Ballisticians in War and Peace

A History of the United States Army Ballistic Research Laboratory

Volume III

1977–1992

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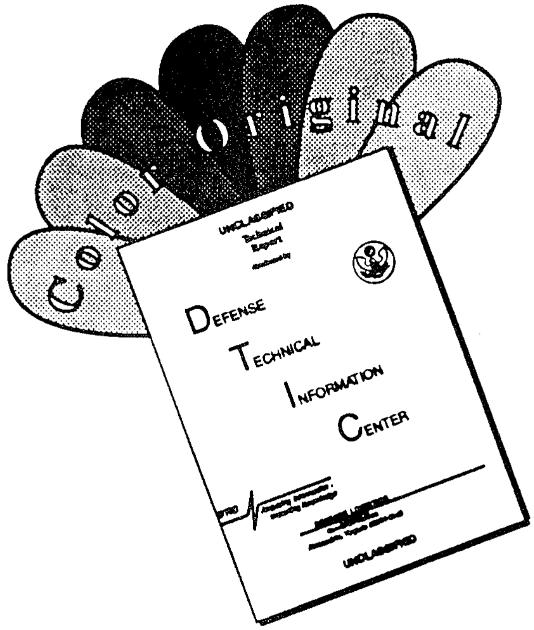

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Ballisticians in War and Peace

Volume III

A History of the United States Army
Ballistic Research Laboratory
1977–1992

Aberdeen Proving Ground, Maryland

Prepared for the United States Army Research Laboratory

by Harry L. Reed, Jr.
31 December 1992

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FOREWORD

This volume is the third and final installment of *Ballisticians in War and Peace*, the history of the Ballistic Research Laboratory and its predecessors. While the activities chronicled in this account are a source of pride to those who participated in them, there is also some sadness to realize that this history is now a completed work.

The 54-year period from 1938 to 1992 marks the formal life span of the Ballistic Research Laboratory, but neither year witnessed a dramatic change in the scientific work of the ballisticians charged with its accomplishment. Perhaps the most significant change was in the simple acknowledgment of a historical turning point and the need for a new vision. The acquisition of a new organizational name in 1938 was a milestone along a continuing path of scientific endeavors. Reconstitution into the Army Research Laboratory in 1992 was a further milestone along that same pathway. Together they marked the onset and culmination of a long historical era of global military confrontations which paralleled and vitalized the work life of the Ballistic Research Laboratory.

As the world moves into the new post-Cold War era, the course of that path is not at all clear, but will certainly hold new challenges for the ballisticians of the Army Research Laboratory. I have every confidence that the pride and tradition of excellence recorded in these pages will continue undiminished, and the torch will be passed on to shine as brightly as ever.

JOHN T. FRASIER
Ballistic Research Laboratory
Director, 1986–1992

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EDITOR'S NOTE

In some cases, parts of quoted material were reformatted to conform with the style practices of the rest of the volume. Any possible misrepresentation is regretted.

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ACKNOWLEDGMENTS

Many people chatted with me, guided me, helped me gather data, and provided constructive criticism. They include:

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Their help has been invaluable; they have my deepest thanks. There were also those whose work I have quoted; some are known and referenced; some are anonymous; all are appreciated.

Some of the material that I reference is not archival. In those instances, I am making sure that the Army Research Laboratory's library at Aberdeen Proving Ground has copies of all material that is not generally available.

I also am deeply in debt to John Schmidt who blazed the trail with Volumes I and II of *Ballisticians in War and Peace*. There is some overlap with Volume II since John did go a bit further than 1976 with his narrative, it is convenient for me to go back occasionally before 1977 to get a running start, and the appreciation of events sometimes changes with time.

I thank Ann Silirie for helping me throughout the entire project and Larry Puckett for his support as the Contracting Officer's Representative and for background material.

Finally, I thank the Ballistic Research Laboratory for a wonderful career and John Frasier for the chance to relive that career as I worked on this portion of its history.

Harry L. Reed, Jr.
31 December 1992

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PROLOGUE

On the 30th of September, 1992, shortly before 5 in the afternoon, the Dixieland band struck up a tune and led the group of members and friends of the Ballistic Research Laboratory to the Aberdeen Proving Ground flagpole. Five howitzers fired a salute as the garrison flag was lowered. The huge flag struggled in the stiff breeze, reluctant to be furled, but was finally recovered by the honor guard. Thus, the proud name of the Ballistic Research Laboratory was committed to history and to the hearts of the well-wishers.

John Schmidt has told the two-volume story of the Ballistic Research Laboratory (BRL) from World War I with the early work of R. H. Kent, through its official start in 1938, until its joining the Armament Research and Development Command in 1977.

Now, with volume III, we close the book on BRL—the specific organization—and leave it to a later date for others to write the history of the Army Research Laboratory (ARL) into which the BRL has been assimilated. While the specific organization has been decommissioned, the people remain with their facilities, their dedication, and their professionalism.

Earlier in the day during the closing ceremonies, Don Eccleshall put it well when he reminded the assembly that the ARL was being made up of a number of organizations, each of which had a proud name and heritage. There certainly is every reason to believe that this synthesis and metamorphosis will result in new accomplishments in new horizons.

There is also a certain irony to these changes.

The BRL was created just prior to World War II and was staffed and assisted by many outstanding scientists who felt the importance of that struggle. The years after World War II were dominated by the Cold War, which posed the serious threat of the massive military force of the Soviet Union—a threat that drove the program of the BRL. Certainly, the BRL made major contributions to the winning of the Cold War—some of those contributions were manifested in the Persian Gulf War that immediately followed the end of the Cold War. By 1992, the world situation has changed dramatically with new promises and new dangers. The U.S. military is rethinking its roles and needs; a fresh look at military research seems appropriate.

Regardless, this is not a twilight for the BRL. Through all the years, it has advanced the understanding of the complex processes of ballistics, it has remained at the cutting edge of the associated technologies, it has made major contributions to the fighting ability of the U.S. Army, and it has become renowned throughout the defense establishments worldwide.

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THE BALLISTIC RESEARCH LABORATORY

THE PROGRAM

The Ballistic Research Laboratory (BRL) [now part of the Army Research Laboratory (ARL)] was created to conduct research in the field of ballistics and in related areas of technology as applied to U.S. Army weapon systems. Volumes I and II of *Ballisticians in War and Peace*[1] describe the BRL's program from its nascent days during World War I, through the formal creation of the BRL in 1938, through World War II, and on through 1976.

The 1970s saw the emergence of a number of important new developments in ballistics—the silver bullet and its ultimate progeny, the M900 and M829 series of kinetic energy (KE) tank rounds; low-vulnerability ammunition (LOVA); the maturing of the armor and ammunition compartmentation for the Abrams tank; and explosively formed penetrators (EFP).

In the case of vulnerability analysis, the 1970s saw the introduction of the point-burst methodology, and we should also mention that the 1980s saw the emergence of the regenerative liquid-propellant gun (RLPG) and live-fire testing with a rejuvenation of the aging vulnerability data base.

As with so many other scientific and engineering endeavors, the activities of the BRL from the late 1970s were strongly influenced by the burgeoning computer technology. The organization that sponsored the world's first electronic digital computer, the ENIAC (Electronic Numerical Integrator and Calculator), now made significant contributions to interactive computing, networked computing, computer graphics, and the applications of supercomputers to solving large-scale scientific and engineering problems. The late 1970s saw the emergence of the Cray supercomputers, although it took another decade for the BRL actually to have its own.

While the computers opened the possibilities of making more detailed and complete solutions of the problems in ballistics, these possibilities could only be achieved with a more complete understanding of the physical and chemical processes involved, with more complete data on the properties of materials, and with an understanding of the validity and stability of the associated mathematical models.

Certainly, the process of rationalization of the field of ballistics continued by Kent and others has reached a level that was probably not expected by those pioneers. But expectations change, and, as in so many other areas of endeavor, the more one learns, the more one finds new areas of ignorance.

As this process of rationalization continues, it becomes more and more the province of people with deep knowledge in highly specialized technical areas; the *complete ballistician* becomes almost an impossibility. The connections between the research and the application become less obvious to the non-specialist, and considerable vision, patience, and trust are required to stay the course. It is thus to the credit of the leaders of the BRL that, over the years, they have been able to see and to articulate the needs for the research and that they have been able to build a world-class laboratory and related program in ballistics.

It is also important to understand that the analytic process is still limited and that the dream of calculating the effects of ballistic processes *ab initio* is far from attainable in the foreseeable future. The processes are complicated, some such as fracture are not easily manageable in an analytic framework, and many of the basic material properties involved must be measured at extreme conditions of loading and rates of loading. Thus, there has been a concomitant need for new and more capable experimental facilities. The demands on experimentation have been heightened by a new awareness of the need to validate engineering predictions and to prove the performance and survivability of military equipment in live-fire tests (LFTs). These concerns have been particularly emphasized by the Congressional mandate to conduct LFTs on the survivability of major military systems.

Thus, over the last decade and a half, the BRL has had considerable growth in its experimental capability, its analytic capability, and its computational facilities.

ORGANIZATIONAL ASPECTS

The Army has created a variety of organizational concepts for the conduct of research and development (R&D) and for the management of its laboratories. As a result, the BRL has reported to a number of different organizations and levels of command. At the beginning of this portion of our history in 1977, the BRL had just become part of the newly formed Army's Armament Research and Development Command (ARRADCOM) with headquarters at Picatinny Arsenal, NJ. In 1983, the BRL was taken out of ARRADCOM and reported directly to the Army Materiel Command (AMC). In 1985, the Laboratory Command (LABCOM) was formed and became the manager of the Army's corporate laboratories—to include the BRL. Finally, the ARL was formed in 1992, and the BRL lost its identity as did the other corporate laboratories as they were incorporated into the ARL.

This number of changes over the decade and a half was not all that unusual as the reader will notice in the other two volumes of this history. Interestingly enough, none of these changes had a significant effect on the technical accomplishments of the BRL, and none of them (with the exception of the creation of the ARL) has had much of an impact on the BRL's internal organization.

For example, prior to joining ARRADCOM, the BRL was composed of seven laboratories. In that reorganization, the laboratories became divisions. The Terminal Ballistics Laboratory and the Detonation and Deflagration Dynamics Laboratory were reunited to form the Terminal Ballistics Division (TBD); the Concepts Analysis Laboratory and the Applied Mathematics Laboratory were joined to form the Ballistic Modeling Division (BMD); the Exterior Ballistics Laboratory was renamed the Launch and Flight Division (LFD); the Vulnerability Laboratory was renamed the Vulnerability/Lethality Division (VLD); the Interior Ballistics Laboratory was renamed the Interior Ballistics Division (IBD); and a Computer Support Division (CSD) was created. Bob Eichelberger, the Director of the BRL, assumed the additional position of ARRADCOM's Associate Technical Director for Research and Technology. John Frasier, the Chief of the Penetration Mechanics Laboratory, became the Deputy Director of ARRADCOM's Large-Caliber Laboratory—later to return to the BRL in 1986 as its director. The major effect of this reorganization was to bring the development community for armaments and the BRL closer together, but there was a certain (albeit slight) stifling effect on some of the activities of the BRL in areas other than armaments.

The organization of the BRL remained essentially unchanged when it came out of ARRADCOM. Probably the main effect was a boost in morale since the BRL reported at a higher level in the Army's chain of command.

The heady feeling was short-lived, and two years later another level of command (LABCOM) to which the BRL reported was created. Again the internal organization of the BRL itself remained essentially unchanged.

LEADERSHIP

Dr. Robert J. Eichelberger was the Director of the BRL from 1969 until 1986.

"Dr. Eichelberger was born in Washington, PA, in 1921. He graduated from Washington and Jefferson College in 1942 with his bachelor's degree in physics. He also earned

Dr. Robert J. Eichelberger.

both a master's degree and a doctorate in physics at the Carnegie Institute of Technology [now the Carnegie-Mellon Institute].

"Dr. Eichelberger joined the BRL in 1955 as Chief of the Detonation Physics Branch, a unit of the BRL's Terminal Ballistics Laboratory. Prior to 1955, Dr. Eichelberger had served 12 years as a research supervisor and research physicist at the Carnegie Institute of Technology, Pittsburgh, PA, managing contract research for the Army and collaborating with the BRL. In 1962, he became the BRL's Associate Technical Director, serving in that capacity until 1965. In that year, he became a consulting physicist with the BRL. In 1967, he became the BRL's Technical Director. In 1969, the top leadership position at the BRL was converted from a military assignment to a civil-service post, and Dr. Eichelberger became the BRL's first civilian director.

"Dr. Eichelberger's technical achievements include work in detonation physics, combustion, high-speed and high-pressure fluid dynamics, and development of computer models and systems engineering. He retired from the BRL in 1986 and now resides in the local area."[2]

Dr. John T. Frasier.

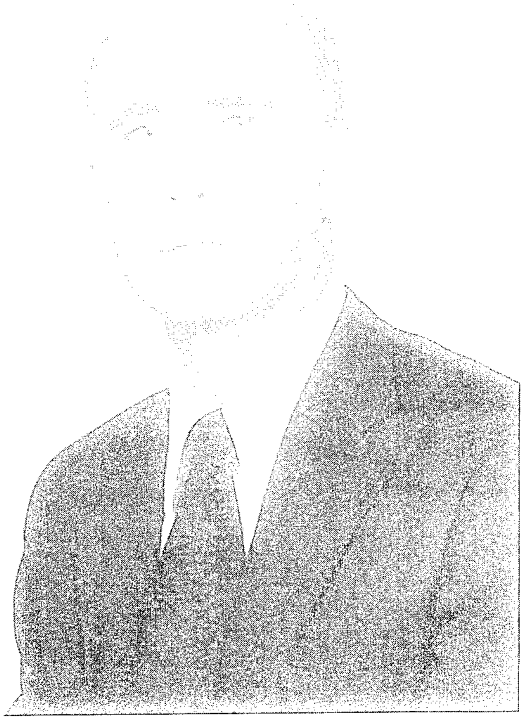
Dr. John T. Frasier served as the Director of the BRL from May 1986 until its closing in September 1992. At that time, he became the Director of the newly formed Weapons Technology Directorate of the ARL.

"From 1962 until 1977, Dr. Frasier worked at the BRL as a scientist and engineer and served as Chief of the Terminal Ballistics Laboratory during the last 6 years of his assignment.

"He then joined the U.S. Army Armament Research and Development Center where he served as Deputy Director of the Large-Caliber Weapons Systems Laboratory (LCWSL) from 1977 until 1983.

"From 1983 until 1986, Dr. Frasier worked in the Naval Surface Weapons [now Warfare] Center (NSWC), first as head of the Research and Technology Department, then as head of the Weapons Systems Department.

"A native of Arlington, VA, he holds a bachelor of science degree in civil engineering from Virginia Polytechnic Institute and a master's degree and a doctorate in engineering mechanics from Penn State University."[2]



Dr. Lawrence J. Puckett.

Dr. Lawrence J. Puckett was the Assistant Director and later Associate Director of the BRL from 1978 through 1992. He received his bachelor of science degree in physics from the Virginia Military Institute and his master's and doctorate from the Georgia Institute of Technology.

COL Robert H. Gomez was the Deputy Director and Commanding Officer from 1976 until 1981. He was a 1954 graduate of the U.S. Military Academy and received a master of science degree from the Georgia Institute of Technology.

COL Robert N. Mathias was the Deputy Director and Commanding Officer from 1981 until 1983. He was a graduate of the U.S. Military Academy and received a master's degree in nuclear physics from Tulane University in Louisiana. He also completed the Command and General Staff College, the Defense Systems Management College, and the Army War College.

COL James Wasson was the Deputy Director and Commanding Officer from 1983 until July 1987. He earned a bachelor's degree in business administration at Lehigh University in 1958 and a master's degree in science and technology management at George Washington University in Washington, DC. He also completed the Armor Officer's Career Course and the Command and General Staff College at Fort Leavenworth, KS.

MAJ Gary R. Davis was Deputy Director and Commanding Officer from July 1987 until November 1987; LTC Charles K. Gailey, III, from November 1987 until April 1991; MAJ Andrew G. Ellis, from April 1991 until July 1991; MAJ Richard A. Koffinke, Jr., from July 1991 until January 1992; and LTC David L. Meeks, from January 1992 until August 1992.

COMPUTER TECHNOLOGY

Computers have been an important tool of the BRL from its early use of the Bush Differential Analyzer and the creation of the ENIAC.[3] While its main association with computers has been with using them to solve the massive computational problems of ballistics in propulsion, flight, terminal effects, and vulnerability analysis, the BRL has also developed a powerful capability for using computers in daily tasks, and it has also made significant contributions to computer technology.

At the inception of ARRADCOM, the CSD was created in the BRL with Ingo Rucker as the chief of the division. CSD was responsible for acquisition, maintenance, and support of the BRL computer assets—hardware and software. The major computer asset was the newly acquired CYBER 76 computer.[4]

Meanwhile, the System Engineering and Concepts Analysis Division (SECAD) was becoming involved in the development of interactive, networked computing which eventually led to the creation of BRLNET as discussed in the following text. In 1984, CSD was merged into SECAD to bring the technologies together and to form the concerted effort for bringing supercomputers to the BRL.

At the time of writing this history (1992), "the BRL operated the Army's largest based campus-area computer network (CAN), BRLNET, with six nodes currently operative that linked the major BRL buildings, the Army Human Engineering Laboratory (HEL), the Army Materiel Systems Analysis Activity (AMSAA), and the Army Chemical Research and Development Center [now the Chemical Research, Development, and Engineering Center (CRDEC)] located 12 miles away. The network linked computers as diverse as the Sun Workstations and the Cray-2. This network was constantly being improved and upgraded (e.g., recently with 80-mb/s fiber optics) and was largely the creation of in-house BRL computer scientists who enjoyed national and international reputations in network theory and topics such as UNIX™ operating-system development and improvement. BRLNET was connected to MILNET/ARPANET and the world-wide InterNet. BRL scientists recently completed the responsibility of implementing ASNET, the Army Supercomputer Network."[5]

As of 1991, the BRL's computer configuration consisted of the following:[6]

Supercomputers	2
Superminicomputers	8
Minicomputers	30
Work Stations	202
Personal Computers	525
Terminals	1,100
Local Area Networks	15
Campus Network	1

"As a result of its unique position among Army Laboratories both with respect to its exploitation of computer technology, and the excellence of its staff in Computer Science, the BRL was chosen to be the home of the Army's first two supercomputers, a Cray X-MP/48 and a Cray-2. These two supercomputers were being extensively exploited to extend the vistas of computing to both compute old on-going problems in a more efficient extended manner plus new problems not envisioned prior to the availability of this new resource."[5] These supercomputers "had single processor speeds (with properly vectorized code) in excess of 500 million floating point operations per second and dynamic fast memories of from 8 to 256 million words. Each BRL supercomputer had four processors."

"Networks were the backbone of the BRL computer environment. The BRL network consisted of a group of local-area networks (LANs) which were connected to each other via a ProNet-10 ring network. Most of the BRL LANs were ethernet with a 10-Mbps (Megabit per second) transmission speed. The supercomputer LANs were 50-Mbps Hyperchannels.

"A major change in [unclassified] scientific computing in the last 10–15 years or so has been the real-time interactive manner in which scientists can exploit modern computing. This greatly has enhanced productivity in that scientists can quickly go from an idea to processing a computer application (from their desks) and in a matter of minutes turnaround a computer run which furthers their thinking or otherwise advances the project toward quick completion. ... Recently, the BRL implemented a secure network that permits scientists to work from several secure enclaves which are networked securely to classified computers."[6]

Typical of the BRL's firsts in computing was the BRL's support of Denelcor's heterogeneous element processor (HEP) computer. The HEP "was developed as a result of a BRL contract designed to research the possibility of specialized parallel hardware architecture. The BRL HEP was used by several teams of university and Government researchers as a tool to develop and exploit specialized parallel algorithms appropriate to the HEP-type architecture.

The nature of the BRL's mission required a continuous striving to acquire and exploit the most powerful computers that vendors can provide. To achieve this end, the BRL was an active participant in an Army project with the Army High Performance Computing Research Center. This project is aimed to better understand the complex algorithm and hardware issues in exploiting emerging parallel computer architectures such as the connection machine, NCube, etc. Through this project the Army research development test and evaluation community will have ASNET access to the most advanced computer architectures the industry provides.

SUPERCOMPUTERS

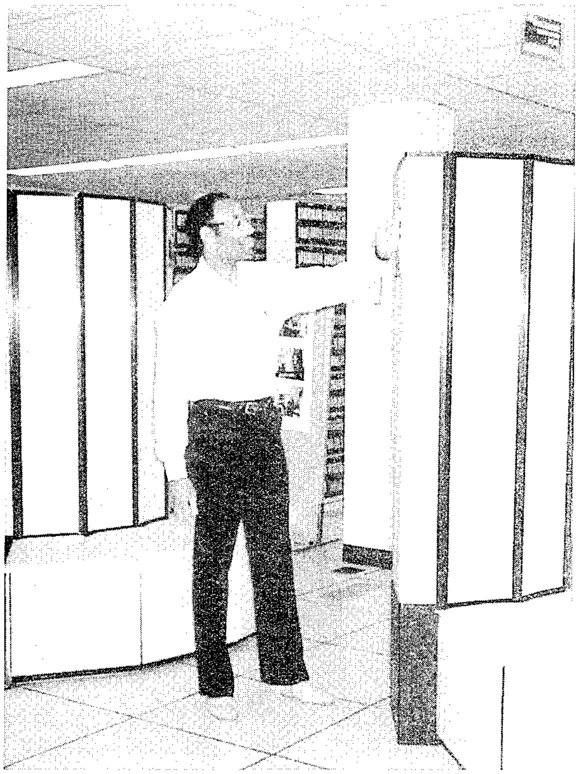
Over the years, the acquisition of computers has often been a frustrating process. For example, by the time that the cumbersome procurement process ran its course, the BRL acquired the last CYBER 76 off the production line at the time that the Cray supercomputers became available. While the CYBER was an important step for the BRL, its limitations in speed and memory soon became apparent, and the ballisticians looked longingly at the newly emerging supercomputers in the Department of Energy (DOE) and National Aeronautics and Space Administration (NASA) facilities.

The people in the BRL had been able to use the supercomputers at other installations and found, among other things, that their analyses of armor was inadequate with the BRL computer—important effects had been found from calculations done on the DOE supercomputers.

As the armor and antiarmor competition escalated, it became clear that the BRL needed a much greater computational capability. R. J. Eichelberger recognized that the newly emerging class of supercomputers, such as the Cray-2 or ETA's GF-10 with their huge random-access memories, represented the appropriate capability and campaigned hard to bring that capability to the BRL. Finally, in December 1984, AMC asked the BRL to develop specifications for a supercomputer.[5]

Thus began a remarkably aggressive acquisition program that resulted in the acceptance of a top-of-the-line Cray X-MP/48 computer 2 years later and a cutting-edge Cray-2 supercomputer after an additional 6 months. The success in pushing this action forward and in bringing the supercomputers into full operation immediately upon their arrival is due to the combined efforts of Harold Breaux and Ingo Rucker.

Since a Cray-2 or GF-10 class computer was not immediately available, the Deputy Under Secretary of the Army (DUSA) defined a three-phase program in April 1985 to expedite the arrival of supercomputing at the BRL. The phases were to take advantage of time-sharing with supercomputers at other installations, to acquire an interim supercomputer, and to



The BRL's Cray X-MP/48 Supercomputer.

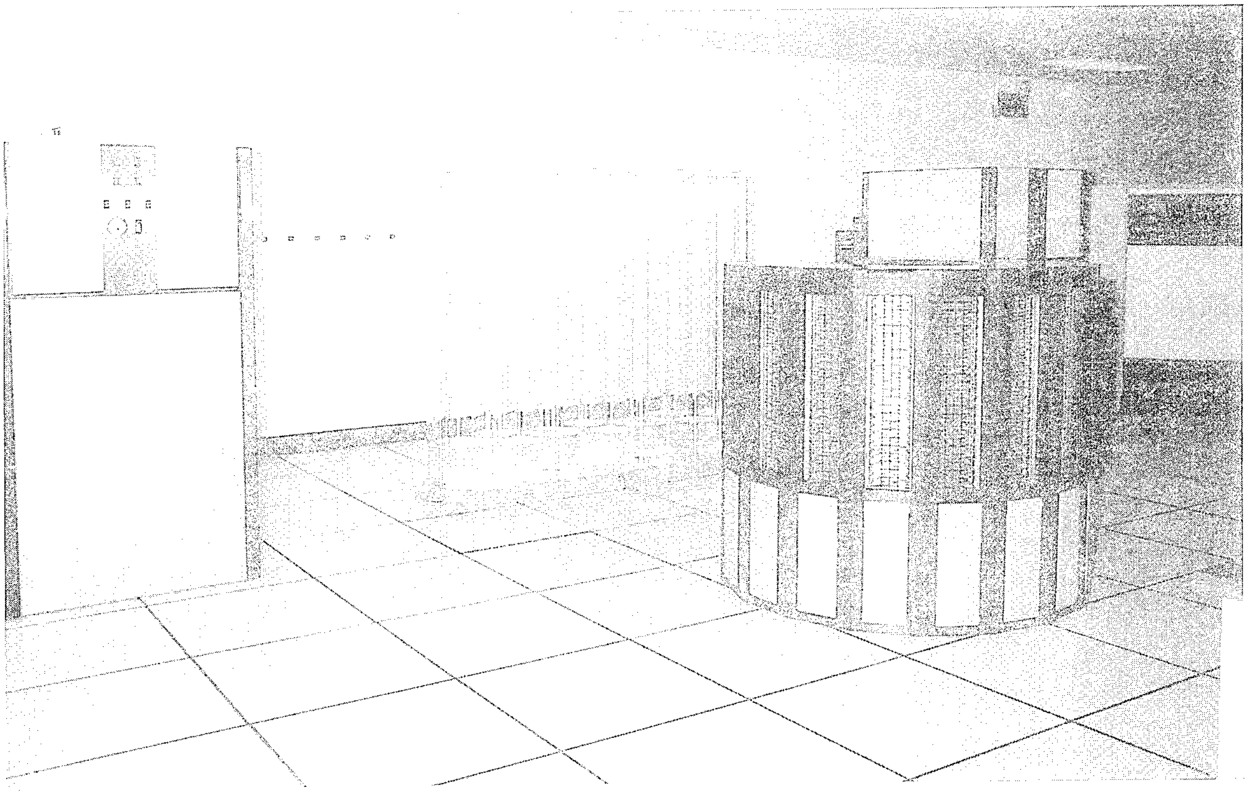
acquire a next-generation machine when available.[5]

The interim supercomputer came to be a Cray X-MP/48 which was an extremely powerful computer in its own right. In fact, there was considerable debate within the BRL over whether the Cray X-MP/48 or a larger-memory computer was better for the BRL. (The concern was over the speed with which individual words could be accessed in the memories.) Later experience did, however, prove that the eight-million word memory of the X-MP was a serious limitation for many problems, and Eichelberger's decision to go with a larger-memory machine has been more than justified.

In November 1986, the X-MP was delivered to the BRL. From the beginning, the computer was essentially used full time for research and development. The original configuration was to use the CYBER front-end computers to interface with the X-MP and to use the Cray operating system (COS). Mike Muuss ported the Cray-station software, originally targeted for the Sun environment, to the VAX and Gould systems in use at the BRL, thus paving the way for an interactive UNIX environment (UNIX Cray operating system [UNICOS]).[7] Initially, three of the processors ran under COS, and the fourth ran under UNICOS. Eventually, all four processors went under UNICOS. This arrangement was dictated by the fact that UNICOS was not very mature and that many of the BRL's applications had been developed under COS on other supercomputers.

Finally, in June 1987, the BRL's Cray-2 was operational.[5] This was only about 6 months after its sister machine was delivered to NASA/Ames and was celebrated on national television as a major technological achievement.

To give some idea of the ability of the BRL's scientists to lead in supercomputer technology, we offer the following: "In mid-1987, Muuss initiated a file-migration and archiving project for UNIX, intended to be generic for all major versions of the UNIX system. The intention of this software was to provide the users of a UNIX system with the impression of having file systems that are significantly larger than the underlying disk hardware that contains them. This additional storage being provided by a hierarchy of storage devices that are hopefully progressively cheaper and probably slower than the system disk hardware. The presence of the additional storage will be generally invisible to the user, except when additional time is required to access a file that has been moved from the system disk to a secondary storage device. This project was done jointly with the U.S. Naval Academy and with the Software Division of Cray Research. While this work was intended primarily to address the need for massive storage on the supercomputers, it is intended that this software will be placed in the public domain, and thus will represent a major contribution to the UNIX community. This



BRL's Cray-2 Supercomputer.

work formed the basis of Cray's standard data-migration software, and will benefit users worldwide."[7]

INTERACTIVE COMPUTING AND BRLNET

A relatively simple event in 1977 had a profound effect on the development of computing in the BRL. Steve Wolff and Bruce Henriksen proposed that SECAD (then BMD) acquire a Digital PDP 11/70 minicomputer, install the UNIX operating system on it, and thus furnish interactive computing for the division—to include scientific computing, document preparation, etc.

Prior to coming to the BRL, Wolff had been a professor at The Johns Hopkins University (JHU). He maintained contact with a group at JHU that had developed a version of UNIX and installed it on a PDP 11/45. One of the undergraduate *gurus* in that group was Mike Muuss who joined the BRL upon his graduation and became a key player in computer-related development in the Laboratory.

With help from the JHU group, with enthusiasm and persistence, and after numerous *crashes*, the SECAD people were able to make the computer system (called the BMD-70) with the JHU UNIX into a highly successful venture. As one might expect, this system created a demand that far exceeded its capabilities, and the rest of this section outlines some of the things that followed. The BMD-70 has been replaced with several generations of hardware such as VAX, Gould, Alliant, Silicon Graphics, etc.

The selection of UNIX has turned out to be extremely fortuitous. Its applicability to a wide variety of hardware has allowed relatively easy porting of software, and one can see the same operating environment on the wide spectrum of computers from a work station to a Cray-2 supercomputer. There also was a treasure trove of software that was freely exchanged by a user's group during the initial days of UNIX.

One of the conditions for the approval of the acquisition of the BMD-70 was that SECAD would demonstrate computer networking. Initially, there were not too many computers to join together, so Harry Reed and Henriksen created a somewhat crude, but workable, connection and software suite that allow the users of the BMD-70 to work interactively with BRL's CYBER computer and to transfer files between the two computers. This not only satisfied the immediate requirement, but it also proved to be a useful capability.

In a more systematic approach, which grew into a powerful CAN, Muuss et al. set about forming a network as various minicomputers were introduced—at first in Building 394, which housed SECAD and the Vulnerability Methodology Branch of VLD and then throughout the BRL compound with connections to the Department of Defense's (DOD) computer network (MILNET).

By September 1979, "The prototype BRLNET was a highly efficient homogeneous network of UNIX systems on a 16-Mbps LAN, with network protocols implemented in the UNIX kernel to support transparent device-level access across the network."[7]

In 1979, considerable work went into "modifying BRL/JHU PDP-11 UNIX to support real-time man-in-the-loop interactive response. The capability was necessary to permit graphics applications to successfully coexist with a time-sharing load on one general purpose computer." In 1980, the necessary operating system driver software and user-mode interface routines were developed "to allow direct user control of ... Vector General 3300 3-dimensional display hardware."[7] We leave the discussion of further work in graphics to the section on VLD.

Early on, the BRL became interested in the ARPANET, which was the precursor to DOD's MILNET. "In early 1980, ... the prototype BRLNET protocols were extended to deal with heterogeneous LAN and routing issues. In late 1980, ... a three-man team ported the University of Illinois ARPANET NCP capability to BRL's PDP-11 UNIX. The team installed a PDP-11/34 system running UNIX to replace BRL's ARPANET Terminal Server (ANTS) system to provide continued ARPANET access to the BRL after the ... conversion of the ARPANET to the new 96-bit leader protocol" on 1 January 1981.[7] The BRL was one of the few DOD sites that could handle the new protocols, and, for some time, it acted as an intermediary for a number of sites for electronic mail, etc.

Electronic mail became a way of life in the BRL; no one could escape from the director's messages—a busy phone was no longer an excuse. In 1981, Muuss adapted the University of Delaware's MMDF Version 0 to BRL/JHU UNIX system, providing the BRL with an initial ARPANET mail system." This included "MMDF's Phonenet capability, allowing all of the BRL UNIX systems which did not enjoy direct ARPANET connections to automatically exchange electronic mail with ARPANET in a store-and-forward fashion, using dedicated serial lines.

"In late 1981, with the prototype BRLNET a success, the Defense Advanced Research Projects Agency's (DARPA) experimental Transmission Control Protocol and Internetwork Protocol (TCP/IP) suite was identified as meeting the BRL's present and future needs in a networking protocol. Rather than extending the prototype BRLNET protocols, Muuss began a project to implement TCP/IP capability for the BRL/JHU UNIX on the PDP-11, to replace the prototype BRLNET."[7] This was an extremely important step since it made the BRL completely compatible with the emerging MILNET and offered all the technology from that project for inclusion in the creation of the BRL's CAN.

"Working with various DARPA committees, Muuss participated in the early development and implementation of these protocols. These protocols have subsequently been published as MIL-STD-1777 and MIL-STD-1778, and form the technological foundation upon which the entire InterNet system (MILNET, ARPANET, etc.) is built. It is estimated that there are over 500,000 computers in the world that use these protocols. Approximately 2/3 of these computers include protocol software and techniques ... developed at the BRL.

"On 2 January 1983, the BRL was a full member of the DARPA InterNet, operating the first LANs interconnected to the ARPANET within the DOD. Over the remainder of 1983, the team remained very active in the ARPANET research community, identifying network operational problems, assisting other sites in debugging their network implementations, and refining the BRL implementation. Numerous copies of the BRL's PDP-11 TCP/IP software were distributed throughout the country."[7]

The BRL had modified the JHU UNIX to meet its needs, especially in the area of security. From a report from FY82, we find, "Copies of the UNIX computer operating system as modified and improved by BMD [SECAD] systems engineers were transferred to numerous requestors including Moravian College, University of Maryland Eastern Shore, JHU, National Institute of Health, National Library of Medicine, and Lincoln High School, Sudbury, MA."[8]

"In 1983, Muuss and Howard Walter developed the plans for a CAN to span the buildings in the BRL, using existing technology (twisted pairs) for Phase I and fiber optics for Phase II. ... BRLNET Phase I (a small-scale ARPANET replica) was acquired and installed."[7]

In 1983, the BRL was chosen to be a beta-testing site for the "DARPA-sponsored Berkeley 4.1c BSD UNIX for the VAX."[7] The BRL continued to be the beta-testing site for a succession of versions of Berkeley UNIX.

