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Model Employee: My 40 Years of Scientific Modeling as a US Army Terminal Ballistician

by Steven B Segletes

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Weapons and Materials Research Directorate, DEVCOM Army Research Laboratory

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14. ABSTRACT

This report recounts the 40-year career of the author, Dr Steven B Segletes, who served as a mechanical engineer, specializing in terminal ballistics, at the US Army Ballistic Research Laboratory, the US Army Research Laboratory, and presently at the US Army Combat Capabilities Development Command Army Research Laboratory. His retirement from federal service is slated for 2021 September 30.

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Foreword

It gives me great pleasure to introduce this documentary report on the esteemed career of Dr Steven B Segletes. While such a report is certainly not our usual fare, in this case, I eagerly accepted the opportunity to have Dr Segletes' career recollections made "official" through this publication. For more than four decades, Dr Segletes has been applying his skills and talents to advance the state of our understanding in numerous fields related to terminal ballistics and impact physics.

Over the span of his career, Dr Segletes has made significant contributions in technology areas of direct relevance to the analysis of Army combat systems, including warhead mechanics, penetration mechanics, computational solid mechanics, condensed matter physics, thermodynamics, explosive/metal interaction, and more. More recently, his "compulytical" approach to addressing the problem of underbody blast is providing the Army with tools to rapidly and accurately assess the ballistic threat posed to Army vehicles from the impulse delivered by an explosively propelled soil bed.

Throughout his career, Dr Segletes has been recognized for his expertise in the analytical treatment of problems in ballistic science. He has authored or coauthored a number of analytical mechanics solutions, including the penetration-mechanics equations of Alekseevski–Tate, the ballistic ricochet problem, the flight of a ballistic body subject to aerodynamic drag, the extended Bernoulli equation, and the inertial properties of ballistic ogives. His work in thermodynamics is also noteworthy, where he has published extensively on the equation of state of condensed matter.

In the course of his tenure, Dr Segletes has received a number of DEVCOM ARL's most prestigious laboratory awards, including the ARL Technical Achievement Award for Science in 1998 and the ARL Award for Engineering in 2012. He also received the LABCOM and Army R&D Achievement Awards in 1989 for his work on warhead spin compensation.

It is my hope and belief that this report and others like it will serve the larger ballistics community, both as a technical resource in the near term and as an archival document for the longer term. At a minimum, it provides a curious glimpse into the career of one of ARL's gifted engineers, upon whose analytical models the US Army will surely rely for many years to come.

Rachel Z Francart
Chief, Terminal Effects Division
2021 August 16

Preface

The impetus for this report was my branch chief, Dr James Cazamias, as my retirement from Federal service loomed on the horizon. He asked for a summary of my 40-year career, since there were few left who could recall my early work history. He believed that any potential citation for lifetime service would require a knowledge of such details. I offered a publication list, but James instead requested a narrative format, to make sense of the publications. That request started a chain of events that eventually led to this somewhat exhaustive (perhaps in more ways than one) recount of my career as a terminal ballistician for the US Army.

The uniqueness of this report should not be taken to mean that my career has been any more illustrious than those of my colleagues. It may merely indicate that I have been meticulous throughout my career in keeping records, which greatly facilitates such a recounting. It is an attempt to let my family know what I did for much of my life. But it also forced me to ponder where my career fit into the larger scheme of Army research at the turn of the new millennium. As I reflected on the themes that prevail in the modern research environment, I recalled a series of philosophical conversations with my dear friend and colleague Dr Michael Grinfeld, which would occur over our lunchtime walks to the Chesapeake Bay and back.

I found most interesting (and relevant to this reflection) the dynamic tension that arises between model complexification and simplification—a tension that is both normal and useful. Complexification, which has been strongly enabled by the digital revolution, occurs when the state of modeling proves insufficient to capture the essence of a physical phenomenon of interest. In an effort to remedy the deficiency, more variables may be introduced to the model. Likewise, the analytical connection between the variables of the problem may be treated with more complex mathematical relationships. The model may become less equation oriented and more discretized and algorithmic in nature. It may tend to include an ever-wider number of input variables, for increased "utility".

Such methodical complexification can improve the quality of correlation between the model and the corresponding phenomenon in the natural world. However, complexification, by its nature, obscures an understanding of the underlying principles at work. It makes it more difficult to ascertain how the relevant variables of the problem interact with each other. Left unchecked, it can become a "black box" that produces answers that may provide a useful accuracy, but are not intuitively understood. Extrapolation of the complexified model to address a wider domain of problems necessarily involves introducing even more complexity.

When such a situation is reached, model simplification is needed in order to advance the understanding of the field. Whereas complexification tends to be methodical in nature, simplification (at least in my case) tends to derive from intuition, creativity, and often times, inspiration. Whereas complexification attempts to understand phenomena as *processes*, simplification views phenomena as a series of *relationships*. When simplification is successful, a complex understanding of a phenomenon can be boiled down to the essential relationships of important variables. When successful, algorithms may be replaced by equations. When successful, an understanding of how a change in one variable affects another is strongly enhanced.

Of course, simplified models are typically constrained by limitations on the initial or boundary conditions of the phenomenon, or by other underlying assumptions. Such constraints inevitably encourage future complexification and the research cycle of complexification/simplification continues unabated.

It is my experience that individual researchers will have a strong affinity for either complexification or simplification, but rarely both. As I reflect on themes that have guided my own research tenure, the one that repeatedly prevails is simplification through analytical modeling. As the digital revolution extends cheap computer capacity into all walks of life, the lure of model complexification is strong. If this recounting of my career as a scientific modeler makes any impression, I hope it testifies to the value of model simplification in the pursuit of scientific understanding.

I have thoroughly enjoyed my employment as a researcher working at the Army's premier research laboratory, on the Aberdeen Proving Ground. I have met the best people through the course of my career, across all facets of the organization—kind, helpful, dedicated, patriotic, intelligent, and creative. I have had a unique opportunity to learn from and collaborate with some of the great analytical minds in Army science, including Drs William Walters, Michael Grinfeld, Jonas Zukas, and George Gazonas. I have said for decades that I have the best job in the world and I mean it. It has been my highest honor and pleasure to serve in this capacity as a researcher for the United States Army.

Acknowledgments

It would be nearly impossible to thank all the people who made, not only this report, but a 40-year career as a ballistic modeler, possible. As to this report, I am indebted to colleague and friend Dr Rahul Gupta for doing me the favor of providing a technical review. Dr John Clayton, Mr Erich Meyerhoff, Ms Talia Maxfield, and my supervisor Dr James Cazamias were instrumental in helping to assure that my recollections didn't run afoul of operational security (OPSEC) considerations. I am further indebted to Dr Cazamias for being the impetus behind this report. Likewise, I extend my thanks to Ms Rachel Francart, the chief of the Terminal Effects Division, for enthusiastically embracing this project and introducing it by way of the Foreword. I am extremely grateful to all of them.

I want to give a special "shout out" to my long-term editor, Ms Carol Johnson, a woman who not only excels with diligence in her editing role, but is an ever-vivacious and witty correspondent. I am also grateful to Ms Johnson for initially striving, in 2013, to see that my methods with the LaTeX typesetting software were incorporated as a component in the laboratory's overall technical-report-production infrastructure. Her current team leader, Ms Jessica Schultheis, has continued that close-working relationship, allowing us to provide an excellent service that today supports many researchers across the laboratory.

Supervisors have so much to do with the success of their people and, through them, the organization. Four former supervisors in my chain of command have truly stood out as archetypal servant leaders who always placed their employees at the front. They include Dr Robert J Eichelberger, Dr Andrew M Dietrich, Dr C Wesley Kitchens, and Dr Todd W Bjerke. Each of them personally intervened in my career at critical moments, in ways that averted adverse or demoralizing outcomes otherwise wrought by the inertia of the bureaucratic "system".

Technical mentors are the heart of any research environment. They are the seed corn that grow the next crop of researchers. All my colleagues are universally excellent people and researchers. However, several over the years have given of themselves to help grow my technical and reasoning skills. Mr Robert L Jameson, my first team leader, taught me what it is to be an Army researcher. Mr David E Towson ingrained in me the value of logical thought in addressing thorny problems for which the solution approach is not known in advance. Dr William P Walters taught me not

only the necessity of perseverance, but opened my eyes to the beauty of nonlinear differential equations and how to attack them. Dr Michael A Grinfeld, in addition to sharing his huge array of analytical skills that were new to me, provided, over a span of years, the most engaging philosophical discussions on the history of science and the nature of research. What they all shared is a thirst for knowledge and understanding, the most essential quality of any researcher.

Beyond the laboratory facade, though, are many who, through the Grace of our Lord, gave of themselves to give me this opportunity. A number of high-school teachers and Drexel professors still stick in the forefront of my memory, as inspirational figures in my education. Even more important, of course, is family. I thank my parents, John and Irene, for the excellent upbringing they gave me—also my four siblings for providing the competition to excel from an early age. My dear wife, Gabriele, and my children Jennifer, Eric, and Jenia, mean the world to me and are a constant source of love, encouragement, and inspiration.

1. 1980s: The Beginning of a Career

I started my US Army laboratory career at Aberdeen Proving Ground (APG), Maryland, as an 18-year-old undergraduate co-op student engineer for the US Army Ballistic Research Laboratory (BRL). Employment began on 8 September 1980, while I was a student of mechanical engineering at Drexel University in Philadelphia, Pennsylvania. The position of student trainee garnered me a GS-03-01 grade at a starting salary of $8952 per annum. Jimmy Carter was the President of the United States.

1.1 The Working Environment: Technology on the Cusp

Working life was different in 1980. There were no flexible work schedules, no such things as cellular phones. Residential wireless communication was one-way, taking the form of AM/FM radio or TV. Mail was always "hardcopy", delivered through the US Postal Service. Theoretical research and model development was done with paper and pencil and maybe a hand-held calculator (research could continue through power outages!). Graph paper was essential. Reports were prepared by a secretary transcribing a researcher's handwritten notes on an electric typewriter (with some sort of memory card features). Personal computers were mainly used for gaming and, being based on 8-bit architecture, were limited to (at most!) 2^{16} = 64K bytes of memory. Programming in Z-80 or 6502 assembly language was a fun hobby but such machines were not found in the office setting. The gateway for modern office computers, the IBM PC, was introduced a year later, in 1981.

However, BRL was a computing leader in that era, having been the proud home of the world's first electronic computer, the ENIAC. By 1980, *the* organizational computing platform was the Seymour Cray designed CDC 7600, an elite platform housed in the basement of the Simon Building (B328). Remote-job-entry (RJE) portals were located around the campus, typically one per building. In the case of the Zornig Building (B309) where I worked, the RJE portal was in the centrally located 2nd-floor photocopy room. Job submission was accomplished by way of Hollerith cards, which had to be individually typed on large, loud, keypunch machines. These cards, stacked in ordered decks, constituted the permanent record of your computer program—code changes were made by substituting new cards into your deck. Each card contained one line (or record) of FORTRAN code, which was individually read and digitally transmitted in sequence to the central site for processing. Printed output (text only) was retrieved by hand from the central site in B328. Sophisticated users could access reel-to-reel tape machines for storing "permanent" data and flat-bed ink plotters for higher-quality graphics.

By mid-decade, a new style of computing began to emerge at the lab, in direct competition with the central number-crunching facility. The computing platforms were smaller machines (*e.g.*, DEC PDP-11), which meant that several could be afforded. These were UNIX-based platforms that gave the user unprecedented control over how their data was stored, moved, and processed. Access to these platforms was accomplished by way of remote "terminals" (screens with keyboards, but no permanent internal storage), *several* of which were made available in each building. Branch chiefs were even provided their own terminals so that BRL Director Robert J Eichelberger could communicate with them by way of the new-fangled invention of email (managers hated email in those early years and generally ignored it).

Most interestingly of all, these newer computers were connected not only across the laboratory but across the ARPANET, a DOD research-funded packet-switched computer network that would eventually morph into today's internet. I was very interested in this style of computing and had an early email under the username steven@brl.mil. The ARPANET was so small at this time that IP addressing was static and there were no nameservers—the complete ARPANET computer "directory" was updated and distributed to each online facility as new computers joined. How small was it? It had not been so many years since its architecture could be drawn on a single piece of letter-sized paper, with each computer individually listed (Fig. 1)! One can note the presence of Aberdeen's PDP-11 on the right-hand side of the figure. It was in this time of great technological change, on the cusp of the Information Age, that I began my research career at BRL.

1.2 The Pull of Analytical versus Computational Modeling

As an exuberant student researcher, I did not stop to consider the nature and types of research. For years, I had greatly enjoyed working with equations. But I was also just discovering, for the first time with hands on, the tool known as the computer that could be programmed with instructions and algorithms to perform complex computational tasks. It was exhilarating for a young mind to be able to dabble in both of these areas. Each offered advantages and disadvantages in the quest to understand nature.

