

While this may be true, once unleashed, this awesome power can trigger other devastating consequences as well. Anti-eye laser weapons are currently being developed that can result in the mass blinding of soldiers, pilots, and tank crews.

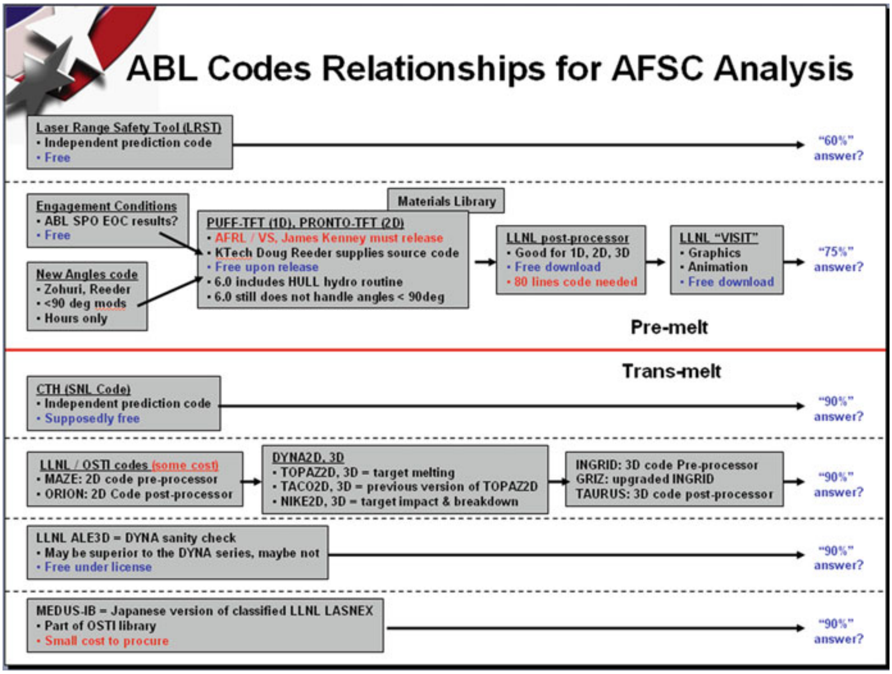
Laser experts Anderberg and Wolbarsht [2] describe the staggering medical, social, and psychological ramifications that the use of laser weapons will entail and becomes as part of our study for laser range safety tool (LRST), which is the subject of this project. Furthermore, we explore the historical development of these weapons and briefly touch the fact that how far other countries, including France, England, and Russia, have progressed in their technology. We also try to serve the purpose of an introduction to the language of directed energy weapon (DEW) for military planners and nontechnical persons who need them to understand the fundamental of what the engineers and scientists involved in their development are talking about by basically touching some physics and mathematics involved in this field. Describe all the difficulties these folks are dealing with and how to overcome these obstacles in order to produce the right tool and technologies that will induce the proper DEW for our defense of our country. A better weapon in hands of our arm force to carry on such defensive task. Any employee found to have violated these policies and procedures may be subject to disciplinary action, up to and including termination of employment.

We have put a collection of software and computer codes that are developed by our engineers and scientist around the nation within national laboratories and defense companies under one umbrella and developed the Windows/PC version of these codes as a source of repository of such capabilities. Most of these codes were developed on main- and macro-frame computing system, and under this project, we managed to migrate them to micro-frame environment for simplicity of running these codes for the purpose of further enhancement and development of LRST and DEW in ABL area. In some cases, we further enhanced the technical capability of these legacy codes in order to serve the purpose of today's technology toward development of the directed energy weapons. Table 1.1 is a good representation of these codes.

Folks who are interested to obtain these codes for the purpose of their work toward the field of DEW should contact either principal of this report or original source that is mentioned in Tables 1.1 and 1.2 in this chapter. Although we tried to gather all existing unclassified computer code together, they are still considered critical military information that requires proper paper work to obtain these computer codes from our data bank, and in some cases it might require licensing query of third-party software.

To obtain most of these codes, you are required to have some direct and related US government contract from appropriate office or agency with the government.

Table 1.1 ABL code relationships for AFSC analysis



Then the offices that are in charge of these codes will arrange for the release of these codes.