"In late 1983 and early 1984, the BRL team developed and implemented the BRL-GATEWAY and its supporting operating system LOS. This gateway software allowed the long-haul/CAN/LAN interconnection to be off-loaded to small dedicated processors to provide for maximum reliability. The BRL-GATEWAY package has been exported to numerous other agencies including NASA, and to industry and universities. The BRL-GATEWAY systems at the BRL experienced a mean time between failure of 400 hours (most failures due to loss of electricity), where each system processed in excess of 1.5 million packets/day.

"Also in late 1983, the BRL assumed the lead in MMDF development nationwide, culminating in MMDF II being released in late 1984."[7]

In September 1986, Howard Walter and Dave Towson began the implementation of a new network called Secure BRLNET, intended for continuous high-speed communication of classified data between the BRL's secure computing resources.

"In November 1986, with the delivery of the Army's first supercomputer, a Cray X-MP/48, Muuss coordinated all the network installation activities to provide immediate access to the supercomputer from BRLNET and MILNET. This included detailed planning of the Hyperchannel hardware and substantial extensions to the existing VAX UNIX Hyperchannel driver software to provide the required level of reliability. He also made the Gould UNIX Hyperchannel driver compatible with the Cray link-level protocol format and

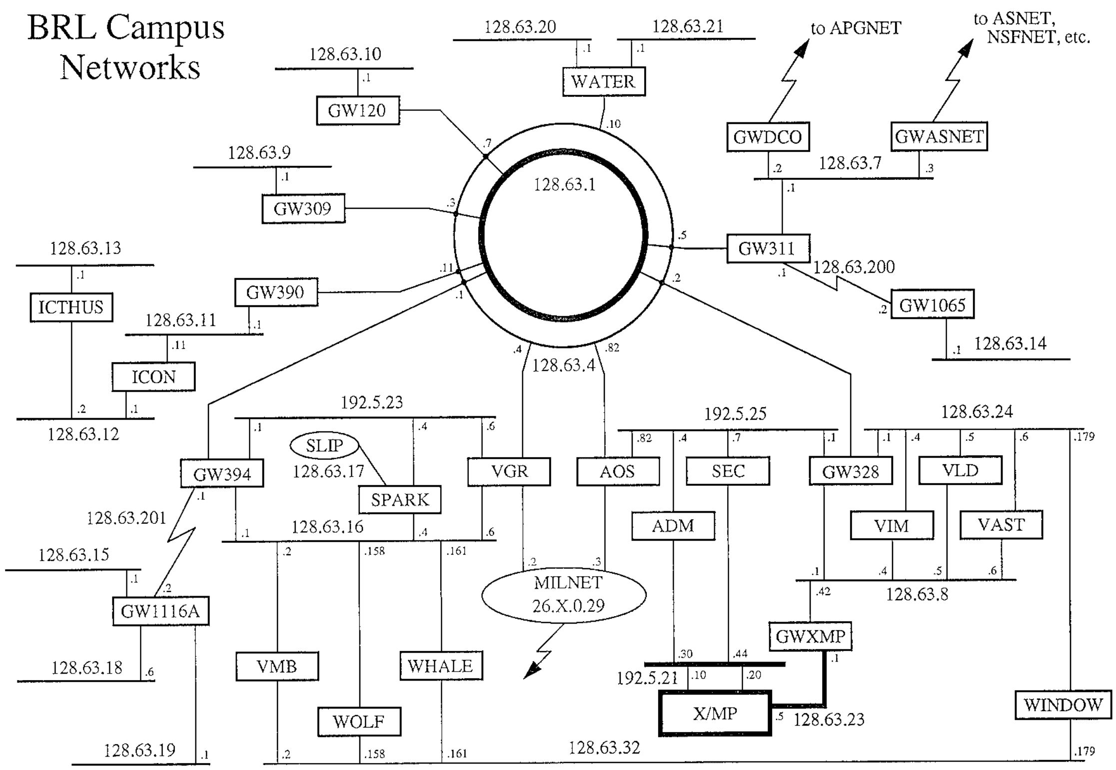


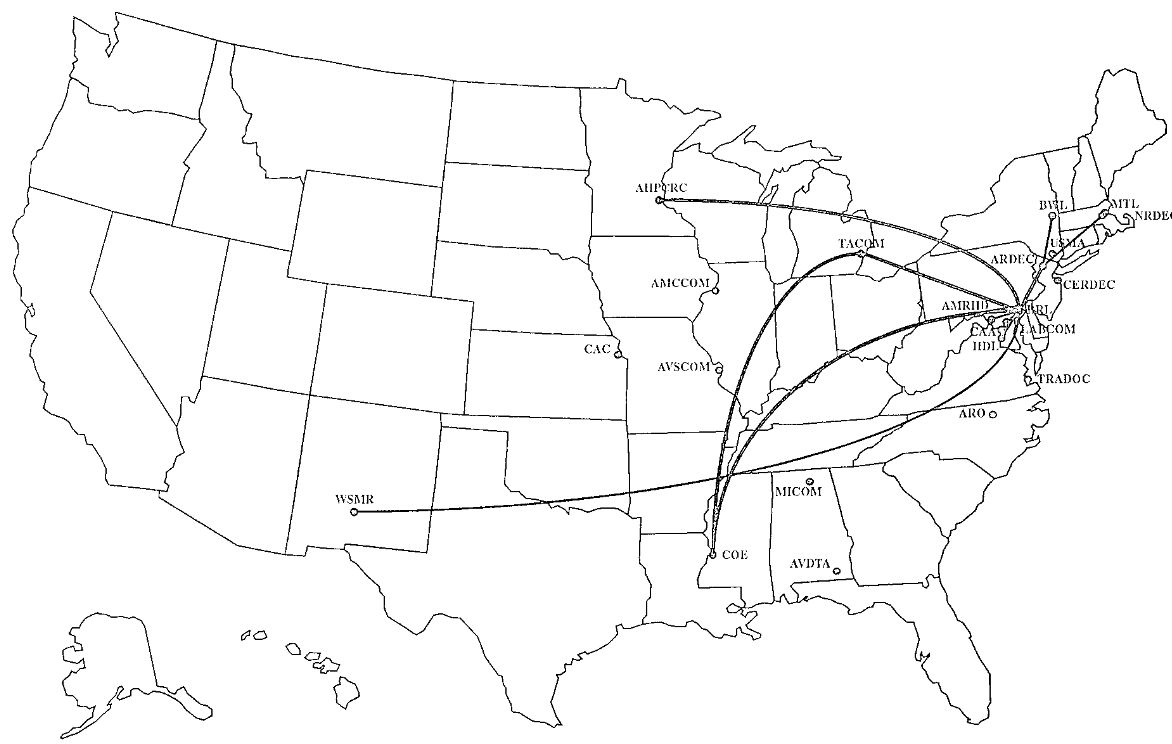
Diagram of BRLNET.

added the necessary reliability modifications. Finally, he ported the Cray-station software, originally targeted for the Sun environment, to the VAX and Gould systems in use at the BRL.

"In early 1987, as part of a joint project with NASA in distributed processing and *telescience*, the BRL became connected to the NASA Science InterNet (NSI) via a dedicated 56-kbps trunk.

"By mid-1987, BRLNET was comprised of nine main BRL-GATEWAY processors and a significant collection of network links providing MILNET access to many other Aberdeen Proving Ground (APG), MD, tenants, including Test and Evaluation Command (TECOM) Headquarters, HEL, AMSAA, and CRDEC. In early 1988, there were over 150 hosts operating on BRLNET, on the BRL campus alone."[7]

"During FY87, the BRL served as technical consultants to AMC on computer networking on the Army Secure Automated Research, Development, and Acquisition/Information Management Plan (ASARDA/IMP) project. The BRL developed the scientific-computing network program (LABNET) that was selected as one of the joint LABCOM cooperative programs. This program established interconnectivity between all nine of the LABCOM organizations for both classified and unclassified data exchange by taking advantage of the Defense Data Network (DDN). Provisions for high-speed data communication, 1.544 Mbps, which is beyond the Defense Communications Agency's (DCA) current capability, will be provided where requirements exist. More importantly, this program was a vehicle to educate all the LABCOM agencies in computer networking. During FY87, two laboratories, Atmospheric



The Army's Supercomputer Network.

Sciences Laboratory (ASL) and Materials Technology Laboratory (MTL) became operational on the network."[9]

THE HETEROGENEOUS ELEMENT PROCESSOR (HEP) COMPUTER

In June 1973, a technology report was published by AMC concerning an advanced hybrid computer system (AHCS). This report described a need for and the advantages of a state-of-the-art patched hybrid computer. The original AHCS committee was enlarged in early 1974 to include all interested parties in AMC, DOD, and NASA. The BRL was represented by Clint Frank and Bill Barkuloo.[10]

Three companies submitted proposals for AHCS, two of which were for systems that were analog in nature with auto-patch in place of the traditional patch panel and cords. The third, by Denelcor, Inc., was for a 32-bit floating-point digital version of an analog computer. A decision was made to pursue all three concepts, but we shall only concern ourselves with that of Denelcor.[10]

The BRL was impressed with the potential for the higher-risk Denelcor concept, and, at its request, the BRL was selected for the site for the prototype evaluation of that concept, which became known as HEP. In response to concerns about the high-speed bus as a limiting factor in the performance of HEP, Denelcor created a concept that not only alleviated the bus problem but also created a computer that could have much broader application that included the solution of partial differential equations. A contract for a demonstration prototype of HEP was signed in April 1975. Frank and Barkuloo, were major proponents for the HEP concept and made important contributions throughout the BRL's involvement.[10]

The demonstration prototype effort originally planned for 4 months was not completed until February 1976, partly because of a major change in the scope of work to make the algebraic unit more powerful with floating-point arithmetic, a program memory, and other features. In the demonstration, HEP ran a set of problems including a five-degree-of-freedom missile problem, but it was only able to run at 1/8 the design speed due to noise and timing problems. However, these appeared to be solvable.[10]

After considerable trials and tribulations, the BRL received and conducted benchmarks on a HEP computer with four program-execution modules in January 1983. Circa 1985, the HEP was advertised to be the fastest scaler computer in the world (four to eight times faster than a CYBER 76). It was completely air cooled. It had considerable multi-user and multi-task possibilities including acting as an interactive graphics engine for high-resolution graphics. It had large amounts of memory including the ability to handle a gigabyte of random-access memory, four 64-megabyte cache memories, and about 75-gigabytes of disk memory.[10]

Most interestingly, HEP's architecture was such that each of the four program-execution modules handled up to eight programs by performing an instruction from each program in sequence. HEP appeared to a user as a set of 32 parallel processors, and, as such, it was very useful in studying parallel processing. HEP was available on the MILNET and was used by a number of researchers in computer science, including investigators from Rensselaer Polytechnic Institute, Los Alamos National Laboratory, and the Fermi Laboratory.[10] The Army Research Office (ARO) sponsored a workshop on parallel computing at Stanford University in January of 1985; a large number of the papers presented at that meeting were based on experiments using the BRL's HEP.[11]

While several other HEP computers were produced, the machine did not mature to a highly reliable computer. Thus, while Nisheeth Patel had considerable success using HEP for research in parallel processing of partial differential equations and Mike Muuss had similar success in using HEP as a graphics engine, the BRL's HEP was extremely difficult to keep working and was decommissioned in 1985.[10]

Starting in 1982, Muuss and co-authors developed a version of "UNIX for the Denelcor HEP." They "implemented a PCC-based C Compiler for HEP, wrote drivers for the LSB and PI interfaces to HEP, implemented a simple HEP/front-end I/O protocol, implemented a HEP hardware debugger and logic tracer, and created a stand-alone test environment on which to base further development. ... creating an assembler for HEP, and porting formula translation (FORTRAN)-77, the loader, archiver, and the C runtime library to the HEP environment."[7]

SUPPORT FUNCTIONS

As with any laboratory, the BRL needed considerable support to provide the fabrication of special equipment and facilities, a complete and current supply of relevant literature, a careful accounting of assets, and a responsive supply system. In fact, the BRL might be considered to be at the high-end of requirements for support in view of its involvement with energetic materials, high-pressure gun systems, materials under very high stress and rate of stress, projectiles in high-speed flight, and materiel systems subjected to severe damage, etc. The BRL has indeed been very fortunate in having an extremely capable and dedicated staff to support its efforts in all of these areas.

In 1992, the BRL's Administrative Support Division had 110 people who represented the Library, Fabrication Shops, Graphics, Resource Management (Budget, Manpower, Program Analysis), Logistics, and a Data-Base Management Team. The shops and the library were added to the division in February 1992. Dave Ore was the chief of the division from March 1988 through September 1992.[12]

The Shops. The Experimental Fabrication Branch operated machine, wood, and welding shops with a staff of approximately 45 people. These shops provide a wide variety of functions from fabricating specific experimental devices and models to providing very broad construction and support for the BRL's ranges and buildings.[13]

Work related to the Abrams tank and the Bradley fighting vehicle (BFV) placed numerous demands on the shops for such things as configurations, targets, test fixtures, and stands to support the development of ammunition compartmentation; fabrication of reactive armor (RA) and armor appliques; and projectiles and sabots to support the development of advanced ballistic systems.[13]

An example of work on a grander scale is the BRL's closed range for firing depleted-uranium (DU) rounds (Range 14). This range was constructed completely in-house. All the shops contributed; the wood shop and the welding shop built the building; the machine shops made special fixtures such as X-ray holders and the hinges for the heavy doors.[13]

The shops have maintained a very stable, skilled work force. The people generally stayed until retirement or until they moved into other BRL functions. They seemed to enjoy the challenge posed by the technical programs, and they appreciated the enthusiastic and cooperative working environment of the laboratory.[13]

Wood Shop. A major new wood shop was finished in May of 1991. The wood shop made a variety of things such as wooden mock-ups of rounds and sabots; Plexiglas mock-ups of ranges, blast facility, shock tubes, etc.; model houses (complete with furniture) as test targets in shock tubes; and manikins (by the hundreds) for live-fire tests. And there was always the need to move partitions around as functions changed in the BRL's buildings.[13]

The construction of mock-ups prior to the construction of new facilities was of particular importance both in the sale of the project and in its design. These facilities were often quite complex with such items as X-ray rooms, shock tubes, firing fixtures, etc., and the ability to *see* the facility and to adjust its configuration prior to construction was invaluable. This was most recently the case with respect to the new Large Blast/Thermal Simulator.[13]

Machine Shop. Prior to 1976, there were a number of machine shops which were scattered around the BRL. These were then consolidated into Building 331 (and were still there in 1992). The machine shop started with computer numerical control (CNC) in 1977. This was done both to facilitate the fabrication of delicate parts (such as high-explosive [HE] molds and projectile sabots) and to make up for the loss of personnel spaces.[13]

The shop has always been called upon to create strange shapes (such as twisted, non-conical shapes for experimental artillery rounds) and to solve tricky problems (such as drilling the complex holes for base pressure measurement of base-bleed projectiles).[13]

A major, recent project for the machine shop has been the hybrid in-bore RAMjet accelerator (HIRAM) facility. Among other things, the machine shop fabricates aluminum projectiles, adds gage holes to the 120mm gun tubes, and fabricates collars that are used to join gun tubes to make a long accelerator.[13]

Welding Shop. The welding shop has moved around a good bit—to Spesutie Island, to the former wind-tunnel building, and finally back to a new facility on the island. It too has moved toward automation with a computer-controlled robotic welder and computer-controlled cutting tables.[13]

Since the late 1970s, the shop has been especially busy fabricating targets for the design of improved armor for the Abrams tank and the BFV and also configurations for ammunition-compartmentation studies.[13]

The Library. The BRL Technical Library has provided support not only for the BRL but also for the other organizations at APG. In 1992, the collection included over 35,000 books and monographs, 800 periodical subscriptions, 350,000 technical reports, 1,000 dissertations, 2,000,000 firing records, and 1,500 archival records. The library had access to over 800 data bases, which resided on 20 retrieval systems.[14]

In 1992, the library was in the process of installing the Scientific and Technical Information Library Automation System (STILAS). STILAS is a commercial system, which is compatible with the Defense Technical Information Center and is also used by a large number of facilities—universities, defense establishments, and other libraries.[15]

STILAS maintains local catalogues. The BRL library can access any other STILAS user on the network. The BRL built the system for multi-library applications—any library's catalogue could be mounted on the system. Since it is on the BRLNET, any user in the BRL could easily access the catalogues. At the time of this writing in 1992, the on-line public-access catalogue for books and journals was operational. Work was progressing on a catalogue of the BRL reports, and an acquisition module was yet to be added by which an individual user can initiate a network-wide request to acquire a document, acquire a bibliography, etc.[15]

Supply Functions. Those who have had experience with the Government's ordering system can appreciate the ordering process that the BRL has been successful in installing. This automated ordering process, which is all done electronically, has reduced the reaction time from 124 days to 21 days. A credit-card concept was installed for items less than $25,000.[12]

Resource Management. The Data-Base Management Team (four programmers with Mary Leiter as team leader) has written the software for a financial-management data base. With this data base, all employees can look at financial data related to them. Managers can also access the data base with tools to look at staffing data—demography, etc.—and the Director can get various breakdowns on the basis of such categories as source and type of money, amounts (e.g., over a certain amount), expiration dates, what is needed for labor, obligations, and dispersements.[16]

The data are available to the individual worker for his account. He can do audits on his money—what he spent it on, what is left, etc. There are also sub-bases such as:

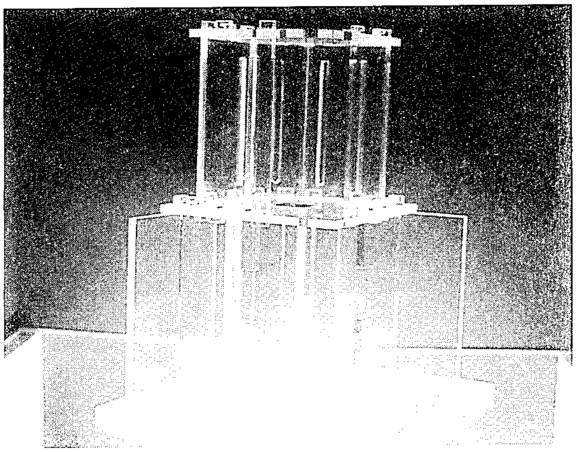
1. A travel data base - who went where, when, how much was spent.

2. Awards - who got what award, when, how much was spent.

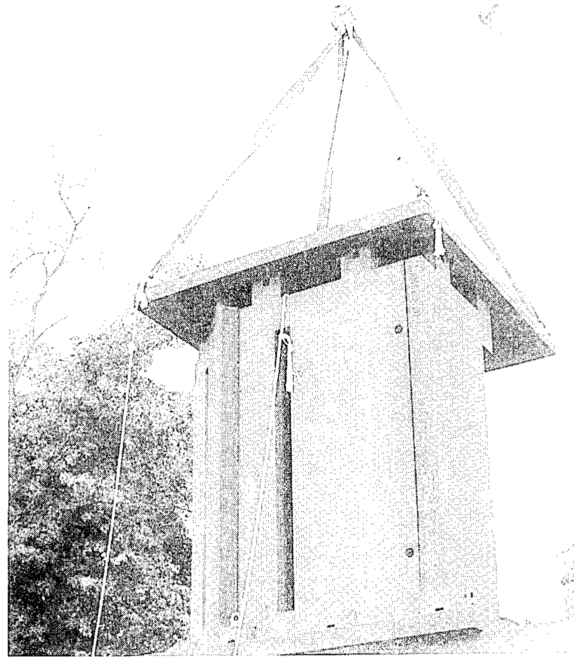
3. Supplies - can be ordered from a terminal - certification by accounting is also done by computer as is the rest of the process.

4. Labor - electronic time cards - timekeeper submits data, which go to payroll, come back to the BRL, and are posted in electronic data base.

5. A contract data base.[16]

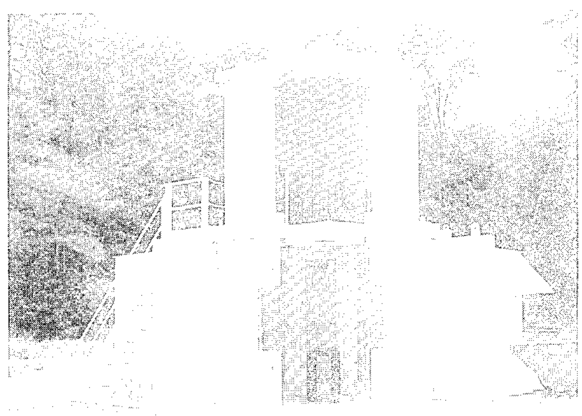


The Plexiglas Model Made by the Wood Shop.



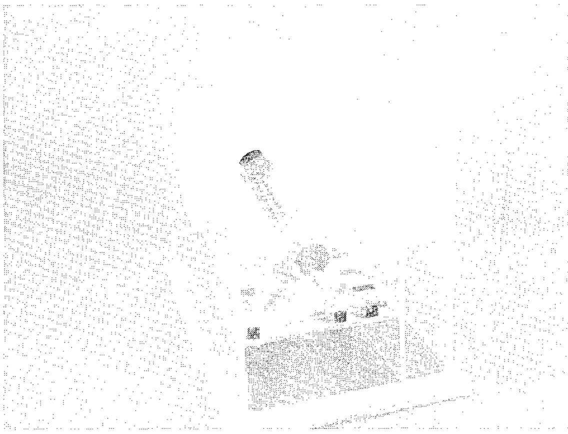
6-in Armor Plate, Cut by the Welding Shop, Being Hoisted Into Place.

The Main Structure of the Test Cell.

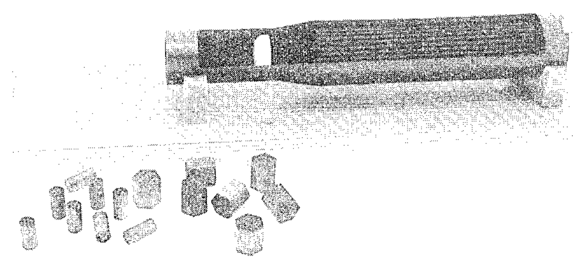


The Finished Product by the BRL Shops.

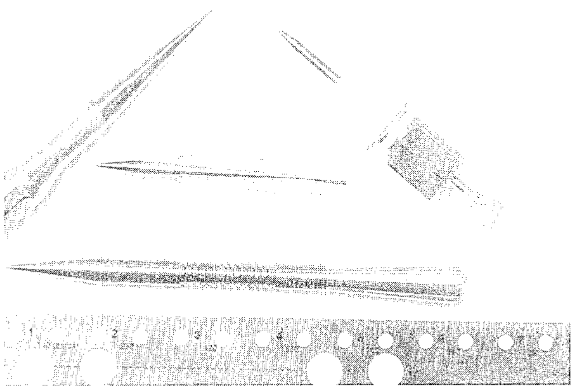
The Evolution of Range 7-A. A Plexiglas Model Was Used to Design the Structure, Which Was Made From 6-in Armor Plates With Mortise-and-Tenon Joints.



Model of the Gun Room on the "Iowa."

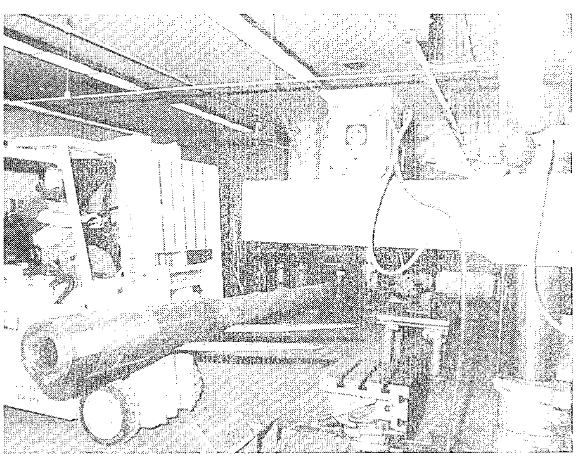


Model of a Cartridge and Propellant Grains.

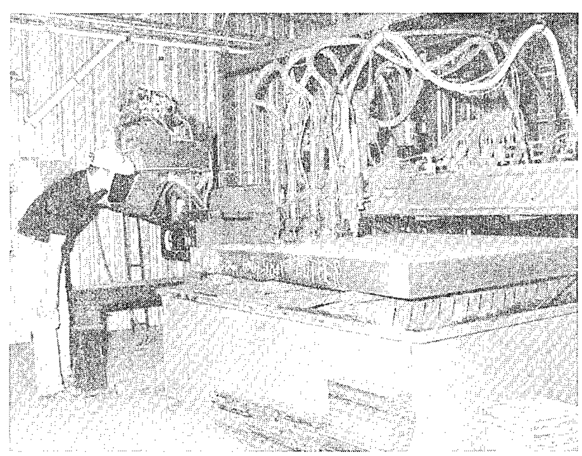


Projectiles Fabricated for Firing.

Control Room for Computer-Aided Design and Computer-Aided Manufacture (CAD-CAM) System.

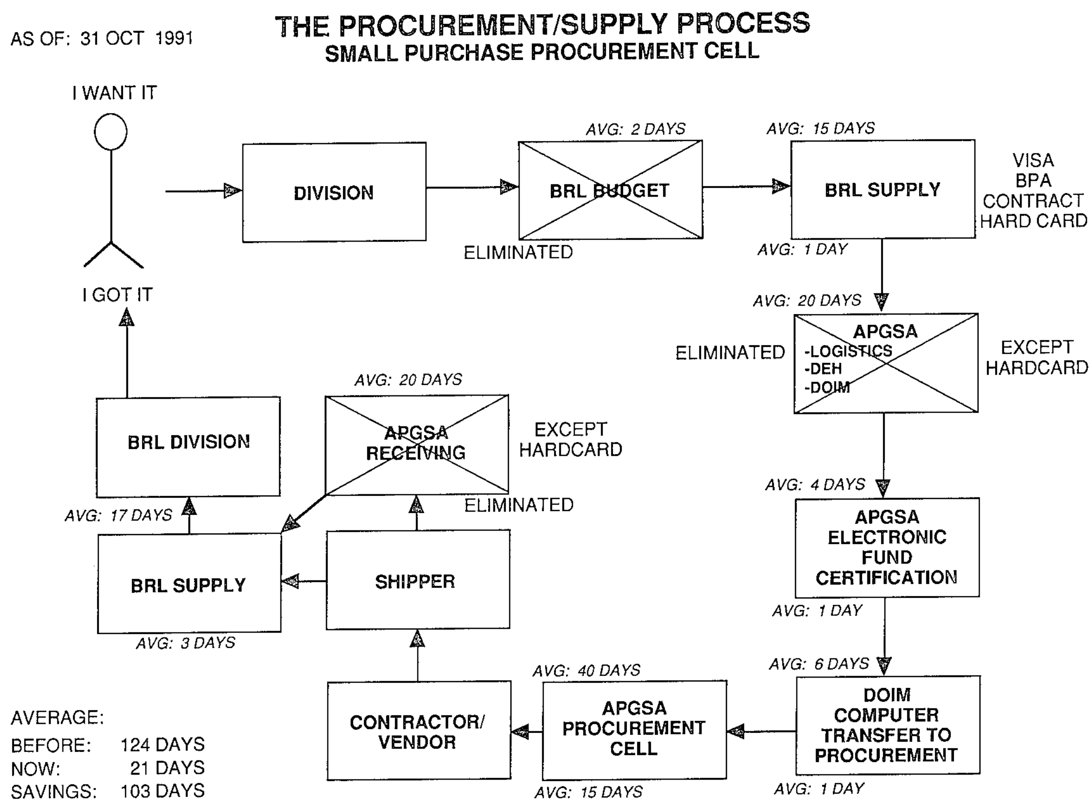


Preparing to Machine Gun Ports in a Gun Tube for HIRAM.



Flame-Cutting Operation on 6-in Armor Plate.

The Evolution of Range 7-A. (continued)

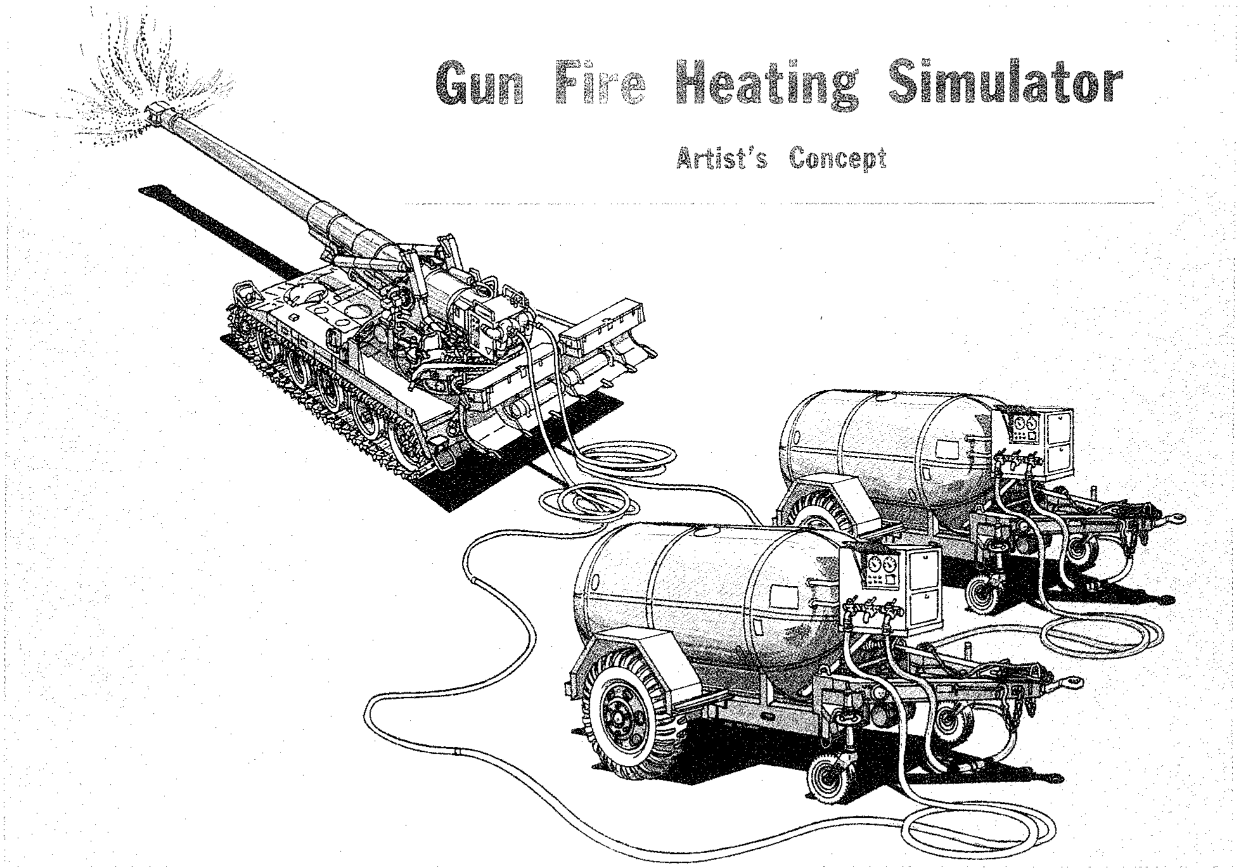


Computer Technology Has Streamlined the Supply Process.

Money comes into the BRL in hard copy. The data are then entered electronically and sent to the performer who breaks out his planned budget electronically. This then goes back into the financial data base.[16]

Graphics. Quality graphical material for reports, briefings, and displays is vital for any organization that must foster its programs and communicate its accomplishments with its clientele. In earlier times, the BRL had the stylish hand work of the likes of Don Kimbell; more recently, more sophisticated techniques have taken over.

In 1980, the graphics group had five drafting tables, a photo typesetter, a color Xerox machine, and a black-and-white self-contained camera. By 1992, they were down to three drafting tables but had seven computer work stations (with color and black-and-white scanning, printing, video editing, and special effects), and a self-contained color camera. The 1992 output was about four times the 1980 output with the same number of people and with a better product (e.g., higher resolution).[17]



The Artist and the Computer Join to Give Life to a System Concept.

BUILDING DEDICATIONS

On 24 September 1974, the Supersonic Wind Tunnel Building (Building 120) was dedicated to Dr. Robert Harrington Kent, "the country's foremost expert in the science of ballistics throughout 40 years of outstanding service to the U.S. Army; a master in gathering competent people and inspiring them do creative research. Ballistician, mathematician, and scientist, R. H. Kent achieved well-merited fame for bringing rigorous scientific methods to ballistics."[18]

On 12 September 1985, the main BRL building (Building 328) was dedicated to MG Leslie Earl Simon, "soldier-scientist, researcher, Director, the BRL 1941–1949; advocated strong technology base program as the key to timely, cost-effective weapons development; attracted international recognition to the BRL scientific staff for development, acquisition, and installation of first U.S. supersonic wind tunnel for ballistic testing in Building 120, and world's first digital computer in this building."[19]

On 28 September 1988, the Terminal Ballistics Building (Building 309) was dedicated to COL Hermann H. Zornig," pioneering soldier-scientist, complete ballistician, and foremost authority on ammunition. Studied ballistics in

Germany under the eminent Professor Cranz in the early 1930s and conceived the idea for American research in ballistic technology. Planned, organized, and developed the initial BRL. First Director of the BRL from 1938 to 1941. Set the standards for excellence and laid plans for growth and major BRL research facilities."[20]

Finally, on 30 September 1992, the BRL's Conference Center (Building 330) was dedicated as the *BRL Hall*, "to the men and women, both past and present, of the BRL. Their expertise, loyalty, and zealous pursuit of excellence combined to build a laboratory of world-wide reputation, trusted and respected for its significant contributions to the U.S. Army and the nation. The BRL, 1938–1992."[21]

AWARDS

The BRL continued to develop its reputation for quality work through its last decade and a half, winning the Department of the Army (DA) Award for Excellence in 1977, 1978, 1979, 1981, 1982, 1983, 1984, and 1988.