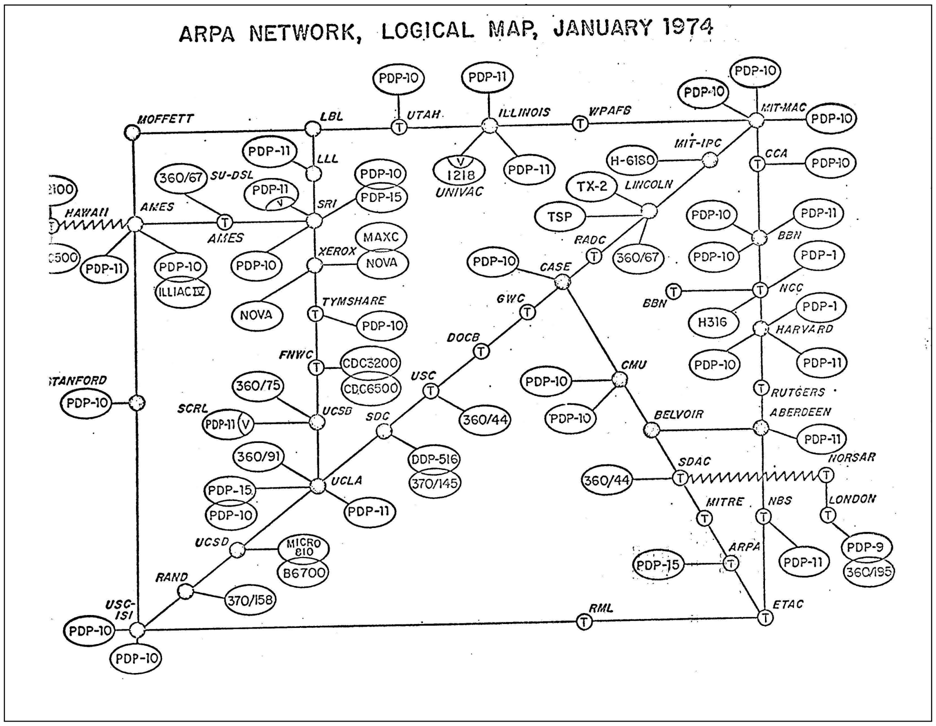

Fig. 1 The ARPANET, January 1974 (from an uncited BRL memorandum)

Over time, it became clear that my greater skill lay in the use of analytical methods. But the world was embracing computational methods, as computing power became increasingly ubiquitous. Years later, in 2010, the organization tasked six of us (in addition to myself were J Powell, M Grinfeld, A Porwitzky, C Hummer, and B Krzewinski) to brief them on "Theoretical Development and Analytical Modeling" in the Weapons and Materials Research Directorate (WMRD).

We chose to formulate our brief in defense of analytical modeling as we found ourselves in a world increasingly dominated by computations. Retaining analytical expertise is a new challenge for this age, for laboratories as well as universities. Great minds in the past have clearly understood the value of analytical methods. The Hungarian physicist Eugene Wigner noted that, as the tool of analytical modeling, "mathematics is unreasonably effective in natural sciences".

While some research investigates as-yet unknown phenomena, modeling often involves looking at a well-observed phenomenon and idealizing it in a clever way. Philosopher Arthur Schopenhauer noted in 1851 that "the task is, not so much to see what no one has yet seen; but to think what nobody has yet thought, about that which everybody sees". Engineering intuition is the sense that permits a proper idealization of complexity into something simpler. It comes from experience in seeing analytical connections across disparate technical areas.

Analytical modeling serves to guide research into those areas most likely to be fruitful. It presents assumptions in unambiguous form. It generates fruitful analogies with distant research areas. It can produce unexpected paradoxical discoveries. It expedites engineering analysis. It is with this perspective that I proceed to reflect upon the details of my career.

1.3 Undergraduate Years—Imperfect Jets

Based on job interviews with all the branches in the Terminal Ballistics Division, I was given the opportunity to choose my initial cooperative-education stint with the Shaped Charge Branch. Shaped charges are technologically fascinating warhead devices in which an explosive detonation focuses a hollow-shaped metallic liner onto the axis of symmetry, producing a stretching hypervelocity jet of metal that is used to penetrate armored targets. They have existed in militarized form since WWII (*e.g.*, the bazooka) and can be emplaced by hand, launched from a cannon, or carried on a missile to the intended target. Their study provided a fertile ground for the analytical mind, which proved to be a forte of this young trainee.

During this period, I performed important work in the area of shaped-charge-jet penetration methodology. Prior to my entry into the field, non-ideal shaped-charge penetration was modeled using a 1-D empirical concept known as $U_{\min}$, which signified a penetration velocity, below which shaped-charge penetration was ineffective. The large values of $U_{\min}$ (several km/s) baffled researchers. How could jet material traveling at several kilometers per second be ineffective? In 1977, Majerus, Kucher, and Simon (BRL-MR-2742), while still operating in the realm of $U_{\min}$ modeling, began to perceive an underlying mechanism: "warhead designs which produce curved jets...must be *avoided* since such warheads are highly susceptible to being degraded by the transverse velocity effects".

But it was left to others, such as myself in 1980, to take that idea and prove it quantitatively. During my initial 3-month co-op stint, I took the radiographs of jets, which were for the first time being digitized with the aid of digital devices,* and was

*For which the user had to write the software.

able to calculate the 3-D axial *and radial* velocity components of each digitized jet particle. I formulated the PENJET code to use this digital information to predict the nonideal penetration crater profile for each digitized jet and met with an excellent correlation to experimental results, such as that shown in Fig. 2.

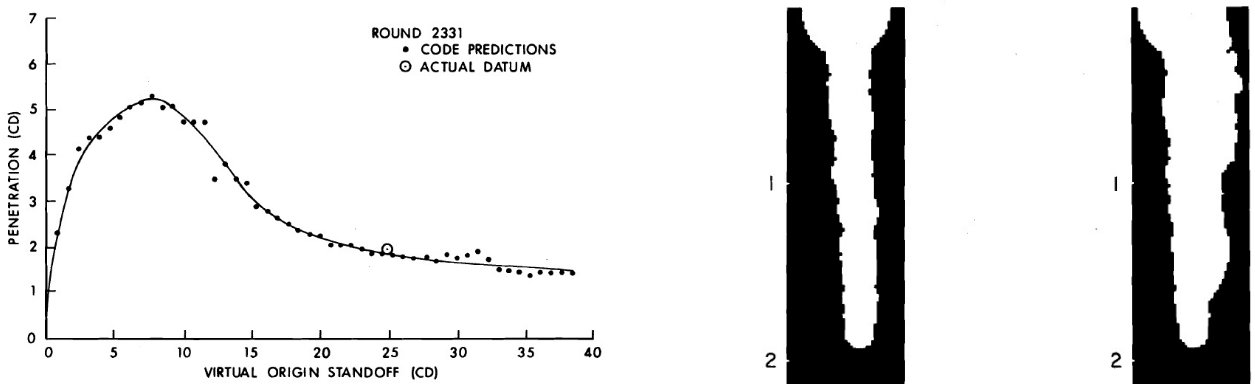

Fig. 2 PENJET-predicted penetration, orthogonal crater profile for a digitized nonideal jet[1,2]

Presented to a division-wide seminar[1] audience in December of 1980, the work was eventually published as ARBRL-MR-03306[2] in 1983. Work in the lateral velocity of shaped-charge jets continued for several years, resulting in the FIDOSC code to account for imposed (rather than nonideal) transverse velocity (BRL-MR-3409[3] [1984]). Additional publications/patents in this area include US Patent 4,513,666[4] (1985), US Statutory Invention Registration H33[5] (1986), and BRL-TR-2823[6] (1987). Transverse drift velocity slowly supplanted U_{min} as the phenomenological impetus for reduced penetration observed with increasing warhead standoff.

This work has retained its value over the decades that followed, as witnessed by its resurrection as a revised PENJET tool to assist with imperfect warhead assessment as part of the Mine-Resistant Ambush Protected (MRAP) program as well as a revised FIDOSC tool, named F2 (ARL-TR-4988[7] [2009]). Later, in support of the F2 code for modeling the interaction of nonideal jets against fixed or moving targets, an adjunct code to model the kinematic interactions of moving plates was developed in ARL-TR-5274[8] (2010). I also extended the framework for codes that model warhead engagement by recasting all the kinematics of warhead/target engagement into 3-D vector mechanics, thereby allowing for azimuthal engagement in the context of F2 or any future warhead interaction model (ARL-MR-0918[9] [2016]). And again, for the Lab Scale Mission Program in 2021, I employed PENJET to predict the long-standoff performance of real-world shaped-charge jets.

I was often called upon by Survivability/Lethality Analysis Directorate (SLAD) and others in my latter career to put to use my experience in evaluating the performance of imperfect shaped charges, for example, to accomplish the following:

- To extrapolate to very long standoff the expected penetration performance of a particular 10-inch charge[10] (2009).
- To estimate the residual mass and velocity for various specified warhead threats against overmatched targets[11,12] (2008–2009).
- To estimate, in support of Program Manager (PM) Abrams, the overmatch penetration capability of a residual shaped-charge jet that is imaged, emerging from the rear of a fielded target package (2017).

In other cases, for example, to support Dr Hornbaker's modeling efforts, I devised a way to back-estimate the *equivalent* jet breakup time corresponding to a single computational simulation result (ARL-TN-0747[13] [2016]).

1.4 Graduate Years—Warhead Spin Compensation

Both my bachelor's (First Honors) and master's degrees were achieved simultaneously in 1984 from Drexel University. Immediately, I re-enrolled with tuition support from BRL to work on my doctoral degree under the internationally recognized ballistician, Prof Pei Chi Chou, who had supervised a number of famous students in the field, including Robert Karpp, Bruce Burns, Joseph Carleone, William Flis, David Leidel, and Chris Weickert, among others.

The thesis topic was to understand the mechanism that enabled shaped-charge spin compensation in shear-formed shaped-charge liners.* Fellow student, Cana-

*One humorous anecdote arising from this time period concerned the references needed for my thesis. Many of these reports on spin compensation had originally been classified when they were produced in the 1950s. While they all had been downgraded to unclassified over the years, they remained of limited distribution, which cannot be referenced as part of a doctoral thesis. My Team Leader, Robert Jameson suggested I place a request through the security office to get these 25-year-old publications reviewed for conversion to unlimited distribution "A".

The request went in. Many months passed, approaching a year. Finally, I received an official correspondence from the Army stating to the effect, "you have been identified as an expert in the area of shaped-charge spin compensation. The Army would ask if you could review this reclassification request to determine if there is any reason the following reports should not be reclassified to unlimited distribution".

Thus, "Segletes" approved the request and returned it. Several more months passed. Finally, I received a note from the Army stating that my request for the reclassification of the given reports had been approved and the Defense Technical Information Center (DTIC) had been notified.

dian Chris Weickert attacked a similar problem, except for fluted, rather than shear-formed, liners. Because shaped-charge jet formation involves taking an element of the warhead's metallic liner at a "large" radius and collapsing it down to the axis of symmetry, any spin of the liner causes the collapsing elements to experience a massive increase in rotation rate, in the manner of a figure skater pulling in their arms close to their body during a spin. Such is the nature of angular momentum conservation. However, the massive rotation rates of the forming jets could produce enough centrifugal forces to overcome the material strength of the jet causing radial disintegration and, thus, performance degradation of the warhead.

Spin compensation is a shaped-charge design approach to counter the deleterious effects of axisymmetric warhead spin. The liner-manufacturing technique of shear forming, even while producing a *geometrically* axisymmetric warhead liner, produces an intrinsically counter-rotating jet and slug, which can be employed to counteract the rotation associated with the preexisting warhead spin. The physics of this spin compensation was not well understood, and thus the manufacturing technique relied heavily on empirical approaches that focused on assessing the [non-axisymmetric] metallurgical orientation of grains in the warhead liner. In addition, the increasing ability to employ spin-free missiles and warhead fins to retard warhead launch spin had the effect of deprecating the need for and thus, the use of, spin compensation. Nonetheless, it remained a problem ripe for analysis.

I decided that the problem required that Newton's laws of motion be applied in order to understand it. I posited three possible mechanisms that could physically produce the observed counter-rotation of jet and slug: residual liner stress, elastic anisotropy (i.e., anisotropy of the elastic constants), and plastic anisotropy (i.e., anisotropy of the yield surface). Each of these mechanisms was quantitatively analyzed for feasibility, using a combination of analytical and hydrocode approaches.

My analysis revealed that, of the three, only plastic anisotropy would have the ability to produce the force magnitudes required for compensation. I created and implemented these models into a hydrocode format that was able to provide computational confirmation of these predictions, as shown in Fig. 3. Results were presented and published at the 1989 International Ballistic Symposium,[14] while the 1988 doctoral thesis[15] was republished as BRL-TR-3090[16] (1990). This body of work resulted in both the Laboratory Command (LABCOM) as well as the Army R&D Achievement awards in 1989.

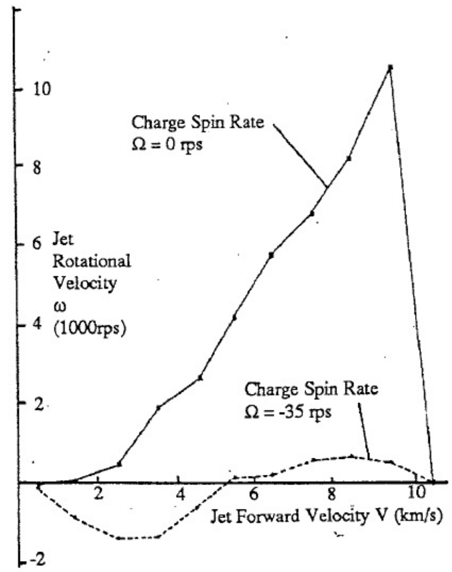

Fig. 3 Jet rotational velocity ω vs. jet forward velocity at $45\mu s$ for a stationary and spinning charges. Note the nearly negligible jet rotation in the latter.[14]

In the aftermath of my thesis work and while still working at BRL, I served several years as adjunct faculty at my alma mater, Drexel University, teaching an evening class in Computational Mechanics, as part of Drexel's Ballistics Institute.

1.5 Anisotropy and Deviatoric/Hydrostatic Decomposition

As part of my thesis, the computational methods created had a far-reaching impact. While the anisotropic constitutive laws I wished to employ were the standard approaches, I needed to adjust their framework to make them compatible with the nonlinear equation-of-state models that populate the hydrocodes.