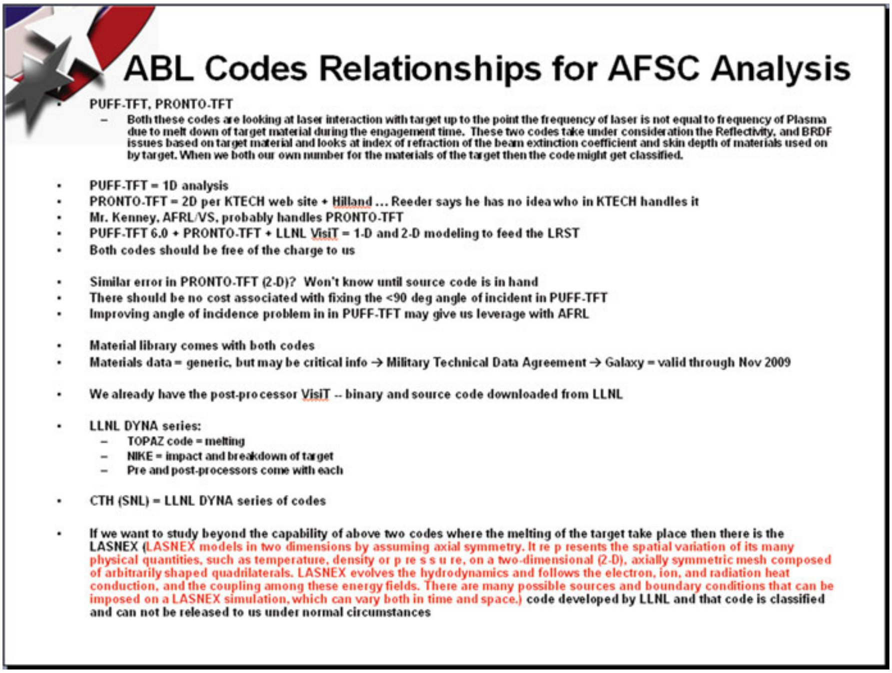
For example, most of codes that are released from Sandia National Laboratory such as CHT or codes such as DYNA3D and other related codes from Lawrence Livermore National Laboratory fall in these categories.

Although the author of this book has most of these codes, in most cases we have to follow the federal government guidelines for the release of these codes as well minus few exceptions. Please get in touch with the author for further discussion of these codes as well as consult his web site at www.gaeinc.com for availability of some of these codes through his company.

We welcome any comment and correction by expert in this field to correct and enhance our assumption on these codes or recommend better computational analysis and software tools.

In the next few sections of this chapter, we introduce unclassified computer codes that may be obtained from the source that is known to this author. Some of these codes although not classified but restricted and are available to US government agencies or their contractors.

Table 1.2 Comments on ABL code relationships for AFSC analysis



1.2 PUFF74: A Material Response Computer Code

The **PUFF74** code is a computer code, which calculates stress wave formation and propagation by numerical integration of the conservation equations in a one-dimensional Lagrangian coordinate system. The code has been under development since 1961 and has evolved from a simple hydrodynamics code to a flexible material response code, which includes the effects of material strength, porosity, and fracture for both homogeneous and composite materials.

The code at present version (Version 4.0) is capable of handling the following physical models:

1. A framework for calculating the material response in composite materials
2. A pressure-volume-energy equation of state model for homogeneous materials or constituents of a composite material
3. A pore-compaction model for porous homogeneous materials or constituents of a composite materials
4. A one-dimensional viscoplastic model for geometric dispersion effects in composite materials

The latest model development for the **PUFF74** code has been accomplished under the CADRE program. As part of this program, studies have been made to determine the dynamic material properties, which govern the response of composite materials to rapid energy deposition.

To facilitate the input procedures for radiation deposition calculations, an automatic initial zoning model was added to the PUFF 66 code in extensive use of the code. Reference [3] presents the description of the automatic zoning model 1969 by Cooper. The guidelines used to develop this model evolved through.

The next addition to the PUFF code was the framework for introducing a free surface into the sample mesh at a location where material fracture is detected. The logic for introducing free surfaces, calculating the response of free surfaces as a function of time, and recombining fractured segments was a developed model in the original coding. Since the coding was written in a modular form, more sophisticated fracture models could be substituted with a minimum of effort.

As model development and calculations of experimental tests continued, a graphics package was added to the PUFF code to allow the user to produce online plots and externally produced plots and data storage (Calcomp or microfilm). Galaxy Advanced Engineering, Inc. (GAE) has used the Universal Graphics products known as UGL to replace the CA-DISSPLA and produce all the following graphics out and show the power of UGL for its CA-DISSPLA compatibilities. The plot package added to the code made extensive use of the general graphics data display programs developed at the Air Force Weapons Laboratory (AFWL) display program existing at ARIL at the time the plot package was added to PUFF. Modifications to the AFWL data display program and to the graphics package in the PUFF code have been made on a continuing basis to improve the efficiency of the plotting procedures.