Program for the Disabled. One area of pride for the BRL was in its efforts in supporting the APG disabled awareness program. In 1989 and again in 1990, the BRL received the APG organizational award recognizing its accomplishments in supporting the disability awareness program. "The APG Committee for the Disabled honors the BRL for demonstrating outstanding support and accomplishments to the disabled awareness program."[22]

Interestingly enough, one of the BRL's more remarkable efforts in this area (and one which shows its compassion and dedication to community service) began in 1990 when Dorothy Kirk, the BRL's Handicap Program Coordinator, made the following suggestion to John Frasier: "I would like to get your thoughts on a proposed program that I would like to look into and develop for your handicap program. There is a program known as *Adopt a School* that I would like to pursue with the principal of John Archer. With this program, the BRL would *adopt* John Archer and would support some of [its] programs and functions during the year. The BRL would provide volunteers to help out with programs in the evening and would also provide people to go to the school and do presentations or demonstrations for the students, and also we would have students visit the lab. I know we are very scientifically oriented, but I think there are people in this lab who would be interested in this program and would be very supportive of John Archer."[23]

The John Archer School in Bel Air, MD, "is a public school designed to meet the needs of students with emotional and physical disabilities. Classes at John Archer are grouped by instructional departments consisting of classes of students of similar ages. The teachers in a department work together to benefit the students and the instructional program. The departments are Preprimary, Primary, Intermediate, Secondary, and Work Experience. The Work Experience Department serves 17-year-old to 21-year-old students. The principal of the school indicated that the emphasis at John Archer is to develop independence and to be able to meet as many daily needs as possible. These daily needs include vocational, social, and self-care skills also known as functional application skills."[24]

John Frasier made the notation "proceed, keep me informed" on a copy of the message, and the following news item that appeared in 1991 tells what resulted: "The BRL recently formed a partnership with the John Archer School in Bel Air. The partnership is a voluntary relationship designed to allow the laboratory to actively participate in the education of John Archer students, while offering them work experience in a closely supervised environment.

"The students, who are paid minimum wage, work 4 hours during school days and 8 hours a day when school is not in session.

John Archer Students Decorating the Lobby of the Main BRL Building.

The students are recommended by a representative of the Harford County School system, and laboratory supervisors interview the prospective employee for selection.

"The purpose of the partnership is to provide mutual benefits to both the Laboratory and the school. The Laboratory's involvement, in addition to providing employment and training, will include providing volunteers to assist with John Archer May Day on 11 May and Field Day in mid-June, host the Student-for-a-Day program with selected students visiting the Laboratory, and host the 1991 John Archer Graduation trip to the Laboratory on 24 May, to include a tour and luncheon at the APG Officers Club. The students will provide clerical and light labor services and participate in Laboratory events, as appropriate, by providing choral-group entertainment, bulletin-board material and handouts, computer-generated banners, signs, and the like.

"Two students from John Archer worked at the Laboratory [in 1992]. Shannon Dowden was assigned to the Administrative Support Division, where she assisted with filing, typing, and mail delivery. She also assisted with tasks related to training, personnel, and awards. Shawn Walker was assigned to the Experimental Fabrication Division, where he performed light maintenance services in the

Machine Shop, such as sweeping, taking out the trash, and oiling certain machines. Safety requirements were strictly adhered to, and Shawn was issued gloves, safety glasses, ear plugs, and safety shoes.

"Rod Ewing, principal of John Archer, recently visited the students at their work sites and said he was impressed with the work assignments and the growth of the students since they began their work at the Laboratory. The [BRL] has been cited for its commitment to the Equal Employment Opportunity program by being named for the past two consecutive years as the winner of the APG Organizational Award for support of disability awareness programs. The Laboratory was also the recipient of the Public Employer of the Year Award for 1990 by the Harford County Committee on Employment of People with Disabilities. Most recently, the Laboratory was recognized as the Medium-size Public Employer of the Year by the Maryland Governor's Committee on Employment of People with Disabilities."[25]

The BRL was even more creative when they "extended their partnership with the John Archer School by establishing a maintenance service contract with the school in September 1991. Twice a week, 4–5 students and a supervisor arrive at the Laboratory to create and maintain various horticultural projects. Indoors, they are responsible for maintenance of live potted plants/flower gardens, artificial plants and arrangements, and relocation of indoor flower beds, etc. The students create many seasonal decorative projects, i.e., for Memorial Day they made arrangements that included small American flags. The program was extended through the summer months so they could maintain the outdoor projects that were started when the contract was awarded.

"The BRL specially leased and outfitted a modern trailer (with heat, air conditioning, rest room, hot/cold water, and refrigerator) for the students to use as a work area/classroom. This trailer provides a comfortable environment for the students to do all the work needed to transplant plants, make seasonal arrangements, grow seedlings, etc. Their tools and equipment are stored in the trailer. These special provisions have enabled the students to get a lot accomplished in a short amount of time, with noticeable results. The students show pride in their work. Many complimentary comments have been received from within the BRL and outside the BRL on this special partnership.

"The expansion of this partnership has been very rewarding, for the BRL as well as the students. For the students, it is a learning opportunity, a chance to practice new skills, to demonstrate teamwork, and a chance to earn a paycheck. For the BRL, it is an opportunity to reach out to the installation, to the community, and to these special students. Through the students' efforts, a more attractive environment has been created. All those entering the grounds of the Laboratory can see the work that has been accomplished through the efforts of the John Archer students. The students were treated at the end of the school year with a tour of the [APG] Ordnance Museum. The John Archer School presented Susan Johnson[26] a Certificate of Appreciation in June 1992 for her support of the program."[27]

The Harford County Chamber of Commerce gave its Partnership Award for Administrative Services given to Harford County Schools during 1991–1992 to the BRL, and Dr. John T. Frasier, Director of the BRL, was cited for his "sincere interest and participation in the Aberdeen High School Partnership Program, 1991–1992."[27]

Awards to the People of the BRL. Over the years, the people of the BRL have received numerous prestigious individual awards including the Army's Exceptional Civilian Service Award, the Army's Meritorious Civilian Service Award, and the Army's R&D Achievement Award. Of particular importance have been the awards that have been bestowed by their peers, the Kent Award, the Zornig Award, and the Director's Award.

The Director's Award. The Director's Award was established by Dr. Robert J. Eichelberger in 1985 to provide recognition for outstanding accomplishments made in direct support of the technical or administrative mission of the Laboratory. Those who have received the Director's Award are as follows:

1985 Mr. Lyle Kirkendall
1986 Mr. Richard Markland
1987 Ms. Joan Ege
1988 Mr. William J. Taylor
1989 Mr. Hughes E. Holmes
1990 Mr. William Thompson
1991 Ms. Diana R. Abbott
1992 Mrs. Nancy Testerman.

The Zornig Award. The Zornig Award commemorates COL H. H. Zornig, the first Director of the BRL. It was established in 1959 by Dr. Curtis Lampson to acknowledge significant achievements in work done by the BRL personnel in a management or management support role. The recipients of the Zornig Award are the following:

1959 Mr. Frank H. Sirangelo
1960 Mr. Herald H. Lambert
1961 Mr. Oliver Steele
1962 Mr. D. C. Jackson
1963 Mrs. Anna Long
1964 Mr. Leonard Stansbury
1965 Mr. Chester W. Wallin
1966 Mr. Howard A. Ricci
1967 Mr. William L. Moody
1968 Mr. Leroy Stansbury
1969 Mr. James D. Wallace
1970 Mrs. Ester Johnson
1971 Mrs. Darlene J. Wilson
1972 Mr. Richard L. Hughes
1973 Mr. Arlington Young
1974 Mr. John Schmidt
1975 Mr. Clarence Bush
1976 Mr. Dale Smith
1977 Mrs. Patricia Roberts
1978 Mr. Julius Meszaros
1979 Mr. Donald Kimball
1980 Mr. John Hurban
1981 Ms. Alice C. Perry
1982 Mr. R. Paul Ryan
1983 Mr. Fred Brandon
1984 Mrs. Myra Hartwig
1985 Mr. David L. Rigotti
1986 Mr. Gary Holloway
1987 Mr. Louis Giglio-Tos
1988 Mr. John R. Jacobson
1989 Dr. Walter F. Morrison, Jr.
1990 Mr. Robert Lieske
1991 Dr. William Gillich
1992 Mr. William Johnson.

The Kent Award. The Kent Award was established in 1956 at the suggestion of Dr. Raymond Sedney to commemorate Dr. Robert H. Kent, the acknowledged founder of the BRL, and is the oldest peer award of the Laboratory. Although its initial purpose was to honor a singular outstanding scientific or engineering feat, the award is now given to acknowledge a career of technical achievement. Those who have received the Kent Award are as follows:

1957 Mr. Howard W. Zancanada
1958 Mr. Frederick Kaufman
1959 Dr. Boris M. Garfinkel
1960 Dr. Joseph Sperazza
1961 Mr. Morgan Smith
1962 Dr. Helmud H. Schmid
1963 Dr. Turner L. Smith
1964 Mr. David C. Hardison
1965 Dr. Lester P. Kuhn
1966 Mr. Harry L. Reed, Jr.
1967 Mr. Arthur E. Thrailkill
1968 Mr. Herman P. Gay
1969 Dr. Charles H. Murphy
1970 Dr. Ceslovas Masaitis
1971 Dr. John T. Frasier
1972 Mr. Leonard J. MacAllister
1973 Mr. Roland G. Bernier
1974 Dr. Franklin Niles
1975 Mr. George D. Kahl
1976 Mr. Orlando T. Johnson

1977 Mr. Donald F. Menne
1978 Mr. Jerome Frankle
1979 Dr. Raymond Sedney
1980 Mr. Charles Lebegern
1981 Dr. William J. Gillich
1982 Dr. Donald Eccleshall
1983 Mr. Alexander S. Elder
1984 Mr. William Mermagen
1985 Dr. Walter B. Sturek
1986 Dr. Terrence Klopcic
1987 Mr. Harold Breaux
1988 Dr. Judith K. Temperley
1989 Dr. Edward M. Schmidt
1990 Dr. Bruce P. Burns
1991 Mr. Albert W. Horst
1992 Dr. Joseph Rocchio.

The BRL Fellows. The organization of the BRL Fellows was established by Dr. Robert J. Eichelberger in 1969 to recognize people in the BRL with outstanding technical achievements and to provide the Director with a core of people who could provide technical guidance advice. As of September 1992, the BRL Fellows were as follows:

Mr. Harold J. Breaux
Dr. William J. Bruchey
Dr. Bruce P. Burns
Dr. William P. D'Amico
Dr. James T. Dehn
Dr. Andrew M. Dietrich, Jr.
Dr. William H. Drysdale
Dr. Donald Eccleshall
Mr. Konrad Frank
Dr. Gordon L. Filbey, Jr.
Dr. Robert B. Frey
Dr. William J. Gillich
Mr. George E. Hauver
Mr. Thomas E. Havel
Mr. Albert W. Horst, Jr.
Dr. Norris J. Huffington, Jr.
Dr. Arpad A. Juhasz
Dr. Nathan Klein
Dr. Terrence J. Klopcic
Dr. Walter F. Morrison, Jr.
Dr. Lawrence J. Puckett
Dr. Joseph J. Rocchio
Dr. Edward M. Schmidt
Dr. Walter B. Sturek
Dr. Judith K. Temperley
Dr. William P. Walters
Dr. Thomas W. Wright.

NOTES

1. The first two volumes of this trilogy were prepared by John Schmidt.

2. Rebecca M. Roling (compiler), *Directors of the Ballistic Research Laboratory, 1938-1991.* The BRL Technical Library Archives, Aberdeen Proving Ground, MD.

3. John Schmidt, *Ballisticians in War and Peace*, Volume I, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, MD, 1956.

4. John Schmidt, *Ballisticians in War and Peace*, Volume II, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1976.

5. From papers furnished by Harold Breaux on 22 July 1992.

6. Arthur D. Coates (editor), Ballistic Science and Technology, Tutorial, System Engineering and Concepts Analysis, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, May 1991.

7. "Experimental Development and Research: Factor IV," Submission for Michael John Muuss, 16 October 1991.

8. BRL Program Accomplishments, FY82, Laboratory of the Year Submission.

9. Principal Technical Accomplishment, FY87, Laboratory of the Year Submission.

10. Discussion with and papers from Bill Barkuloo on 19 October 1992.

11. At the workshop that followed in 1986, Intel's Hypercube computer was the basis for most of the experimentation.

12. Discussion with Dave Ore on 10 November 1992.

13. Discussion with Bob Callahan (Chief of the Experimental Fabrication Branch), Dean Jarvis (Wood Shop), and Mike Rose (Machine Shop) on 17 November 1992.

14. *The ARL Technical Library (APG)*, October 1992.

15. Conversation with Ida Johnson on 17 November 1992.

16. Discussion with Nancy Testerman, budget officer for the BRL, on 17 November 1992.

17. Discussion with Ted Lariviere on 17 November 1992.

18. From the dedication plaque on Building 120.

19. From the dedication plaque on Building 328.

20. From the dedication plaque on Building 309.

21. From the dedication plaque on Building 330.

22. Based on a discussion with Dotti Kirk and Susan Johnson on 4 December 1992.

23. E-mail from Dotti Kirk to John Frasier, "BRL Handicap Program - 1991," 26 October 1990.

24. 1991 BRL Application for the Organizational Award Recognizing Accomplishments Supporting the APG Disabilities Program.

25. From the *APG News* in 1991.

26. Susan Johnson took over as Handicap Program Coordinator from Dotti Kirk in July 1991.

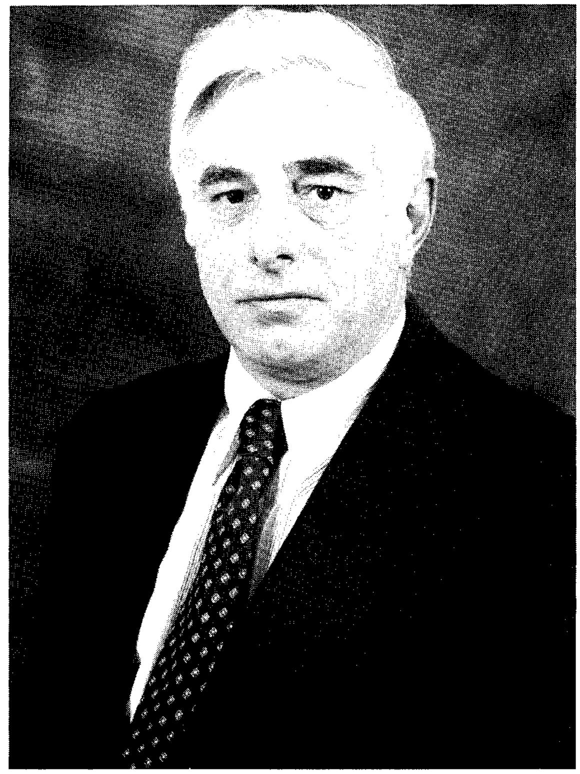
27. 1992 Nomination of the BRL for the Organizational Award Recognizing Accomplishments Supporting the APG Disabilities Program, October 1992.

INTERIOR BALLISTICS

The first thing that Ingo May (the Chief of the Interior Ballistics Division [IBD]) did in an interview[1] for this history was to show a video tape of a variety of time-dependent computer simulations. He was very excited about this capability that allowed the researcher to gain new insights into complicated events, which could not be achieved with previous stacks of tabulations or even with static snapshots. For example, one segment was a simulation of the combustion process in a liquid-propellant gun (LPG); one could clearly see the motion of the combustion waves and get a feeling for the process.

IBD's interest and exploitation of computers is not new. Its interests have spanned the spectrum from the more exotic quantum-mechanical calculations of George Adams to applications for the gathering and analysis of experimental data. For an example of the latter, we find in 1980: "Significant achievements in data analysis were attained, both in the completion of software and in the acquisition of hardware. Specific applications of digital-filtering techniques to diverse problems were completed, including those for tank ammunition-compartment blast data and for accelerometer base-line "shift" corrections. A mobile experimental research facility was completed, and more sophisticated data reduction and analysis equipment is nearing delivery. These accomplishments permit the rapid analysis of data, intelligent separation of *noise* from measurements, salvage of heretofore unusable data, tailoring the data analysis to the specific phenomena, and the interfacing with the CYBER system where advanced numerical models can be used to analyze data. The savings projected through enhanced personnel productivity, salvaged experiments, and enhanced assessment of ordnance components are partially intangible, but potential cost savings are believed to be large."[2]

Much has happened in interior ballistics (IB) in the period from the mid-1970s until 1992:



Mr. Leland A. Watermeier, Chief of IBD From 1969 to 1986, Received a Bachelor's Degree From Blackburn College, a Master's Degree in Physical Chemistry From the University of Delaware, and the Diploma of the Imperial College (DIC) From the Imperial College of Science and Technology in London, England.

When Lee Watermeier, Chief of IBD, retired in 1986, John Frasier used a series of rotational assignments to allow all the branch chiefs of IBD to act as the chief of the division. Mr. John Hurban served from September 1986 to December 1986; Dr. Bruce Burns, December 1986 to March 1987; Dr. Ingo May, May 1987 to June 1987; Mr. Albert Horst, June 1987 to August 1987; Dr. Austin Barrows, September 1987 to December 1987; and Dr. Joseph Rocchio, January 1988 to March 1988.

Dr. Ingo W. May, Chief of IBD From 1987 to 1992, Received a Bachelor's Degree in Chemistry From Gannon University, a Master's Degree From Western Reserve University, and a Doctorate in Physical Chemistry From Case Western Reserve University.

In interior-ballistic modeling, the one-dimensional, Nova 1-D, code was introduced and now [1992] Nova 2-D has provided the ability to understand catastrophic behavior. The BRL is using interior-ballistic codes to determine the sensitivity of various components and design parameters for such things as unitary-charge design and to evaluate changes to parameters on the computer.[1]

The ideas for LOVA propellants emerged circa 1973, starting as an appreciation by May, Rocchio, and Juhasz of the results of the Arab-Israeli War in which many armored vehicles were destroyed due to the initiation of ammunition. The efforts on LOVA finally have produced the M43 propellant, which was used in Operation Desert Shield/Storm.[1]

The work on LOVA resulted in revolutionary thinking about propellant. Vulnerability could no longer be something only the charge designers had to think about. The total system must be considered: igniter, packaging, composition, stowage, etc. Now this concept is appreciated worldwide.[1]

This is also the period that saw liquid propellant (LP) move from a laboratory curiosity that was difficult to control to the system of choice for the Army's new howitzer (the Advanced Field Artillery System [AFAS]), which is in engineering development.

However, much remains to be learned about LP systems. The tolerance for failure is high in solid-propellant systems; if there is a problem, conventional wisdom expects it to be solved. There is no such confidence for LP technology, which is new and largely unknown. Note that even for solid-propellant systems (with their history of many firings under myriad conditions) there are still surprises for the unwary who innovates.[1]

Sabot design is highly critical for high-performance KE tank-gun rounds. The conceptional rethinking of sabot design from saddle to double-ramp design has resulted in a 40% reduction in mass, and the associated design process is now *flying* on the computer. Even more important is the appreciation for the total design of propulsive systems. There has been outstanding cooperation among the military and industrial communities in an incredible program of bringing together the charge, sabot, and penetrator.[1]

In addition, advances in instrumentation and computer simulation have led to a new capability for understanding the in-bore dynamics of projectiles, which has significant influence in their accuracy and their survivability.[1]

Finally, there are exciting new possibilities for novel propulsion concepts such as electromagnetic (EM) and electrothermal-chemical (ETC), which offer the possibilities of not only increased muzzle energy but also of hypervelocity performance.[1]

ADVANCED CONCEPTS

Rick Morrison was the Chief of the Advanced Concepts Branch of IBD until 1992 when he became Acting Chief of TBD, and Tom Minor became the acting chief of the branch. The principal activities of the branch have been LP, ETC propulsion, and hypervelocity solid-propulsion.[3]

Liquid Propellant Guns (LPGs). The BRL had been working on the concept of using liquid propellants (sharing the acronym "LP" with liquid propulsion) in guns since the 1950s. From that time until the mid-1970s, the approach was limited to bulk-loaded systems. While much good research was done, and much useful experience was gained, a practical system was elusive.

Bulk-loaded systems are deceptively simple. The chamber is filled with the liquid, and it is ignited at the breech end. The goal is to have the hot gasses accelerate the unburned propellant which remains in contact with the projectile. This keeps the combustion process (and its high pressure) close to the base of the projectile. However, once the ignition process occurs, the simple configuration becomes complicated. The hot gasses that push on the higher-density liquid produce a large cavity (Taylor instability) in the liquid, and there is further fine-scale turbulent cavitation (Helmholtz instability). All this has a serious effect on the burning surface area and often leads to catastrophic instability.

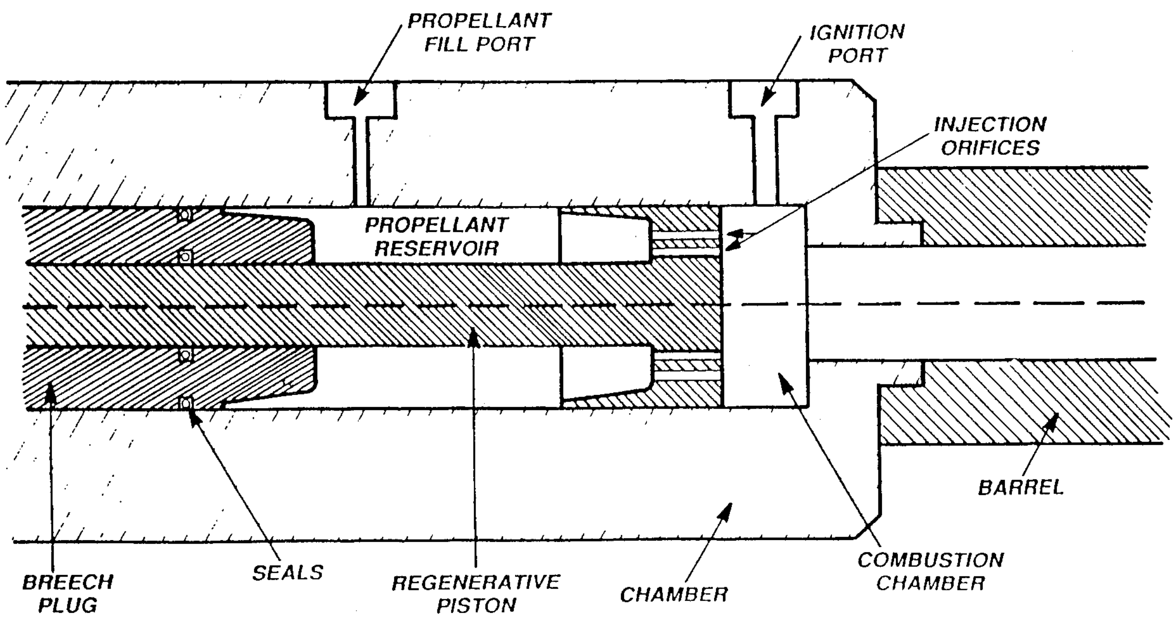
Dick Comer (then Chief of the Deflagration Physics Branch) had been working on bulk-loaded LPGs with support from in-house, the Navy, and DARPA. There were three projects running: an automatic cannon for the Naval Air Command (NAVAIR), a 75mm antiarmor gun for the high mobility and agility (HIMAG) vehicle, and a large-caliber cannon for ship use for the Naval Sea Command (NAVSEA). The hydroxyl-ammonium nitrate (HAN) family of propellants came from this latter effort. They were originally torpedo fuels.[3]

In the summer of 1976, Pulse Power Incorporated blew up two 75mm, DARPA cannons in two tries.[3] One possible culprit was adiabatic compression, heating, and ignition of bubbles in the liquid.[1]

There was a multiyear hiatus in Army funding for LP weapons. Congress decreed no work on LP systems until ignition, combustion, and explosive properties of LP were properly understood.[3] Bulk LP systems rely on a fortuitous combination of Taylor and Helmholtz instabilities. It is not realistic to expect them to be "reproducibly unstable."[1] The problems seemed endemic to bulk-loaded LP, although there probably had also been too much hurry in the program.

Circa 1974, General Electric (GE) started on an internal R&D program on LPGs and marketed their ideas to the Navy and Army circa 1976–77. Chuck Church (Advanced Concepts Team in the DA) decided to fund GE for a 105mm demonstration of an RLPG. This started out as a tank cannon but became more of a generic cannon demonstration. Dick Comer became the technical monitor for the program, which lasted through 1981. (Comer left the BRL around the summer of 1980.) GE fired the 105mm about 1982 and achieved full artillery performance.[3]

The issue was, "How do we control the combustion process?" GE proposed metering in propellant with a controlled injection like a liquid rocket motor. In the case of the RLPG, the pressure of the combustion powers the injection process by driving a piston into the



Design of a Simple In-Line RLPG.

propellant storage chamber. "We trade off mechanical simplicity for combustion control. By buying into mechanical complexity, we must pay attention to reliability, seals, etc."[1]

R. J. Eichelberger put money into the RLPG around 1982–83 and asked for an Army LP program. May, Larry Puckett, and Morrison laid out a strategy. They put together a technical briefing that including all system aspects. They contracted with the Naval Ordnance Station (NOS), Indian Head, MD, for a production study to include the cost of the propellant. BMD did the logistics part. GE did weapon-system layouts. Work was also done on hazards, toxicity, etc. Fortunately, Nate Klein et al. had developed considerable data on HAN-based propellants in the late 1970s, and the program focused on the use of these. Also, due to Comer's foresight, there was a considerable amount of useful data on many practical issues such as safety, shipping, etc.[3]

The following item appeared in the BRL's accomplishments for 1982: "LPG technology has been advanced on several major frontiers: (1) The BRL developed a new class of LPs that satisfy the Army's temperature specifications, and with performance characteristics greater than M30 solid propellants; and (2) IB and muzzle velocity have been shown to be controlled, and as reproducible as solid-propellant guns. Major cost savings are associated with the production and use of new LPs."[4]

During 1983–84, the BRL developed the RLPG program in conjunction with the rest of the Army and with GE. Work actually started about 1985.[3]

In January 1986, LABCOM requested a Memorandum of Understanding (MOU) with the Army's Armament Research, Development, and Engineering Center (ARDEC) to create a joint effort with the BRL demonstrating the RLPG cannon and then transitioning the program to ARDEC for further development. A joint program office was set up between the BRL and ARDEC to accomplish the task.[3]

For 1986, we have: "The goal of the LPG demonstration program is the technical demonstration of a 155mm RLPG system for artillery applications. Both gun and propellant development are addressed in this program. Progressive testing will be accomplished in 30mm, 105mm, and finally in 155mm configurations. In FY86, the principal accomplishments were successful completion of high (+65° C) and low (-50° C) temperature test firings in a 30mm RLPG. The results indicate that due to the temperature insensitivity of LP, no propellant-temperature correction is necessary in the fire-control procedure, as is traditionally required for solid propellants. Moreover, the lack of dependence means that LPGs may be operated safely at higher chamber pressures than solid-propellant guns and, therefore, achieve higher muzzle velocity. The first successful test firings of an advanced-concept 105mm RLPG using HAN-based propellants were accomplished including firing at full charge. The first phase of an LP packaging and handling study has been completed, resulting in the development of alternate concepts for packaging of LP in the Army logistics system. A demonstration of the feasibility of chemical-analysis procedures, both for the Laboratory and for the control of a fully automated LP production facility has been completed. The first phase of an LP production-process development has been successfully completed."[5]

For 1987: "The objectives of the LPG demonstration program are to develop and demonstrate 155mm brassboard LP artillery fixtures, and, in parallel, develop the propellant and gun-technology bases required to support a decision to proceed with proof-of-principle and full-scale development (FSD). Technical achievements this year included: (1) safe firing of a 30mm LPG from -45° C to +65° C, with zero temperature coefficient; (2) testing of advanced gun concepts in 105mm, with muzzle-velocity repeatability better than an equivalent solid-propellant gun; (3) fabrication of internal components for the first 155mm LPG; (4) the second phase of a propellant process-development effort successfully completed by Olin Chemical; (5) a state-of-the-art analytical laboratory completed at the BRL to support propellant research projects and to provide detailed chemical analyses for all LP used in the program; (6) an engineering concept study addressing the packaging and handling of LP from the production facility to the combat vehicle completed by Bell Aerospace Textron. A follow-on program to demonstrate a large-caliber, high-performance LP cannon for antiarmor applications was initiated at the BRL in August 1987; the ultimate goal of this effort is to exploit the synergism of all gun systems on the battlefield using a single propellant. In summary, the BRL has brought LPG technology to a level of maturity where, for the first time, the transition of this technology from the Laboratory to the development and engineering center is in sight. [The technology has been] transitioned to ARDEC."[6]

For 1987: "Characterization of HAN-based LPs was carried out in areas related to the (1) analysis of chemical composition, (2) characterization of the destabilizing effects of metallic impurities, (3) spectroscopic measurements of structure and bonding in the aqueous HAN solutions, (4) characterization of conditions required for phase separation including crystal polymorphism in crystalline HAN, (5) measurement of physical/chemical properties of the propellants as a function of concentration, temperature, and pressure, and (6) characterization of droplet evaporation/ ignition. These studies are providing the data required to predict and model the behavior of the propellant during manufacture, storage, transportation, injection, and ignition/ combustion in the RLPG."[6]

Full-scale tests were successful in 1988: "During FY88, the first full-scale 155mm RLPG was test fired. In the ensuing successful test series, an outstanding record of muzzle-velocity reproducibility (standard deviation of 0.2%) was achieved (almost twice as good as the artillery acceptance standards)."[7]

The program is summarized in a 1989, *Update* article by Charles Leveritt: "The objective of the present program is to demonstrate a brass-board 155mm RLPG and propellant system, and to develop the supporting technology base in preparation for the gun system propulsion decision for the AFAS in FY91.

"The LP, a mix of materials similar to those found in common fertilizer, will compete with the current solid-propellant system that uses a more sensitive granular charge.

"The Army's Production Base Modernization Activity has confirmed the BRL's estimate that the LP can be manufactured and packaged at 25% of the cost of current solid systems besides being safer to manufacture, store, and handle.

"It remains to be seen whether these advantages offset the increased complexity of the LPG. If the gun proves reliable, the next decade could see it begin to replace the Army's standard self-propelled howitzers. The LP technology can also be used by other guns, as well as by fellow members of the North Atlantic Treaty Association (NATO); Great Britain and West Germany are also experimenting with LPs.

"Gun component development and testing has been conducted in 30mm, 105mm, and 155mm fixtures. Performance and muzzle-velocity repeatability equivalent to fielded systems [has] been demonstrated. Burst-firing tests are now being conducted in 30mm.

"Firing tests in the first 155mm artillery fixture were initiated by the Army in July 1988. Excellent performance and repeatability have been demonstrated at the equivalent of zone 5 and zone 7 firings. Zone 8 equivalent firings are now in process. Testing will continue through FY90. Design of the second-generation 155mm LPG is underway. Testing will begin in May 1990 and continue through the end of the program in FY91.

"The propellant development program has paralleled gun development with focus on characterization, production, and logistics. In addition, efforts are underway to identify and evaluate potential issues associated with the future fielding of an LP weapon system.

"The LPG program is a joint ARDEC/LABCOM effort, with the BRL currently having overall program responsibility. As a result of the technical progress in the program, transition of program responsibility to ARDEC is planned for this month."[8]

Transition to ARDEC occurred in June 1989. The BRL remained in a supporting role (interior-ballistic modeling, propellant development, ignition studies, combustion studies, vulnerability aspects, etc.).[3]

The RLPG program started as a BRL program (with ARDEC as deputy) in which the BRL developed the propellant and GE developed the gun under contract. After the system met the transition criteria on performance, repeatability, and the ability to model, the program became an ARDEC program with the BRL as deputy. After the transition, the BRL maintained the lead in propellant-producibility studies, interior-ballistic modeling and basic phenomenology, and pressure-oscillation studies.[9]

In March–June of 1991, firings of the 155mm RLPG at Yuma demonstrated a 45-km range with the M549 rocket-assisted projectile.[3]

In September 1991, the RLPG was established as the propulsion system of choice for the AFAS, which is currently [1992] in engineering development.[3] The RLPG is preferred for AFAS (which still needs time and patience) with a modular charge as a backup.[1]

While regenerative LP eliminates the low-frequency longitudinal oscillations of the bulk systems (which are also the high-energy oscillations), high-frequency oscillations have been observed in RLPGs. These radial oscillations are of lower energy and do not produce effects other than in heat transfer and in shock on the round. Similar high-frequency oscillations were common in LP rockets, and baffles were used to reduce them.[1]

Solid propellant has longitudinal pressure oscillations with frequencies on the order of a couple hundred hertz. RLPG has radial and tangential in the frequency range of 1 kHz–100 kHz. The current [1992] concerns are as follows: What's causing them, how to get rid of them, how to live with them, can we live with them, will they will affect fatigue life, and with respect to wear and erosion, do the oscillations reduce the *cooling effect* of the liquid boundary layer? Fortunately, safety is probably not an issue; the energy content is low.[9]

The effect of the high-frequency oscillations on the payload (e.g., improved conventional munitions [ICMs], fuzes, sensors) is unknown. Reliability is easy to satisfy on a one-time basis for a particular round, but a more general basis for safety is a problem.[1] There is such a wide spectrum of frequencies. How they interact with various components in the fuze and guidance devices (springs, small parts, HE, etc.) is an open question.[9]

Work in the Laboratory includes a spray-splitting device to spread the propellant spray, using other formulations with higher burning rates (which decreases the level of oscillations as predicted by modeling), and absorption of the oscillations by flexible chamber walls (but the walls wear out quickly). Note the difficulty in igniting the propellant at low pressure (a good property from the LOVA stand point) exacerbates the problem. At a low point in the oscillation, propellant builds up and then burns in a spurt when the pressure rises.[9]

There is a spectrum of models for LP (similar to those for solids) including bulk parameter models and a two-phase, two-dimensional model, which has been used to identify appropriate parameters, etc.[9]

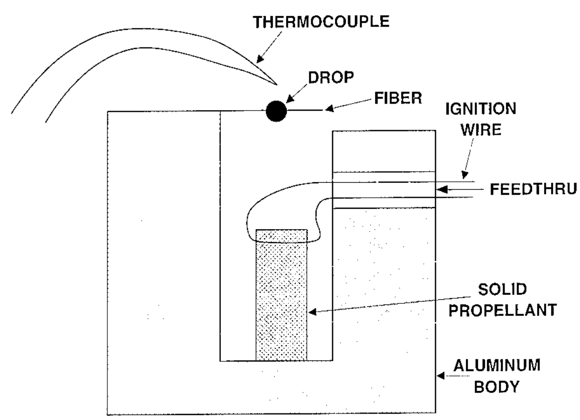
The following excerpt is from a 1992 *Update* article by John Knapton and Aviezer Birk on spray combustion: "Numerous power and propulsion systems involve liquid spray combustion. They range from the ubiquitous residential oil furnace to diesel and turbine engines and culminate in powerful rockets such as the Saturn V, that placed men on the moon, and the present day space shuttle. The RLPG is arguably the most exotic propulsive system utilizing liquid injection and spray combustion. The RLPG operates at pressures at least an order of magnitude higher than other propulsion systems and achieves combustion intensities as high as in the Saturn V rocket. While RLPG technology has matured to the point where a fieldable 155mm howitzer developed by GE is routinely fired successfully, technical issues remain, among them high-frequency pressure fluctuations.