To accomplish this, I had to formulate a self-consistent method for separating the hydrostatic stresses and strains from the deviatoric. For isotropic materials, this separation falls out naturally. However, for anisotropic materials, it is the case that hydrostatic stresses produce deviatoric strains and deviatoric stresses are required to produce a hydrostatic strain. Thus, the decomposition is problematic.

The approach I took posits calculating a new type of "deviatoric" strain that is not merely a departure from the spherical strain condition but, rather, a departure from the strain condition arising from spherical stress. It is this revised deviatoric strain that brings about true deviatoric stress. This revised deviatoric strain also possesses a spherical component, which must be decremented from the spherical strain as the proper impetus for a hydrostatic stress response, used as input for the equation of state.

This methodology appeared in my doctoral thesis,[15] but also as a standalone report BRL-TR-2825[17] (1987). This work also provided me with the background and interest for future work in equations of state, a key theme for future decades. This newly developed consistent method for separating hydrostatic and deviatoric components for anisotropic materials was, years later, adopted as the transversely isotropic (TI) model in the widely used CTH hydrocode, as implemented by Sandia National Laboratories' Paul Taylor (SAND95-2750). I later coauthored a review article with Dr Alexander Lukyanov, "Frontiers in the Constitutive Modeling of Anisotropic Shock Waves" in *Applied Mechanics Reviews*[18] (2011), in which the early work on anisotropic modeling is revisited in detail (also republished as ARL-TR-5878[19] [2012]).

2. 1990s

In the 1990s, my work prominently featured equation of state modeling. However, it started out with a classic paper, coauthored with my esteemed colleague and friend, William Walters, in which the time-honored 1-D long-rod penetration equations attributed to Tate (1967) and Alekseevski (1966) were analytically solved for the first time.

2.1 An Exact Solution of the Long-Rod Penetration Equations

William Walters, a legend in the field of shaped-charge mechanics, has been a close friend of mine since the first days of my federal employment. He served as an early mentor to me and even sat on my PhD thesis committee at Drexel University. It was Dr Walters who, while working to produce an exact solution to the Alekseevski–Tate equations, introduced me to the problem around 1990.

The Tate model has been the archetype for long-rod penetration mechanics since the 1960s. However, solution required numerical integration because of the highly nonlinear formulation of those four simple-looking equations that constitute the model. Using an unlikely and inspirational transformation of variables, Walters and I were successful at *analytically* solving Alekseevski–Tate using a series solution. The results appeared in BRL-TR-3180[20] (1990) and *Int J Impact Engng*[21] (1991).

This work, and the mentorship of Dr Walters, created for me a lifelong love of analytical modeling and exact solutions to differential equations. More than a decade later, he and I revisited the work, confident that improvements and extensions could be had. A beautiful closed form solution, valid even under special cases of the input conditions, was obtained for the eroding rod length, $L(V)$:

$$\frac{L}{L_0} = \left(\frac{\sqrt{\gamma}U - \dot{L}}{\sqrt{\gamma}U_0 - \dot{L}_0}\right)^{\frac{1}{\sqrt{\gamma}}\left(\frac{R}{Y}-1\right)} \exp\left[\frac{V_0\dot{L}_0 - V\dot{L}}{2Y/\rho_r}\right] \quad ,$$

since U and $\dot{L}$ can be expressed algebraically in terms of V. Expressions for the variables (including penetration) in terms of time t are still solved in terms of a series solution but, unlike the original paper, it is a single sum of Bessel functions, rather than a double summation. The paper addresses the latter stages of penetration, as well, when eroding-rod penetration transitions to either rigid-body penetration or else simple-rod erosion upon a rigid target. Finally, the full range of special case solutions, such as $\rho_r = \rho_t$, $R = Y$, $R = 0$, $Y = 0$, and $R = Y = 0$ are all addressed. This latter work was published as ARL-TR-2855[22] (2002) and also appeared in *Int J Impact Engng*[23] (2003). It was also presented at IMPLAST '03 in India.[24]

2.2 Equation of State

In the classical theory, when a pure material is subjected to a given density (*i.e.*, specific volume) at a given temperature, the remaining intrinsic characteristics of the material (its pressure, entropy, *etc.*) are uniquely determined in what is called its "state". The characterization of the multitude of possible states in which a material can find itself is called the equation of state (EOS), the study of which falls in the branch of engineering known as thermodynamics. In particular, thermodynamics comprises not only the study of material states, but the theory associated with the *transition* from one state of a material to another. For example, if you compress a piece of copper from one density to another at constant temperature, you will end up at a different state than if you had done so by way of adiabatic shock compression.

My interest in EOSs grew out my study of their application and implementation in hydrocodes, to which I was first exposed during my graduate studies. I had already been pursuing hydrocode design and application outside of the government lab setting (for which I asked and received a blessing from BRL), as the principal developer of the ZEUS hydrocode, along with my external employer and mentor, Dr Jonas A Zukas.* There appear a number of publications by Segletes and Zukas in the time frame 1989–1993 concerning these ZEUS-related activities.[25–32] Additionally, ZEUS was prominently featured in Zukas' treatise, Introduction to Hydrocodes. Inside BRL and later ARL, however, my bent was on the more theoretical aspects of EOSs.

2.2.1 EOS Stability

In the early 1990s, one of the occasional modes of hydrocode failure was an uncontrollably diminishing timestep that seemed intricately intertwined with the EOS specification. These failures generally occurred under extreme loading conditions or, alternately, extreme distortion of a Lagrangian cell within the simulation. I noted a linkage between these failures and the functional specification of the Grüneisen material parameter, Γ, a thermodynamic function that provides a linkage between the mechanical and thermal behavior of a material. The mechanical description of the material is characterized through a thermodynamic $p(V)$ reference curve. While, in theory, any reference curve would do, hydrocodes universally adopted the shock Hugoniot† as the reference, since that is the thermodynamic curve for which high-pressure experimental data was most readily available.

Because of the difficulty in obtaining useful material data, the experimental understanding of the functional behavior of Γ was quite limited. Thus, hydrocodes tended to use *ad hoc* specifications for Γ, ranging from a constant to one of several empirical functions that monotonically decreased with increasing compression. While in the most general thermodynamic sense, $\Gamma = \Gamma(V, E)$, all hydrocodes make use of the Grüneisen assumption that $\Gamma = \Gamma(V)$ alone. This very important assumption in thermodynamics is based on a 1926 paper by Eduard Grüneisen.‡ The statement that $\Gamma = \Gamma(V)$ follows logically from assuming that the frequencies of all mechanical vibrational modes in the crystal lattice of the material change in a similar propor-

*Note that the name ZEUS was coined by me, not as homage to a Greek god, but as a unique conjugation of the first two letters of ZUkas and SEgletes.

†The Hugoniot does not represent a thermodynamic path, but rather represents the locus of final thermodynamic states that can be obtained from an initial state by way of shock transition.

‡The paper, "Zustand des festen Körpers", appeared in *Handbuch der Physik* (1926 V10, p1), a German encyclopedia of physics. Interestingly, the English translation of this lengthy seminal article, performed by NASA in 1959, remained limited in its distribution until I, as a private citizen, requested a Freedom of Information Act (FOIA) reevaluation of the distribution (I was legally unable to place the request under my purview as a government employee). The downgrading to public distribution was accomplished December 2012. The report's translated title is "The State of a Solid Body", a NASA republication, with the report number RE 2-18-59W (AD0215056).

tion, for a given change in lattice volume. With this Grüneisen simplification, the (incomplete) EOS may be characterized as

$$p - p_{\text{ref}} = \frac{\Gamma}{V}(E - E_{\text{ref}}) \quad ,$$

where "ref" is any thermodynamic reference curve for which the (p, V, E) states of the material are known. This is the form seen in nearly all hydrocodes, since (p, V, E) data is precisely that which derives from high-pressure shock testing.

My initial contribution was in constraining the EOS specification so as to avoid unstable mechanical response in the material. Several criteria were initially developed: 1) the local Hugoniot slope must exceed the slope of the pre/post shock Rayleigh line, 2) the value of $\Gamma(V)$, during a shock from V_0 to V, must satisfy the relation $0 < \Gamma < 2V/(V_0 - V)$, and 3) the bulk sound speed along the compressive isentrope from V_0 must remain positive for stability to be retained. This work was published in the *J Applied Phys*[33] (1991) and BRL-TR-3214[34] (1991). The latter work was awarded the Terminal Ballistics Division Report of the Year, as noted on the long-standing plaque in the lobby of the Zornig Building (309) at APG.

From this work grew the understanding that Γ and the Hugoniot are intimately related. Yet, hydrocodes did not treat them that way.[35] The specification of Γ was done independently of the Hugoniot reference curve $(p_{\text{ref}}, V, E_{\text{ref}})$, which would occasionally lead to a violation of the stability criteria that I had posited. This understanding was a turning point and would lead to much of my work for years to come, as you will read in Section 2.2.2.

My extensions on the subject of EOS stability continued through the 1992 transition from BRL to ARL, with *J Applied Phys*[36] (1994), ARL-TR-234[37] (1993), in Computational Mechanics '95,[38] and as a chapter in Constitutive Laws.[39] Recently, in 2019, I learned that Sandia National Laboratories had incorporated my stability constructs from this era into their CTH formulation as a means to pre-check the EOS stability of the specified material properties (SAND2018-12925).

2.2.2 Segletes EOS and the Grüneisen function, Γ

In early work on lattice mechanics, harmonicity (lattice springs whose stiffness does not change with lattice spacing) was often postulated for the sake of simplicity. Grüneisen was able to show that such a postulate leads to a trivial case of $\Gamma = 0$.

While the Grüneisen function Γ is typically expressed thermodynamically as $\Gamma = V(\partial p/\partial E)_V$, Grüneisen, through statistical mechanics, was able to relate the function to the characteristic vibrational frequency ω of the lattice in the following way: $\Gamma = -d\ln\omega/d\ln V$. This characteristic frequency is, in fact, proportional to the characteristic temperature of the lattice $\omega \propto \Theta$, a key term of specific-heat theories (therefore, $\Gamma = -d\ln\Theta/d\ln V$, as well). Thus, the lattice parameter Γ, which relates the compressive and thermal properties of the lattice, can only capture the real world with anharmonicity, when the lattice stiffness varies with compression.

I was familiar with analytical offshoots of Grüneisen's work from the 1950s and prior, in which researchers (Slater, Dugdale and MacDonald, Vaschenko and Zubarev, Pastine) had attempted to establish linkages between Γ and a material's so-called "cold" (low-temperature isotherm/isentrope) compression curve. Since that time, however, much of the work on lattice vibrations had become computational through the use of molecular dynamics and other methods. However, there remained some analytical work on expressing low-temperature isotherms $p_c = p_c(V)$ or $E_c = E_c(V)$ at constant T. One such model, in particular, intrigued me: the so-called universal EOS by Rose et al. (1984), given as

$$E_c = E_b[1 - (1 + a + 0.05a^3)\exp(-a)] \quad ,$$

where E_b is the lattice binding energy and a is the independent variable directly proportional to the lattice extension (and hence a function of V). Note that, despite the name "EOS" applied to this model, it is in fact a mere isotherm and tells nothing of the behavior of thermodynamic states located distally from the cold isotherm.

My earlier work on EOS stability had taught me that a material's compression curves such as the Hugoniot and isotherm are intimately related to its Grüneisen function Γ. Grüneisen had demonstrated the relation between Γ and the characteristic frequency of the lattice ω. In 1996, I had an important revelation about high-pressure EOSs—namely, in a moment of inspiration, I considered a transformation of the universal EOS, one in which E_c could be expressed solely in terms of ω (or Θ) as

$$E_c = E_b[1 - (1 + f)\exp(-f)] \quad ,$$

where

$$f = -K\ln(\Theta/\Theta_0) \qquad \text{and} \qquad K = \frac{C_0}{\Gamma_0\sqrt{E_b}} \quad .$$

While the equation looks in many ways like the universal EOS (with f replacing a), here f is formulated as a function of lattice vibration, rather than lattice extension. This insight came as the result of two steps. First, solving the complementary solution of the Grüneisen EOS, given as $p_c V/\Gamma - E_c = 0$, reveals $E_c \propto \Theta$ (long known to Einstein and Debye in their specific heat work). But second, in the simplest departure from the complementary solution, in which $p_c V/\Gamma - E_c \propto \Theta$, the particular solution of the Grüneisen equation is $E_c \propto \Theta \ln \Theta$, which leads one almost directly to the form above proposed by myself.

Since $p_c = -dE_c/dV$, a Grüneisen-style EOS can be assembled that captures both compressive and thermal behavior automatically. Furthermore, these behaviors are intertwined in the EOS and cannot be separately specified as a form of curve fitting. If one thermodynamic path is fit, all others proceed from that. The result is

$$pV/\Gamma - E = \left(\frac{C_0}{\Gamma_0 K}\right)^2 \left\{\left[(\Theta/\Theta_0)^K - 1\right] + K(K-1)(\Theta/\Theta_0)^K \ln(\Theta/\Theta_0)\right\} \quad .$$

Parameter K is difficult to experimentally measure* and is, therefore, fitted. Unlike prior approaches, such as the universal EOS that could predict an isotherm, this EOS could accurately predict *all* of the various thermodynamic paths for materials, such as the isotherm *and* the Hugoniot, out to extreme pressures, using handbook constants and what amounts to a single fitting parameter, an unheard of feat for an analytical EOS. Such examples are shown in Fig. 4, where the modeled pressures extend to levels recorded in nuclear-explosion tests.

My initial publication of this result (ARL-TR-1270[42] [1996]) was followed by many more refinements and side studies. Presentations at Virginia Tech[43] and the 1997 and 1999 SCCM conferences,[44,45] as well as articles in *Int J Impact Engng*[46] (1998) and *J Phys Chem Solids*[47] (1998), garnered a significant interest in the work internationally. Such interest paved the way for me to receive the 1998 ARL Science Achievement Award† (the first to do so as a sole recipient).