The following is a random selection of graphics output of PUFF74/UGL combined (Fig. 1.1).

1.2.1 Availability of PUFF74 Computer Code

The Windows/PC version of this code is available from Galaxy Advanced Engineering, Inc. for purchase price. This version has been modified from its original version that used to run on VAX/VMS computer, and users need to obtain their own copy from this company. Contact the Galaxy Advanced Engineering, Inc. for its Windows/PC version. To our knowledge the code is no longer available from government agencies or its contractors. You can find more detail on how to obtain and purchase by referring to the following URL: https://www.gaeinc.com.

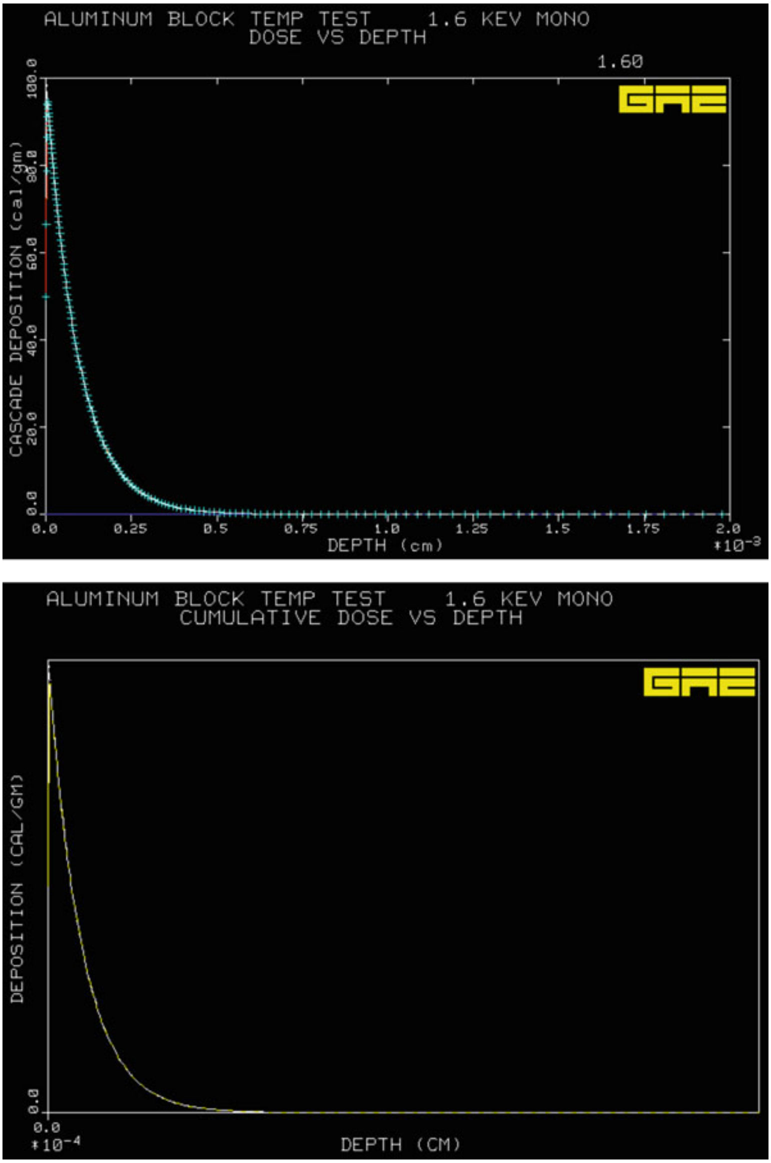
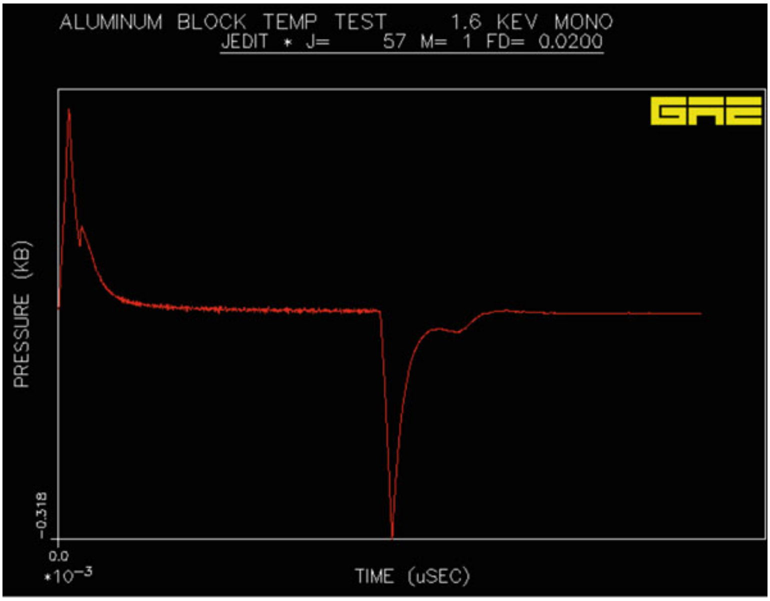