"Virtually all RLPG systems developed to date, from 30mm up, exhibit large high-frequency pressure fluctuations in the combustion chamber at some point in the combustion cycle. While overall performance is little affected by these fluctuations, they may have an adverse effect on projectile components. Of course, pressure fluctuations in liquid-spray propulsion systems are not new, having been encountered in many liquid-rocket engines.

Analysis of pressure fluctuations reveal that, in general, they have coherent as well as incoherent content, the latter sometimes referred to as combustion noise. The coherent structure, in most cases, relates to acoustic waves which depend on the global geometry of the particular combustion chamber. In liquid rockets, most of the energy in the pressure fluctuations is stored within the coherent fluctuations, while in RLPGs the opposite is true. (It is interesting to note that the coherent fluctuations in RLPGs are transverse acoustical waves, while the pressure waves which were encountered in the past in solid-propellant guns were longitudinal and had substantially lower frequencies.) Engineering solutions to date have been successful only in the elimination of coherent fluctuations in LP systems, including RLPGs. For example, a recent application of a jet dispersion device in an experimental 30mm RLPG in the BRL resulted in the elimination of coherent transverse fluctuations. ... Nevertheless, the high-frequency, incoherent fluctuations persisted, rendering the modified P-t curve indistinguishable from the base curve.

"Substantial research effort is currently focused on eliminating the pressure fluctuations in RLPGs. The mechanisms driving pressure fluctuations in RLPGs are controversial but can be related to the temporal distribution of LP in the combustion chamber. That is to say, that if the liquid burned instantaneously upon injection there would be no pressure fluctuations since they arise from the interaction of gas dynamics with the combustion process of the liquid being dispersed within the chamber. The characteristics of liquid dispersion and burning, referred to here as spray combustion, are therefore a most important aspect of research within the overall effort for pressure fluctuation elimination.

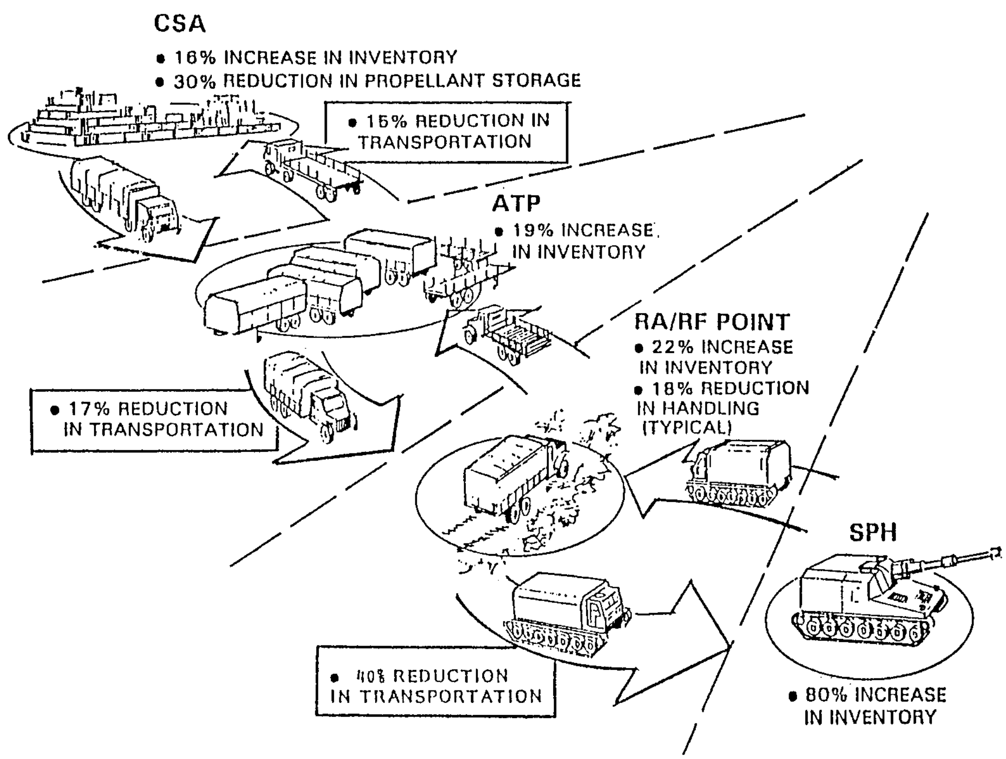
"Spray-combustion research as related to guns was initiated in the BRL in the mid-1980s. While spray research is perennial with many research organizations, experimental work with liquid-monopropellant spray combustion at gun pressures is unique to the BRL. Within the BRL, emphasis is placed on visualization of gun-type combustion processes in clear gas such that liquid dispersion and the mode of burning actually can be seen. Visualization of the combustion process in actual guns has been very poor due to their restricted geometry and the optical density of the combustion process.



Pressurized Chamber for Investigating LP Combustion.

"A first-generation spray research facility in the BRL has been in operation now for 2 years. The facility provides test times as long as 1 s and is rated for operation up to 45 MPa at propellant injection rates of one to two orders of magnitude smaller than typical 30mm RLPGs. While studies of liquid atomization at high pressures are routinely done elsewhere at room temperatures, the BRL facility is unique in enabling such studies in gas temperatures as high as 550^0 C. This extends its utility to the study of liquid-spray evaporation, ignition, and combustion, albeit at the low end of the typical RLPG pressure ranges. The operation of the facility is as follows. A flow of nitrogen is regulated from a high-pressure reservoir, heated by a particle bed heater, and introduced into a windowed test chamber to provide the environment for spray combustion. A regenerative-type injector injects either solid circular or annular jets of liquid monopropellants into the hot compressed nitrogen. The propellant jet is photographed as it breaks, atomizes, and burns by means of high-speed cinematography employing copper-vapor-laser stroboscopy. Large rectangular sapphire windows (3.9 in x 1.4 in) provide excellent access for visualization and spectroscopy. Instrumentation measures injection velocity and pressures in the system. To date, experiments have been conducted to 38 MPa in 500° C nitrogen with injection velocities approaching 250 m/s. Test data have provided clues to the combustion mechanism in the RLPG at higher pressures where pressure fluctuations are most evident.

"An important goal of the experimental program was to determine whether LP burns supercritically. In supercritical processes as related to sprays, surface tension between the liquid and the gas disappears as there are no clear boundaries between gas and liquid particles. This results in disintegration into even finer droplets which would enhance the pressure sensitivity of supercritical combustion and, therefore, the sensitivity to pressure fluctuations. Experiments conducted to date with LP reveal that they burn subcritically at the lower gun pressures, with the attainment of surprisingly large globules of liquids being locally in vortices shed away from the jet spray



Logistical Advantages of LP.

boundaries. Investigations of supercritical evaporation of liquid (ethanol and nitromethane) jets revealed liquid dispersion patterns quite distinct from subcritical ones. Considering that in guns the LP consumption rates are far higher than presently tested, random poppings of localized burning are consistent with pressure fluctuations at high pressures. This tends to confirm an hypothesis that measured pressure fluctuations are manifestations of combustion noise, which would explain why pressure fluctuations in guns are most prevalent at frequencies above 25 kHz, and are independent in this range of combustion-chamber geometry. This picture of spray combustion in an RLPG was first proposed by Professor Martin Summerfield in 1983. Flow recirculation patterns in the chamber are also clearly important. High-speed photography has revealed that burning is highly turbulent and can reach very near to the injection port despite the high liquid-injection velocity.

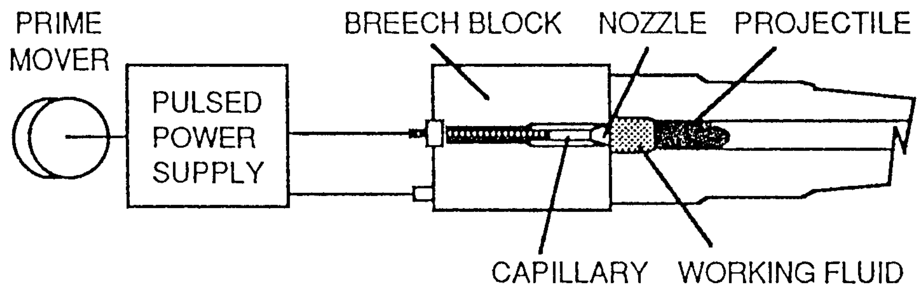
"A second-generation spray research facility in the BRL is intended for operation up to 150 MPa, i.e., at more realistic gun pressures. Unlike the present facility, the new facility will employ a ballistic compressor process which will compress and heat selected test gases into which the LP will be injected. Based on the experience with the present facility, the visualization to be obtained with the new facility should be excellent. The new facility will enable exploration of combustion processes at pressure ranges where there is experimental evidence that the propellant burn rate becomes very sensitive to the ambient pressure. It will also reveal if the LP burns supercritically.

"Because of the excellent visualization obtainable in the present facility, it has been used to assess the combustion characteristics of an alternative LP developed recently which is more reactive than the standard LP. Rationally, if a particular propellant burns faster at any given pressure, then, at any given time, less of it is expected to exist in unreacted form in the combustion chamber, thus eliminating the energy sources for sustaining the pressure fluctuations. The alternate propellant tested was found more reactive, and it awaits testing in actual gun firings. It is expected that both the present spray facility and the planned new facility will continue to provide valuable information for the effort to eliminate pressure fluctuation. The physics which will be revealed experimentally will be utilized for the more detailed interior-ballistic modeling required for the next generation of high-performance RLPGs. The BRL efforts on the understanding and reduction of pressure fluctuations are an important part of a coordinated liquid-propellant program managed by the Program Manager (PM), AFAS, ARDEC, and a cooperative DOD/DOE program with Sandia National Laboratories."[10]

Looking to the advantage of having only one propellant on the battlefield, the BRL has established a small task to look at high-performance RLPGs for application to tank cannon, etc. The concept, which is in the very early stages of experimentation, involves the use of a reverse annular piston. This more compact design is appropriate for automatic fire and can squirt propellant down the bore, allowing higher pressures to be maintained at the base of the projectile. A 30mm firing fixture has been built in the hope of developing interest.[9]

Electrothermal-Chemical (ETC). Electrothermal (ET) propulsion concepts, in which an inert fluid is vaporized and heated by plasma arc, appear in the hypervelocity literature in the 1960s.[3] However, the entire energy must come from the electrical power source with the attendant problem of obtaining an adequately portable source.

But there has been a serious quest for a propulsive system that can produce significantly higher velocities than conventional chemical propulsion systems. "The armor/antiarmor battle has raged for centuries. Steel body



ETC Gun Concept.

armor, the longbow, muskets, tanks, the German flak 88, and the Russian T-72 tank; each was an attempt to better the enemy's armor and antiarmor capability. We now have a modern battlefield with composite, RA, and long-rod penetrators. One potential improvement for many Army cannons, not just the tank, may result from the ETC program. Since 1983 ..., the BRL has been involved in the development of the ETC concept for future tactical weapon systems. It is projected that the Army will need increased penetration to defeat future threat armored vehicles, artillery with greater range to deliver and avoid counter-battery fire, and antiaircraft cannons with high velocities and rates of fire. The ETC gun offers the potential to meet many of these needs in existing cannons.

"As the name implies, ETC does not do away with chemical propellant, but uses electrical energy to augment and control the rate at which the propellant reacts. The pulse forming network (PFN) delivers a high-energy electrical pulse to the gun breech. This initiates a plasma arc in the cartridge. The arc ablates the material of the cartridge walls, feeding material into the plasma, which is then injected into and reacts with the propellant. By controlling the amount and duration of electrical energy discharged into the cartridge, the feeding of the plasma into the propellant bed can be controlled, theoretically controlling the rate of propellant-gas generation to take advantage of the gun tube's ideal pressure profile. Initial investigations indicated potential projectile KE increases of up to 50% over conventional guns."[11]

Around 1984, the BRL had a contract with GT Devices to work on ET, and by 1987 they had begun using energetic working fluids.[3] There was a clear need for a research role to determine if there was a good thing here. "Is there a pony in this technology?"[1]

FMC started their own program around 1986, and by 1989 they had scaled up to 105mm. The BRL had given them a gun tube under an unfunded study agreement.[3]

General Dynamics Land Systems (GDLS) became involved with GT Devices around 1988 and was testing a 120mm device by the spring of 1989.[3] GDLS saw big production opportunity for retrofit in the M1A1 tank if they could get the performance of a 140mm gun from a 120mm gun.[9]

Bill Oberle, BRL, manages the ETC propulsion research for the Electrical Armaments Program Office at PA, NJ, which, in turn, manages all electric gun programs.[9]

For 1988, we find the following report: "A new computer-analysis capability for determining the thermochemical properties of plasma-working-fluid combinations for ET guns was established. This capability was utilized in establishing a thermodynamic basis for evaluating ET gun propulsion potential on behalf of the Army. A systems evaluation of military applications of ET gun propulsion was completed."[7]

From an *Update* article on ETC by Steven Bunte and William Oberle, we have: "The ET accelerator is an advanced hypervelocity gun-propulsion concept currently under study jointly at the BRL and ARDEC. In the ET process, electrical energy is introduced into a plasma-generating capillary through a wire connecting the forward and rear electrodes on the capillary. A high current flows through the wire, causing it to explode, thereby establishing the plasma. The plasma flows rapidly out to the capillary and into the chamber containing a working fluid. The resulting dissociation of the working fluid results in a pressure rise and subsequent acceleration of the projectile. The ability to introduce controlled amounts of electrical energy permits a tailoring of the impetus (force) of the resultant gases.

"A theoretical study was undertaken using the BLAKE thermochemical-equilibrium code to evaluate the relative merit of potential working fluids through an analysis of their thermochemical properties. These properties were then used in interior-ballistic codes to estimate the performance of the fluid as a propellant in an ET weapon by computing the velocity of the projectile. ... This study has shown that ET, even with common chemicals such as octane/peroxide, would obtain impetus levels approximately 50% greater than conventional propellants. Although substantial assumptions are involved, interior-ballistic modeling predicts muzzle-velocity increases up to 25% above conventional propellants. With exotic chemical fuels, it may be possible to triple conventional propellant impetus levels, with correspondingly higher gun performance. Experimental and theoretical studies are currently underway to provide the required detailed characterization of these high performance systems."[12]

With claims of a breakthrough, it became necessary for a moment of truth. In the summer of 1989, the BRL supported the creation of a firing facility at the Defense Nuclear Agency's (DNA) Green Farm facility to allow experimentation with the FMC and GDLS concepts. The BRL managed the firings in which each contractor fired several dozen shots. Each experienced severe pressure excursions, and, while no guns blew up, both concepts experienced stretching of the guns.[3]

"Large-caliber tests conducted at Green Farm (spring 1990) demonstrated the feasibility of ETC, but also exposed serious problems with the technology. The flaws showed that the ETC process was not well understood. These tests added impetus to an ongoing, coordinated diagnostic and modeling effort. The initial diagnostic phase included the development of a multiple-electrical-pulse system to produce a variety of pulse shapes with flexibility for future applications. In concert, a model to predict plasma capillary performance was developed and validated to aid in the PFN design."[11]

The contractors saw that there was a possibility to get the performance of a 140mm tank cannon in a 120mm gun. The Army had to sort out fact from fiction, and thus the tests at the Green Farms facility. After the frenzy, we are back to a more sensible program.[1]

While there still was heavy contractor participation (GDLS and FMC) after the unsuccessful crash program, the effort went back to a more orderly technology-based program. First, work was to be done in medium caliber (with an eye to either tank or artillery application—contractor's choice). That work had to meet requirements on performance (an increase in muzzle energy) and on the controllability of velocity, pressure, and pressure rise. Additionally, there must be no obvious *show stoppers* for the propellant [e.g., red-fuming nitric acid would not be acceptable]. Only then could the contractors go to a large-caliber system with a new set of tighter specifications.[9]

The BRL is doing ETC modeling much like LP modeling. They are also doing diagnostics in closed bombs (e.g., looking at the ETC capillary that is used for ignition). They are also using an ignition simulator with a sapphire window (to observe the ignition process) and with a blow-out panel (to preserve the sapphire window).[9]

"A ballistic diagnostic system has been developed at the BRL to examine propellant and electrical-energy (plasma) mixing processes under closed-bomb (static) and dynamic gun (moving projectile) conditions. Tests have demonstrated that charge geometry is critical to ETC propellant performance. Initial testing was also used to provide a basis for the modeling effort and to validate programs as they were developed. These tests also exposed flaws and suggested improvements in the design of the PFN. A higher energy PFN incorporating improved design has been completed in the Laboratory; low-energy tests have validated the improvements. This PFN will be joined with a recently delivered 30mm test fixture for additional small-caliber gun testing. This fixture will be used to examine distribution of plasma energy in the propellant bed and to examine the initiation of potentially destructive pressure waves in the chamber, as well as other ballistic phenomena. Both small- and large-caliber diagnostic work is planned under contract with the FMC and GDLS corporations. In preparation for this, IBD of the BRL and FMC tested a 120mm ETC cannon at Range 18, the large-caliber gun test facility, in November 1990. This test demonstrated the capture of in-bore ballistic data without EM interference from the high-energy pulse of the gun firing.

"The BRL modeling effort incorporates several issues involving ETC technology. A significant area of concern at Green Farm was the development of pressure waves in the chamber. The fundamental cause of these waves is unknown. Investigations using a one-dimensional ETC interior-ballistic code provide general agreement with the structure of the experimental observations. The planned incorporation of chemical kinetics may provide better understanding of the pressure waves. Inverse codes, which accept experimental data as input, have been used to determine more ideal ballistic-component configurations. Using first principles of plasma physics, a steady-state, one-dimensional model of the plasma cartridge has been developed. This code provides good agreement with experimental data produced in testing at the BRL and North Carolina State University, and can provide feedback to a model of the PFN. Ultimately, all of these separate codes will be modified to develop a multicomponent (power system, plasma cartridge, combustion chamber, and tube), multiphase, interior-ballistic model of the dominant physical processes in the ETC gun."[11]

The BRL is also looking at solid propellants for application to ETC since burning surface (plasma interface) control is such a problem for LPs—ergo, solid-propulsion electrothermal chemical (SPETC). To get the appropriate high density of loading, they use compacted propellant and break it up with the plasma.[9]

ETC research has also entered the international arena, "Under a joint BRL/Israeli program, a 16% increase in muzzle energy was demonstrated by using an ETC technique vs. the standard powder technique to ignite a *benchmark* propellant. The performance gain was even 2% higher than for the *optimized* conventional propellant (first time this has been demonstrated). The goal of the program is to demonstrate a 25–45% increase in muzzle energy over the optimized conventional propellant."[13]

Traveling Charge (TC). One of the long-time problems for ballistics was to realize a TC propulsion system in practice. In the simplest terms, TC involves attaching the propellant to the base of the projectile. It burns throughout the projectile's travel in the gun tube, and thus the high-pressure products of combustion are kept at the base of the projectile where they are needed. In conventional systems, the high-pressure gasses in the chamber lose much of that pressure expanding to *catch up* with the projectile.

The need to attach and maintain the propellant at the base of the projectile means that the propellant cannot have many small grains. This creates the requirement for a very high burning rate (VHBR). Clearly, the propellant also has to have sufficient mechanical properties to remain intact during the acceleration process. For decades, people had tried to create suitable propellants and demonstrate TC propulsion.

Such propellants, based on the use of Hiverlite, were demonstrated in 1984. "In the area of advanced propellants, BRL research has developed the methodology for formulation of VHBR propellants for TC application. One such formulation has demonstrated a five-fold increase in burning rate (to 250 m/s) over last year, thereby removing the major obstacle for the hypervelocity TC cannon."[14]

"This year [1987] saw the experimental and theoretical demonstration of the TC and its beneficial effects on muzzle velocity in a 14mm test gun. Measured pressure-time profiles clearly indicated the contributions to pressure due to TC burning. Projectile velocity profiles demonstrated the accompanying acceleration. Theoretical computations using a two-phase hydrodynamic interior-ballistic code closely matched experimental firings. Potential payoffs of 20–25% muzzle velocity improvements for high charge-to-mass ratio systems, at no additional maximum pressure, are indicated by the theoretical simulations."[6]

That year also "saw the first application of a state-of-the-art technique to determine the combustion mechanism of VHBR propellant. In an attempt to incorporate a VHBR propellant in a monolithic grain configuration into a propelling charge, irreproducible results and anomalously high pressures were obtained, indicating potential propellant breakup or burning in an extended reaction zone. A joint program between the BRL and Aerojet Ordnance Company was put in place to investigate the burning of VHBR propellants under conditions of interior-ballistic relevance. Pennsylvania State University was contracted through ARO to apply an X-ray cineradiographic system to the problem. The first X-ray movies taken of the burning grain at low pressures indicated normal, laminar burning with no indication of grain breakup or burning in an extended reaction zone, corroborating the behavior seen in other diagnostic testing at these pressures. Additional tests at higher pressures, where we would expect to see differences in the combustion method, are scheduled."[6]

"The TC concept for achieving velocities in excess of 2 km/s from solid-propellant guns has been demonstrated for the first time [in 1988]. Experimentally measured pressure-time and projectile velocity and acceleration profiles clearly indicated a velocity boost in a solid-propellant gun. The research team received the DA R&D Achievement Award for this work."[7]

Shortly after this, the program died for lack of funds.[9]

APPLIED BALLISTICS

Presently [1992], Al Horst is Chief of the Applied Ballistics Branch, which has responsibility for the development of interior-ballistic models, work on advanced solid-propellant technology, and Range 18 at which the in-bore RAMjet is being tested.

Interior-Ballistic Modeling. "Over the past three decades, the field of interior-ballistic modeling has undergone a number of major advances. Early lumped-parameter models, which began to appear in the early 1960s (e.g., the Baer-Frankle code, 1962), provided the charge designer with a powerful tool to perform large, parametric interior-ballistic studies rapidly and efficiently. These codes embodied such assumptions as uniform and instantaneous ignition of the entire propellant charge, with combustion taking place in a temporally varying but spatially uniform, well-stirred mixture of grains and gases. A pressure gradient within the gun tube was typically superimposed on this picture of a *space-mean pressure* to provide an appropriately reduced pressure acting on the base of the projectile, but such codes were unable to address the physical hydrodynamics of such problems as ignition-induced pressure waves. Nonetheless, lumped-parameter codes have been and still are used [by organizations and people] throughout the world (including the BRL) for most basic interior-ballistic systems and charge-design studies. Today's applications may even combine their use with thermochemical codes and perhaps other constraints as expert systems (ES) for solution of the overall propellant formulation/charge-design optimization problem."[15]

"In the early 1970s, the world of interior-ballistic modeling, however, was forced to change. The prevalence of gun malfunctions, particularly charge-related breechblows (rather than projectile in-bore explosions), the origins of which were ultimately traced to ignition anomalies and pressure waves, motivated serious development of multiphase-flow interior-ballistic models."[15] Two-phase codes were emerging; by the mid-1970s there were multiphase codes that used average phenomena (essentially separate amorphous entities competing for space and exchanging energy and momentum), and now codes are addressing issues regarding individual grains, etc.[16]

"First on the scene were one-dimensional, two-phase flow models, the primary purpose of which has to assess the influence of the ignition stimulus on flamespreading and pressure waves. At least in the United States, probably the most successful and certainly the most used of these models has been the NOVA code, developed and advanced by Paul Gough Associates (PGA) in conjunction initially with the NOS at Indian Head, MD, and subsequently and more extensively with the BRL. NOVA provides a macroscopic treatment of two-phase flow in the gun environment (a local description but still averaged over regions large with respect to the scale of heterogeneity, i.e., the individual propellant grains) and is commonly called an *inviscid* model, as the governing equations are formulated to neglect the effects of viscosity and heat conduction in the gas phase. Essential to the model, however, is the coupling between gas and solid phases through heat transfer, interphase drag, and combustion, allowing for treatment of the effect of a local ignition stimulus on flamespreading in the main propellant charge as well as the associated formation of potentially deleterious longitudinal pressure waves. An abundance of successful applications of this code can be found in the literature, with more recent efforts addressing the incorporation of finite-rate kinetics for treatment of unique ignition and combustion problems associated with the use of LOVA propellants, and the explicit inclusion of stress-induced propellant fracture to allow treatment of a vital physical link between pressure waves and breechblows."[15]

We have the following report from 1980: "The development and implementation of the two-phase interior-ballistic computer simulation technique, ALPHA, is another major accomplishment. The framework of the method now provides for the simulation of the interior-ballistic cycle from primer burn and packed-bed ignition to the projectile exit at the muzzle. Using ALPHA, the BRL interior ballisticians have predicted the complete multidimensional flow field behind a 20mm projectile in the Lagrange gun geometry. By assuming the conditions of complete combustion of the propellant when the projectile motion begins, analysts can predict pressure history, temperature and velocity profiles, and the projectile velocity. The predictions of ALPHA are in excellent agreement with an analytical case for the core flow reported by other workers. The advances in the simulation of multiphase, multidimensional IB will lead to better knowledge of input conditions used in the prediction of muzzle-blast environments and may provide design information for blast suppression and muzzle brakes."[2]

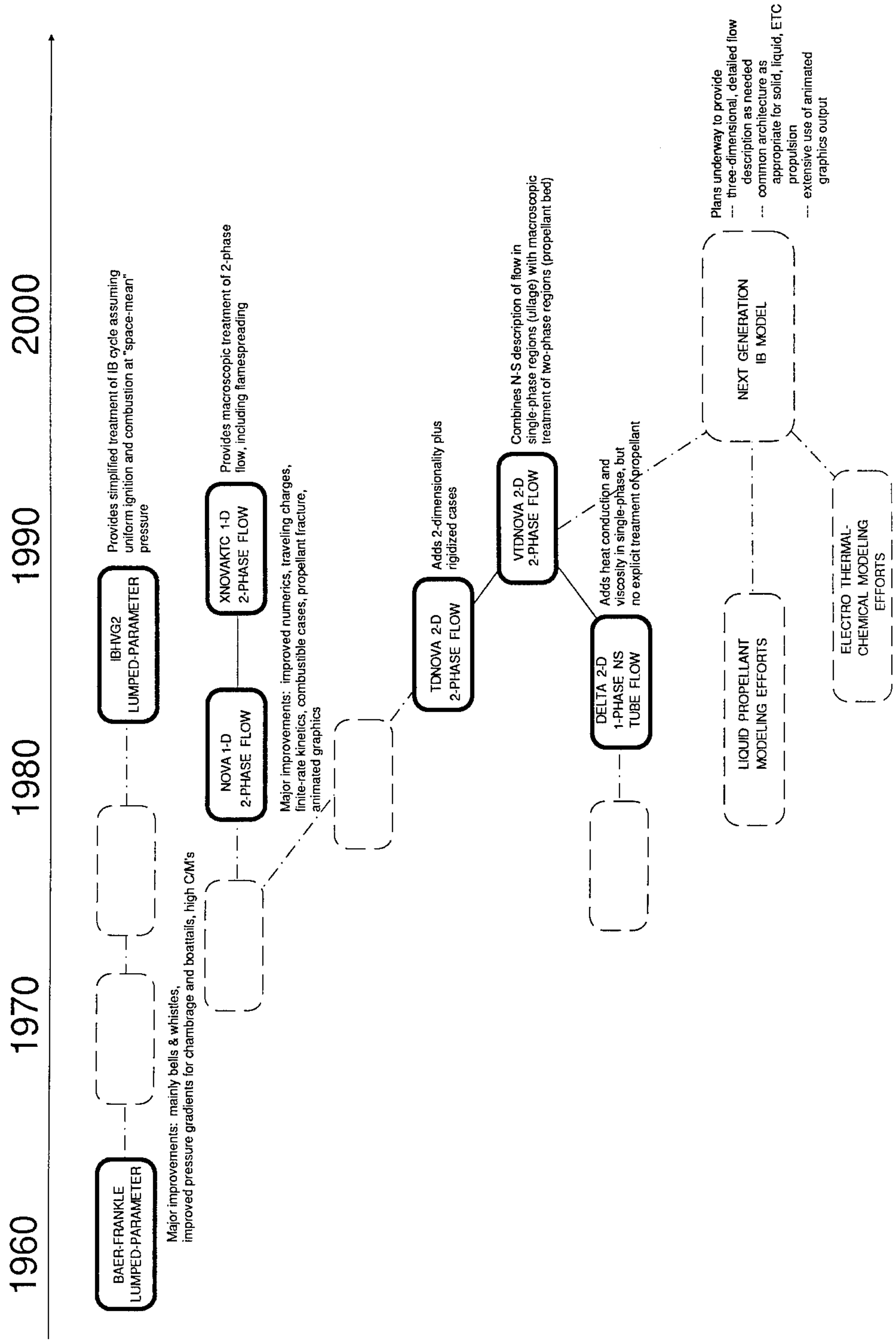
And later, for 1988, we find: "For the first time, the interplay between ignition stimulus and propellant characteristics can be investigated in an automated fashion to assess both the detailed performance and safety of candidate propellant designs without risking limited test resources. This capability, which has resulted from the expansion of XKTC, a two-phase flow interior-ballistic code, to include the effects of ignition-induced grain fracture on gun performance, represents a significant improvement in understanding and ability to prevent breechblows."[7]

"Next in the progression of U.S. modeling efforts were several quasi-two-dimensional treatments, in which coaxial regions of propellant and circumferential ullage (regions of free space in the gun chamber, external to the propellant charge) were treated as coupled regions of one-dimensional flow. Thus, the influence of ullage external to a bagged artillery charge on the path of flamespreading and the equilibration of pressure gradients could be estimated. Such formulations were short-lived, however, as fully two-dimensional models soon displaced them.

"For nearly a decade now, the BRL has been advancing (with PGA) and applying the TDNOVA code, a fully two-dimensional axisymmetric treatment, to model the behavior of both granular and stick propelling charges, including the influences of propellant packaging (e.g., bags, cases) as well as the distribution of ullage. These later features were made possible by the explicit recognition of internal boundaries between the two-phase region (i.e., propellant bed) and single-phase region (i.e., ullage), with finite jumps in mass, momentum, or energy associated with these boundaries to reflect the behavior and influence of the propellant container. TDNOVA has recently been applied with much success to various artillery-charge configurations, including UNICHARGE, as well as playing a key role in investigation of the 16-in gun malfunction aboard the USS IOWA.

"Concurrent with the [previously mentioned] efforts, numerous other efforts at the BRL and throughout the world focused on development of a full Navier-Stokes description of single-phase flow in a gun tube. One such code, known as DELTA, was developed at the BRL during the late 1970s and later extended through a cooperative effort with the Ernst-Mach-Institut in Germany, where work focused on development of the unsteady boundary layer and heat transfer to the tube.

"The next reasonable step was the combination of TDNOVA and DELTA into the VTDNOVA code, providing a macroscopic description of flow in the two-phase region,



Evolution of Interior-Ballistic Modeling.

coupled to a full Navier-Stokes treatment in the regions of ullage. This code remains under development today, but the center of emphasis for interior-ballistic modeling is once again shifting in response to the interests and needs of the Army.

"While the emphasis of this section has been on interior-ballistic modeling of solid-propellant guns, much effort has been expended during recent years on modeling of alternate gun-propulsion approaches, particularly LP and ETC guns."[15]

Industry is much more active in the areas of LP and ETC, and there are far fewer Government precedents and fewer facilities; so the field is far more open than was the case for more conventional systems. There is a great need for methodology that can provide uniform evaluations of solid LP and ETC. Also, the recent trend has been toward complete interior-ballistic codes—covering the phenomena from ignition to exit (and beyond) and including the response of sabots and projectiles.[16]

"While more detailed information on [LP and ETC] is covered elsewhere, suffice it to say here that much useful interior-ballistic modeling of these approaches has come either from modifications to the above NOVA family of codes or from sources external to the BRL, with a full range of attendant problems—even proprietary issues. Interior ballisticians at the BRL are currently considering the possibility of a next-generation supermodel, structured to take full advantage of emerging computational architectures, and formulated to provide an overall framework based on common conservation laws, solution algorithms, output graphics, etc., as well as concept-specific but physically comparable levels of constitutive physics for each of today's propulsion approaches. Thus, meaningful comparisons of alternative approaches could be made, using a code family which embodies both the best physics and numerics, maintained, advanced, and distributed by the BRL. This goal is as technically challenging, if not more so, than anything the interior-ballistic community has faced in the past, as well as testing the will of investigators from what have sometimes been competing fields to pull together to meet the yet unclear technical and political challenges of the future."[15]

Advanced Solid-Propellant Technology. This work includes computational and experimental consideration of issues such as perforations, layering, fracture, flow and erosion in the grain, ignition, and flame spreading.[16] The recent work on the ignition of UNICHARGE that is discussed in succeeding paragraphs is typical.