*In later work (ARL-TR-1757[40]), K was refined to $K = [\Gamma_{\mathrm{vol0}} + 1 - 3/2 \cdot \Gamma_0 (d\psi/dV)_0]/\Gamma_0$, where $\psi = V/\Gamma$. In theory, this is a knowable quantity, but difficult to measure.

†In addition to the ARL publication of the year award, the top three researcher awards at the ARL comprise, respectively, the Science, the Engineering, and the Analysis Achievement awards, which are given annually. In addition to the Science Award in 1998, I later was awarded the ARL Engineering award in 2012, and was WMRD's nominee for the 2008 Analysis Award. I consider my nomination for all three awards, *each as a sole recipient*, and my garnering two of the three, as my highest professional achievement, indicating the breadth of my research activities.

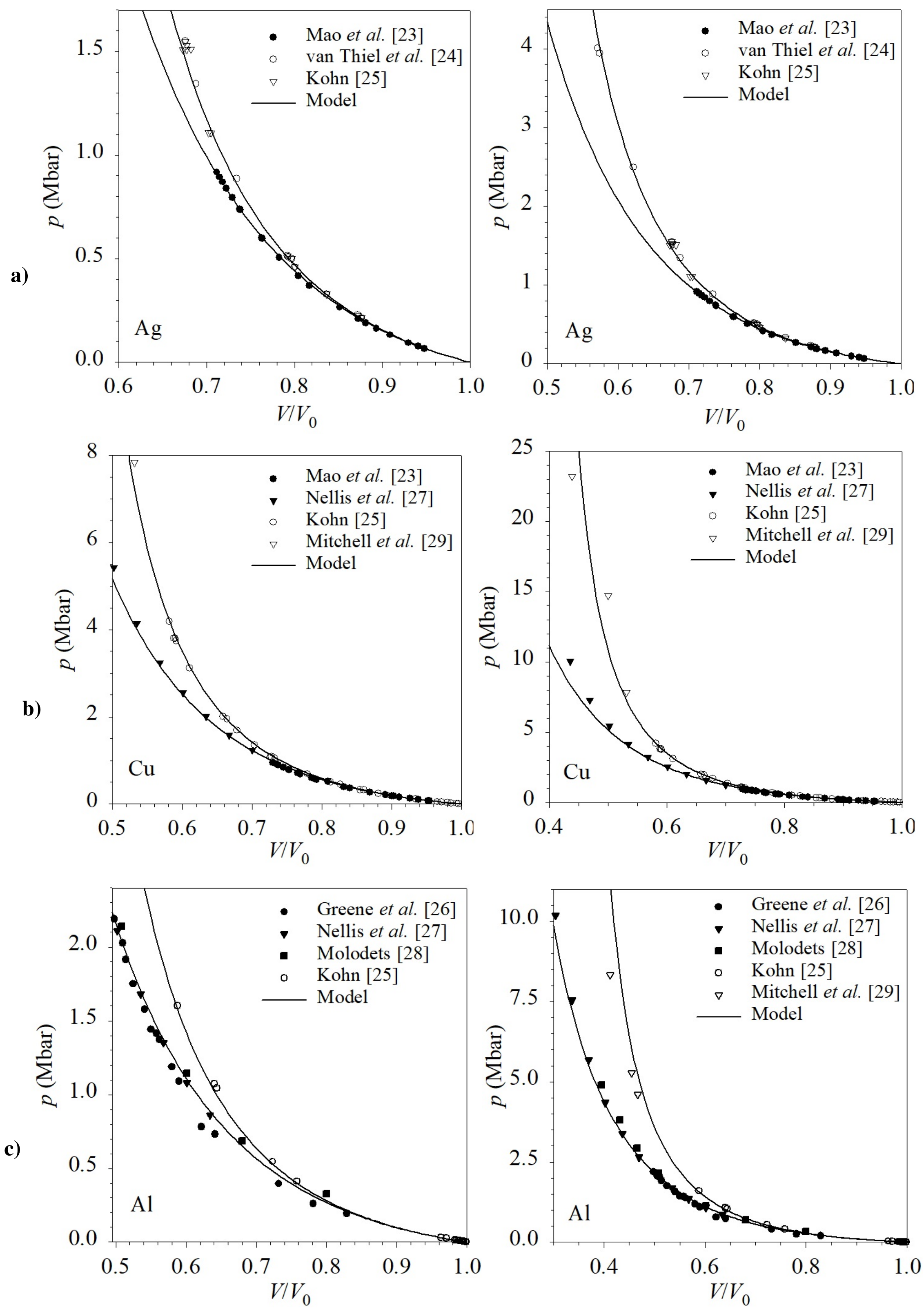

Fig. 4 Cold-compression and shock-Hugoniot curves from the Segletes EOS, at low and high pressures for a) silver to 1.5 and 4 Mbar, b) copper to 8 and 25 Mbar, and c) aluminum to 2.2 and 10 Mbar. Note that cold-compression comparison data are filled symbols and shock-Hugoniot data are open symbols.[41]

My ongoing research in EOS, extending for decades, focused on the following:

- Unifying historical Grüneisen descriptions into a single framework (ARL-TR-1303[48] [1997], SCCM-1997,[44] ARL-TR-3881[49] [2006]).
- Understanding and describing the differentiation that arises between a volumetric and vibrational stiffness in a lattice, arising from anharmonic interactions with non-nearest lattice neighbors (ARL-TR-1403[50] [1997], SCCM-1999,[45] ARL-TR-1757[40] [1998], ARL-MR-0900[51] [2015]).
- Quasi-harmonic approximation to the Segletes EOS (ARL-TR-1357[52] [1997]).
- Thermodynamic relations along the principal Hugoniot (ARL-TR-1641[53] [1998], *Shock Waves*[54] [1998]).
- An important result was established a decade later in ARL-TR-4041[55] (2007): "Any macrothermodynamic model which purports to describe a material with a temperature independent Grüneisen function is thermodynamically constrained to simultaneously describe entropy and C_V as sole functions of ω/T (or, alternately, of T/Θ)". Put another way, if entropy S and specific heat C_V are both expressible solely in terms of a third [implicit] variable, then it follows that, for Grüneisen materials, $C_V = C_V(S)$.
- A paper examining the underpinnings of the popular Jones-Wilkins-Lee (JWL) EOS are presented in ARL-TR-8403[56] (2018).

A comprehensive overview of my EOS research through 2002 was published in an invited page-1-volume-1 article of *Recent Res Devel Phys Chem Solids*[41] (2002), later reprinted as "Classical Methods for Frequency-Based Equations of State" ARL-RP-166[57] (2007).

2.3 Generalized Bernoulli Equation

Just as the decade had begun with an important analytical solution in collaboration with William Walters, the Alekseevski–Tate equations, so the decade closed with one: "A Note on the Application of the Extended Bernoulli Equation" (ARL-TR-1895[58] [1999], *Int J Impact Engng*[59] [2002]). In this important work, the venerable Bernoulli equation workhorse, relating the pressure, velocity, and elevation potential of material points along a streamline, was rederived from the ground up, but without making all the simplifications common for pedagogical instruction. The resulting integral equation, shown below, allows for unsteady, compressible, rotational, viscous flow in a noninertial reference frame with arbitrary body forces (not just gravity). Because of its utility for advanced instruction, it continues to receive respectable citations in the literature to this day.

$$\overset{\text{unsteady}}{\int_{R_1}^{R_2}\left(\frac{\partial V_{xyz}}{\partial t}+\frac{d^2S}{dt^2}\right)\cdot dR} + \overset{\text{rotational}}{\int_{R_1}^{R_2}(\nabla\times V_{xyz})\cdot(V_{xyz}\times dR)} +$$

$$\underset{\text{noninertial}}{\int_{R_1}^{R_2}\left(2\Omega\times V_{xyz}+\Omega\times(\Omega\times R)+\frac{d\Omega}{dt}\times R\right)\cdot dR} = \left(\underset{\substack{\uparrow\\ \text{body-force}\\ \text{potential}}}{\Phi} - \frac{V_{xyz}^2}{2}\right)\Bigg|_{R_1}^{R_2} + \int_{R_1}^{R_2}\left(\underset{\substack{\uparrow\\ \text{elasto-}\\ \text{viscoplastic}}}{\frac{s_{ij,j}}{\rho}} - \frac{\nabla p}{\rho}\right)\cdot dR$$

2.4 Other Work

Other topics on which I published in the 1990s included:

- Working with the Navy's Explosive Ordnance Disposal (NAVEOD), we developed a reusable render-safe device for unexploded bomb fuzes (ARL-TR-665[60] [1995], *Int J Impact Engng*[61] [1996], ARL-TR-1620[62] [1998]), eventually resulting in a 2002 US patent 6,363,828.[63]
- A 1998 US Patent 5,847,312 on a novel warhead design.[64]
- Linear shaped demolition-charge simulations (ARL-TR-788[65] [1995], ARL-TR-976[66] [1996]), again for NAVEOD.
- A treatment of homogenized penetration (ARL-TR-1075[67] [1996], *Int J Solids Structures*[68] [1997]), an analytical method for treating the impact of heterogeneous bodies at hydrodynamic velocities. This was part of a larger effort directed at theater-missile defense.
- A compact analytical fit to the Exponential Integral $E_1(x)$ (ARL-TR-1758[69] [1998]). This approach has been adapted (with citation) by several researchers.
- The soft recovery of a (large yet fragile) ballistic projectile (ARL-TR-2034[70] [1999]).

3. The 2000 Decade

With the new millennium, my focus on EOS slowly curtailed and my efforts returned to my ballistic roots. With an increasing emphasis on computational approaches, there nonetheless remained a need for analytical and reduced-order approaches to problems, especially in the case of our sister directorate SLAD (now the

US Army Combat Capabilities Development Command Data & Analysis Center), who required fast-running models that could be statistically probed over millions of Monte-Carlo iterations.

3.1 1-D Penetration Model: The Frank–Zook/Walker–Anderson Hybrid

The archetype for 1-D long-rod penetration models is the Alekseevski–Tate model. However, it suffers several deficiencies in its modeling. It assumes a slender rod, in which the rod diameter is always far smaller than the length. This assumption can become poor late in the eroding-penetration process if the residual rod length shrinks toward zero. In addition, the idealized model assumes a monolithic semi-infinite target. Thus, there is no way for the model to sense an impending target interface.

The Frank–Zook (FZ) model (BRL-MR-3960 [1992]) was a numerically integrated version of the penetration equations, suitably modified in an attempt to remedy the intrinsic deficiencies of Tate–Alekseevski. It worked very well, but it too suffered a deficiency: it could sense only one target interface in advance. This empirical "sensing" took the form of smoothly adjusting the target resistance from the current layer's value to the new layer's value, as the rod/target interface approached the new layer. For a layered target composed of thick slabs, such an approach is wholly sufficient. But with potential shotlines of interest clipping target element edges and corners, this approach suffered in a fundamental way.

In reality, the target resistance, a scalar value in the range of 3–5 times the material's uniaxial strength, arises from an integral effect of the target deformation field ahead of the rod–target interface. Thus, any target layer that deforms in advance of the rod–target interface, in fact, contributes toward the scalar value of target resistance. If the element thickness along the shotline is small, the target-deformation field could span several target elements, each of which contributes some resistance.

At that time, I searched the literature and came across a paper by Walker and Anderson (WA; 1995), which proposed a consistent deformation field ahead of a generic eroding rod–target interface, and was able to analytically integrate that field to calculate the target resistance. I combined the WA concepts into a model construct based on the FZ scheme, and the resulting FZWA model was able to build up the capability of the underlying FZ approach.

The effort is documented in ARL-TR-2336[71] (2000), as well as the proceedings of the 22nd Army Science Conference[72] (2000) (also ARL-RP-23[73] [2001]), where the poster was briefed to the Secretary of the Army, Louis Caldera (challenge coin accepted!).

3.2 Erosion Transition

I also spent time investigating the interesting phenomenon of erosion transition. Coming from an extensive background in modeling eroding penetration, the conditions necessary to erode a rod seemed clear: the combination of target resistance and inertial load on the rod–target interface must produce enough stress to overcome the intrinsic strength of the rod. Once this condition is met, rod erosion seems a foregone conclusion. But, much to the surprise of many (including myself, initially), that is not always how it happens! I learned of prior test results and simulation of this phenomenon from colleagues Dr Magness and Mr Scheffler.

If the impact velocity is moderate and the target density low, a situation can arise in which the energy deposition rate into the eroding target is small enough to inhibit large radial flow. The resulting crater finds the target laterally impinging on the penetrator with significant stress, a condition not contemplated in the Tate–Alekseevski equations, thus making them inappropriate to describe the situation.

The net result is not only that rod erosion is prevented, but that the stress that the rod is able to bring to bear on the rod–target interface is augmented by the lateral target stress, thereby permitting the rod to penetrate as a "rigid" body with an apparent strength far beyond the actual rod strength. The rod is not *actually* rigid—it may grow slightly in diameter and diminish in length—however, it retains its essential pre-impact shape because there is not enough radial inertia to establish an eroding interface. This phenomenon is highly dependent upon the initial nose shape of the rod: flat-nosed rods are not prone to it, whereas spherical-nosed and especially ogival-nosed rods are most prone.

I studied the kinematics of the erosion transition event and reformulated penetration equations that would take into account the effect of the target's lateral constraint (Fig. 5). To that end, I formulated a strain-based transition criterion that would predict how long the noneroding phase of penetration could endure before transitioning to full erosion. In sum, I brought quantitative analysis to bear on this poorly understood phenomenon.