Fig 1.1 Sample output of PUFF74 using Universal Graphics Library from GAE

1.3 PUFF-TFT: A Material Response Computer Code

The PUFF-TFT code has now been updated (version 5.0) to allow modeling of sample responses to sudden energy loading (e.g., X-rays or lasers) for arbitrary starting temperatures. Problems can be run for any initial temperature, both



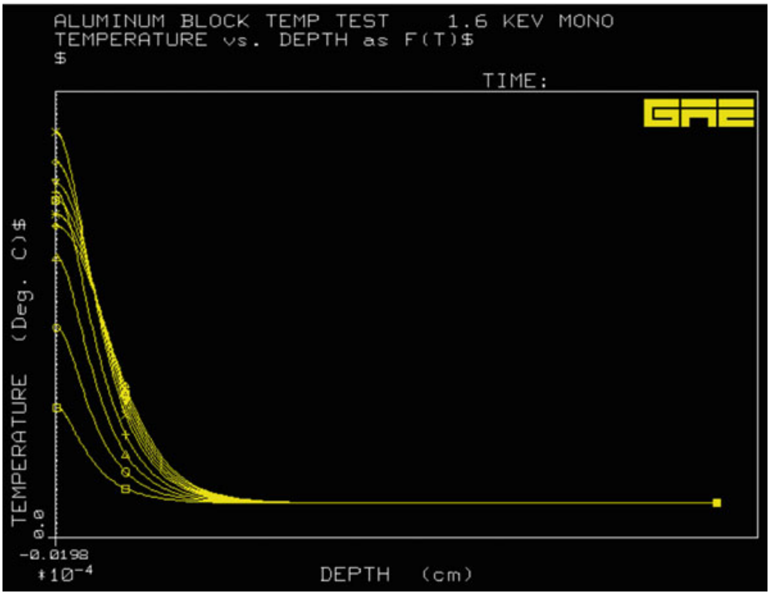
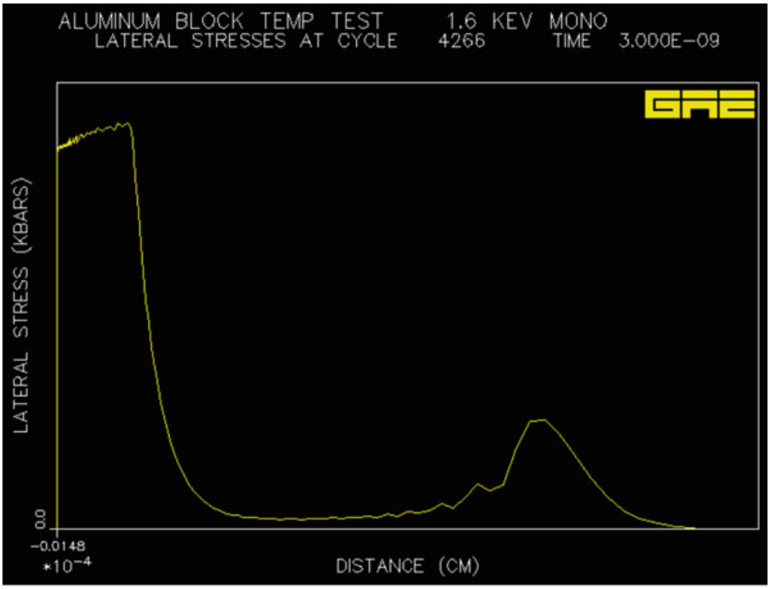


Fig 1.1 (continued)

elevated and, most importantly, for cryogenic conditions. Updates have also been made in the stress response for the "thermal-only" mode, especially for the cool-down stresses after plastic flow. Likewise, the code tracks material properties (yielding, shear module, spall strengths) for cryogenic conditions.