State of the Technology. The following text summarizes the state of some of the interesting approaches in solid-propellant technology:

Multiperforation. "[The] requirement for a progressively burning surface has led to the use of what are known as *progressive grain geometries*. Single-perforated, right-circular cylinders have given way to 7-, 19-, and even 37-perforation grains, the increasing numbers of perforations providing an increasing proportion of the total grain surface that grows with burn distance while the *regressive* exterior surface remains relatively unchanged. ... A velocity increase of 2–3% has been demonstrated in numerous gun systems by replacing the standard 7-perforated grains with those of the 19-perforation geometry."[16]

Deterred or inhibited propellants. "Chemically deterred ball propellant has long been used in small-caliber guns. Application to large-caliber propellant configurations focuses on the use of deterrent or inhibitors on the outer regressive surfaces of multiperforated grains to reduce or even eliminate burning in these regions, thereby increasing the net effect of burning on the progressive perforation surfaces." While the use of deterrents is not generally attractive, "inhibitor coatings, both simpler in concept and perhaps more universally applicable, are receiving considerable current attention, but, as of yet, present formidable production challenges."[17]

Consolidated charges. "[The] concept is based on achieving higher loading densities by compacting conventional granular propellants through the use of solvation and/or heat. The initial reduction in available surface resulting from the intimate contact between grains followed by a subsequent increase in surface area as the compacted charge deconsolidates during burning may also be a means of increasing progressivity of the overall charge. While extremely attractive in computer simulations, the concept is hampered in reality by an incomplete understanding of and control over the deconsolidation and flame-spreading events and by manufacturing and reproducibility problems."[17]

Ignition of UNICHARGE. UNICHARGE is a single-element charge that can be used to obtain five zones in the present 155mm howitzers (M109 or M198) and six zones in the developmental AFAS howitzer. UNICHARGE is the backup propulsion system for the AFAS as well as the new system for the present howitzers. George Keller has been using TDNOVA to model the ignition and combustion process of UNICHARGE and has been using graphics developed by Ron Anderson for visualization of the processes.[17]

For the calculations, Keller has been using a Silicon Graphics workstation which takes about 6 hours for a run as opposed to about a half hour on a single processor of a Cray supercomputer. Nevertheless, this is an eminently practical and efficient approach for this operation.[18]

While the presence of rigid cases on the charges has introduced a major new level of complexity (bag charges are far easier to simulate), Keller has been able to develop a model that is based largely on fundamental physics and engineering and on measurements of basic material parameters. With this model, he has been able to parallel the development process at ARDEC. This has allowed analysis of experiments, understanding of the processes involved, and help with fixes.[18]

Various system parameters, such as outside diameter, diameter of the ignition tube, length of the charge, and propellant formulation and geometry, can be varied. The model can also consider hypothetical situations such as uniform ignition.[18]

Graphics allows a two-dimensional view of the processes with multiple displays of various parameters. The representation has allowed the observation of a number of interesting phenomena such as choking of the flow, breaking of the combustible cases of the charges, flame spreading, pressure waves, and movement of the charges. A particularly interesting event is the sequence of ignition that starts in the breech end and then shifts to the muzzle end of the chamber. This behavior is the result of choking of flow in the ignition tube, subsequent flow outside the charges, and break-up to the walls of the charges.[18]

Hypervelocity Solid Propulsion. A program was conducted to use the high-energy JA-2 propellant to achieve hypervelocities. The sticks pack well, can be used to achieve a high density of loading, and can be ignited with a base-pad igniter.[9]

"The BRL has demonstrated in a real, conventional-type weapon, a solid-propellant technique for launching projectiles of significant masses (kilograms rather than tens of grams) at velocities far in excess of those previously achieved.

"The performance attained with a solid-propellant charge is the result of the competition of the rate of gas generation by the burning propellant and the rate of volume expansion behind the accelerating projectile. Since gas-generation rate is proportional to the surface area of the burning propellant grain, the classic route to increasing the rate of gas generation—and thus increasing performance—has been to employ evermore progressive grain geometries with multiple internal grain geometries with multiple perforations whose burning surfaces increase with burn distance to more than offset the decreasing area of the outer burning surfaces. Such multiperforated geometries have [been] limited generally to granular geometries with length-to-diameter (L/D) ratios of 1–3 to 1 to ensure that gases generated within the perforations exit rapidly enough to avoid overpressurization of the perforation and fracture of the grain, which results in unprogrammed generation of burning-surface area that may lead to potentially catastrophic overpressurization of the weapon. While the use of another type of propellant grain—stick propellant—for high-performance weapons offers many advantages such as the reduced potential for pressure waves in the combustion chamber and applicability of simple base-ignition systems, the stick propellant is not easily adapted to a multiperforation geometry. For this reason, stick-propellant geometries have generally been limited to the slotted single-perforation configuration, with the slot providing the ventilation for the gases generated within the perforation.

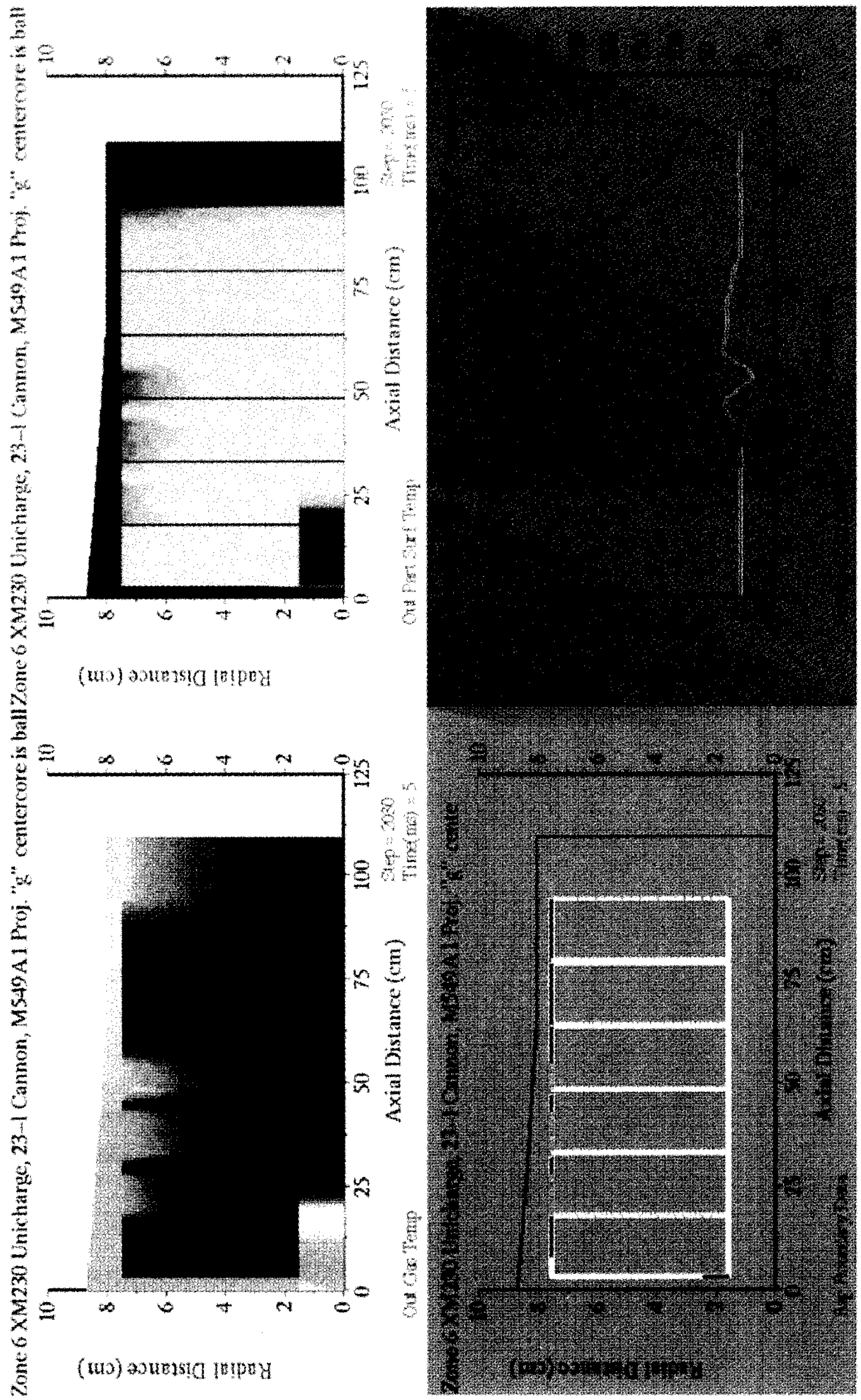
"The BRL has developed a new design for propellant grains which vents combustion gases through slots located at periodic intervals along the length of a multiperforated grain and thus assures that the perforations are not pressurized to the point of grain fracture. The technique employed, [is] called partial cutting. ... The investigations at the BRL focused not so much on the particular venting technique as on demonstrating the interval at which the perforations must be vented. In order to reduce the initial surface area of the charge, the number of vents must remain as small as possible and yet be frequent enough to prevent over-pressurization. The venting interval depends on the burning rate of the propellant, which determines the rate propellant gasses are produced and on the diameter of the perforation, which determines the extent to which these gases exit from the perforation.

"After much theoretical study of this partially cut stick-propellant concept, lumped parameter, and experimental test of candidate configurations, the technology was demonstrated at the LABCOM Technology Symposium in June 1989. A 3-kg projectile was launched from a 120mm, XM25 ballistic cannon using a partially cut, 19-perforation, JA-2 propellant charge at velocities between 2,400 and 2,500 m/s at each of the technical presentations. Immediately following the shot, internal gas pressure data were reduced and compared to the predictions of a multiphase flow interior-ballistic code. In all cases, the agreement of the model with the experimental results was excellent, demonstrating that solid propellants still offered considerable room for performance growth. Furthermore, successful multiphase flow simulations performed on the BRL XM/P-48 supercomputer have provided a routine capability for exploitation of this technique for achieving hypervelocity in a diversity of applications.

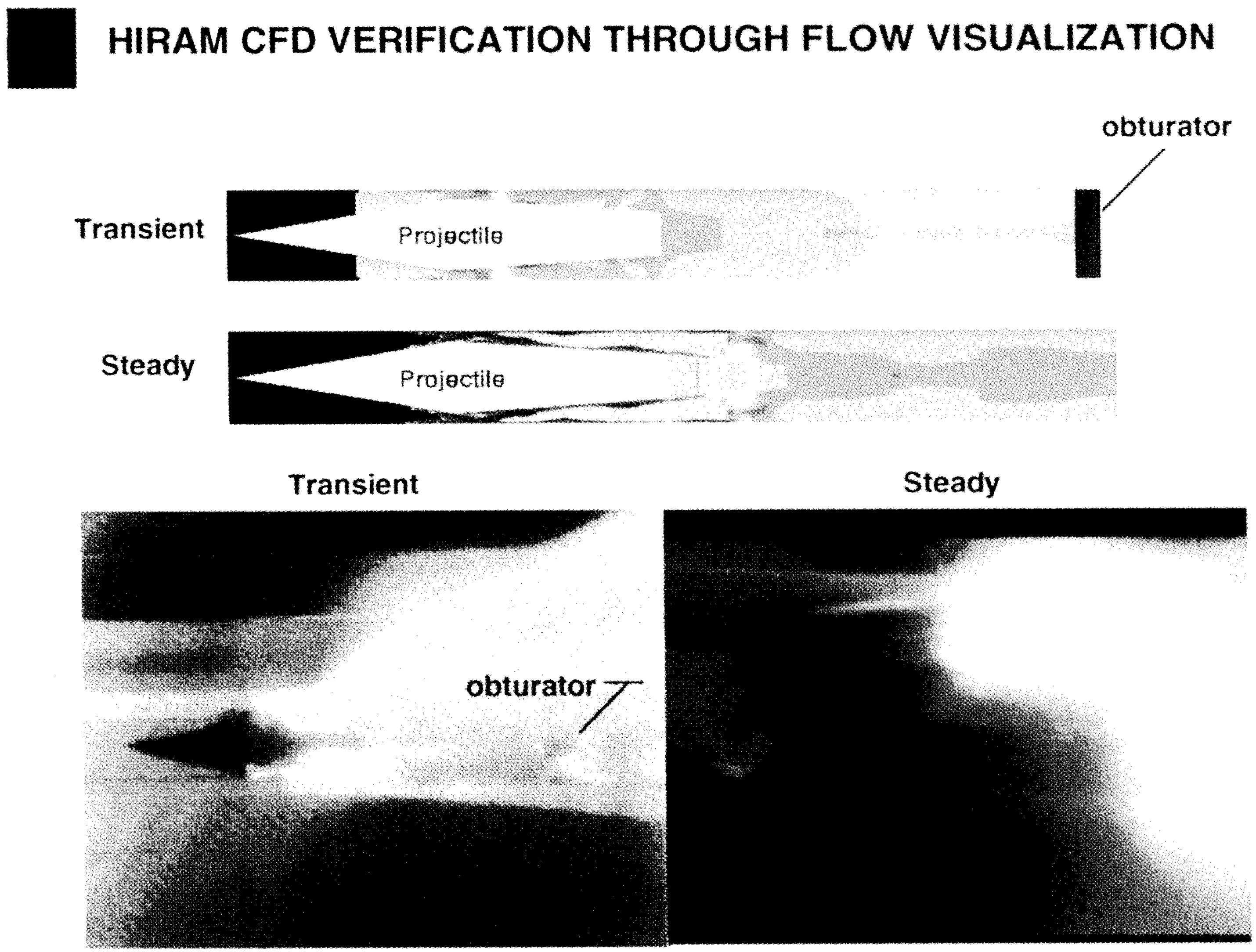
"Subsequent development and testing of the concept with similar charges have resulted in the successful firing of a 2-kg projectile with velocities in excess of 2,700 m/s,"[18] and a 5-kg projectile has been launched from a 7-in, 86-caliber HARP gun to over 2,800 m/s.

RAM Acceleration. An in-bore RAMjet is now [1992] being tested at Range 18 with considerable interest from many agencies (DOD, NASA, etc.).[16]

In 1990, "the hybrid in-bore RAMjet (HIRAM) concept was evaluated for feasibility as a laboratory device for hypervelocity launch of large-caliber projectiles. A unique scale-model projectile to test HIRAM hypotheses was designed, fabricated, and successfully launched. An accelerated program has been



A Baseline UNICHARGE Simulation Showing Hot Gas Flow, Solid Propellant Heating and Ignition, Bag Boundary Data, and Pressures Generated During Firing.



Comparison of Computational Fluid Dynamics Calculations and Experiment in 120-mm RAM Accelerator.

started to develop and fabricate a full-scale large-caliber gun facility for terminal-ballistic applications of hypervelocity munitions."[19]

The following description of HIRAM comes from an *Update* article by Dave Kruczynski: "RAM acceleration is the most recent of high-velocity launcher technologies being pursued today. The same principles that are used to propel RAMjet airframe engines are used within a gun-like environment to accelerate payloads to very high velocities. This application was first demonstrated at the University of Washington (UW) in Seattle, WA, by Hertzberg, Bruckner, Knowlen et al., in 1986, and research has continued there ever since. For a little over a year, the BRL has been working with UW to exploit this concept and apply it to the development of hypervelocity propulsion.

"A RAMjet airframe engine ... is only able to operate at high speeds. It can maintain operation at a local Mach number of about 2.5 (two and one-half times the local speed of sound) by the injection of fuel in the shock-heated flow. The exhaust gases are ejected from the rear after the combustion process and produce the thrust, which can accelerate the airframe to even higher velocities. A RAMjet engine contains few moving parts, making it a simple enough system to adapt to the gun environment.

"... The gun tube in the RAM accelerator corresponds to the engine cowling in the RAMjet, the function of the center body is performed by a projectile of similar shape, and the fuel injectors are no longer needed because of the premixed gaseous propellant that fills the gun tube. The projectile must be injected into the sealed tube at a velocity sufficient to ignite the premixed gas behind the projectile, thereby starting the RAM process. When properly started, the combustion process can produce significant positive thrust, which travels with the projectile to accelerate it to very high velocities. The UW researchers and others have proposed combustion schemes that indicate projectile velocities above 7 km/s are possible. They have demonstrated projectile velocities exceeding 2.7 km/s and have conducted over 900 test firings to date.

"Like any technology capable of producing extremely high projectile velocities, RAM acceleration has many potential applications. These include hypervelocity flight, terminal effects studies, ground-based and space-based interceptor applications, long-range artillery, possible tactical-launcher velocity boost, materials research, and ground-to-space cargo launchers, to name a few. In addition, because of the RAM accelerator's ability to obtain very high Mach numbers, it is well suited for the study of the fundamental process of combustion in hypersonic engines.

"In the hope of developing these applications, experimental and computational research programs have been sponsored and conducted by the U.S. Air Force (USAF), NASA, and the BRL. In addition, a very active research program is ongoing at the French-German Research Institute at Saint-Louis (ISL), France, which now has a 90mm diameter RAM accelerator in operation, and is constructing an advanced design, 30mm hypervelocity facility.

"The BRL is exploiting RAM acceleration through a HIRAM accelerator program. This program will provide a hypervelocity (above 2.5 km/s) launcher for full-scale testing of new projectile and armor packages. As currently designed, the launcher will be capable of delivering significant masses (5–10 kg) through the use of an integrated system of solid-propellant launch with RAM acceleration. While the initial program goals are to provide a low-cost, hypervelocity test bed, the capabilities and fundamental physical processes of the system will also be examined. As the technology develops, higher velocity propulsion modes will be made available for potential strategic and tactical applications."[20]

IGNITION AND COMBUSTION

Combustion Research. When ARRADCOM was formed in 1977, the BRL divested itself of its interest in aeronomy (upper-atmospheric research). The chemical physicists who had formed the Aeronomy Branch were dispersed. Frank Niles who had formed the branch went to White Sands; George Keller and Joe Heimerl stayed on at the BRL to work on a new initiative in combustion research in the Ignition and Combustion Branch with Austin Barrows as branch chief. Combustion research led to a better understanding of the properties of propellants and of their formulations. It also contributed to kinetic data for use in interior-ballistic codes.[21]

The major new approach was the use of laser diagnostic techniques for probing the reaction zone and helping to understand the relation of the transition phase on the surface of the propellant to the gaseous reaction zones.[22]

While lasers have the important advantage of being a non-intrusive probe, their use is presently limited to pressures of no more than a few atmospheres. The propellant can be preheated to achieve a high burning rate at such low pressures, but the reaction zone is still quite thick (about 1 cm) under these conditions, and the relation to very-high-pressure combustion in guns is strained. Nevertheless, laser spectroscopy is a very valuable tool.[22]

Another technique that was tried out in the 1980s was X-ray tomography (similar to the medical computerized axial tomography (CAT) scan) to look at the burning process inside a gun barrel. This turned out to be infeasible. It required high-energy X-rays (1 MeV as opposed to 100 keV for medical applications), scattering from iron was a problem, and time resolution was needed in the sub-millisecond regime.[22]

Tomography worked well, however, for bare propellant. "CAT technology has been applied successfully for imaging of propellant grains in a demonstration experiment; good propellant grain contrast was obtained, thereby providing a technique for direct, very short exposure time, two-dimensional and three-dimensional observation of processes that previously could only be conjectured."[4] Unfortunately, measurements inside the barrel did not work well.[22]

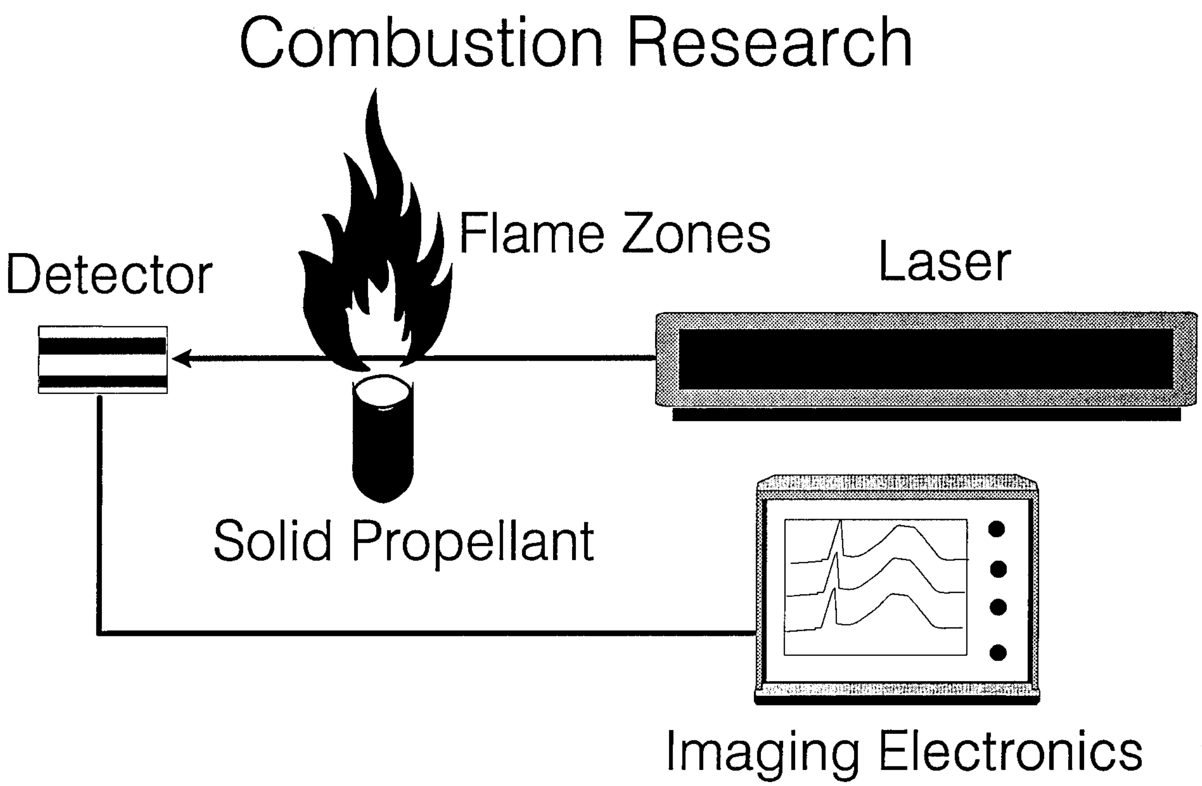
The following is extracted from a paper on the combustion research program:

"*Combustion.* Combustion is a self-sustained chemical reaction that produces hot gas. The combustion rate, the quantity of heat evolved, and the molecular weight of the final gases determine ballistic utility. The last two are fixed by material properties. The rate is the product of the surface-regression rate and the amount of surface area. It is the surface-regression rate which may provide combustion control.

"For most propellants, the combustion begins and ends at the propellant surface in that it occurs on a scale very thin compared to any practical dimension in the gun. Rate control must come from control on that thin zone.

"*A Case for Chemistry.* Because combustion is a highly exothermic chemical reaction, chemistry must be the control. But the zone is too thin for direct chemical measurements on burning propellants. The chemical reactions must be removed to the laboratory.

"Clues to the combustion come from observations that regression rate is faster when pressure increases, initial temperature increases, the hot product gases flow rapidly across the surface, or when certain salts are added. These suggest, but do not demonstrate, that the gas chemistry dominates. Another credible hypothesis suggests a major contribution from the solid near the gasification surface.



Laser Diagnostics for Combustion Research.

"Porous propellants present another dimension. If combustion product gases can penetrate the solid through interstices, heat transfer to the solid is no longer merely conduction. Here mechanics, heat transfer, and chemistry can combine to produce a much more complicated behavior.

"If chemistry is to be the means to propellant behavior control, it must first be understood. The reactions must be known over the entire combustion zone. Even though the zone is thin, it has a complete transition in chemistry from one end to the other. Controlling regression rate by chemical changes in the solid implies a knowledge of the heat-release chemistry. Control of specific reactions requires a relatively detailed knowledge of the reactions. A triage procedure must select from too many candidates. Research to date has suggested key reactions, but not their kinetics or their exact roles.

"Evidence that the burning can be chemically changed comes from the plateau-burning propellants where a few percent of lead or copper salts alters regression rate up to about 10 MPa. The mechanism is unknown because the thin reaction zone bars conclusive experiment. Recent research has also found that regression may be dominated not by sublimation, but by intermolecular forces in the undecomposed solid. This represents a potential new chemical handle for regression-rate control.

"The attack on the chemistry must concentrate on a few particular reactions suspected to dominate the heat feedback from the flame.

"*Laser Spectroscopy.* Laser spectroscopy can measure temperature and concentration profiles in steady flames. From such profiles can be inferred the chemical mechanism. A steady flame serves as a model for the reactions dominating the heat feedback from a propellant flame. The active involvement of oxides of nitrogen (N_2O, NO, NO_2) differentiates propellant combustion from the classic hydrocarbon combustion. These nitrogen compounds produce species (e.g., NH N_2, CN) well suited for laser-spectroscopic measurement. Steady burner flames can isolate a few reactions while keeping a temperature variation. Lowering the pressure lengthens the flame reaction zone to a scale where laser beam intersection volumes allow fine enough spatial resolution.

"Simple concept; difficult practice. Laser spectroscopy itself is in relatively early development. New tools and techniques are continually being developed in several U.S. laboratories which would like these answers. Propellant chemistry, RAMjets, and gas turbines, among others, need in-situ measurements at high pressure and temperature.

"Spectroscopic signature is known for only a few molecules; research must precede tracking any molecule's role in the flame. CARS, Raman, and laser-induced fluorescence (LIF) spectroscopies are currently being used. More advanced spectroscopies are being considered such as multiphoton excitation. Each, however, needs considerable development.

"*Mathematical Models.* Mathematical modeling, needed to interpret measurements, continually exploits advances in computer technology. A steady-state model incorporates the detailed chemistry and fluid dynamics of the steady laboratory flame. A transient model of an inclosed highly transient combustion probes the sketchily understood deconsolidation mechanism in frangible propellant. This modeling benefits from the extensive U.S. research in computational fluid dynamics (CFD). A boundary-layer model analyzes a convectively driven ignition and transient combustion.

"Some key reactions must be estimated from first principles of intermolecular interaction. Theoretical chemistry can now provide a few answers on estimates of unimolecular reactions. More complex reactions must await a considerable advance in knowledge and computing efficiency.

"*Transient Combustion.* In a gun, the rapid pressure changes may cause substantial deviations from steady-state burn rates. Although it is usually assumed that the burning rate can adjust instantaneously to the environment, this approach seems much too simple. Calculated transient burning rate effects during gun-chamber pressurization vary from none to runaway. These effects are difficult to approach experimentally, and definitive results are not available.

"There are many opportunities for research on transients. New propellant concepts, especially pressed powders, raise new questions. Propagation by mechanical response adds a new aspect heretofore safely ignored. Two-phase combustion, surface fracturing, stress propagation, and convective penetration all combine to present a potential growth of transients even to the point of detonation. The [detonation/deflagration] research pursued so vigorously by the USAF/Navy now becomes an Army concern as well. Simple experiments confirm a transition to a new mode of combustion under frequently encountered conditions. New numerical approaches are needed to handle the complicated and sensitive set of differential equations describing the combustion. Even for homogeneous propellants there are unanswered, but fortunately less crucial, questions on transient behavior.

"*Ignition*. Ignition uses external energy, usually hot gas, to start the combustion. The reactants are similar, but the temperature and pressure are lower than for combustion. Criteria for ignition are needed for ballistic calculations, but can now be only crudely approximated.

"Ignition is more art than science. Striking a balance between low-vulnerability propellant and reliable ignition requires a better knowledge of how igniters work and how propellant ignites. Pressure-wave problems in large-caliber, densely packed charges require design rules with a firmer scientific base. Ignition has been carefully measured only for radiant igniters. The results are not readily extended to convection plus hot-particle heating of a granular bed. Questions on unreacted gas penetration and subsequent gas-phase flame spread have been posed for slow-ignition anomalies. Slow ignition may also lead to a transient combustion condition by too deep heating of the propellant. Ignition of many new propellants, like the pressed charges, has never been systematically studied. Extension of simple thermal processes has been assumed to be adequate.

"The chemistry debate has mainly focused on the gas phase. A potentially important but practically unknown body of chemistry lies in heterogeneous reactions at the propellant surface. Autocatalysis of decomposition by NO_2 attack is but one debated phenomenon. The fact that NO_2 is not seen in a propellant fire, but is seen in decomposition experiments, suggests its consumption near or under the surface.

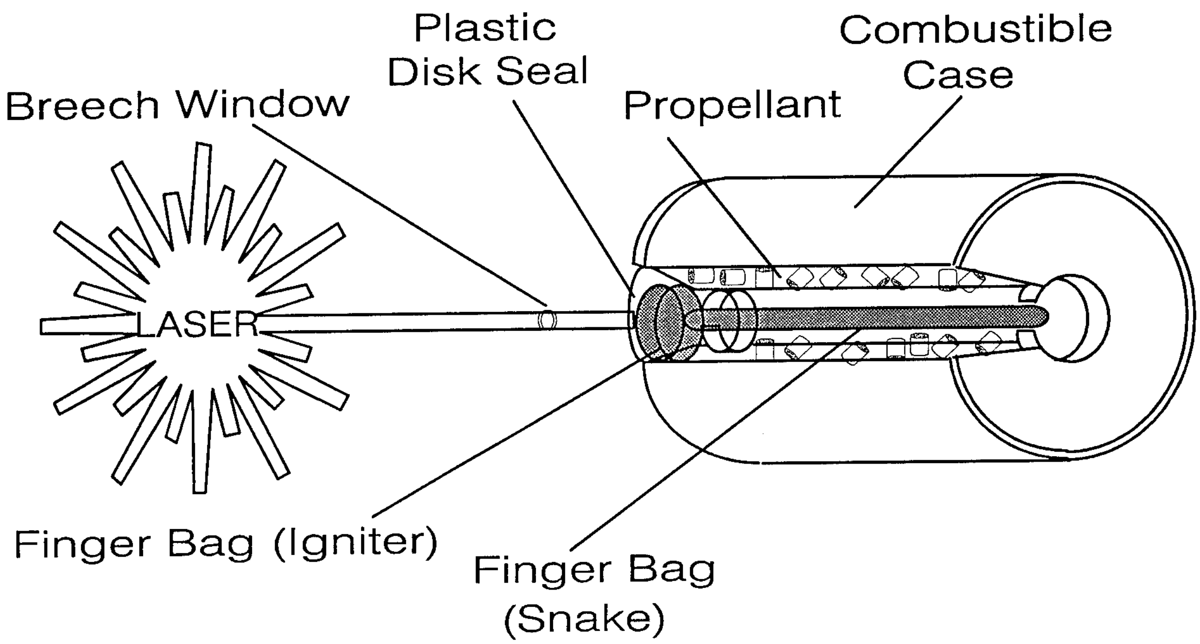
"*Perspective*. This research will provide information to support searches for new propellants. It will provide clues to combustion control although not necessarily to more energy. It will ease exploitation of new propellant developments, it will develop tools which can spin-off into unforeseen applications.

"The laser-based spectroscopy research has great potential for spin-off. Laser-based science is itself new. It promises to probe the interior of guns and rockets, to shrink the sample volumes for greater spatial resolution, to locate and map transitory and sparse species."[22]

Laser Ignition. In addition to studying the process, lasers also have potential application to the actual ignition process as considered in the laser ignition in guns, howitzers, and tanks (LIGHT) project.

"The use of non-standard projectile configurations (e.g., long-rod penetrators), high-loading-density (multicomponent) propellant charges and two-piece ammunition has increased the difficulty of achieving rapid, reliable, and reproducible ignition throughout the propellant bed in Army gun systems. In order to overcome these problems, distributed-ignition systems have been developed which demonstrate near-simultaneous ignition (isochronic ignition) in propellant beds. The anticipated benefits of isochronic ignition are the reduction of pressure waves for improved system safety and reliability, reproducible and uniform flame spread throughout the propellant bed, and potential impact on performance. Replacement of the primer in AFAS by a laser transparent window would greatly simplify autoloader requirements. Furthermore, a distributed ignition system will facilitate the accommodation of intrusive projectile configurations in ammunition.

"The simultaneous and rapid distribution of energy throughout a propellant bed can be readily accomplished through the use of a laser and optical fibers. This concept has been investigated in the early 1980s. Unfortunately, it was found that the propellant bed could not be ignited directly using a distributed optical fiber network without the incorporation of sensitizers (igniter material) in the ignition



Laser Ignition.

train. However, the desirable elimination of igniter material from large-caliber gun ammunition would lead to a substantial reduction in overall ammunition vulnerability. The impetus for the formation of the LIGHT program is to achieve direct propellant ignition without the aid of conventional igniter material.

"A number of foreign countries are currently investigating various types of laser ignition, including [Great Britain], who [is] currently transferring laser energy into the gun chamber through a sapphire window to directly ignite a black-powder basepad, and [Germany], who [has] successfully ignited a single module in a UNICHARGE configuration in a 155mm cannon. Laser ignition in a 120mm cannon is being tested at a BRL range facility for the purpose of safety and improved instrumentation.

"The LIGHT program addresses the basic physics and chemistry of laser ignition of propellants and potential applications to complete solid-propellant charges currently under development for [the 140mm advanced tank cannon] ATAC and [the Army's new howitzer] AFAS. The multiple elements and increased length of these charges require unique approaches to achieve rapid transfer of the ignition stimuli and uniform ignition. In the near term, laser ignition could solve ignition problems with UNICHARGE and AFAS by distributing the ignition stimulus using optical fibers.

"In the longer term, direct ignition of propellants may be feasible by double pulses designed to first vaporize and subsequently ignite the combustible gases with a laser frequency tuned to fundamental absorption bands of the vapor. This kind of approach should improve laser energy requirements (efficiency), as well as ignition timing.

"These concepts also are likely to have application to ignition of insensitive energetic materials, such as LOVA and insensitive high explosives (IHEs), rocket motors, and energetic fluids as well. The BRL has a modestly funded 6.2 effort begun in FY90 and continuing in FY91. ARDEC personnel are very supportive of this work and are interested in developing a 6.3A effort to work jointly with the BRL to exploit and demonstrate this technology in the emerging large-caliber gun systems. An MOU between ARDEC and the BRL has recently been signed to further these efforts.

"Recent experiments at the BRL have shown that a Nd:YAG laser (1.06 µm) could reliably ignite propellant grain samples (JA-2 and LKL, for example) at atmospheric pressure in ambient air with a single laser pulse (2, 3, 5 ms; 3–6 joules) coupled through an optical fiber. It was also found that a single grain of JA-2, which was similarly ignited as above, could, in turn, ignite LOVA propellant (XM43 and XM39). Here JA-2 serves as a laser-sensitizer with the primary attribute of greatly reduced vulnerability relative to conventional igniter material. This ignition concept is currently being evaluated in a gun test fixture (simulator).

"Also, the aforementioned double-pulse laser-ignition experiments have been initiated. The approach involves the ignition of pyrolysis gases which are produced at the propellant surface from the first laser with the focused high-peak-power output of a second tunable ultraviolet laser. Enhanced interaction has been observed when the wavelength of the second laser has been tuned to multiphoton absorption wavelengths of both atomic hydrogen and oxygen.

"A joint effort with Hercules Corporation has resulted in two tests in a ballistic simulator with a two-piece ATAC ammunition configuration. Simultaneous ignition was attained, and more tests are planned. A joint effort with ARDEC will begin shortly which will look at laser ignition for a UNICHARGE configuration.

"Replacement of the primer by a laser in large-caliber gun systems using standard igniter trains has been accomplished. It has also been demonstrated that distributed laser ignition using fiber optics works well when standard ignition elements are incorporated. It remains to be shown conclusively that direct propellant ignition can be accomplished in large-caliber gun systems."[23]

Quantum Chemistry. With all the other initiatives at the BRL to model physical processes, it should not be surprising that an attempt should be made to understand the fundamental properties of energetic materials by modeling their electronic states. What was wishful thinking in the 1970s has become a practical tool in the 1990s with the rise of computer power.