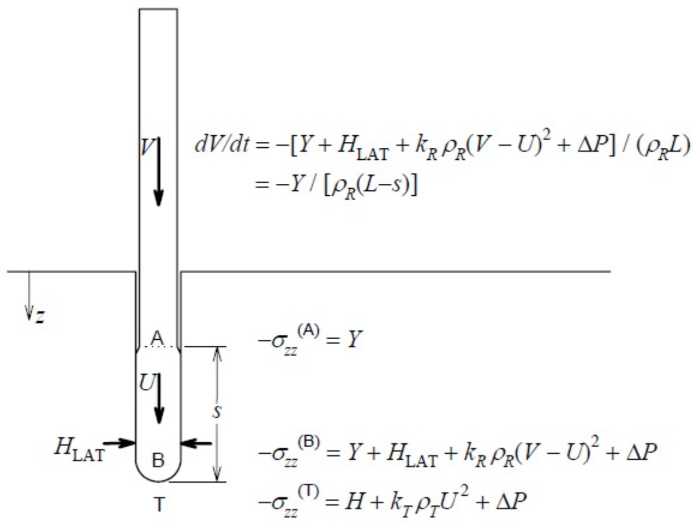

Fig. 5 Schematic depicting the prevailing equations for the phenomenon of noneroding penetration, which differ markedly from the classical penetration equations because of the target's lateral interference at the nose, inhibiting rod erosion[74]

Publications arising from the work included ARL-TR-3075[75] (2003), ARL-TR-3153[76] (2004), and *Int J Solids Structures*[74] (2007). In addition, I used this concept of erosion transition to make sense of dynamic indentation data that had been gathered to study penetrator dwell into ceramic targets (unpublished notes[77–80] [2004]).

3.3 Long-Rod Ricochet

The topic of projectile ricochet is one of great ballistic importance. And while the nose shape of the rod can play a significant role, models tried to instead examine various sorts of kinematic balance. Several analytical models for it were in existence before I reexamined the situation. A model by Tate (1979) existed, which was based on morphology of a rigid rod. In the model, the rod–target interface could exert lateral force on the rigid rod, causing it to rotate about its center of gravity (CG). If enough rotation rate in the rod could be developed so as to change the net velocity of the rod tip parallel with the target surface, ricochet was deemed to have occurred.

Later, Rosenberg (1989) developed a model in which the rod–target interaction force did not rotate a rigid rod, but rather, acted locally in an attempt to redirect the interacting rod mass away from the target surface. In both models, a critical ricochet angle was defined in terms of material strength and density parameters, as well as striking and penetration velocities of the interface. In the case of Tate's model, the rod geometry also plays a role.

I adopted a totally novel approach, after seeing radiographic imaging by Senf *et al.* (Sixth International Symposium on Ballistics, 1981), in which the ricochet of long rods occurs by way of progressive bending and redirection of rod material. Based on this, I considered the morphology of ricochet as one in which a moving rod is fed into a stationary "plastic hinge" zone, in which the rod momentum of the intact rod material is redirected, such that the original rod material exits the plastic hinge traveling along or away from the target surface, rather than into it (Fig. 6). The ricochet criterion that arises considers the following question: is the target interaction force and moment large enough, so that acting over the full duration of rod bending, a steady-state flow-turning of the rod can be established while conserving momentum? If the answer to this question is yes, then the model envisions the situation where the complete rod enters the plastic hinge from one direction and leaves it going in a new direction, with the target interaction forces being large enough to effect this change. Excepting the situation when the rod velocity is very slow, the rod length is immaterial to the ricochet process.

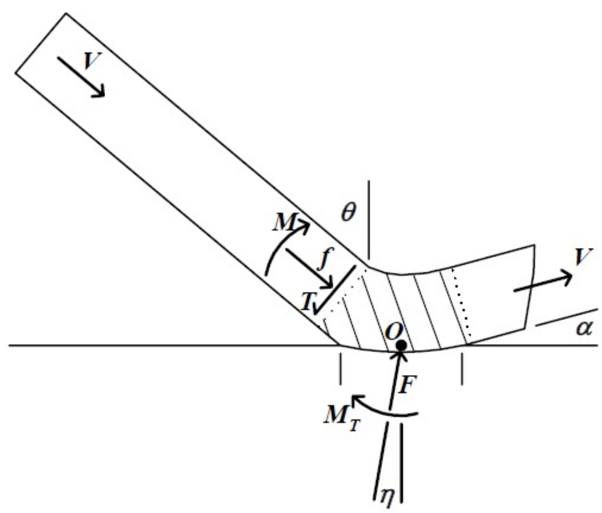

Fig. 6 A macro-view of ricochet phenomenology, depicting forces and moments upon and fluxes through the plastic hinge contained within the shaded control volume of the rod[81]

I published these results in ARL-TR-3257[82] (2004), *Int J Impact Engng*[81,83] (2006,* 2007), and ARL-RP-164[84] (2007).

*This work had the distinction of being the subject of a 2009 plagiarism scandal in which Iran's Science Minister, Kamran Daneshjou, was accused by *Nature* of plagiarizing several western papers, including my own ricochet model! Daneshjou had, as part of the Interior Ministry, played a key role in returning Iranian President Mahmoud Ahmadinejad to power (see Appendix).

In the years that followed, I collaborated with Prof Bakhtier Farouk, *et al.*, at Drexel University to revisit rod-ricochet modeling, this time augmented with computational comparisons (IMECE-2016,[85] *Defense Sci. J.*[86]). Additionally, cases of ricochet off air–water interfaces were studied in *Int J of Multiphysics*[87] (2019).

3.4 MRAP

One highlight of my career was my contribution to the MRAP and expedient-armor programs—high-profile programs involving many engineers and researchers at ARL. The overarching purpose was to develop armor solutions for a new and existing vehicles that would successfully defeat improvised explosive device (IED) threats being experienced in the Iraqi and Afghan war zones. Representative warhead threats were established, but unlike any warheads of prior wars, these were very low-precision threats. Therefore, the domestically produced representative surrogates were intentionally constructed with low precision.

This decision caused a major problem in the evaluation of candidate armor systems. If a candidate armor failed during proof testing, was it because the candidate armor was a poor design or was it because the *particular instance* of threat surrogate was performing at the high end of the large standard deviation in performance? If it was the latter cause, then one might accidentally discard an otherwise good design for the wrong reason.

Experimentalists captured radiographic images of the flying warhead particles for each test, prior to their striking the candidate armor designs. Subjective assessments were made of warhead *quality* on the basis of these images, as a way to try to answer the underlying question of outcome *cause*. The approach left much to be desired.

I was approached to resurrect my former PENJET model from the 1980s, which would provide a *quantitative* assessment tool for evaluating warhead quality. Adaptation was required, as the warhead particle characteristics were different than those historically addressed by PENJET. The model was reconstructed and coded and, in a classified setting, I set about taking the digitized inputs from literally hundreds and hundreds of ongoing tests and using PENJET as a warhead quality assessment tool. Rather than merely classifying the warhead as excellent, good, fair, or poor, as the qualitative approach had, PENJET was able to assign a numerical value to the warhead used in the particular test, corresponding to the expected penetration into a hypothetical monolithic rolled homogeneous armor (RHA) block (recall, actual tests were into candidate armors, not RHA blocks).

These quantitative assessments, done in the immediate aftermath of testing, helped guide the armor designers in selecting proper designs for the various MRAP armors. For this work, I was the WMRD sole nominee for the prestigious 2008 ARL Analysis award. While I did not go on to receive the award that year, two anecdotes from the nomination package sum up additional impact that the use of PENJET brought to the table:

> In one case, a cheaper, widely available, domestically supplied target material was being considered by the armor designers as a replacement for a more expensive, limited-supply, foreign manufactured material. The domestic variety was nearly discarded from consideration on the basis of several screening tests. However, subsequent PENJET analyses indicated that the warheads which defeated the domestic material were of superior quality. On this basis, the domestic material was subjected to a full battery of testing, which corroborated PENJET's conclusions. The material is, as a result, still under consideration as a viable MRAP armor component. Dr Scott Schoenfeld, ARL's Mitigate Technical Manager, declared Dr Segletes "a hero" for this use of PENJET, given the materiel acquisition constraints and the potential to simultaneously save soldier's lives and taxpayer's monies.
>
> Dr Segletes has extended his use of PENJET, in support of MRAP, beyond an analysis of candidate armor designs. For example, twice in 2008, Dr Segletes raised a red flag and said that his PENJET analyses were indicating that the performance of one particular standard MRAP surrogate warhead design seemed to be changing over the span of several months, both in terms of mean performance as well as standard deviation. In both instances, additional testing of the device was ordered into RHA baseline targets to assess the accuracy of Dr Segletes' warning and its implication for the program. In both instances, the RHA retesting corroborated the results predicted by PENJET. The LMB has since embarked on a separate program to correlate surrogate warhead performance to some identifiable measure of manufacturing quality and/or lot-to-lot manufacturing variation.

A summary of my efforts in this multi-year project are documented in a classified 2019 ARL technical report. During the period, I also shared briefs of the work with our UK allies. There does exist an unclassified status briefing[88] of the PENJET approach, delivered near the very outset of my involvement in the project.

3.5 Gelatin Penetration

With a renewed interest at ARL in small-caliber bullet design, there was a focus on ballistic gelatin, which is considered a standard surrogate for living tissue. Its hyperelastic qualities make it different and unique as compared with other ballistic target materials. I created an interesting analytical model for the penetration into ballistic gelatin, using a strain-rate dependence, in ARL-TR-4393[89] (2008). It provided a clear improvement in calculating the late-time deceleration and arrest of the projectile over the prior "state of the art", which had used Resal's Law as employed by Sturdivan. Because of the extreme popularity of gelatin penetration in the non-professional class of game hunters, this paper enjoyed, for a time, wide discussion and use in various small-arms and hunting weblogs and online discussion boards.

3.6 LaTeX

A review of my career would not be complete without at least touching on my devotion to the typesetting software prevalent in the scientific community, known as LaTeX. What started out initially as an effort by myself to avoid onerous constraints placed on ARL authors using Microsoft Word would blossom into a force of its own.

The public-domain TeX software has been around since 1978 (LaTeX is a standardized collection of macros written in TeX). It is essentially, a programming language for scientific typesetting. It is extremely powerful as a typesetting tool—however, the user interface requires a programmer's mindset. Nonetheless, so-called packages and document classes can be written, that is, *programmed*, for particular document layouts that streamline and simplify the user interface. Ideally, the user merely needs to enter the report's intellectual content and the resulting compilation produces a finished document, formatted to the current layout standards of the organization.

Halfhearted attempts at creating these packages existed in ARL when I got involved in 2006. So I decided to make a go of it and create a document class and stencil that would allow me and others to easily formulate complete (cover-to-cover) ARL tech reports, without the user having to worry about all the formatting issues. The document class I created steadily improved and became widely distributed around ARL for use by many authors.

I asked for and received permission, as part of my continuing professional education, to actively participate in the international online LaTeX forum, `tex.stackexchange.com`, in which users can ask and answer questions about LaTeX and its underlying TeX engine. Such interactions greatly enhanced my LaTeX skills. Over time, I have become a contributor, having written a number of *packages* that benefit the LaTeX user community internationally (see `ctan.org`[90]).

In April 2013, Ms Carol Johnson, acting team lead of ARL Technical Publishing (Tech Pubs) (and project lead for LaTeX), reached out to see if I could work with Tech Pubs to standardize *my* approach to the whole of ARL, for all authors wishing to use LaTeX. Later, when Ms Jessica Schultheis took over the team lead role for ARL Tech Pubs, she too heartily embraced this collaboration. Ongoing coordination with Tech Pubs has been required as document formats and standards evolve. Eventually, however, even Tech Pubs technicians are becoming proficient in creating ARL reports using my foundation. At this point, researchers across all campuses of ARL are using the so-called "arlticle" document class with the report stencils I have created in order to document their research in a beautiful, efficient manner. This very report is created with my ARL report stencil and document class.

I am often solicited for LaTeX assistance from researchers, not only in the laboratory, but around the world. I am only too happy to assist, as both the mastery of the TeXnique and a desire to help others brings me great joy.

4. The 2010s

After being challenged by my branch chief, Dr Todd Bjerke, to use analytical methods to develop a model to predict underbody loading from buried-explosive blast, I devoted myself, in what became a multi-year project, to developing an approach to what would come to life as the suite of programs known as MINE. For this work, I was awarded the 2012 ARL Engineering Award.

The citation specifically recognized me for making critical advances in modeling the vertical impulsive loading on a vehicle that results from a buried explosive charge, or IED, detonating underneath the vehicle.

4.1 The MINE Code for Underbody Loading

I developed a first-of-its-kind engineering tool called MINE, Momentum-Impulse Numerical Evaluation. The MINE model, which is compact in size and efficient in execution, provides a physics-based fast-running alternative to conventional shock-physics hydrocodes that easily facilitates parametric exploration of buried IED effects on vehicles. Also notable is the fact that my development allows for fully 2-D and quasi-3-D results to be obtained at the cost of a 1-D numerical integration.

Consider first the axisymmetric problem of a buried-charge detonation and the prediction of the axisymmetric soil response over time. Without an analytical solution, one might feel compelled to resort to a 2-D hydrocode to simulate the problem. Through the use of several key assumptions, the MINE software reduces the order of this problem through a what it calls a *compulytical* approach—a hybrid of computational and analytical methods.

With the approach, the radial equations of motion are separable from the polar-angle equations. Furthermore, the radial equations can be solved analytically, while the polar-angle domain is discretized. The resulting problem is reduced to a 1-D formulation, which can then be speedily integrated over time, to reveal the fully 2-D displacement-over-time behavior of the forming soil bubble, as well as the residual pressure state of the high-explosive (HE) products inside the bubble.