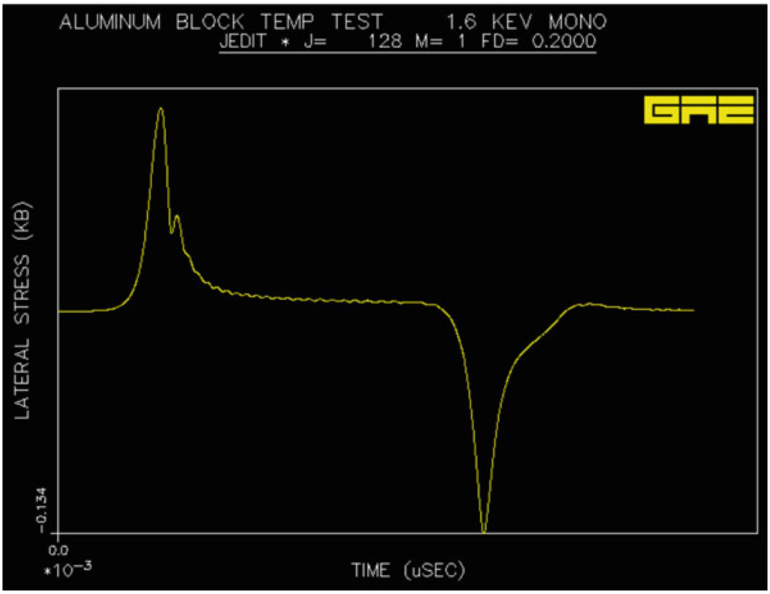


Fig 1.1 (continued)

The code amendments have been done in a "transparent" manner for the user, requiring the minimum of input parameter changes. To activate this, the code maintains the existing convention of:

$$\text{Enthalpy} = 0.0\ \text{cal/g at temperature} = 25\,^{\circ}\text{C}$$

and temperature continues to be in degrees centigrade. Consequently, for that equal to 25 °C, the code will start with a nonzero enthalpy. For $T > 25\,^{\circ}\text{C}$, this initial enthalpy will be positive, whereas for $T < 25\,^{\circ}\text{C}$, the enthalpy is negative.

The previous code version did not distinguish between "dose" (the added energy due to X-rays, thermal flow, etc.) and "enthalpy." This was appropriate, since both terms initialized with a common value of zero. The new code makes the distinction, since dose still starts from zero enthalpy.

The "transparent" amendments are such that the user continues to use the existing database for such parameters as melt energy, vapor energy, and latent heats. Likewise, for $T > 25\,^{\circ}\text{C}$, the existing polynomial coefficients to describe specific heats, enthalpies, and conductivities are maintained.

The code was written for the Air Force Weapon Laboratory (AFWL) primarily to allow evaluation of thin-layer stack response to X-ray deposition resulting in one-dimensional (1-D) strain stress response. The code takes into account the X-ray generation of secondary cascade particles (photoelectrons, Auger electrons, and fluorescent photons) using a cascade routine and incorporates a thermal condition routine allowing the effects of rapid thermal diffusivity to be included.

The output of the X-ray/cascade/thermal routine is used as input to an updated version of the PUFF74 hydrodynamic code, which includes hydrodynamic, elastoplastic, porous, and dispersive material responses in a fully coupled manner, and also accounts for simple phase changes.

The formulation of differential equations follows either Eulerian or Lagrangian descriptions. The Eulerian description is a spatial description; while the Lagrangian is a material description. In an Eulerian framework, all grid points, and consequently cell boundaries, remain fixed with time. Mass, momentum, and energy flow across cell boundaries. In a Lagrangian description, the grid points are attached to the material and move with the material. In this formulation, mass within a cell is invariant, but the volume of the cell may change with time because of expansion or compression, of the materials.

The PUFF-TFT code calculates stress wave formation and propagation by numerical integration of the conservation equations in a one-dimensional Lagrangian coordinate system. The TFT package accounts for the effects of dose enhancement due to the transport of secondary particles with ranges comparable to the thickness of the thin material layers and thermal conduction between thin material layers. These two modifications (among others) more accurately portray the degree of energy sharing between thin layers, thereby modifying the expected energy depositions based on normal X-ray interactions and possibly altering the anticipated thermomechanical response of the medium.

The PUFF74 code, originally developed in the mid-1960s, has undergone a number of revisions to become a flexible material response code that includes the effects of material strength, porosity, and fracture for both homogeneous and composite materials. The code calculates stress wave formation and propagation