George Adams had been at Picatinny Arsenal, NJ, in the early 1970s as a theoretician in the propulsion group. He also worked there with an experimental group in explosive research.[24] In 1973, he came to the BRL as a quantum chemist and interacted with people in explosive research. "The propulsion people were more likely to be pulled off research for *fire drills*." About that time, Art Gauss was working on classical-mechanics analysis of chemical reactions.[25]

In the late 1970s, most of the work in quantum chemistry concerned looking at the properties of isolated molecules with little concern for reactions. Molecular dynamics was based on potential energy surfaces.[25] Problems such as understanding the plateau effect of adding lead salts to propellants were addressed but not resolved.[25]

Even in the early 1970s, Adams tried "somewhat harebrained" to predict properties of molecules as complex as TNT by using the many-body perturbation theory of quantum chemistry along with Battelle, Columbus, OH. The theory was new, but it worked well with changes in energy, and some work was done with excited states and ionization potential.[25]

From 1978 to the mid-1980s, the work turned to looking at the dissociation of molecules and radicals (e.g., HCO) for reaction rates in flames.[25]

In the early 1980s, Adams recruited Paul Saxe and Mike Page as post-doctoral fellows. They learned to use minicomputers to compute structures based on energy gradient, the Hessian, and iteration. Some codes were developed.[25]

In 1987–88, Mike Page (now at the Naval Research Laboratory [NRL]) developed codes to find a transient state and then to walk backward to the initial state or forward to find energy levels of the products of dissociation. He used the Cray X-MP to do the reaction CH_2NNO_2 -> CH_2N + NO_2. Note that CH_2NNO_2 is a common product of nitramines, an important class of explosives.[25]

Heats of formation have been a major area of interest recently using the many-body perturbation theory (1982–88 techniques).[25]

Results of the program were reported for 1987: "Quantum-chemistry calculations can now be conducted for much larger molecules, those of interest in the high-energy-density materials program. In essence, this new level of computational power combined with continuing enhancements in simulation capabilities, has generated vast new possibilities for us to consider."[6]

"Quantum chemical methods for studying the chemical stability of metastable species have been refined and extended. This provides the ability to predict the state lifetime and energy release of virtually any molecular state for any molecular species. The methods have been used to study candidates species for the high-energy-density materials program. In general, those species that appear stable at a restricted level of theory are shown to be unstable when a method that includes all important molecular effects is used. In addition to eliminating a number of proposed species, thereby canceling experimental efforts to isolate the materials, the BRL has provided intermolecular force data to dynamicists studying metastable species containment."[6]

And for 1988: "An efficient and extremely accurate quantum-chemical technique that predicts heats of formation of reactive combustion molecular species has been developed. The method uses a modestly complex theoretical method coupled with an extended mathematical basis to predict molecular energies. Analysis of these results relative to a single reference molecule provides nearly perfect predictions of these important thermochemical data. This program is providing major leverage to Army and USAF programs in high-energy-storage molecules with potential for future fuels, propellants, and explosives—a nationally recognized contribution."[7]

The Complete Active Space (CAS) theory has become very popular in the late 1980s with commercial organizations including the pharmaceutical houses. CAS involves creating a set of basis functions, each of which is an important part of an intermediate process. The tool is very powerful but requires much iteration. CAS is of particular interest for finding transition states and is of nascent interest for ballistic applications.[25]

The following, taken from an *Update* article, describes the Brooklyn codes for examining the spectrographic properties of excited electronic states.[25] "The installation of an integrated vector processor at the BRL's Molecular Workbench Facility has led not only to award-wining research efforts, but to the development of the world's most sophisticated quantum-chemical computational tools. The new methods, developed by the BRL scientists in collaboration with scientists at the JHU, are part of the recently announced BROOKLYN89 system of computer codes. Dr. George Adams of the BRL's IBD has won awards at both the 1986 and 1988 Army Science Conferences for research performed using these codes and the other quantum-chemical software installed on the Alliant FX8 superminicomputer acquired with productivity capital-investment program (PCIP) funds in 1986.

"BROOKLYN89 may be described as the code that begins where well-known quantum-chemical packages stop. The methods developed and programmed by the BRL and Johns Hopkins researchers provide the ability to determine the energy-storage capability of exotic high-energy-density materials such as propellants and explosives. These computer codes provide the only reliable way to determine accurately the energy-storage capability of many of these materials.

"When combined with the other quantum-chemical and molecular modeling facilities installed on the vector processor, the structure and properties of almost any chemical species of interest to the Army can be accurately predicted. These tools have been used effectively in wide-ranging studies of chemical agents, providing crucial information on the toxicity of proposed systems, as well as providing predictions of spectral information needed for detector design. Methods developed to solve the latter problem are now being used to detail the interactions that dominate mechanical properties of propellants.

"Most of the software is available to outside users. Thus, not only has the project generated an average annual savings of $704,000 per year through cost avoidance and provided a needed facility to the BRL scientists, but an additional benefit is provided to scientists and engineers at other sites. Both the CADPAC and MESA quantum-chemical packages are resident on the Cray X-MP at the BRL, and the porting of the BROOKLYN software is underway. When that task is completed, Army scientists at any laboratory should be able to use these powerful predictive tools."[25]

MECHANICS AND STRUCTURES

While most of IBD is concerned with the pressure pulse that drives the projectile, the Mechanics and Structures Branch is more concerned with what happens to the projectile and barrel when the pressure works on them. Its varied responsibilities during the last half of the 1970s through the mid-1980s included continuum mechanics, automatic weapons, the electronics of fire-control componentry, advanced analysis of radar signals, the proof of the precision aim technique (PAT), and the successful prototypes of the firing-port weapon for the BFV and squad automatic weapon (SAW). The technologies discussed here are those that are related to the mission of the branch after it bifurcated in 1986.[26]

As an interesting aside, Bruce Burns, the chief of the branch said that, "R. J. Eichelberger set a new tone for the BRL around 1973 when he got excited about system engineering. The BRL really changed then [for the better]."[27]

Modeling. The goal of the modeling effort is to develop a total model that includes the recoil system, cradle, gun, sabot, and projectile. Burns hopes to have this capability this year [1992] based on the work of Steve Wilkerson.[27]

Some of the earlier efforts of the branch are typified by the following two reports. From 1980, we have: "Efforts relating to in-bore structural analyses of projectiles and to the exploratory development of projectiles, such as the 120mm XM829, have also provided significant advances. For example, the transfer of the latest finite element simulation [technology developed for] the rear of the [Chemical System Laboratory's] 8-in XM736 binary projectile to LCWSL and on to the PAD ensures use of the latest interface modeling to estimate launch stresses and, hence, permissible manufacturing defect size [for the entire family of artillery projectiles]. Earlier analysis would have led to an overestimation of the stresses and a likely redesign."[2] This latter point was demonstrated by the work of Jim Bender to rationalize the analysis of anomalies for the M718 projectile.[27] "The concept of casting and molding sabots (both metallic and filled composites) has progressed. The cost saving offered by the avoidance of expensive machining processes can open up the effective application of long-rod penetrator technology to automatic cannon. Initial tests are projected for next year."[2]

And from 1982, we have: The "XM877 (8-in intermediate viscosity agent [IVA]) projectile production schedule was slipped due to launch-related fractures in the projectile base. The BRL analysis of the solid mechanics and in-bore dynamics revealed areas of design weakness. An improved design was developed by the BRL and has been demonstrated successfully at Dugway Proving Ground."[4]

Circa 1987 through 1991, Mark Kregel and Tom Erline developed the RASCAL model, which is personal-computer (PC) based. RASCAL uses two decoupled one-dimensional models for the horizontal and vertical flexures of the barrel and the projectile.[27]

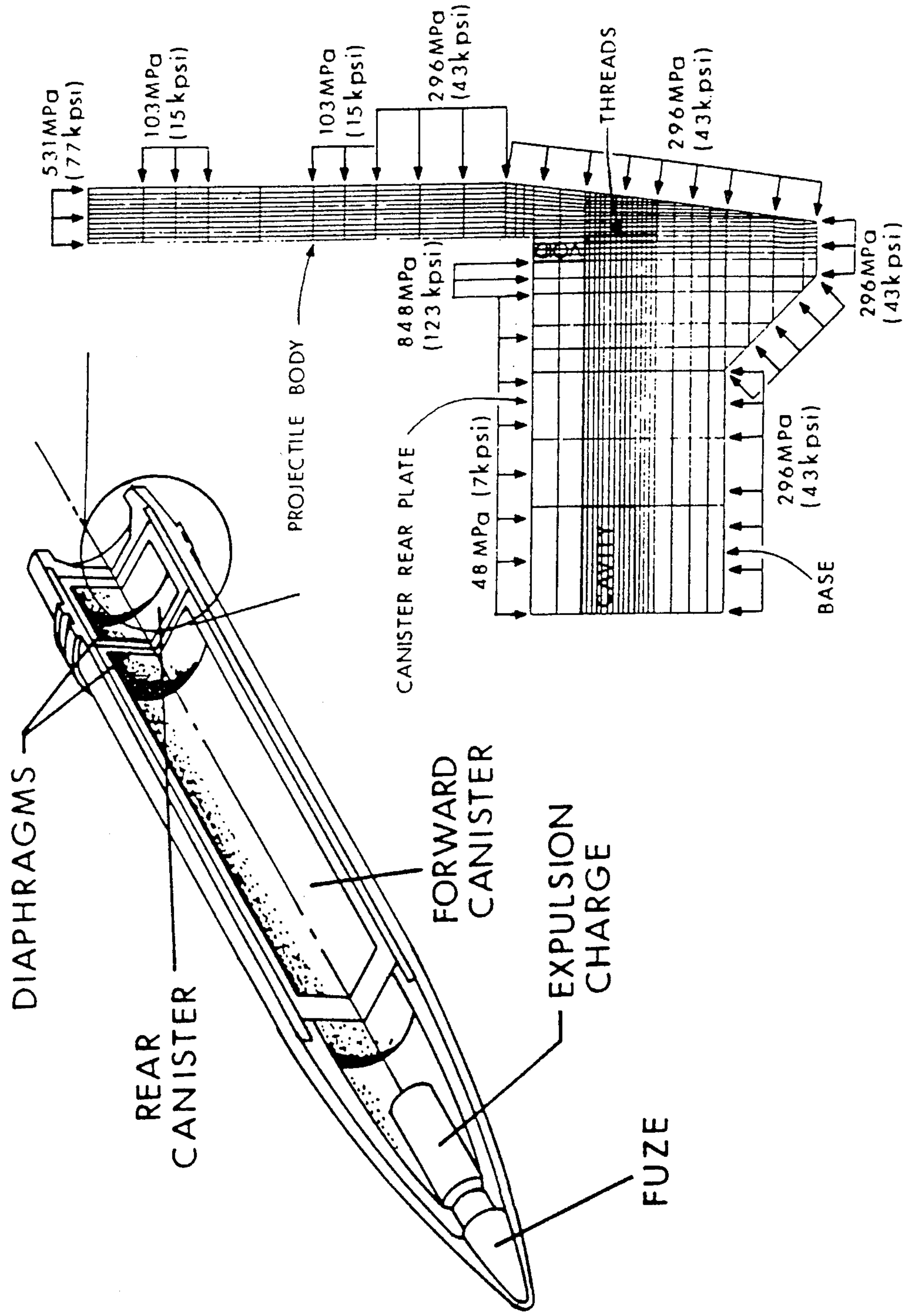
Another model, SHOGUN, was developed by Dave Hopkins as an offshoot of Martin Soifer's DYNA-GP code. It is an intermediate model between the PC-based model and the full three-dimensional model. SHOGUN uses a 6-degree-of-freedom, lumped-parameter, beam-like representation for the projectile, the gun barrel, and the mounting structure.[27]

As part of the tank-gun accuracy program in the late 1980s, Don Rabern at Los Alamos used Dyna 3-D to model the gun, sabot, and projectile for the 120mm tank gun. Rabern had contacted the BRL for guidance and partial support for his doctoral thesis. No interior-ballistic code was used in his model; the force that acted on the projectile was precalculated. Projectile flexure at regions near the muzzle of the gun was measured for actual firings using 2-MeV flash X-ray instrumentation, and the calculated test case for this ab initio model compared well with those measurements.[27]

Circa 1990, Hopkins started using a two-dimensional transient model with loads calculated from a one-dimensional transient propulsion model. He simulated the transient hoop stress rise in the barrel (due to pressure behind the bullet) captured at the base of bullet. This captured energy can result in a three-fold to four-fold increase in the overstress and subsequent undershoot at critical velocities. The wave velocity associated with this stress is slower than common muzzle velocities (even those of tank guns). The problem of holding muzzle sights in place is one manifestation of this problem; a second is related to launch velocities greater than about 2.0–2.5 km/s.[27]

The BRL now has a computational model of slip obturators through a joint DA/DOE program. The model, which was developed at Sandia National Laboratories, Livermore, CA, and was extensively exploited by Bob Kaste, uses a mechanistic torque-transfer model with supporting experimental data. It can accurately compute the functioning of the obturator through the forcing cone and into the main bore for smooth-bore guns. The problems associated with engraving for a rifled system remain to be addressed.[27]

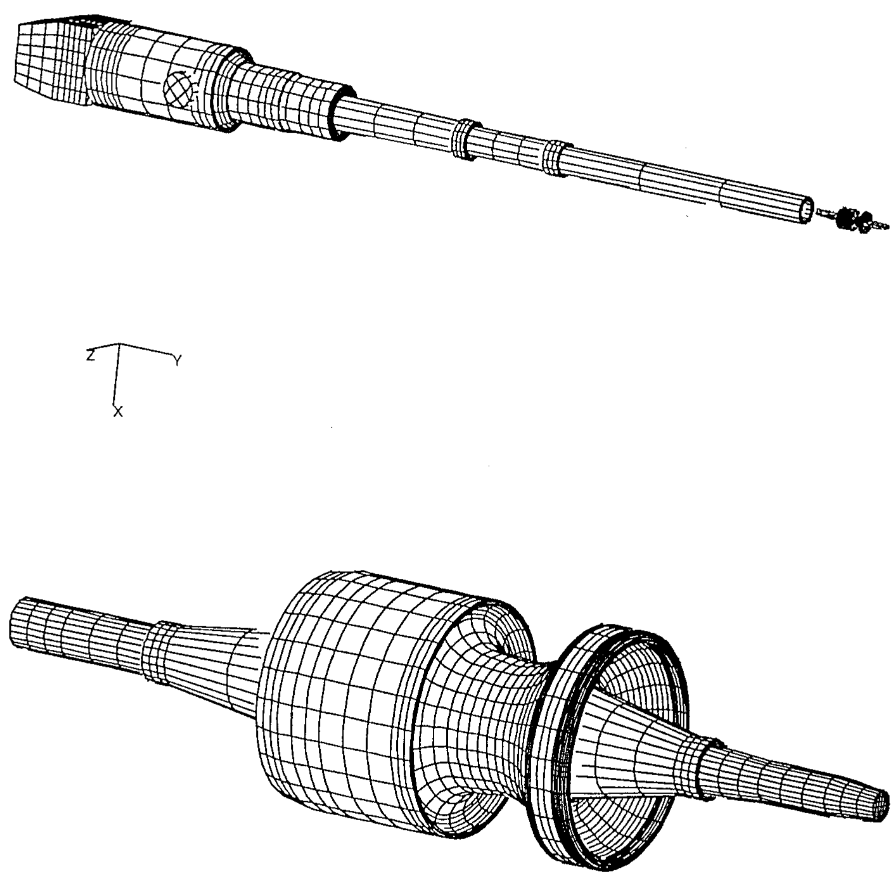
There has been considerable interest in thick composites. A good deal has been learned



XM736 Projectile With Loading Conditions.

about the three-dimensional behavior of composites under compression (work by Travis Bogetti and Jerome Tzeng).[27] "A three-dimensional modeling technique employs an analytic model to predict the effective homogeneous properties of a representative small section of the composite structure and local-average stresses to build up the detailed ply-by-ply stresses throughout the structure. This technique represents a highly computationally efficient, user-friendly tool, which permits rapid, accurate design and analysis of thick-section, multilayered composite structures."[13] Recent work by Bogetti has reduced these complicated issues to color plots of likely mode-of-failure (most critical mode) normalized to critical-mode ply allowables.[27]

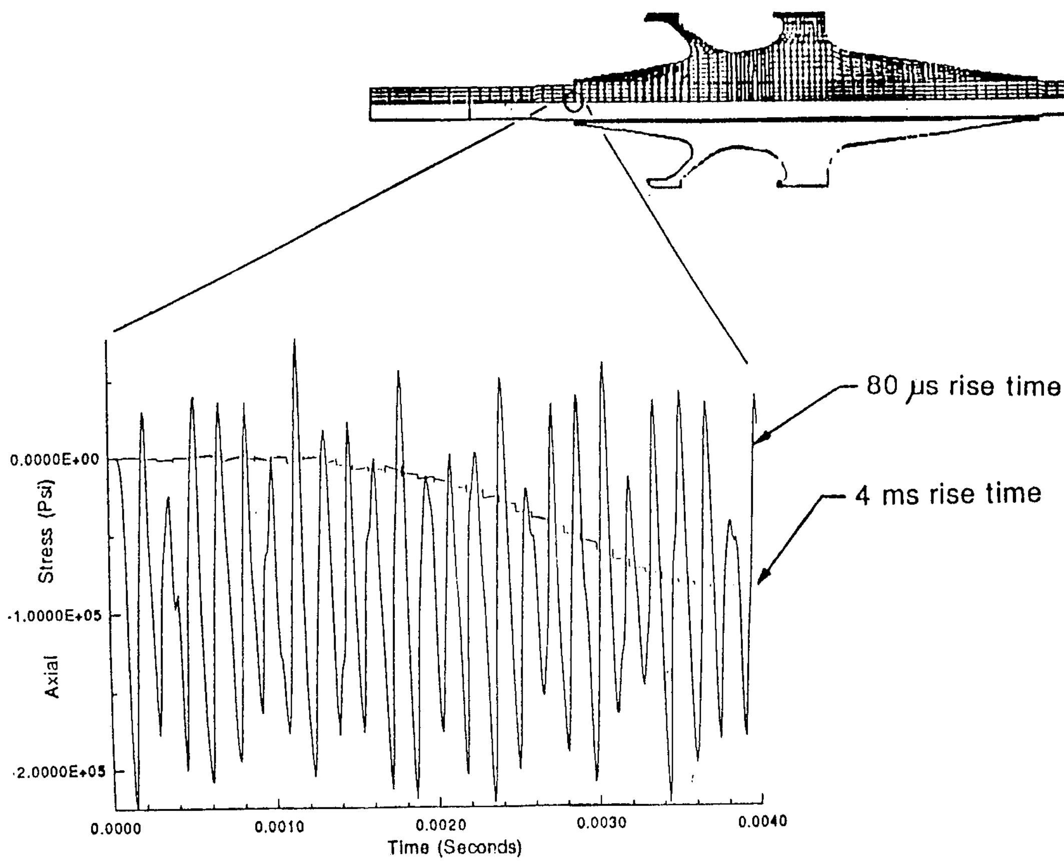
The following *Update* article by Ken Bannister discusses some of the history of the modeling efforts: "The determination of the in-bore motions of projectiles has bedeviled ammunition designers since time immemorial. We are no less plagued by this problem today with modern KE projectiles such as the 120mm M829 round. ... The perennial problems we face are: (1) Will the projectile survive gun launch? and (2) Will dynamic interactions between



Geometric Configurations Used for Finite-Element Models.

projectile and barrel affect accuracy on target? We need an answer to the first question because the bullet must survive the 50,000–100,000-g launch environment without breaking up in-bore. Such accelerations are not uncommon in modern gun systems. This leads naturally to the second question about projectile-barrel interaction effects which we have discovered greatly affect the accuracy of tank guns and is a problem which has come to the fore with saboted-rod KE penetrator projectiles. Since the rod, being long and flexible, picks up vibrations in-bore, it will enter free flight with initial rigid-body motions that influence aerodynamic flight and accuracy on the target. The rod vibrates because it must navigate the twists and turns of the barrel. Due to wear, machining tolerances, and gravity droop, no tank-gun barrel is ever straight! Also, during the 5–10 ms it takes for the round to traverse the barrel, the barrel vibrates so that the path followed by the projectile changes with time.

"It turns out that the tremendous advances in supercomputing and robust finite-element modeling techniques in the past 10–15 years



Elastic Transient Response.

allow us to model transient in-bore structural-response problems, like barrel/KE projectile interactions, to a degree heretofore impossible to imagine. While design improvement of 120mm projectiles is a good example where this methodology has been applied, we also have applied (and are applying) the methodology to other high-priority tasks such as (1) prototyping of new concepts for a 105mm KE round and a 155mm sub-munition high-capacity artillery projectile [HICAP] (lead item in a potentially large family of lightweight 155mm ammunition); (2) impact/fracture studies of M30 and JA-2 propellant grains for improved interior-ballistic performance; (3) non-linear transient structural analyses of several design concepts for a Navy 40mm perimeter-defense grenade; (4) transient response of the 155mm artillery cargo projectile family subjected to LP transient pressure loadings [currently under extensive investigation by Erline, Hopkins et al.]; (5) the response of projectiles to a wide variety of EM and electric-augmented propulsion schemes; and (6) an extensive array of hardware troubleshooting exercises and accuracy-related questions for 105mm and 120mm KE tank-gun projectiles.

"Since 1987, considerable progress has been made in realizing a hierarchy of transient modeling tools to attack in-bore response problems. The short-term goal is to provide an array of reliable modeling tools to bring to bear on advanced ordnance systems, but the long-term goal is to model the entire interior-ballistic event, from shot start to muzzle exit.

"The hierarchy of modeling tools consists of simpler beam-element-type gun-dynamics computer models, plus higher-order, two-dimensional and three-dimensional, transient, nonlinear finite-element codes. The beam-element codes were developed in-house, whereas the solid-element codes were developed by numerical analysts from the DOE and other agencies and have been adapted for local use. ... Work is in progress on coupling the higher-order codes with special-purpose, BRL-developed (or sponsored) interior-ballistic codes. In their present stage of development, these are one-dimensional models, either in lumped-parameter or continuous two-phase format, of the propellant burning processes inside a gun barrel. This coupling is a major step towards a comprehensive gun model which will ultimately allow detailed, efficient parametric and trade-off studies for designs of future Army weapon systems. Our experience thus far working with the structural models in the hierarchy shows that they are complementary, with no one code clearly able to replace the others. Beam models allow faster problem setup/solution turnaround time than the higher-order codes, thus are good for parametric studies. In contrast, higher-order models provide very detailed rate-dependent information on local deformations, strains, and stresses, but with obviously greater manpower and computational expense.

"Ultimately, the behavior we seek to model is three-dimensional, transient, and non-linear, thus finite-element computer models are *de rigueur*. Non-linearities creep in due to the presence of sliding contact surfaces (with and without friction) and large-deformation plastic flow of obturator materials. In addition, the three-dimensional transient nature of the analyses requires Cray-class computer power. ...

"With supercomputer technology and the evolving hierarchy of structural modeling tools described here, rapid progress is being made toward a model of the entire interior-ballistic cycle. We are now able to handle effects of high-rate-of-loading and barrel/projectile interactions during in-bore travel, and predict transient behavior of the projectile at muzzle exit. This includes critically important initial conditions, such as projectile cocking angle at shot start. As further dramatic evidence of the practicality of the transient modeling methodology we have developed, it has been used during the past 3 months to resolve two difficult problems. The first problem concerned unacceptably large flexure of 120mm rod projectiles observed during a major experimental program being run by the BRL's TBD. As was demonstrated by our beam-based gun dynamics models, the problem turned out to be due to unforeseen projectile/barrel interactions, requiring a down-select to an appropriately straight launch tube. The second problem, of a somewhat more subtle nature, concerned reducing dispersion of the 105mm XM900E1 KE projectile by redesign of its sabot. Extensive full three-dimensional, transient analyses by the BRL Cray X-MP/48 were required (10–20 central processing unit [CPU] hours each) in the redesign. Results of the analyses of the new sabot geometry, compared with the old, showed that yaw rates at muzzle exit were drastically reduced, hence dispersion was reduced. ARDEC has accepted this design, and test hardware is now being fabricated. These real-life engineering examples thus directly illustrate how a hierarchy of modeling capabilities for in-bore problems is absolutely essential."[27]

Bannister, Wilkerson, Erline, and Jim Bender are presently interested in transient effects on artillery shell. This includes the effects of high-frequency LP instabilities, shot ejection stress, etc. This also relates to the HICAP program discussed [in the following text].[27]

Sabots. Sabot design is specially critically for antitank KE rounds. High velocity is important, as is every joule of energy. The round is essentially a very slender rod of high-density material, and any yawing motion in-bore can have a deleterious effect on accuracy—if it does not produce a catastrophe.

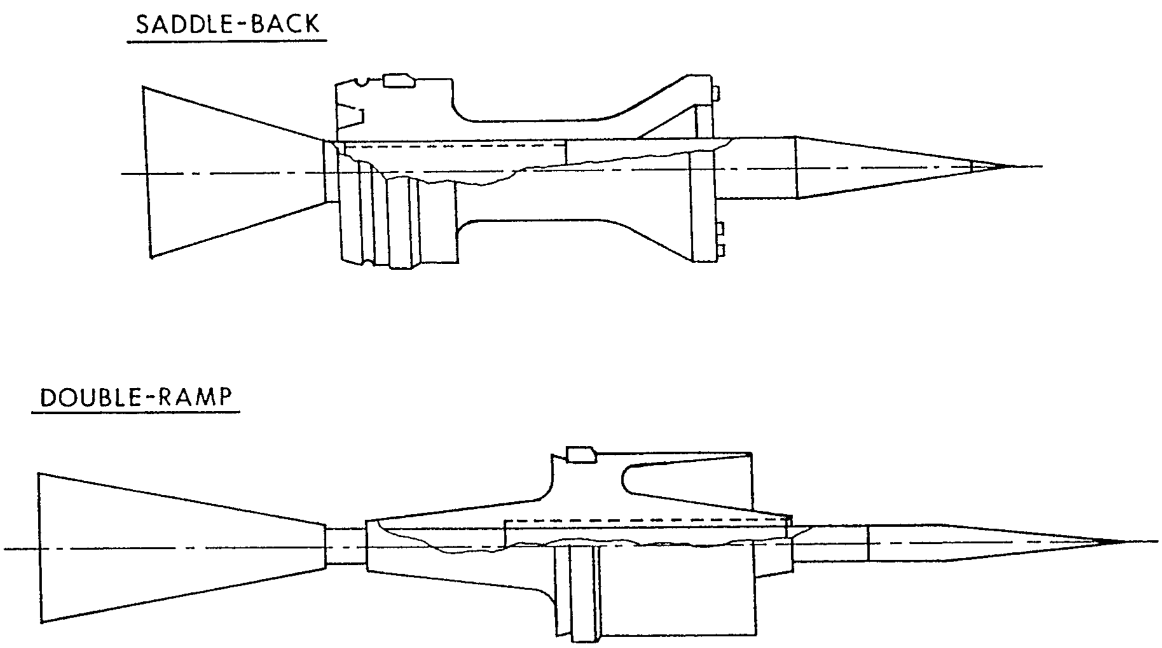
"The Arrow and Delta Programs, conducted in the 1950s and into the 1960s furnished the technology for the 152mm tank-gun system (XM150) for the XM803 tank (main battle tank [MBT]-70), which was to succeed the M60 tank.

"The medium-caliber antiarmor automatic cannon (MC-AAAC) program was initiated [after] the MBT-70 program had just been canceled, and the difficulties with the 152mm KE projectile that was under development were never adequately resolved."[28]

Circa 1973, as part of the MC-AAAC program, IBD, and Burns in particular, worked out the mechanical principles for the single-ramp sabot. It was this single-ramp sabot concept that was used in 1974 in the Silver Bullet program, which led to the improved version of the 105mm XM735 round. In both the MC-AAAC and Silver Bullet, the round was stable in-bore (the center of gravity was behind the hinge point), and the sabot was self-sealing and adequately supported the monolithic, high-density, long-rod penetrator.[27]

In 1977, IBD started on improvements of the MC-AAAC round and then addressed the 105mm KE round. This led to the addition of a small forward ramp by Burns in the MC-AAAC prototypes. This, in turn, was followed by the extension to the current, now commonly found, and highly successful double-ramp solution, which was due to the excellent work of Bill Drysdale, Dick Kirkendall, and Louise Kokinakis. This was used in the initial development of the 105mm M833 round.[27]

A prototype full-double-ramp sabot for the 120mm smooth-bore gun was pioneered by Drysdale, Kirkendall, and Kokinakis and was used in a demonstration program for the Germans in 1979 for a round similar to the M829 family. The double-ramp sabot was used in the development of the 120mm M829 family and also in the 105mm M900. "In research applied to projectile performance, the BRL had two accomplishments with far-reaching effects for munitions lethality. First, a new BRL-designed long-rod KE penetrator, fired from a 120mm gun, set a new armor perforation record. This achievement provided the foundation for the 120mm XM907 KE technology demonstration program Honey Bee, as well as the 105mm XM900 advanced KE round, which is now in advanced development.



Common Types of Sabots Used to Launch KE Projectiles.

These accomplishments will extend the effective lifetime of the M1 and M1A1 armaments. The second accomplishment is the incorporation of rate dependency in the formulation of the theory of plasticity, which provides a new scientific basis for refined sabot designs to reduce mass and increase muzzle velocity of antitank KE munitions."[14]

The M829 family (including the A1 and A2 versions) and the M900 cartridge have given U.S. tanks a very powerful antiarmor capability, and the double-ramp sabot has become *industry standard.* The 25mm armor-piercing fin-stabilized discarding sabot (APFSDS) KE rounds M881 and M919 for the Bushmaster automatic cannon on the BFV also use the double-ramp sabot concept. The extraordinary success stories of the M829A1 and M829A2 rounds (especially the sabot for the latter) are not yet in the public domain and cannot be included here. It can be stated, however, that major new performance advances were proved with the M829A2 sabot technology.[27]

The following *Update* article by Wilkerson and R. P. Kaste discusses the design process: "A new KE sabot design concept has been successfully developed at the BRL. This new projectile design was conceived as part of BRL's ongoing gun accuracy program and the continuing desire to make better and more accurate tank munitions. The design's concept centers around the use of longitudinal ribs along the aft and center sections of a modern-day sabot to stiffen the projectile's in-bore dynamic response. Additionally, the concept accomplishes this task without adding any additional weight. ...

"A significant factor in the development of the new sabot was the use of computational analysis on the Cray supercomputers at the BRL for predicting the effects of the design changes. In order to understand the significance of this accomplishment, it is important to briefly review how such improvements have been made in the recent past. Often, bullet designs have evolved through iterative processes with heavy emphasis on experimentation. That is, once a concept or new design was proposed, an analyst would check the design to assure that it was structurally sound using a variety of methods. The mathematical or engineering modeling of the design was examined using a number of numerical and analytical techniques. For example, gun dynamics codes are routinely used with good success to analyze the gun tube and projectile interactions. Also, axisymmetric finite-element analyses have been used to examine the peak stresses in the projectile as it travels down the gun tube. After such analysis, prototypes were produced and tested. From there on, more subtle design changes were incorporated, and a cycle of building and testing was continued until an acceptable bullet configuration was derived. Much of this costly build-and-test philosophy was necessary due to the extremely complicated nature of interior and exterior gun dynamics. Until now, most of the numerical and analytical tools being used in the design of KE bullets were incapable of examining the effects of subtle design changes with any degree of accuracy.

"More recently, individuals at the BRL and scientists at the Los Alamos National Laboratory have combined their talents to study the problem of interior gun dynamics with the power of three-dimensional finite-element techniques. Much of this recent work has been made possible by the use of supercomputers. The new methods focus on modeling both the projectile and gun tube with finite-element techniques and then incorporating more detailed and accurate boundary conditions and assumptions. These techniques are capable of examining the peak stresses and strains with a high degree of accuracy as well as predicting the effects of balloting on the kinematics of the bullet as it leaves the gun tube.

"Therefore, when this new sabot concept was proposed, it was decided to try to use these new three-dimensional finite-element techniques to evaluate the proposed design. The new concept ... represented substantial design modifications, and it was desirable to predict how these modifications would affect the projectile's performance prior to building and testing it. It was also of some importance to determine whether the new concept would survive the in-bore environment. Therefore, experts within the BRL's IBD and LFD teamed with key personnel from the Los Alamos National Laboratory to investigate the proposed design change. In order to ensure the structural integrity of the new sabot design, the BRL employees working with Los Alamos personnel, developed a three-dimensional transient finite-element model of the design and subsequently analyzed it on the BRL Cray supercomputers. The proposed design changes not only proved to be structurally superior to the existing projectile design, but the design also exceeded expectations on its performance. Since that time, this new sabot design has been successfully built and tested at APG. In addition to proving the performance benefits of new sabot design, the tests served to validate the new three-dimensional model for predicting sabot performance. Thus, the Army now has both a proven new sabot and computer analysis tools for use on future projects."[29]

Recently, the integration of several critical ballistic technologies for system analysis of advanced cartridges using both current state-of-the-art capabilities and assessments of future technology improvements have been orchestrated in the branch by Larry Burton. He has played a key role in infusing modern technologies into a variety of contractor-executed programs focused on futuristic candidates for advanced propulsion concepts.[27]

High-Capacity Artillery Projectile (HICAP). The BRL is participating in a program to look at a new modular concept for an artillery round. HICAP is a fin-stabilized round that will "break the L/D ratio mold," get away from stability problems of high L/D ratio rounds, and reduce the need for heavy walls to produce large axial moments of inertia. The walls can be thinner and lighter using high strength-to-weight materials (e.g., fiberglass or graphite in a polymer matrix), and the round (having been lengthened in a mass-efficient manner) can carry twice the payload of a conventional cargo projectile.[27]

HICAP breaks into two pieces for handling and tailoring for mission needs. The front and back modules could have different payloads or could include a rocket motor, etc. A Memorandum of Agreement (MOA) in place among the BRL, the MTL (formerly the Army Material and Mechanics Research Center [AMMRC]), the Harry Diamond Laboratories (HDL), and ARDEC for a cooperative program including joint contributions of funds. The 6.2 effort is managed by the BRL (first by Burns and then by Bender). When the technology is demonstrated to be mature, it will transition to ARDEC.[27]

In 1990, "A metal-joint concept to secure two pieces of the [HICAP] concept was successfully tested in 155mm launchings with low-, medium-, and high- (8S) zone charges. Design decisions were made for a wrap-around fin concept, and projectile roll histories were predicted. Non-optimized graphite/epoxy aft body prototypes were successfully tested at high stresses typical of those encountered in-bore."[20] The efforts of Bogetti, Tzeng, consultants, and critical industrial partners were subsequently blended to extend the strength of new composite prototypes to levels commensurate with the highest pressures and acceleration levels envisioned for artillery systems.[27]

A briefing to industry on HICAP was held on 8 August 1992, and the following white paper was prepared for that meeting:

"A novel artillery shell which substantially increases cargo without significant weight increase is currently undergoing 6.2 development. Recent advances have been made in the area of high-performance materials to allow them to replace steel for the shell of cargo-carrying artillery projectiles. The weight savings are reinvested in cargo, thus increasing the per-round lethality and effectiveness. It is intended that HICAP be compatible with most existing submunitions and propelling charges and AFAS.