MINE is equipped to take this forcefully propelled axisymmetric soil bubble and calculate its impulsive interaction (as a function of both time and space) with a flat plate suspended above the ground. But that is not all. An adjunct module called *TARG* can be used to construct 3-D target structures and another named ***ORBIT*** can project, in 3-D, the soil impulse onto the elements of *TARG*'s discretized 3-D structure (Fig. 7).

MINE has the ability to pass its loading functions on as discretized inputs to the LS-DYNA solid-mechanics code, for cases where the target's deformation response is a vital part of the analysis. A number of users outside of ARL employ this code,

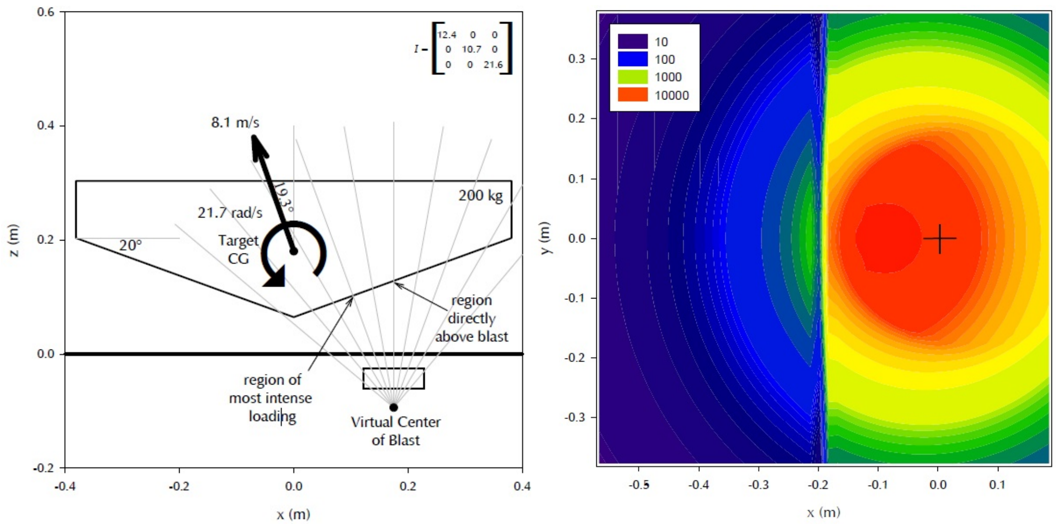

Fig. 7 An example of the MINE suite's ability to predict the blast loading distribution on a 3-D wedge structure, to include the resulting kinematic response[91]

including Capstone Project students at West Point, for several years running (ARL-TR-8917[92] [2020]).

I have published extensively on MINE, including the debut paper (GVSS[93] [2010], ARL-RP-312[94] [2011]), the theory paper (ARL-TR-6047[95] [2012]), a version for open-air near-field detonations (ARL-TR-6048[96] [2012]), an expansion adiabat formulation for nonideal explosives (ARL-TR-6567[97] [2013]), a MINE suite user guide (ARL-TR-6919[91] [2014]), and the theory behind the extensions to 3-D structures (ARL-TR-7597[98] [2016]). The work was briefed[99] to the National Academy of Science's Technical Advisory Board to ARL (TAB) in 2011, as well to the US/UK Armor Technology Working Group[100] (ATWG) in 2014, resulting in a transfer of the MINE code to the UK Ministry of Defence.

4.2 Projectile Trajectory Under the Influence of Drag

Dr Walters and I were tasked to estimate the safe range distance for an explosive device capable of producing several hypervelocity particles. While the work resulted in the report ARL-TR-5612[101] (2011) that directly answered the question, it sparked our interest in the more general problem of projectile trajectory under the influence of gravity and drag. This question, in modern times, is purely academic—computational fluid dynamics (CFD) methods are so pervasive and efficient that analytical approaches to simple aerodynamic drag problems are passé.

Nonetheless, because of the historical significance of the problem (having been formulated and studied by Galileo, Huygens, and Newton), Walters and I worked to solve the problem analytically with significant but not total success. In particular, the result in ARL-TR-5822[102] (2011) addresses the problem in curvilinear coordinates, such that the projectile's velocity components are solved as a function of the angle of trajectory. Additionally, the path length of flight is also available as a function of the trajectory angle. An approximation has also been obtained for the flight time as a function of the trajectory angle, for trajectories that are suitably flat. Still analytically elusive, however, are the Cartesian coordinates x and y of the projectile as a function of the trajectory.

4.3 Other Work

I had the chance to examine a vast number of new independent topics this decade, as well:

- During this decade, many fruitful collaborations developed with my good friend and mentor, Dr Michael Grinfeld. One such collaboration covered the area of mechanochemistry of fracture, in which a thermodynamic approach was applied to the topic of incipient decohesion. The simplest 1-D model was initially studied in which a constant, distributed bonding stress remains active in the process zone of decohesion of two attached but flexible films. This was affectionately known as the "velcro model".

  Results were developed both with energy methods (ARL-TR-5309[103] [2010]) as well as a force/displacement mechanics approach (ARL-TR-5310[104] [2010]). The work was presented at DAMAS 2011.[105] Other work followed, including Dr Bjerke in the collaboration, presented at the 2015 HVIS.[106]

- In 2012, I was asked by Dr Gary Haas of the Vehicle Technology Directorate (VTD) to conduct a safety analysis on their experimental "hovercage" facility, which was used to test lab-scale rotary-wing devices. The analysis considered the unexpected disintegration of rotary-winged devices operating at high rates of revolution. I conducted the ballistic analysis[107] on the existing facility design and made recommendations to VTD on how to improve protection for the laboratory personnel, in the event of unanticipated rotary-device malfunction.

- Dr Grinfeld, Mr Stephan Bilyk, and I collaborated and presented at the 2013 HVIS[108] on *operational* EOS, which is a historical technique for automatically generating models from the underlying data that is available—a very interesting approach that was adapted here to the application of EOS.

- Again, Dr Grinfeld and I studied and enhanced the thermodynamic concepts of latent work and latent heat associated with liquid/vapor phase transformations in ARL-TR-7008[109] (2014). In particular, it was shown that these concepts are rightly described as path-dependent (and not state) functions. The traditional concept of latent heat is a state function, but it only describes phase transformation processes that occur at constant pressure and temperature.

- In ARL-TN-0760[110] (2016), I analyzed the process of long-rod penetration with a twist: what if some repulsive body force could be applied to the rod from the moment of impact? How much body force would be required to make a ballistically significant reduction in the rod performance?

- In 2017, I performed a curious intellectual exercise in which I conceptualized a device that employs an explosively controlled actuator to intercept an event's line of action. I derived all the equations showing how it should work. While not yet built nor tested, the device may provide a way to achieve mass efficiency against ballistic attack (ARL-TR-8061[111] [2017]).

- I performed a very exhaustive study on the rigid-body dynamics of a spinning axisymmetric body that undergoes an impulsive (unbalanced) ejection of mass. The work, ARL-TR-8561[112] (2018), received praise from colleagues and was used to help determine the viability of certain armor concepts meant to disrupt the flight stability of threat projectiles.

- In 2018, I continued my long-standing collaboration with Dr Grinfeld, this time to examine an inconsistency in the classical electrostatics of metallic conductors. The inconsistency is the fact that, in classical theory, both negative and positive charges are treated symmetrically—in both cases as mobile charges. While this paradigm may be approximately true of ionic fluids, for the case of metallic solids, positive charges are locked in the lattice, quite immobile.

  Further, when a charge imbalance exists on, for example, a conducting sphere, classical theory posits that the excess (mobile) charge congregate on the body surface, distributed in a zero-thickness layer. While the areal density of charge may be finite, the volumetric density of this zero-thickness layer approaches the infinite. For the case of metallic solids, because positive charges are locked in the fixed lattice, they are constrained to a fixed volumetric charge density that falls short of the infinite idealization given by classical electrostatics.

Dr Grinfeld and I, often with Misha's son, Professor Pavel Grinfeld of Drexel University, worked to both recognize and resolve this inconsistency in ARL-TR-8365[113] (2018), ARL-TR-8492[114] (2018), 2019/20 SEM Annual Conference,[115] and for the spherical case, in ARL-TR-8631[116] (2019). Work to begin addressing the density singularity for excess negative charges began with ARL-TR-8897[117] (2020).

- While many might consider ARL-TN-0941[118] (2019) to be a "throw away" report, I am quite proud of it. Here, I analytically express the inertial properties for both tangent and secant ogives in closed form. Such work is useful for anyone needing to characterize the volume, CG, or moments of inertia of a given ballistic ogive, as part of a larger rigid-body or kinematic analysis. Its calculations are orders of magnitude more efficient than the comparable numerical integration alternative.

5. 2020 and Beyond

My career under the federal employ of ARL is reaching its end in 2021, though I hope going forward to remain active in research. Below, I recount two technical areas that drew my attention in 2020–21. Nonetheless, the most rewarding thing I did in 2021 was to shepherd the life work of former BRL researcher John Kineke (deceased) through to publication as ARL-TR-9253[119] [2021].

5.1 Electrical Conductivity in Mixed Computational Cells

My initial topic of focus this decade was the electrical conductivity of mixed computational cells. This topic had direct significance to the use, by others, of ALEGRA-MHD in addressing topics of terminal-ballistic interest by way of magnetohydrodynamics (MHD).

At the suggestion of my colleague Dr Grinfeld, I metaphorically conceptualized the material in a mixed cell as a network structured as a square or cubic electrical lattice. One might envision the linkages in the network as analogous to randomly distributed material in the mixed cell. The network can be studied statistically by considering the random distribution of linkage properties throughout the network (*e.g.*, $x\%$ conductor A, $y\%$ conductor B, with the balance as insulating void). Such statistical examination can help predict, for example, the likelihood of electrical connectivity across the network or even the expected value of network conductance.

While material in a real-world mixed-computational cell may not be randomly distributed, the results of such an analysis are instructive and may serve as a useful analogy. I have published my ideas in this area, as ARL-TR-8899[120] (2020), ARL-TN-1040[121] (2020), and ARL-MR-1030.[122]

This was not the first time I employed a statistical approach to address a problem in my field. In 2003, I authored the appendix to ARL-TR-3038,[123] performing the combinatoric analysis to calculate the likelihood of survivability for multiple random hits on an N-tile target array, where a threshold number of hits are required to defeat any given target tile.

In my latest report in the area (ARL-TR-9212[124] [2021]), I modeled the electrical conduction through materials in the mixed computational cell as an *equivalent* electrical subcircuit. Such an approach provided a direct test for model consistency, in that both effective conductivity as well as joule-heating distribution among the cell constituents follow directly from the circuit design. The behavior of various mixed-cell averaging models that I examined, including my own (AL-TR-8979[125] [2020]), could be verified through a comparison to the equivalent circuit that they represented.

5.2 Point Explosion, Line Explosion, and Crater Growth

In the summer of 2021 (with 3 months to go until my retirement), I suggested to Dr Grinfeld that we revisit the problem of point explosion, a result which we had originally presented to the 2016 APS Meeting.[126] That meeting produces no proceedings and I thought it a shame if that result were not otherwise published outside of a slideshow artifact. The original problem is a classical one, famously addressed by Sedov in the 1960s. In it, an explosion takes place instantaneously at a singular point and imparts its energy to the surrounding fluid media. In Sedov's treatment, a self-similar solution was developed, in terms of time and radius, for the case of a point explosion in the middle of an infinite expanse of fluid.

In our 2016 treatment, Dr Grinfeld, who had led our original derivation, generalized the scope of the problem to include an initial cavity of finite radius in the fluid as well as finite outer extent to the fluid bed. Further, the sphere of fluid was made to sit in an idealized reservoir at elevated pressure. By doing work on the expanding spherical shell of fluid, the reservoir pressure eventually arrests the crater expansion caused by the explosion. This generality ruins the self-similarity, but provides a rich problem to study. He sharpened his pencil and rederived the result, taking into account points that I had raised on various facets of the approach. Thus, we represented the unpublished 2016 result as ARL-TR-9247[127] (2021).

One point still niggled me, concerning the outer boundary condition of the point explosion. Dr Grinfeld correctly felt that addressing it in ARL-TR-9247 would have distracted the reader from the primary result. So I followed up in the immediate aftermath of publication and addressed the point with a short tech note ARL-TN-1074[128] (2021).

With my full interest piqued to the problem, I became inclined to rederive the complete result of ARL-TR-9247, but to do it for axisymmetric, rather than spherical, geometry. In the back of my mind, I knew that penetration mechanics is formulated along an axis, rather than at a point, and I sensed a possible connection between the problems. Dr Grinfeld, already focused in other areas, gave me his blessing to pursue it.

For this axisymmetric case, the point explosion becomes a "line explosion", in which an explosive situated along the 1-D axis of a cylindrical fluid shell instantaneously explodes and transmits its energy to the fluid. As in the case of the point explosion, the outer reservoir at elevated pressure performs work to arrest the crater expansion of the cylinder. This rederivation proceeded with no impediments and was quickly published (ARL-MR-1037[129] [2021]).

I then turned my sights on trying to connect the line-explosion solution to the problem of crater growth for the situation of eroding penetration. In both problems, energy is released along an axis which goes toward radially expanding the surrounding medium. One big difference, however, is that in the line explosion, the complete axis of explosive detonates *instantaneously*, whereas in eroding penetration, the deposition of energy along the axis is *progressive* in time and space. I reasoned that, because the progression of penetration is often very rapid, the plane-strain character of crater expansion is largely retained in the case of monolithic penetration.

Becoming comfortable on this point, the path forward was direct: for each of the five inputs to the line-explosion solution, develop a one-to-one correspondence to an input in the penetration mechanics problem. I visualized the problem as one in which the penetrator first created an axial indentation of its own diameter into the target. The radius of this initial indentation corresponds to the inner cylinder radius in the line explosion. Then, energy of the eroded penetrator not consumed in creating the axial indentation applies its remaining balance radially. This energy-deposition rate can be calculated on a basis per indentation depth and thus corresponds directly to the energy-per-axial-length input of the line explosion.

Without delving into the details here, I concluded that the outer diameter of the fluid cylinder in the line explosion corresponds directly to the diameter of the plasticity zone in the ballistic target. The outer reservoir pressure in the line explosion directly corresponds to the ballistic resistance of the target.

With a full one-to-one correspondence in place, the solution to the problem of time-dependent crater growth in the target translates into the solution of the equivalent line-explosion problem. The solution is elegant and direct, and was demonstrated in ARL-TR-9271[130] (2021)!

6. Epilogue

Working for the US Army at BRL and ARL has been the opportunity of a lifetime for me. How many people have the chance to use skills, for which they trained in the university, every day as part of their employment? How many have had the opportunity to spend their full career in a single role that they love? I cannot think of another place that would have provided the breadth of research topics to pursue, ranging from the purely theoretical to things that were so immediate and applied, so as to impact the lives of Soldiers in the field. The consistently high caliber of my colleagues always inspired me to do my best.

During my federal career, I remained active in technical matters outside of the laboratory, as well: serving as adjunct faculty at Drexel for a period, serving on Drexel's Mechanical Engineering and Mechanics Department Advisory Council, co-writing the ZEUS commercial software package in computational solid mechanics, supporting and promoting the use of the internationally accepted LaTeX scientific typesetting program, as well as tutoring local high school students in math.

As a loving son, I have enjoyed giving science, technology, engineering, and mathematics (STEM) presentations around the region on the topic of my father's own role in designing the heat shield that led to the world's first successful atmospheric reentry and payload recovery, Discoverer XIII (also known as the world's first spy satellite program, CORONA).* For reasons of classification, I did not learn of these and other of his stellar career achievements until the final years of his life, as he struggled in his battle with cancer.

For as long as I can remember, I have always wanted to follow in my father's footsteps—go to Drexel University, become a mechanical engineer, and work in a high-technology field. I cannot overstate the joy he brought when, just weeks before his passing in November 2012, he insisted to my mother that they travel several hours on the arduous journey to APG to see their son receive the 2012 ARL Award for Engineering (Fig. 8). I have been blessed!

Fig. 8 Steven B Segletes with his wife Gabriele and his parents Irene and John A Segletes, at the 2012 ARL Awards Ceremony at APG, Maryland

*In the last year of my father's life, I used the FOIA process to get several of his 50-year-old reports, documenting the Discoverer heat-shield development, declassified and released, including "Development and thermal performance of the Discoverer heat shield" (AD0328815) and "Thermal restudy of the Discoverer Mark 2 (bio-med) vehicle" (AD0362544); see Fig. 9.

I also was able to get our alma mater, Drexel University, to feature his story: https://drexel.edu/engineering/news-events/news/archive/2012/July/it_was_a_great_time_to_be_an_engineer/.

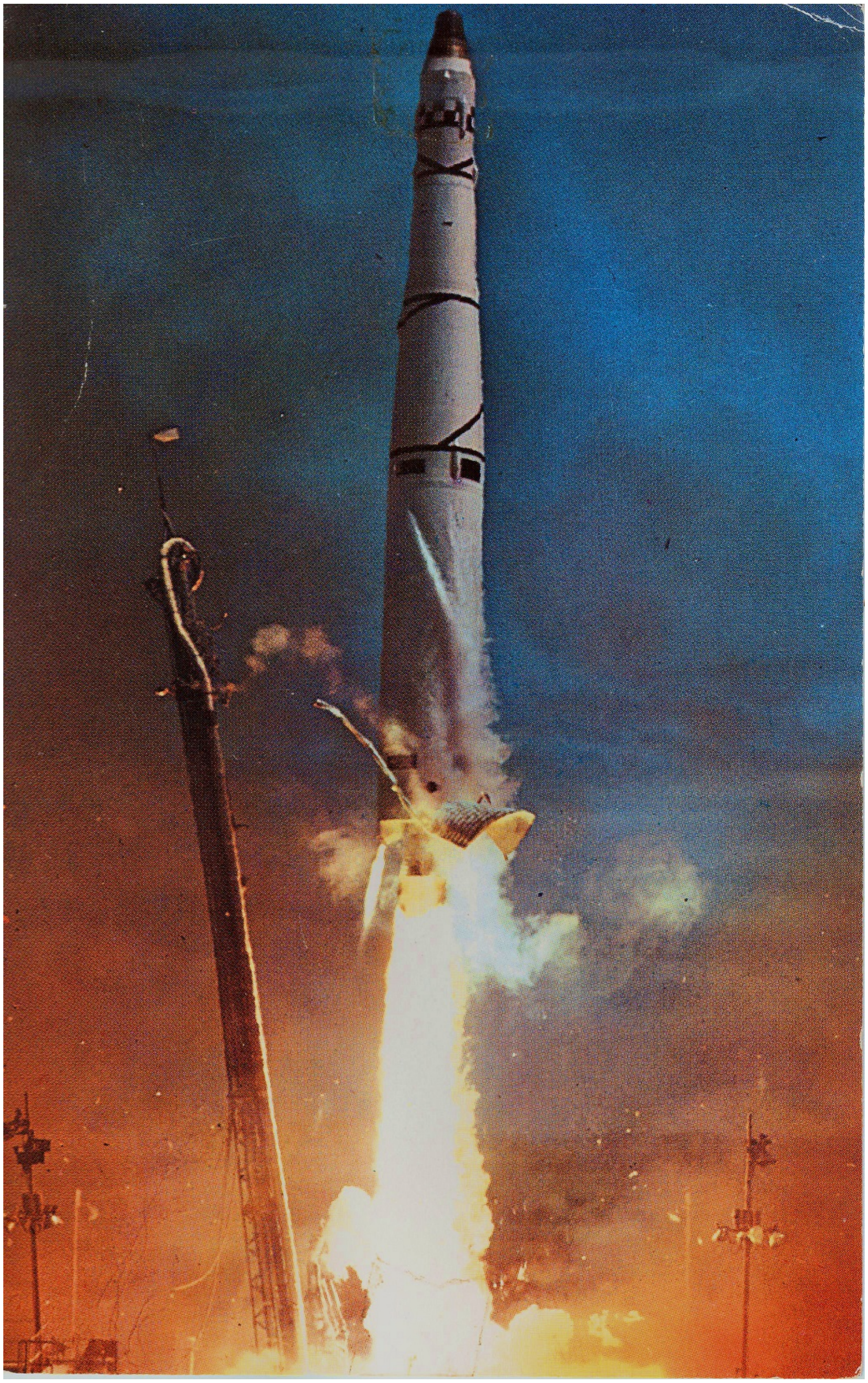

Fig. 9 John A Segletes played a key role in the design of the heat shield that sat atop the Discoverer rocket payload, allowing, for the first time ever, the successful recovery of an intact object from orbit in August 1960

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Appendix. Anatomy of a Scandal

I may be one of the few American military scientists that can claim, through an indirect chain of events, to have provoked protest demonstrations in a foreign capital. How did this strange set of events come to pass? On 2009 September 27, I was contacted by Declan Butler (Fig. A-1), a senior reporter for *Nature*. In it, he asked for my comment on his emerging story that accused Kamran Daneshjou, the Science Minister of Iran, of plagiarizing several western papers, including my own 2006 ricochet article that had appeared in the *IJIE*.

Segletes, Steven (Civ,ARL/WMRD)

From:	Declan Butler, reporter, Nature [@.]
Sent:	Sunday, September 27, 2009 8:31 AM
To:	Segletes, Steven (Civ,ARL/WMRD)
Subject:	Fwd: Urgent query from journal Nature re plagiarism allegations
Attachments:	A SIMPLE MODEL TO PREDICT CRITICAL RICOCHET ANGLE IN LONG-ROD; A SIMPLE MODEL TO PREDICT CRITICAL RICOCHET ANGLE IN.pdf; A SIMPLE MODEL TO PREDICT CRITICAL RICOCHET ANGLE IN LONG-ROD; Lee_Woong-2002.pdf; richotet.pdf

A SIMPLE MODEL TO PREDICT CRIT... A SIMPLE MODEL TO PREDICT CRIT... A SIMPLE MODEL TO PREDICT CRIT... Lee_Woong-2002.pdf (742 KB) richotet.pdf (630 KB)

Dear Steven

Please find below a message I have just sent to the editor of the Journal of Mechanics. It concerns a 2009 paper, which contains large amounts of text identical with your 2006 article "A model for rod ricochet." I would be very grateful for your assessment of the later paper, and the extent of plagiarism, as well as your own reaction as a scientist to this. Parts of your text also appear in other papers by the same authors.
Many thanks for any help.
Best regards
Declan

Declan Butler, PhD
Senior reporter, Nature
France
Tel: 33 (0) 247357215
Email: d.butler@nature.com
Web: http://www.nature.com <http://www.nature.com/>
Blog: http://www.declanbutler.info/

Fig. A-1 2009 email to Steven Segletes from *Nature* reporter Declan Butler

As I saw it, this story had the potential to become a huge international incident between the US and an adversarial Iran. The last thing I wanted was to become a pawn in a game of international politics.

My branch chief, Dr Todd Bjerke, grasped the potential ramifications and immediately elevated the issue to the level of then WMRD director, Ms Jill Smith. They both were extremely supportive and, after discussions with the Security Office, we developed a wholly sensible position of non-response. That is, we would ignore the request for comment. When the scandal broke in hardcopy, days later, reference to my work was very indirect, as had been our hope (Fig. A-2).

Iranian ministers in plagiarism row

Nature investigation reveals duplications in papers by government's science and transport chiefs.

EXCLUSIVE

Two Iranian government ministers have co-authored peer-reviewed papers that duplicate substantial amounts of text from previously published articles, according to an investigation by *Nature*.

Three journals have already confirmed that they will retract papers co-authored by Iran's science and education minister Kamran Daneshjou, a professor in the school of mechanical engineering at the Iran University of Science & Technology (IUST) in Tehran. Before being appointed science minister in early September, Daneshjou was also head of the interior ministry office overseeing the disputed presidential elections in June that kept Mahmoud Ahmadinejad in power. A further publication by Iran's transport minister and his deputy has also been called into question.

In an online story last week (see *Nature* doi:10.1038/news.2009.945; 2009), *Nature* revealed that substantial sections of text in a 2009 paper in the journal *Engineering with Computers*[1] by Daneshjou and IUST colleague Majid Shahravi were identical to a 2002 paper[2] by South Korean scientists in the *Journal of Physics D*. New York-based Springer, which publishes *Engineering with Computers*, has told *Nature* that it will retract the paper. The work also duplicates smaller amounts of material from papers given by other researchers at conferences[3–6], as well as a 2006 article[7] in the *International Journal of Impact Engineering*.

Similar duplications also appear in other papers by the same co-authors in Springer's *Journal of Mechanical Science and Technology* (*JMST*)[8], the Taiwanese *Journal of Mechanics*[9] and the Iranian journal *Mechanical & Aerospace Engineering Journal*[10] — the text of which is almost identical to that in their paper in *Engineering with Computers*[1].

Mark de Jongh, publishing editor of the *JMST*, says that the journal intends to retract the second Springer article[8]. "I conclude that the paper in question contains about 50% identical content as the formerly published

Kamran Daneshjou faces plagiarism questions.

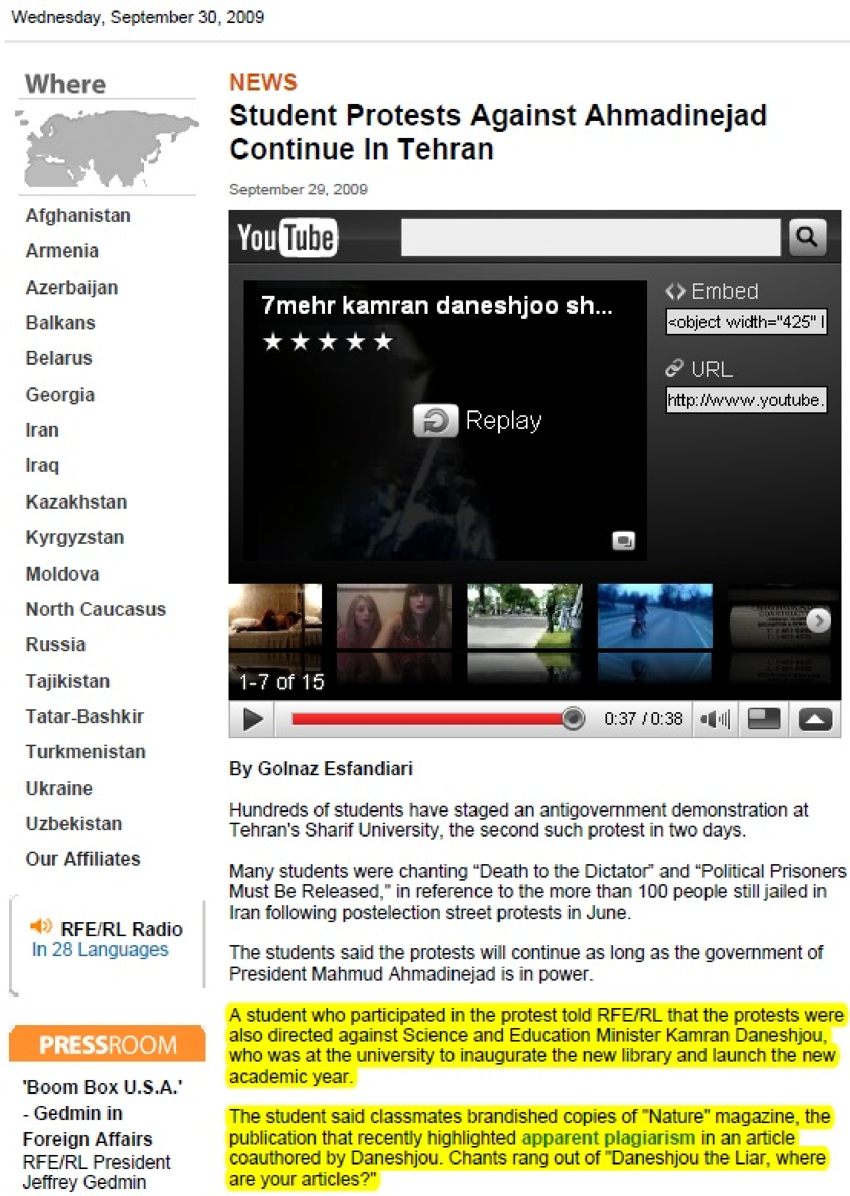
A. TAHERKENAREH/EPA/CORBIS

Fig. A-2 2009 September 30 *Nature* story on the Plagiarism Scandal

Our continued hope was that the story, if it grew, would not focus on a connection to a US Army scientist being plagiarized by a controversial Iranian political figure—and controversial he was. Daneshjou had, as a former Interior Ministry official, overseen the recent re-election of Iranian President Mahmoud Ahmadinejad. His appointment to the position of Science Minister, several months hence in September 2009, was seen by some as a reward for loyal service.