"This initiative exploits recent advances in high-strength lightweight structural materials, i.e., composites, resulting in the design of an artillery shell capable of delivering nominally twice the payload on target of a conventional round. This is accomplished by substituting lightweight material for the heavy steel shell body and investing the weight savings in additional payload such as grenades, smoke and obscurant, scatterable mines, or others. The addition of deployable fins will stabilize the round since the flywheel (shell body) is no longer of sufficient mass to spin-stabilize the projectile. Alternatively, the weight savings could also be invested in a rocket motor to deliver a payload equal to that of current rounds to nearly double the range of top-zone launches.

"To obtain the desired launch weight and to house the increased payload, the projectile would become longer than current projectiles in the 155mm family. The projectile would be split into two modules, fore and aft, and assembled just before loading and locked together in the breech at shot start. This modularity provides the capability of mixing payloads in the same round, i.e., smoke fore and grenades aft, grenades fore and rocket aft, and the like.

"The concept has a logistical advantage over current artillery projectiles in that an equal amount of submunitions can be delivered on target for half the amount of propelling charge and using half the number of bullets and fuzes. For example, if a mission were to call for the delivery of 24 M483 artillery rounds, the supply vehicle would need to deliver 24 rounds (2,400 lbs), 24 charges (720 lbs), and 24 fuzes. With HICAP, only 12 rounds (1,440 lbs) would be needed and 12 propelling charges (360 lbs) and 12 fuzes. Both missions would deliver 2,112 grenades (88 in a standard deck) on target with a supply weight savings of 1,360 lbs or 43%.

"Survivability of the firing battery is also increased since counterfire detection would have only half the number of fires available to detect the location of the battery.

"Early design efforts have resulted in the successful launch of a lightweight aft body at near top-zone charge. Also, a unique joint to hold the two modules together has been demonstrated to survive top-zone launch conditions.

"This technology has been investigated for the 155mm family but in no way is restricted to that system. Laboratory testing has shown that all aspects can be scaled up or down to suit virtually any artillery size.

"The development of this technology addresses the Army's need for increased lethality and enhanced survivability. The program also has the full support of the Field Artillery Center at Ft. Sill.

"This research effort has received start-up funds for the BRL (lead); ARDEC, for cargo dissemination, shell design, and compatibility studies; MTL for lightweight-materials research; and HDL for fuze applications.

"Once developed into a system, this technology would enable the user to accomplish a fire mission of equal lethality with nominally half the number of rounds and half the amount of propelling charge. Additionally, enemy counterfire assets would only have half the opportunity to locate the source of delivery. Using the rocket option in the rear module would permit the delivery of a conventional amount of payload to significantly greater ranges—as much as double that of current rounds depending on payload and method of dispersal. The technology also readily lends itself to the incorporation of on-board guidance taking advantage of current smart or brilliant technology.

"There is strong indication that the development cycle for HICAP is compatible with that of AFAS.

"HICAP will be able to use most of the currently inventoried submunitions and can be made compatible with any new submunitions."[30]

PROPULSION SYSTEMS BRANCH

In addition to working on propellant systems as the name implies, the Propulsion Branch also has a Weapon-Dynamics/Robotics Team.[31]

However, before we discuss the branch's programs, it seems worthwhile to note the following quotation from Joe Rocchio, the Chief of the Propulsion Systems Branch: "The BRL's involvement with ARRADCOM had at least one positive aspect. It began to breakdown the *us-vs.-them* between the BRL and Picatinny Arsenal. They were divergent cultures, but they came together for the time that we were one organization. It gave us entrees into the operation at Picatinny Arsenal, it gave them a better understanding of what the BRL could do, and gave an appreciation to the BRL of the trials and tribulations of being a weapon developer."[32] This reflects the close relation between the BRL that was especially evident in the development of the main armament for tanks.

Low-Vulnerability Ammunition (LOVA). LOVA is a concept to reduce the vulnerability of ammunition in fighting vehicles that includes all aspects of the system: armor protection, locations of the ammunition, venting of the ammunition compartment, protection against sympathetic initiation, and the use of insensitive propellants and explosives in the munitions.

The idea for LOVA propellants went back to an effort to develop caseless small-arms ammunition during the Vietnamese War. Cigarettes were a hazard to ammunition carried on soldiers' bodies. Nitrocellulose was easily ignited; so a new material was needed. Composite rocket propellants that use HMX were considered, but the short reaction time for small arms precluded adequate ignition of the material, and the effort died in 1972. However, when concerns with tank-cannon rounds arose, the material looked good, and there was a good scientific basis for ferreting out the chemical and other properties.[32]

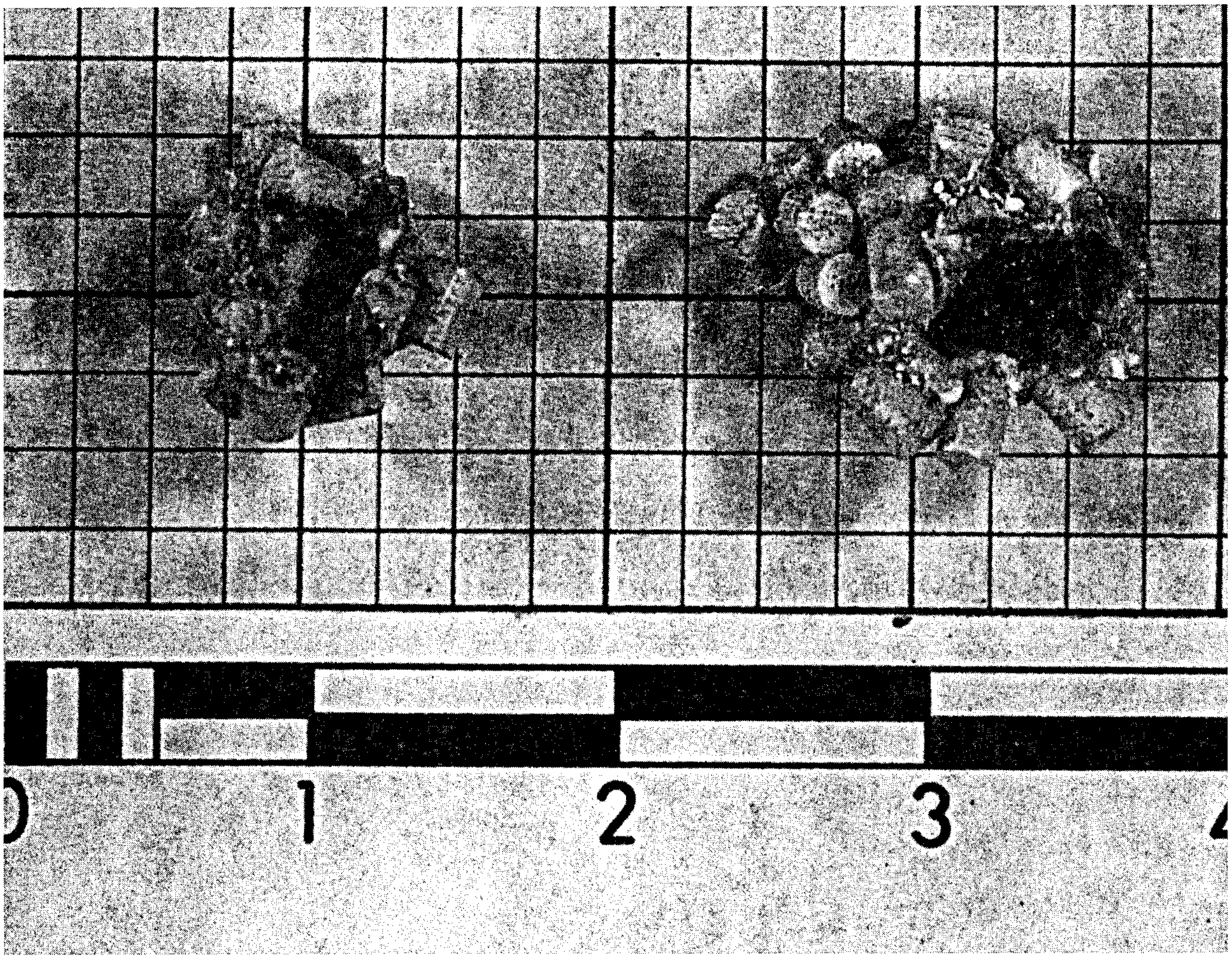
The hallmark of LOVA propellants is their difficulty in being ignited at low pressures. Therefore, while LOVA propellants are good in high-pressure tank guns, they are not so good in artillery howitzers because of low pressures at the low zones. This is not a problem for LP (which also has LOVA qualities) when used in a regenerative system. LP has an additional LOVA advantage since it can be stored low in the howitzer and pumped up as needed.[16]

The concept for LOVA first started in 1974. By 1977–78, the data were available to define the problem and to show that it should be tractable.[32]

In 1976, Rocchio was canvasing the services for interest, but it was not until 1978, when the DOE came up with ideas for IHE, that the LOVA program got a real boost. Rocchio told some DOE representatives what he was doing, and IHE soon became IHE and insensitive high explosives and propellants (IHEP).[32]

A Joint-Service/DOE study was conducted in the period 1978–80 to look at technology, system applications, cost-benefit analyses, etc., for IHEP. The BRL data were fed into the study, and the afterthought (low-vulnerability propellant) became the major item for expedition.[32]

AMC and ARRADCOM provided support for accelerating the LOVA program through 1980–82. This effort defined the properties of the material and showed that its manufacture was practical.[32] "The Army and Navy currently have a joint program to develop a LOVA propellant which will help improve weapon-system survivability. This effort is being conducted as Task I of the IHEP program. As part of this task, the BRL tested gun interior-ballistic performance and analyzed vulnerability characteristics of candidate LOVA propellants. During FY80, LOVA propellants used to fire KE projectiles [XM735] from a 105mm, M68 tank gun developed projectile muzzle velocities equal to velocities attained with standard, triple-base, M30 propellants. Results from small-scale laboratory fixtures and full-scale 105mm gun tests, showed erosion for the nitramine/inert binder LOVA propellants to be clearly less than that for the standard M30 propellant, as would be expected from the lower flame temperatures of the LOVA propellants. In laboratory tests with hot fragments and in field tests with both controlled fragment impacts and shaped-charge-jet-generated spall and fragments, a polyurethane/HMX LOVA propellant withstood much higher temperatures and much higher velocities without burning. Considerable strides were made toward the critical goal of understanding the mechanisms by which LOVA propellants resist inadvertent initiation. Recognition of mechanisms which make one inert binder far superior to another, permits the formulation of improved candidate LOVA propellants."[2]



Spall Particles Are Shown Imbedded in LOVA Propellant Grains; Melting and Decomposition Have Occurred to Dissipate the Energy, but There Was No Ignition.

In 1982, LOVA was sold to the Armaments and Munitions Command at Rock Island Arsenal, IL, and an engineering study was established to show that a Product Improvement Program (PIP) was appropriate to enhance system safety. That engineering study identified a formulation that would provide suitable ballistic performance and that would be producible.[32]

Once the technology had been demonstrated, the PIP (including production engineering, quality control, etc.) was conducted from 1984 through 1987. This resulted in the XM39 propellant for 105mm M456 high-explosive antitank (HEAT) round. XM39 was the first new Army propellant in about 25 years. However, XM39 was shelved since there was already a surplus of HEAT rounds. The BRL also started to look at a propellant for 105mm KE rounds, but the 120mm system dominated.[32]

About 1987, a 6.2 program was initiated to find a high-energy low-vulnerability ammunition (HELOVA). The armament enhancement initiative (AEI) program provided the impetus, and circa 1988 one of the first propellants, high-energy low-vulnerability ammunition propellant-1 (HELP-1), performed very well in some 105mm tests (low-temperature sensitivity, low erosion, etc.). There was an application to the high-performance M900 round for the 105mm gun. The high-energy (not LOVA) JA-2 propellant from the 120mm M829 program was too erosive for the 105mm gun. The 120mm smooth-bore gun was chrome plated; the rifled 105mm was not.[32]

The 105mm M900 was to be killed for lack of a suitable propellant. The BRL interested ARDEC in the possibility of using HELP-1. Tests with M900 slugs showed not only that HELP-1 would work but also that the nominal pressure could be increased because of the low-temperature sensitivity of HELP-1. HELP-1 became the M43 propellant that was type classified for limited production for use with the M900 in 1989 and classified standard in 1991.[32]

The M900 rounds with M43 propellant went to Operation Desert Shield/Storm with the 105mm guns on the M1 tanks, which were deployed much earlier than the heavier M1A1 tanks with their 120mm guns. M900 rounds that were at APG for test were appropriated and flown to the Persian Gulf.[32]

The BRL is now [1992] looking for a more energetic, survivable propellant to replace JA-2 in the 120mm.[32]

The BRL participated in the IB for the 120mm M829 and the ATAC 140mm systems. This included system studies, charge design, and ignition studies. In the case of the 140mm system, the long chamber and two-component propulsion system created special ignition problems.[32]

It is important to consider the ignition process for LOVA. After all, LOVA propellants are supposed to be hard to ignite until pressure is built up. The process is studied in stages, the igniters by themselves, the igniters in an inert propellant bed, and the igniters in a live propellant bed, to map out the process.[32]

Now, with an Ignition Simulator, the BRL can watch the step-by-step process at a 1-to-1 scale through transparent walls, which allow the test to proceed to a pressure of several thousand psi before rupture, at which point the ignition process is well established.[32]

Fracture. IBD has been working on the mechanical properties of LOVA propellants. No one knows much about mechanical properties of propellants; so they had to start more or less from scratch. In this regard, the properties of the material and a model for fracture are needed. The properties must be defined in relation to types of failure (e.g., the relation of the surface created by a crack to a breechblow). Then it is necessary to learn to design propellant with proper characteristics.[32]

The following is extracted from an *Update* article by Robert Lieb on propellant fracture: "It is known that propellant fracture during ignition and combustion causes significant loss of ballistic efficiency, at the very least, and can lead to catastrophic gun failure (breechblows) if the fracture is excessive. In the last 10 years, all breechblows, at low temperature for which there were enough instrumentation to determine the cause, were traceable to the fracture failure of the propelling charge.

"Briefly, a breechblow scenario might proceed as in the following. Assume that the propellant is cold, which tends to embrittle propellant. Also, assume that the igniter has been damaged so that a good distribution of igniter gases is prevented, and ignition is localized at the breech end. Either one of these conditions, by itself, may not be enough to cause excessive pressures to occur; however, in concert the overpressure possibilities are greatly enhanced. The ignition gases exert a force on the propellant grains, and in a charge such as a tank round, a mechanical stress wave can be started through the propellant. The drag between the gas and grains moves the charge toward the forward end of the chamber. The low pressure at the front of the charge keeps the propellant in front of the stress wave weaker and more likely to fracture. The result is a propellant being subjected to mechanical shock and impact conditions that are likely to produce fracture. As the flame front follows, too much propellant burns too quickly, which adds to the pressure difference in the chamber, and promotes further fracture and even more rapid burning. In this manner, high-amplitude excessive pressures are generated which can lead to gun failure.

"Efforts have been underway for some time to characterize the mechanical response of gun propellant under conditions as close to operational as possible. It was recognized early that high strain-rate response measurements are required and that excursions into higher pressures would have to be made if proper propellant characterization were to be accomplished. The part that was not known, and in which many new understandings have been discovered, was the proper method to relate the measured information to the processes that control the pressure generation during combustion.

"Apart from the performance, other questions with regard to system vulnerability may also be dependent on propellant fracture. Significant threats to weapon-system survivability arise due to the ignition of on-board propellant. The ignition threat comes from two sources, behind-the-armor spall and shaped charge jet (SCJ) direct impact. Propellant that has a brittle response to impact will provide a more violent response to the spall threat. It is important, therefore, to maintain propellant integrity as much as possible to limit the response. The SCJ interaction is more complex. The initiation of the grains by the SCJ is probably not affected significantly by the propellant mechanical properties. The jet produces a detonation-like response in the propellant that it hits directly. However, in the region surrounding the zone of direct interaction, the propagation of this very violent response and the time needed to transition to ordinary burning may be heavily dependent on propellant mechanical response.

"Within the IBD, much research has gone into the characterization of propellant fracture with some good results. The development of LOVA, successfully designed to counter the spall threat, has progressed successively to higher and higher energy formulations to meet the requirement for greater performance. At each stage in the propellant development, the mechanical properties of the candidate were measured and evaluated. This monitoring provides critical feedback and helps prevent extensive development of a propellant that has a critical flaw which will stop it from being fielded (this happened in the 1950s). The HELP-1 series, which evolved from the LOVA program, resulted in a propellant that has the energy it needs, has retained the LOVA characteristics needed to defeat the spall treat, and possesses mechanical properties that are optimum for that system."[32]

Precision Aim Technique (PAT). PAT relies on the idea that it is not necessary to hold the gun on the target if the time at which the gun is properly aimed at the target can be anticipated. This is similar to the technique taught to riflemen for off-hand shooting. PAT requires knowledge about the motion of the gun, the delay between the decision to fire and the exit of shot, and the location of the target relative to the muzzle.

PAT was first conceived by Mark Kregel in the late 1970s as a way to provide more accurate fire from helicopter-mounted automatic cannons. PAT was proven to work with the Cobra helicopter. However, air-to-air gunfire was of more interest, and the reduction in rate of fire associated with PAT was a drawback.

Shooting at maneuvering aircraft is usually not helped by high precision; in fact, dispersion is a convenient means of making a large pattern.[32]

The precision associated with PAT seemed more appropriate to armored vehicles for the main guns on tanks and for the automatic cannon on infantry fighting vehicles.

From 1982, we have: "PAT has demonstrated burst-fire accuracy, from a vibrating automatic cannon, equal to single-shot accuracy from a rigid mount."[4]

The interest shifts to tanks, and in 1984 we find: "The objective is to increase both the aiming precision and armament-system ballistic accuracy of armored fighting vehicles and heliborne armament systems, when fighting both stationary and on-the-move. The expansive program involves gun-tube manufacturing, environmental effects, ammunition, computer-controlled PAT and precision imaging system (PIMS). [The BRL] field-tested PATs on the M1 discovered unexpected gun tube vibration from vehicle track motion; interfaced PAT with heliborne components and conducted successful laboratory tests; expanded gun tube dynamics predictive capabilities; and demonstrated an integrated PAT-PIMS system using an indoor fixture."[14]

From 1987, we have: "There were several significant tank-gun developments in FY87. The BRL developed and successfully demonstrated 1) an automatic boresight retention system for the M1A1 tank, 2) an electronic module to interface PAT and TADIRAN to the fire-control computer of the M1A1, 3) an interface for PAT, a specially designed gun cradle, and a modified M230 30mm chain gun, and 4) an electronic control module that interfaced with PAT to accurately fire a weapon system while the mount was undergoing one type of vibration (2 Hz) and the gun tube was undergoing a second vibration (25 Hz) to reduce target dispersion by a factor of 30. The improved accuracy when using a PAT system while firing a modified M230, 30mm chain gun from a Cobra helicopter airframe was demonstrated. Also, an electronic sequencing scheme was developed to prolong the operating life of the laser transmitter and detector of the TADIRAN. The BRL, with Benet Weapons Laboratory, ARDEC, developed a soft-ride mirror mount for the 120mm gun."[6]

The strain patches originally planned to measure gun motion for PAT were too fragile, indicating the use of a muzzle-reference system. However, the sampling rate of existing muzzle reference systems was too low for PAT. Recently, work with Princeton Scientific on using a laser diode has demonstrated a capability to sample at 10 kHz. Another problem, however, is that PAT's algorithms can only predict well to about 15 ms, which is short with respect to the cycle time of the 120mm ammunition. Circa 1991, it was found that by monitoring tube motion and locking-out firing during periods of excessive motion, at least 75% of PAT's performance could be realized. This is similar to the practice of gunners when either the tank is bouncing too much, or the target is jinking too much.[32]

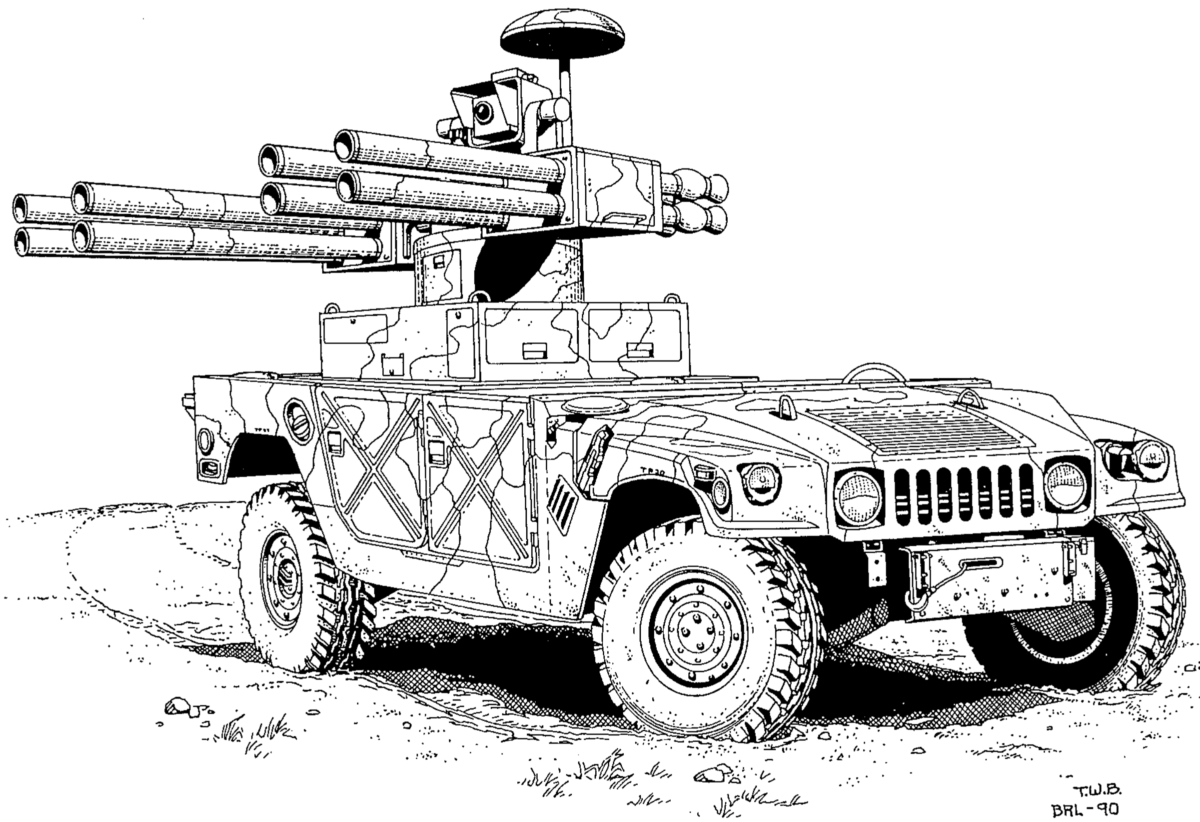
It was also found that the drift of a cold gun tube affects the course of firing significantly. This provides an extra argument for the use of a continuous muzzle reference system with PAT.[32]

A variant of PAT is called the inertial reticle. In this concept, once the target is established by the operator, an inertial system remembers that target's orientation. The PAT algorithm uses that *remembered position*, and the gun is fired when the PAT algorithms predict intersection of the aim of the gun with the inertially remembered position.[32]

Robotics. The Weapon-Dynamics/Robotics Team has been working with the DOD program on unmanned ground vehicles (UGV). In particular, they have been developing a pointing and aiming system demonstration for firing a recoilless launcher from a UGV (for the demonstration, this would be a high-mobility multipurpose wheeled vehicle [HMMWV]). The demonstration involves automatic target acquisition with authorization by the operator for firing. The system then aims and fires with no complicated tele-operations involved. A successful demonstration at APG's Churchville Test Area was completed in the summer of 1992.[32]

Shrouds. One of the contributors to inaccuracy is motion of the gun tube due either to differential heating by the sun or to air currents that are generated by the heat of the tube itself from firing. Thermal shrouds provide two functions: they mitigate the direct heating from the sun, and they help maintain uniform temperatures in the hot gun tube.

From 1986, we have: "In order to test thermal-shroud performance on tank cannon, both environmental (solar heating and rain) and firing-induced thermal loadings must be simulated. Based on examination of existing test practices, the BRL developed a new procedure, which provides improved simulation of the battlefield environment. The test procedure was used to examine the relative performance of four different candidate shrouds



A Robotic System. Recoilless Rifles, Mounted on a HMMWV, Are Used to Launch Smart Projectiles at Targets That the System Acquires.

for the 120mm M256 cannon. To complement the experimental results, the BRL developed a mathematical model describing tube response to both external and internal heat transfer. The model explains the performance variations observed with different shroud concepts and has led to the design of a unique, integral thermal shroud which has been fabricated and currently awaits test."[5]

And a year later: "Finally, a new thermal shroud which compensates for external and internal heating asymmetries was designed this year, and four candidate shrouds were tested for the M256 cannon."[6]

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22. Draft of Combustion Research Program, 1 June 82.

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25. George Adams, "Vector Processor Produces Awards and BROOKLYN89," *BRL Update*, vol. 1, no. 3, May 1989.

26. Discussion with Bruce Burns on 29 June 1992 and subsequent corrections to a draft.

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LAUNCH AND FLIGHT

"The mission of the Launch and Flight Division (LFD) [was] to perform experimental, theoretical, and computational research in order to improve the basic technology relating to the aeroballistics of spinning and fin-stabilized projectiles. In addition, LFD [was] responsible for providing the Army with firing tables and aiming data for all its weapon systems."[1] The division was to:

"Plan, manage, and conduct studies of the flight mechanics and aerodynamics of projectiles and missiles from their launch through their flight phases in order to provide improved weapon-design technology. Mission responsibilities include the provision of necessary theoretical, computational, and experimental research in fluid dynamics, aerodynamics, and flight mechanics.

"Plan, manage, and conduct basic and applied theoretical, computational, and experimental investigations in the fields of aerodynamics, flight dynamics, projectile/payload interaction, and projectile environment. Develop on-board instrumentation for full-range testing of existing and proposed flight vehicles. Operate, maintain, and extend the development of large- and small-caliber aerodynamic range and flight-simulation test facilities. Develop techniques for modeling gun-launch muzzle blast and projectile disengagement effects on weapons systems. Develop computational modeling techniques to provide for prediction of complex flows such as projectiles with mass injection in the base region, high-supersonic velocity real-gas effects, stabilizing fins at high-supersonic velocities, and flight at large angles of attack.

"Provide firing tables and associated aiming data for all land-combat weapons such as mortars, small arms, tanks, and field and antiaircraft artillery. Develop rational bases for NATO and quadripartite standardization agreements (STANAGs) with reference to firing-table elements, theory, and applications. Provide information to U.S. forces relative to the interchangeability of NATO ammunition."[1]

Dr. Charles H. Murphy, Chief of LFD From 1970 to 1992, Received a Bachelor's Degree, Cum Laude, in Mathematics From Georgetown University and a Master's in Mathematics, a Master's in Engineering and Aeronautics, and a Doctorate in Aeronautics From JHU.

COMPUTATIONAL AERODYNAMICS[2]

There were some efforts in the BRL on CFD on the ENIAC in the 1950s. These were inviscid, supersonic calculations that were based on the characteristic equations. Much has happened since then.

The period covered by this volume has seen the realization of CFD techniques as practical tools for aerodynamic research and engineering in areas that involve viscous effects. Two related important events from about 1977 were the acquisition of the CYBER computer by the BRL and the emergence of the Cray supercomputers that were used by NASA, the

DOE laboratories, and others for continuum-mechanics calculations—technologies leveraged by the BRL.

Prior to 1978, inviscid codes with boundary-layer considerations were the usual thing.[3] "Initial computational efforts at the BRL started with two-dimensional turbulent-boundary-layer code development in 1970. The first efforts to predict the aerodynamic forces on projectiles [were] performed on contract with Professor Harry Dwyer at the University of California-Davis in 1971. The result of this contract yielded initial predictions of the Magnus force for laminar boundary layers on a spinning cone at supersonic velocity. The predictive technique consisted of merging solutions for three-dimensional inviscid flow and three-dimensional boundary-layer development. The predictive capability was enhanced through in-house efforts to include turbulent viscous effects for ogive-cylinder and ogive-cylinder-boat-tail shapes from 1973–1978."[1] "Satisfactory predictions for Magnus effects for turbulent boundary layers on ogive-cylinder shapes were achieved; however, similar predictions for boat-tailed shapes were unsatisfactory. The reason for the unsatisfactory results for boat-tailed shapes was believed to be a result of the significant flow-field expansion at the cylinder-boat-tail junction which was not modeled accurately by the coupled viscous-inviscid flow procedure."[4]

In the 1977–79 period, the first successful development of thin-layer implicit Navier-Stokes codes was accomplished by NASA. At the time, there was divided opinion over their practicality. Walt Sturek (Chief of the Computational Aerodynamics Branch) and Charles Nietubicz brought these codes into the BRL, which served as a beta test site for them. The BRL was the first agency in DOD to use the codes for application to ballistic problems.[3] "At this time, the thin-layer, Navier-Stokes codes developed by Steger, Pulliam, and Schiff of NASA/Ames became operational, and the emphasis of the research shifted to the application and development of these Navier-Stokes codes. The initial application and development of these codes to Army projectiles at the BRL [were] performed by Nietubicz. The Navier-Stokes codes have several advantages over the coupled-viscous-boundary-layer/inviscid code technique. These advantages are: (1) viscous/inviscid flow interaction computed in a conceptually exact manner; (2) generalized-geometry formulation for handling irregular shapes; (3) application for transonic and supersonic velocities. The codes currently in use have evolved from the Navier-Stokes codes acquired in 1978. Improvements have been made in the areas of numerical stability, robustness, and zonal topology; but the codes in use today are largely the same basic modeling concept as the initial Navier-Stokes codes."[1]

Now the ballisticians could attack the Magnus moment, which was fundamentally related to viscosity for realistic Army projectile shapes. This was specially important since numerical codes were the only way to go for general shapes. (Prior to the development of numerical modeling techniques, the Magnus effects were estimated by highly approximate methods for very simple shapes, and their subtle but important variations were not manageable.) Originally the two-dimensional axisymmetric codes were all that the BRL could handle for the transonic time-marching codes. Three-dimensional calculations were possible using the parabolized codes for supersonic flow.[3]

"It is convenient to classify the application of the computational technique on the basis of spin-stabilized projectiles and fin-stabilized projectiles."[1]

Spin-Stabilized Projectiles. "For spin-stabilized projectiles, the aerodynamic coefficients of greatest interest are pitching moment, Magnus moment, drag, and pitch damping. The capability at supersonic velocities is much advanced over that at transonic velocities due to the nature of supersonic flow which allows a marching technique to be used to predict the flow field. At supersonic velocities, a well-established predictive capability exists for small angles of attack. At transonic velocities, where the solution must be obtained through a computationally lengthy iterative process, the ability to predict the critical behavior of pitching moment just recently has been achieved. Further effort is required to verify the accuracy for the other coefficients."[1] The application of the time-marching Navier-Stokes codes to spin-stabilized projectile shapes at transonic velocities was spearheaded by Nietubicz and Jubaraj Sahu.[4]

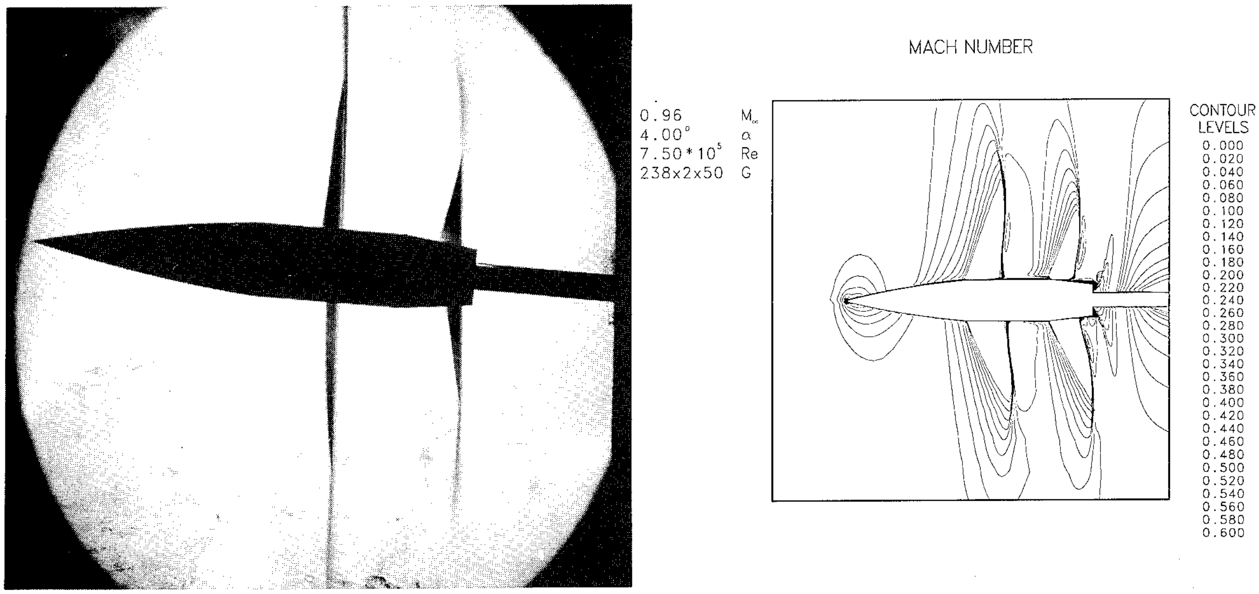
By 1980, we find encouraging reports: "Newly developed parabolized Navier-Stokes (PNS) computational techniques were applied to compute Magnus effects for boat-tailed shapes at supersonic velocities. Excellent agreement resulted between computations and experiments from Mach 2 to Mach 4."[5] The Navier-Stokes codes allowed the first satisfactory results for boat-tail shapes. "This was a truly exciting result."[3] These were limited to supersonic calculations since the time-marching codes were too much for the BRL's CYBER computer.