Our position proved to be the wise course of action. The scandal indeed grew to international proportions, being reported on in top publications such as the *New York Times*, the *Wall Street Journal*, Frontline, Radio Free Europe, and NPR, as well as top scientific publications, the likes of *Nature*, *Science*, *The American Scientist*, and so on. Student academic blogs around the world discussed the issue. However, the original *Nature* story had set the tone—I was rarely mentioned by name (just "a US scientist") and never by affiliation. Generally, citation in derivative sources was limited to the words "a 2006 article in the *International Journal of Impact Engineering*", and that suited me just fine.

Student protestors in Iran used the plagiarism incident to protest Daneshjou's appearances at universities, waving "brandished" copies of the *Nature* article at him (Figs. A-3). Regardless of the authenticity of the infraction, it is clear that the plagiarism row served as a convenient pretext to attack a politico who served as a proxy for a despised leader.



Wednesday, September 30, 2009

Where

Afghanistan
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Iraq
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Kyrgyzstan
Moldova
North Caucasus
Russia
Tajikistan
Tatar-Bashkir
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'Boom Box U.S.A.' - Gedmin in Foreign Affairs
RFE/RL President Jeffrey Gedmin

NEWS

Student Protests Against Ahmadinejad Continue In Tehran

September 29, 2009

By Golnaz Esfandiari

Hundreds of students have staged an antigovernment demonstration at Tehran's Sharif University, the second such protest in two days.

Many students were chanting "Death to the Dictator" and "Political Prisoners Must Be Released," in reference to the more than 100 people still jailed in Iran following postelection street protests in June.

The students said the protests will continue as long as the government of President Mahmud Ahmadinejad is in power.

A student who participated in the protest told RFE/RL that the protests were also directed against Science and Education Minister Kamran Daneshjou, who was at the university to inaugurate the new library and launch the new academic year.

The student said classmates brandished copies of "Nature" magazine, the publication that recently highlighted apparent plagiarism in an article coauthored by Daneshjou. Chants rang out of "Daneshjou the Liar, where are your articles?"

Fig. A-3 2009 September 30 Radio Free Europe story on Iranian student protests

By December of that year, editors at several journals had issued retractions of papers by Daneshjou and his students (Fig. A-4). I am savvy enough to understand that, in all likelihood, the plagiarism was accomplished by his graduate-student co-authors. While that does not alleviate Daneshjou from responsibility, the story was clearly used to reinforce other unrelated grievances. I am very grateful that, in the heat of the event, I managed to remain submerged in the background clutter.

EDITORIAL RETRACTION OF A PAPER

Kuang-Chong Wu

Editorial-in-Chief

Erratum to: Journal of Mechanics, Vol. 25, No. 1, pp. 117–128

A Simple Model to Predict Critical Ricochet Angle in Long-Rod Penetration by Kamran Daneshjou and Majid Shahravi was published in *Journal of Mechanics* in the March issue of 2009 (Vol. 25, No. 1, pp. 117–128).

The article of Kamran Daneshijou plagiarized two earlier articles, one published by Steven B. Segletes in Elsevier's *International Journal of Impact Engineering*, Vol. 32, pp. 1403–1439 (2006)[1] and the other one published in *Journal of Physics* D: *Applied Physics*, Vol. 35, pp. 2676–2686 (2002)[2] by Woong Lee, Heon-Joo Lee and Hyunho Shin.

It was discovered that the introduction was practically reproduced word for word from the 2006 article with only a minor change of added words and abridged sentences. Furthermore, it was found that there were large chunks identical to the 2002 article in the sections of numerical analysis, experimental, and results and discussion. **With this apparent plagiarism, we hereby retract the Daneshjou paper**. Dr. Daneshijou, being contacted both by e-mail and printed letter, has not replied to the editorial office about this affair and neither has the co-author.

The publication of papers with scientific fraud and plagiarized material is not acceptable. We cannot allow this fraudulent behavior to occur in either *Journal of Mechanics* or any other journal. The editorial office will scrutinize the future submitted papers to prevent any plagiarism.

Fig. A-4 2009 December 4 *Journal of Mechanics* article retraction

List of Symbols, Abbreviations, and Acronyms

ABBREVIATIONS AND ACRONYMS:

ALEGRA	a family of multi-physics codes developed at Sandia National Laboratories; one member of the family is ALEGRA-MHD
APG	Aberdeen Proving Ground, Maryland
APS	American Physical Society
ARL	US Army Combat Capabilities Development Command Army Research Laboratory
ARPANET	Advanced Research Projects Agency Network—the experimental packet-switched computer network out of which the world-wide internet grew.
ATWG	Armor Technology Working Group
B309	Building #309 at APG—the Zornig Building
B328	Building #328 at APG—the Simon Building
BRL	the former US Army Ballistic Research Laboratory
CDC	the former Control Data Corporation
CFD	computational fluid dynamics
CG	center of gravity
DAC	US Army Combat Capabilities Development Command Data & Analysis Center
DAMAS	International Conference on Damage Assessment of Structures
DEC	the former Digital Equipment Corporation
DOD	US Department of Defense
DTIC	US Defense Technical Information Center
ENIAC	Electronic Numerical Integrator and Computer—the world's first electronic computer, built for the US Army by the University of Pennsylvania in 1946 and delivered to its buyer, BRL on APG
EOS	equation of state
FIDOSC	FIre DOwn Shaped Charge, software written by Segletes to evaluate shaped charge penetration under the influence of imposed transverse velocity

FOIA	Freedom of Information Act, a law permitting private citizens to petition the US government for information
FORTRAN	Formula Translation, a computer language originally developed for scientific calculation in the 1960s
FZ	Frank–Zook, denoting a BRL-era computer program to calculate rod penetration into a target
FZWA	a computer program written by Segletes to calculate rod penetration that adapted the FZ program with elements taken from a paper by Walker and Anderson
F2	a modernized sequel code to FIDOSC, written by Segletes
GVSS	Ground Vehicle Survivability Symposium (hosted by the US Army Combat Capabilities Development Command Ground Vehicle System Center)
HE	high explosive
HVIS	Hypervelocity Impact Symposium (hosted by the Hypervelocity Impact Society)
IBM	International Business Machines Corporation
IED	improvised explosive device
IJIE	*International Journal of Impact Engineering*
IMECE	the International Mechanical Engineering Congress and Exposition (hosted by the American Society of Mechanical Engineering)
IMPLAST	International Symposium on Plasticity and Impact Mechanics
LABCOM	the former US Army Laboratory Command
LMB	Lethal Mechanisms Branch (of WMRD)
LS-DYNA	a general-purpose finite element program capable of simulating complex real world problems
MHD	magnetohydrodynamics
MINE	Momentum Impulse Numerical Evaluation, software developed and written by Segletes to evaluate the vertical impulse delivered by buried explosive upon vehicle targets of interest
MRAP	Mine-Resistant Ambush Protected (vehicle development program)
NASA	National Aeronautics and Space Administration

NAVEOD	(Office of) Naval Explosive Ordnance Disposal
OPSEC	Operational Security
ORBIT	3-D buried-blast evaluation software, part of the MINE code suite
PC	personal computer
PDP-11	Programmed Data Processor, a series of 16-bit minicomputers sold by DEC from 1970 into the 1990s
PENJET	a computer program originally developed by Segletes in 1980 to account for the adverse effect of nonaligned jet particles; revised circa 2008
PM	(Office of) Program Manager
RHA	rolled homogeneous armor
RJE	remote job entry (coincidentally, the initials of BRL's famed director, Robert J Eichelberger)
SCCM	Shock Compression of Condensed Matter; a conference and topical group of the the American Physical Society
SEM	Society for Experimental Mechanics
SLAD	the former Survivability/Lethality Analysis Directorate of ARL
STEM	science, technology, engineering, and mathematics
TAB	Technical Advisory Board to ARL (hosted by the National Academy of Sciences)
TARG	target-geometry generation software, part of the MINE code suite
Tech Pubs	Technical Publishing Team of ARL
TI	transversely isotropic
VTD	Vehicle Technology Directorate of ARL
WA	Walker–Anderson, denoting a 1995 research article
WMRD	Weapons and Materials Research Directorate of ARL.
ZEUS	a hydrocode computer simulation program, developed by JA ZUkas and SB SEgletes

MATHEMATICAL SYMBOLS:

a	the parameter of the universal EOS that provides a measure of the lattice extension
C_v	the specific heat of a material
C_0	the bulk speed of sound in a material
dR	in ARL-TR-1895, an infinitesimal segment of length along the streamline of interest
E	the thermodynamic property of internal energy
E_b	the binding energy of a material's crystalline lattice
E_c	the internal energy associated with a material's "cold" compression curve, as the material temperature approaches absolute zero.
E_{ref}	the internal energy along a given thermodynamic reference path
F	in mechanics, denotes a force
f	the parameter of the Segletes EOS that provides a measure related to the lattice vibrational frequency; in mechanics, denotes a force
H	a measure of the target's resistance to penetration (sometimes denoted R)
H_{LAT}	in cases where rod erosion is precluded, a measure of the lateral stress applied by the target to a penetrating rod
K	a parameter in the Segletes EOS, originally defined as $K = \frac{C_0}{\Gamma_0\sqrt{E_b}}$, later evolving to $K = [\Gamma_{\mathrm{vol0}} + 1 - 3/2 \cdot \Gamma_0(d\psi/dV)_0]/\Gamma_0$, where $\psi = V/\Gamma$. In practice, it is fitted.
k_R and k_T	the rod and target's shape parameter during a penetration event ($k_R + k_T = 1$)
L	rod length
$\dot{L}$	the rate at which the rod or jet penetrator is being consumed during an erosive penetration event
L_0	initial rod length
M and M_T	measures of engineering bending "moments"
O	in mechanics, frequently used to denote an origin reference point
p or P	the thermodynamic pressure

p_c	the pressure associated with a material's "cold" compression curve, as the material temperature approaches absolute zero.
p_{ref}	the pressure along a given thermodynamic reference path
R	in penetration mechanics, a measure of the target's "resistance" to penetration (sometimes denoted H); in ARL-TR-1895, the coordinate along the streamline of interest relative to the noninertial xyz frame of reference
R_1 and R_2	two points along a fluid "streamline" of interest
S	in thermodynamics, the entropy of a material; in ARL-TR-1895, the vector position of the non-inertial xyz frame of reference relative to an origin the fixed universe
s	in ARL-TR-3153, the length of the rod's plastic zone at the rod–target interface
$s_{ij,j}$	the spatial derivative of the deviatoric stress tensor, $\partial s_{ij}/\partial x_j$
T	in mechanics, used to denote surface traction
t	time
U	the penetration velocity of a rod or jet penetrator, denoting the instantaneous velocity of the penetrator/target interface in the reference frame of the target
U_{min}	the minimum "effective" penetration velocity associated with a shaped-charge jet
U_0	the initial penetration velocity, in the moments after impact
V	in penetration mechanics, the velocity of the rod or jet penetrator, in the target's frame of reference; in thermodynamics, the current volume occupied by a material specimen
V_{xyz}	in ARL-TR-1895, the velocity of a point relative to the noninertial xyz reference frame
V_0	in impact mechanics, the initial velocity of the rod or jet penetrator, at the moment of impact; in thermodynamics, the initial volume occupied by a material specimen
Y	a measure of the rod's strength during a penetration event
ΔP	in ARL-TR-3153, the impact pressure in the target arising from non-steady effects

∇	the mathematical "gradient" operator
∂	the partial derivative operator
Φ	in ARL-TR-1895, the body-force potential
Γ	the Grüneisen parameter, whose value connects the mechanical and thermal properties of a material
γ	the square root of the density ratio of the target to the penetrator, $\sqrt{\rho_t/\rho_r}$
ρ	density
ρ_r or ρ_R	density of rod penetrator
ρ_t	density of impacted target
σ_{zz}	the axial stress at a point along the centerline of the rod
Θ	a measure of the characteristic temperature of a material's crystalline lattice
Ω	in ARL-TR-1895, the rotational velocity vector of the non-inertial xyz reference frame relative to an origin in the fixed universe.
ω	a measure of the characteristic vibrational frequency of a material's crystalline lattice
θ, α, η	in mechanics, frequently used to denote angular measures

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