"These same techniques have been applied to transonic speeds to accurately predict surface pressures for bodies of revolution. Since critical aerodynamic behavior occurs at transonic speeds where complex shock-boundary-layer interaction effects dominate, the results are important for shell design. Three-dimensional finite-difference flow-field computational techniques have been used to generate a comprehensive parametric data base for ogive-cylinder shapes at supersonic velocities. Cones, secant-ogives, and tangent-ogives for projectile lengths up to seven calibers were included in the data base. Ten aerodynamic coefficients were tabulated and enable the computation of static, gyroscopic, and dynamic stability parameters. The results have been substantiated by wind-tunnel and free-flight-range experimental measurements."[5]

In a paper published in 1984, Sturek discusses predictions of the aerodynamics for the M549 shell using the thin-layer Navier-Stokes codes.[6] This includes: "... the flow about a spin-stabilized shell with rotating-band effects..."[7] The predictions compared favorably with experimental data from the wind tunnel at supersonic velocities, but the comparison was not favorable at transonic velocities.[6] This is the first of three efforts on the M549 that were made at 4-year intervals. As we shall see, things get better, and yet better. The M549 was a round for which there were a lot of data so it could be used to validate computational models at transonic velocities and to determine appropriate grid sizes. It was also a round for which the base flow was critical.[3]

Prior to the arrival of the supercomputers at the BRL (the Cray X-MP arrived in December 1986; the Cray-2 arrived in July 1987), the people in the branch were getting what time they could on NASA and National Aerodynamics Simulation supercomputers (and those at other sites). This use was important because the BRL's CYBER computer was saturated. Also, the experience allowed the newly arrived supercomputers to be instantly used very profitably.[3]

With the Cray-2, which has two-billion bytes of RAM memory, great things happened.[3] "[Prior to the arrival of the Cray-2], the full capability for predicting transonic aerodynamics about projectiles [had] not yet been reached. There exists a limited capability for predicting the total drag for [no yaw]. Viscous and pressure drag are well predicted [for no yaw]; however, the base-drag predictions are poor at low-transonic and subsonic speeds. Recent results for the pitch-plane aerodynamics show promise. A major limitation for the transonic calculations has been very limited machine memory. The availability of a Cray-2 with 256-million [8-byte] words should provide the required machine capability. A full three-dimensional grid, when made equivalent to a supersonic marching solution, would require



Transonic Critical Behavior
Experiment vs. Simulation.

40 million words of memory. This is well within the capacity of the Cray-2. Unfortunately the time required for these large grids is excessive. At present, three-dimensional calculations being run for code validation are taking up to 30 hours on the Cray-2. This is considered a significant problem due to the number of runs required for validation efforts."[8]

Work on the M549 appears again in 1988: "Computational results have successfully predicted the critical behavior of the static pitching moment for a secant-ogive-cylinder-boat-tail model and the M549 artillery-shell configuration."[9] "Navier-Stokes computations were performed for the M549 projectile configuration. The angle of attack was fixed at 2°, and results were obtained over the critical Mach-number range. ... The shock asymmetry ... has been correctly modeled. The comparison with experimental data is considered to be good. These calculations were performed on the Cray-2 computer at the BRL. Each calculation for a specific Mach number and angle of attack required approximately 20 million words of memory and 10 hours of computer time to achieve a converged solution. The results ... represent a historic first achievement for this highly complex flow-field modeling problem."[1] However, there still are problems: "Although the Navier-Stokes results do well at predicting the maximum [transonic] value of the pitching moment, ... the behavior on either side of the critical value does not follow the experiment."[8]

And finally in 1992, we have: "A further test of the validation accuracy [of the transonic calculations for spinning shell] can be established by predictions of fielded Army shell. A series of computations have been performed for the M549 configuration. ... The static aerodynamic coefficients have been obtained over the computed Mach-number range [0.7 to 1.5]. The critical aerodynamic behavior computed is in generally good agreement with the experimental data. At most, the discrepancy is 5–7%, which is within the experimental accuracy of the flight data in the transonic regime."[10]

The Magnus moment appears to be in hand also: "A pacing item in projectile aerodynamics has been the accurate determination of the Magnus effect on a spinning projectile at transonic speeds ... Computations using the F3D code were performed [by Sahu] for [a wind-tunnel model] at angles of attack of 0°, 4°, and 10°, and for spin rates of 0 and 4,900 rpm. ... The grid developed for this fully three-dimensional problem consisted of three zones and required 82 million words of memory. The run time for each case on the Cray-2 was approximately 80 hours. ... The results ... are shown to be in good agreement with the force-balance results."[10]

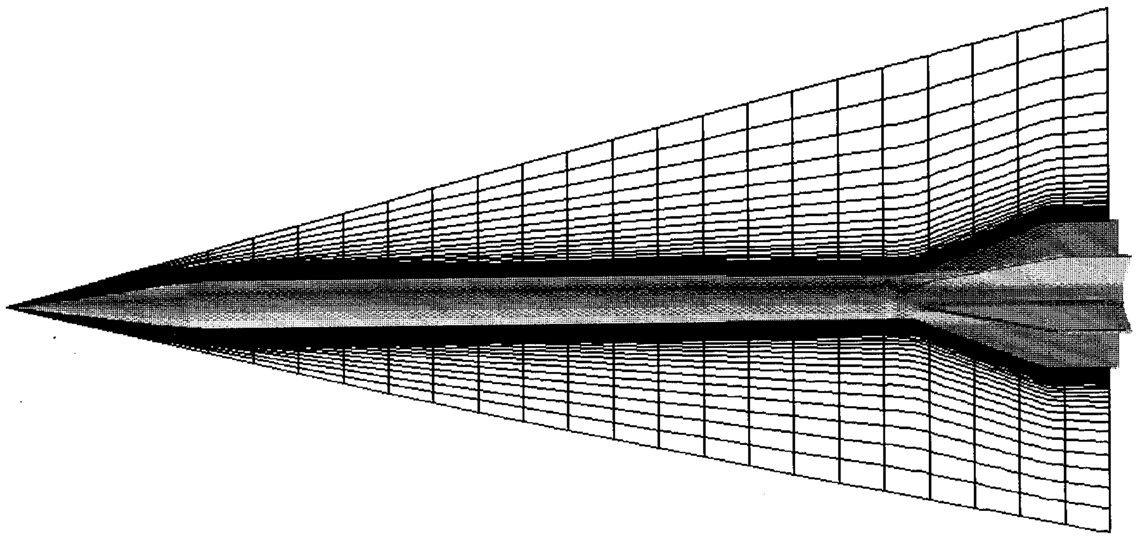
Circa 1984, Nietubicz and Karen Heavey developed "a computational capability for predicting both the external and internal flow fields for hollow projectile configurations."[11] Nisheeth Patel was successful in demonstrating a capability for predicting the flow in a solid-fuel RAMjet by applying a zonal code, and he achieved good results therefrom.[3] While the training-round application of the solid-fuel RAMjet was abandoned, the experience has implications for other applications such as the RAM accelerator.

Fin-Stabilized Projectiles. "For fin-stabilized projectiles, the space-marching technique is applied to KE-finned projectiles, and a highly sophisticated design capability is emerging. Recent progress has resulted in the ability to predict the steady-state roll rate and pitch damping of finned projectiles."[1] "The initial predictive capability for finned projectiles as implemented at the BRL was developed at NASA/Ames by M. M. Rai and D. Chaussee. This initial capability was extensively developed, refined, and applied to Army shell by Paul Weinacht."[4]

From 1980, we find: "An aerodynamic heating and ablation code (ASCC) was acquired under contract with Acurex/Aerotherm Corp. to predict unsteady heat conduction of artillery shell. This computation capability was successfully applied to predict nose-cap recession and in-depth heat conduction for several configurations of the XM797 training round."[5] "The M797 used a zinc nose cap that was to melt and permit the three segments of the round to fly apart and thus limit the lethal range of the round. This worked well at Yuma, AZ, but not at Fort Greeley, AK. The calculations helped diagnose the problem, and the concept was dropped as unsafe. The predictive capability for the in-depth thermal response of shell to aerodynamic heating has been continuously updated and refined. This capability is now being used for a variety of studies including: the heating of fins and nose caps for simulated launch at velocities up to Mach 12; the infrared (IR) signature of finned projectiles; and evaluation of materials for high-velocity projectiles for EM launchers."[4]

By 1984, the branch applied "three-dimensional computational techniques to spin and fin-stabilized projectiles to provide engineering design capability. ... [It also] completed aerodynamic heating code to model thin, swept fins, and multimaterial bodies."[7] The heating code was applied to the M774 KE round to define the sweep angle of the fins.[3]

About this time, the KE projectiles became quite important. The analysis of these was particularly suited to the parabolized code since they involved supersonic flight, low angles of attack, and thin fins. These codes were used by Weinacht and Guidos to analyze the M735, M829, and M900, etc., series.[3] "The PNS technique is being applied to compute the aerodynamics of KE projectiles. The PNS technique is suited ideally for the flight regime of these projectiles—supersonic flow and low angles of attack. The PNS technique allows the flow to be computed in a single sweep through the computational grid (from nose to tail) and, consequently, is very efficient. A typical computation for a KE projectile requires between 1 to 2 hours on a Cray X-MP or Cray-2 supercomputer. These computational times have allowed the PNS technique to be applied



Computational Grid for the M829 Projectile.

to advanced KE projectiles currently under development."[1]

Spin effects were of particular interest in these calculations: "A [finned] projectile must have a certain amount of spin to achieve accuracy but not so much as to have structural problems. The computational capability to predict the roll characteristics of KE-finned projectiles was developed this fiscal year [1987], which includes three-dimensional and viscous effects. This capability provides aerodynamic performance information which cannot be easily obtained in firing tests while the projectile is still in the concept stage prior to fabrication. ..."[12]

In 1988, aerodynamic heating is again of interest: "Fin integrity on KE antitank projectiles is a vital factor in flight stability, accuracy, and hit probability. Unfortunately, KE penetrator fins degrade in performance due to melting induced by in-bore and aerodynamic heating. A new simulation [developed by Dwyer and Sturek], featuring three-dimensional fin geometry and a quasi-three-dimensional, two-phase modeling of a melting fin, has been used to evaluate new fin designs with protective coatings."[9] This was an extension of earlier work on heating with the addition of in-bore effects and of protective coatings on the fins.[3]

"The use of supercomputers combined with numerical techniques for solving Navier-Stokes equations has provided the ability to accurately predict projectile aerodynamics and provide insight into the associated fluid dynamics, especially in the new frontier of hypervelocity flight as promised by the new liquid and electric propulsion systems. Computational results have been obtained [by Sahu and Nietubicz] for segmented KE penetrators exiting a parent projectile flying at Mach 4.4. The computed flow field has been integrated to determine the aerodynamic forces acting on the parent projectile and the trailing segments. Various configurations of the parent projectile were computationally studied [by Weinacht] to provide the optimum aerodynamic behavior. Trajectory simulations using the computed aerodynamics were then conducted. These data provide valuable design guidance and will be used to help design aerodynamic range tests for these projectiles."[13] This computational aerodynamics study was DARPA sponsored. There is no way to get experimental data on these phenomena; CFD is the only way.[3]

Finally, by adding Coriolis and centrifugal forces into the Navier-Stokes modeling, the ability to predict the pitch damping of shell from a steady coning motion was achieved. This significant new capability was developed by Sturek and Weinacht in collaboration with Lewis Schiff of NASA/Ames. The pitch damping is very important for long rod penetrators, since this parameter is not at all easy to measure in the spark ranges. (The bullets are so heavy that the forces are slow acting.) Magnus effects are not very important for the slow spin of KE rounds.[3]

"The stabilizing fins for [long, thin] KE penetrator projectiles are made of aluminum alloy. Since the melting temperature of aluminum is approximately 960 K, these fins are vulnerable to the effects of in-bore and aerodynamic heating. No direct experimental measurements of the heating rates or temperature response of these fins are available due to the difficult environment and thin geometry of the fins. However, qualitative visual and photographic observations during flight tests, which reveal structural deficiencies such as altered planform shape and *burning* of the fins, are available to indicate that melt temperatures [are] reached for these fins.

"Several studies to model the in-bore and free-flight aerodynamic heating for these fins have been performed. A recent study ... reports results in which a newly developed finite-volume heat-conduction code was utilized to predict the benefit of protective coating materials for fins. The computations included the effective retardation of the projectile in flight through time-dependent boundary conditions for convective heat transfer and recovery temperature based on the known flight trajectory."[10]

The following paragraphs from a 1992 paper summarize the state of affairs for the KE rounds: "The M735 and M829 are long-L/D, high-velocity projectiles for which extensive aerodynamics-range test data are available for comparison with computational results. ... Computational results for pitching-moment coefficient ... show the same trend with Mach number as the experimental data; however, the computed results are consistently higher, by about 5%, than the experimental data. ... The capability to predict [roll damping and pitch damping] is permitted through the incorporation of the effects of centrifugal and Coriolis force into the PNS computational code. ... In general, the computed [roll results] pass through the scatter in the experimental data. These coefficients were obtained with considerable difficulty in free-flight range tests. Thus it is of particular interest to have a predictive capability." The comparison of pitch damping results were not very conclusive; the experimental data were poorly determined.[10]

Base Effects. In 1986, we find the beginning of a sequence of calculations of the effects of modified base configurations: "Recent firing tests of the M483 projectile fitted with a modified base configuration indicated that the modified base significantly affected the drag of the projectile. This modified base configuration, called a domed base, was installed on the projectile as a product improvement to provide better structural performance. The BRL initiated a computational study to determine if the geometry of the base region was the cause of the observed change in drag. A series of computations was performed [by Sahu and Nietubicz] using the BRL axisymmetric

Navier-Stokes base-flow code and using one of the NASA/Ames's Cray supercomputers. The results verified not only that the modified base geometry affected the total drag of the projectile but also that the magnitude of the predicted change was nearly the same as that measured in the firing tests. These results were significant in that a sophisticated computational predictive capability was applied to a development problem and results were achieved in a timely fashion to verify an unexpected experimental observation."[14]

The majority of previous base-flow computations and analytical studies considered the base of a projectile to be a flat surface. However, general opinion was to the contrary: "Range firings of the M825 and computations for the M864, both of which have base cavities, provided evidence that the base configuration can indeed affect the base flow and, in turn, have a significant affect of the aerodynamics."[10]

The M864 and M825 both had similar problems. These artillery rounds had recessed bases which were modified for ease of manufacture. In both cases, the modified rounds showed different ranges than the original rounds. Nietubicz and Sahu pursued this problem. The generation of the computational grid for the highly irregular base cavity proved to be a significant challenge. After a year experimenting with grids, they were able to show that drag and lift did change with the change in design and that these changes were consistent with the range data. It took approximately 2 years to complete the project; the drag was done first with the axisymmetric code, then lift was done in three dimensions. Both transonic flight and supersonic flight were considered.[3]

In 1987, we find: "... the capability to numerically predict the effect of highly irregular projectile-base configurations on the aerodynamic drag was successfully demonstrated this year. The predictions confirmed an experimental observation that was previously unexplained."[12] This was for the axisymmetric calculations for the M825 and M864.[3]

And in 1988, they were able to report: "Three-dimensional models of irregular base configurations have been favorably compared with experimental flight data."[9] This was for the three-dimensional calculations for the M825.[3]

"The M825 projectile has an aluminum/ steel base which is configured as a flat (standard) cavity. A recent PIP, undertaken to reduce production costs and improve shell integrity, resulted in the design of a new base configuration made from steel and containing a dome cavity. Range firings of the new dome configuration indicated small but identifiable differences in flight performance. A computational study has been undertaken to predict the differences in the aerodynamic coefficient data and to further understand the fluid dynamic mechanism responsible for such behavior."[1]

"Computations were made for two versions of the M825's base configuration and were in agreement with experimentally observed differences in aerodynamics. An evaluation of the computational velocity vectors indicated that the changes were due in part to a displacement of the shear layer near the base corner of the standard configuration, which weakened the expansion at the base corner."[10]

The flare-stabilized, tank-training round, M865, had a problem in that its tracer was not visible for the full range of interest. "In an effort to uncover a cause for this unsatisfactory performance, a computational study was carried out in which the pressure distribution in the wake of the projectile was computed. ... An analysis of the base-flow results [by Sahu] indicated the presence of a pressure spike located along the axis near the base of the projectile. ... The rapid pressure change [at about Mach 3.0] was considered as a potential reason for the premature tracer burnout. ... In an attempt to reduce or eliminate this problem, a modified cavity design was proposed, and computations were performed. ... The comparison between the original and modified configurations shows that the original pressure spike has been reduced."[10]

Base bleed became interesting and could be addressed—in fact, in general, base bleed, rocket assist, transonic aerodynamics at angle of attack, all could now be attacked.[3] "The development and application of Navier-Stokes computational techniques have had a significant impact in determining projectile aerodynamics. Of particular importance is the determination of the pressure, viscous, and base drag components. These components form the total aerodynamic drag of a projectile. Initial applications of the Navier-Stokes base-flow code have modeled the projectile base as a flat, solid surface. Recent projectile designs have begun to include two major changes: (1) an irregular or dome base surface and (2) the addition of base bleed and base burn. These additions required an extension to the existing Navier-Stokes codes to include these effects. The developmental effort [by Nietubicz, Sahu, Danberg, and Heavey] has continued to include hot mass addition."[1]

CFD had gone from *gee-whiz* to a serious tool that can provide customer support with analysis of experimental results and detailed results suitable for design, etc. (e.g., Danberg's work on base bleed[15,16] that coupled aerodynamic data for angles of attack and Mach number with the simulation of flight and described total system performance).[3]

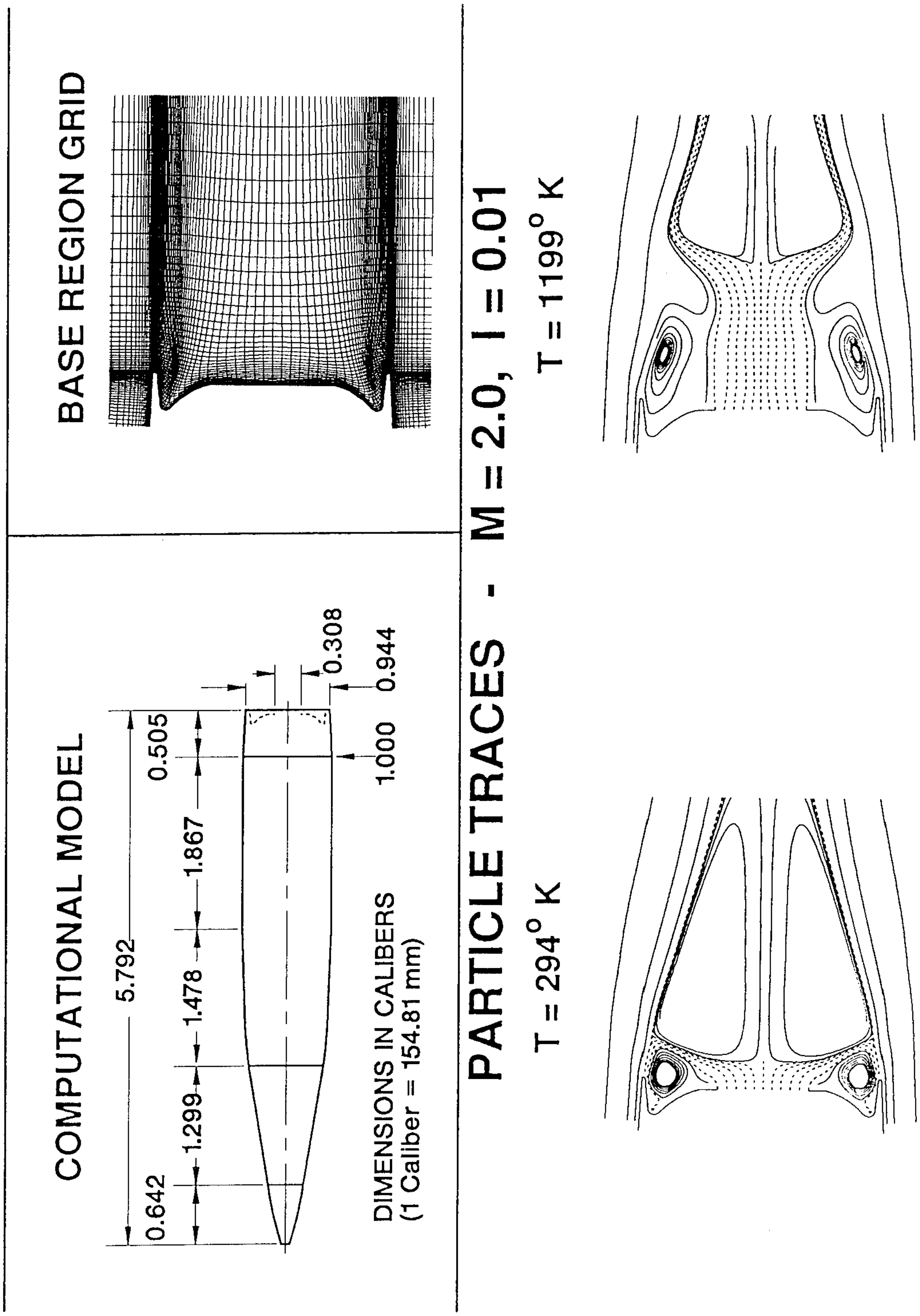
Some Final Thoughts. In the last 4 years or so, CFD has received considerable customer interest. It has allowed such diverse things as the design of base bleed and the analysis of the flight of segmented penetrators. Such things are becoming routine.[3]

But technology marches on as does the demand for more complete representations. One area of considerable promise is that of massively parallel computers.

From 1990, we have: "The BRL and the Army High-Performance Computational Research Center (AHPCRC) personnel collaborated on a project to convert a serial two-dimensional Eulerian code into a version that would run on a massively parallel processor (MPP), specifically the 64,000-processor CM-2 at the University of Minnesota. Scientific visualization techniques were used to render the CFD results from that code into a dynamic simulation that has proved very useful to aerodynamicists and to fluid-flow researchers."[13] With regard to the AHPCRC MPP results, Patel had the M549 code running in a month on the CM-2 connection machine.[3]

MPP studies continued in 1991: "The BRL worked closely with AHPCRC to include implementation of CFD computations on the CM-2 and CM-5 investigating problems in domain decomposition and scalable massively parallel processing on single-instruction/multiple-data stream (SIMD) and multiple-instruction/multiple-data stream (MIMD) architectures."[17] Also, "as a part of a DARPA research program, an eight-node Touchstone iPSC 860 was acquired for the BRL. Projects involving penetration mechanics, CFD, and computational EMs are currently underway with the California Institute of Technology."[17]

With regard to scientific visualization: "The BRL designed, acquired, and installed both classified and unclassified visualization facilities and initiated (with various degrees of completion) numerous projects for exploiting scientific visualization for major computational research projects in ballistic phenomena."[17] Visualization techniques for CFD include the following:



M864 Base Bleed.

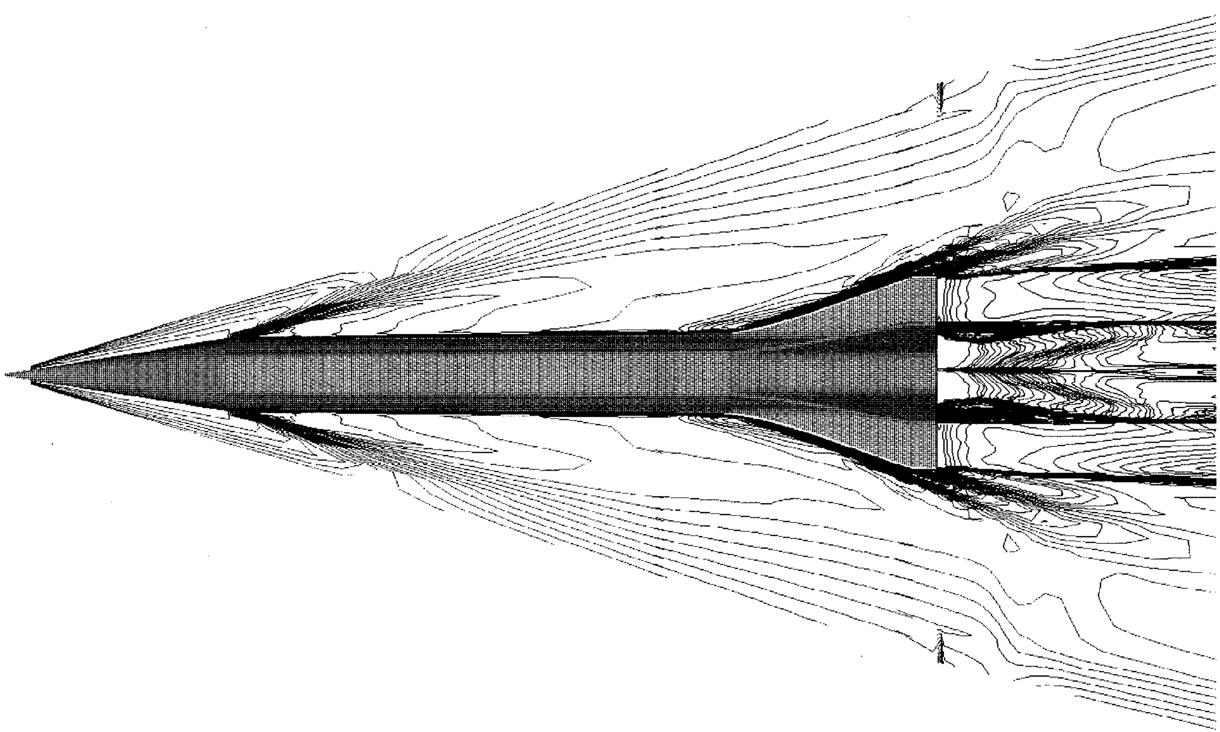
"Besides providing aerodynamic coefficients, the computational approach allows the projectile designer to examine details within the flow field. ... Each particle represents the path followed by a particle as it travels through the flow field."[1]

Flow-field visualization techniques using density contours were also developed. In this case, the density of the fluid is represented by the local intensity of the plot (in somewhat the same way as a Schlieren photograph records the gradient of density).[1]

EXPERIMENTAL AEROBALLISTICS

Experimental aeroballistics is largely the purview of the Free-Flight Aerodynamics Branch (FFAB). The FFAB derived its name from the Free-Flight Aerodynamics Ranges, which were developed early in the history of the BRL.[18] These ranges, especially the large Transonic Range, have remained a major source of flight data on a wide variety of objects (models of aircraft, high-performance KE projectiles, shell for atomic cannon, models of reentry vehicles, etc.). The basic simplicity, versatility, and precision of this facility have made it a valuable tool for over four decades.

On 21 October 1982, the BRL's Aerodynamics Range in Building 328 was declared a *National Historic Mechanical Engineering Landmark* by the American Society of Mechanical Engineers. "During the 1930s, research into advanced ballistic measurement techniques was begun at APG. Before the German Army entered Poland, exceptional data on the flight of projectiles were being provided. The crisis of World War II gave incentive to



Flow-Field Visualization Using Density Contours.

incorporate this pioneering research into the design and construction of the Aerodynamics Range at the BRL. The facility was unique for its time and established the capability to study, in detail, the aerodynamics of bodies in supersonic free flight. The sequential, high-speed photographic instrumentation in the range has recorded the flight of projectiles, missiles, and aircraft important to the national defense. Personnel, working in this original installation, have contributed to technical disciplines ranging from photography and high-speed circuit design to the theory of flight. The range is recognized as the prototype for similar installations in the United States and abroad."[19]

In this volume, we shall concentrate more on newer on-board instrumentation that allows measurement of details of the performance of a round in its full-scale flight and on a facility that allows a round to be subjected to rigid-body trajectory motions in the laboratory.

However, we first note that the branch maintains a considerable capability to produce high-velocity firings to support the development of KE rounds for tank guns. The 7-in High-Altitude Research Project (HARP) gun is still healthy and is the centerpiece of this capability.[20] All rods in the BRL's KE developments have been tested there first. The gun is very flexible with respect to charge design. "Just move the bullet forward a bit and add more powder."[21] The 7-in HARP Gun is a smooth-bore gun that features projectile travel of up to 600 in, a maximum chamber pressure of 70 ksi, and chamber volumes of 2,271 in^3 or more. In addition to firing more conventional KE projectiles at their usual velocities, the gun has achieved higher performance such as launching a 5-kg slug at 2,880 m/s.[22]

There is also an extended 120mm gun that can fire production rounds at higher velocities with its very long barrel. This, in addition to preheating the charge to the maximum operating pressure, can add 100 m/s or so to the muzzle velocity.[21]

Liquid-Filled Shell. Bill D'Amico, the Chief of FFAB, quipped that his "career has been wrapped up with support of the Chemical Center at Edgewood."[21]

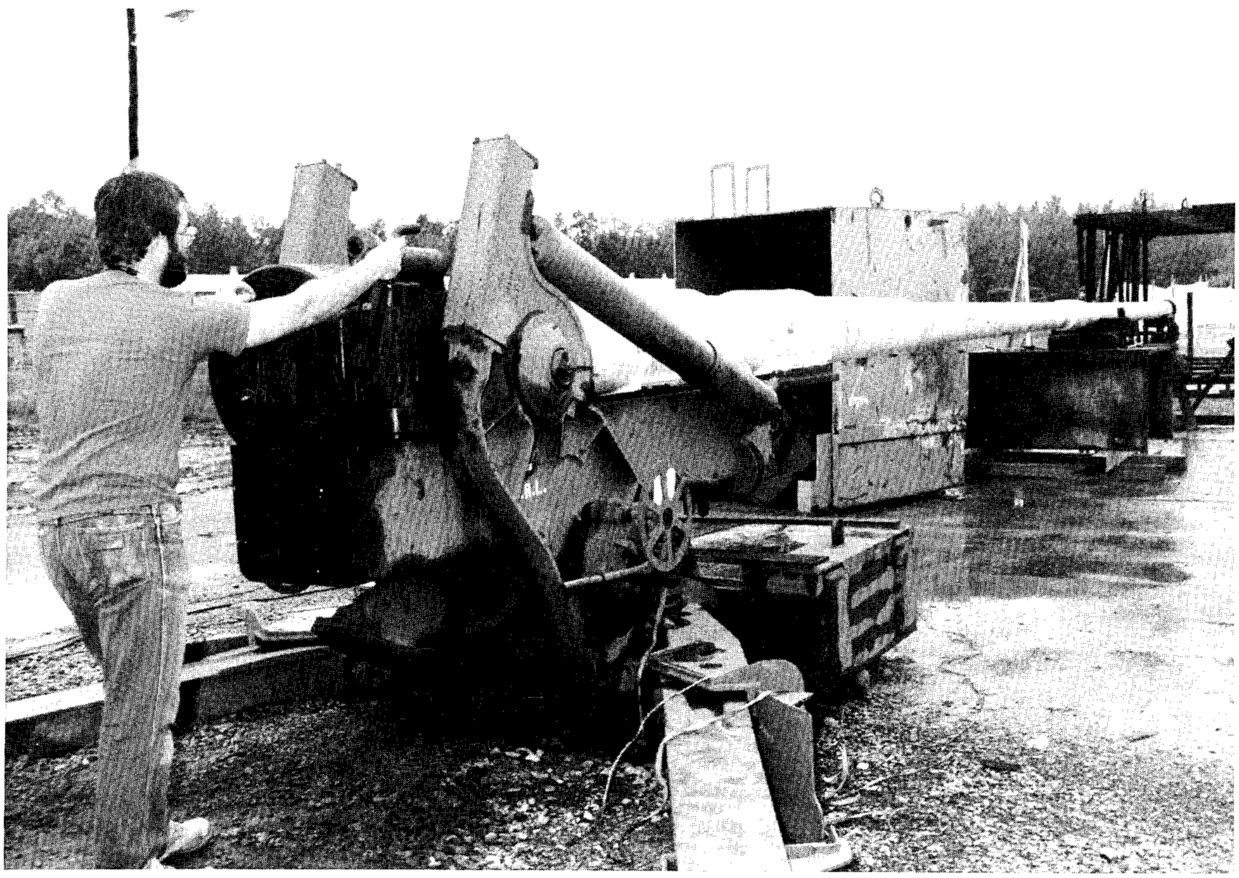
This started in about 1968 with the binary chemical round. In this concept, two non-toxic liquids are stored in separate compartments. Upon the set-back of launch, a disc that separates the liquids is ruptured, and the spin of the round causes mixing.

Bill Dee from Edgewood called D'Amico and John Frasier to describe binary concept. He wanted to make the round simple to understand and design. They suggested using right-circular cylinders for the compartments, and that configuration was adopted.

The resulting system provided the first test of theory in artillery-caliber hardware. In particular, Edgewood wanted to change the wall thickness of a plastic insert, and the BRL's analysis said that the suggested size would not work. Edgewood tried it anyway, and the round proved unstable.[21]

Circa 1970, Edgewood wanted to fill the M483 ICM round with its material. That round already had a nascent stability problem—the boat tail was too long, but the problem only showed up under extreme conditions of high atmospheric density such as in tests at Nicolet in Canada. The binary application exacerbated the problem and made the BRL consider both the aerodynamic and internal dynamic problems together.[21]

Things came to a head around 1971 when sheep were killed in Skull Valley, UT. This put an end to open-air testing of rounds with the actual materials; so Edgewood created simulants which required considerable testing to demonstrate their efficacy. Here the BRL's ability to do on-board testing became



7-in HARP Gun Used for Experimental Firings.

invaluable. A number of properties of the surrogate materials were important—both chemical properties (e.g., temperature after reaction) and mechanical properties associated with stability. The BRL was able to show through flight tests that even the chemical results from paddle wheels in beakers were not representative of full-scale conditions in the pressure confinement of the round.[21]

The M825 smoke projectile posed a similar but new set of problems. To create a round that would put white-phosphorous (WP) smoke on the ground rather than high in the air, the designers replaced bulk-loaded WP with wicks that were essentially 6-in strips of patio wick impregnated with WP. This turned out to be a very difficult material to analyze, which was dubbed a fourth state of matter by frustrated analysts. At this time, the nuclear round's problems were taking a lot of attention, but, from that analysis, Murphy noted what appeared to be a general relation between the destabilizing moment and the despinning moment.[23] With some assumptions as to the validity of the large-yaw motion as a representative of small-yaw motion, this allows a powerful diagnostic tool in which one induces coning motion at a large angle in a laboratory fixture and relates the measured despinning moment with the desired destabilizing moment. Miles Miller at Edgewood has taken up this tool and exploited it to great success.[21]

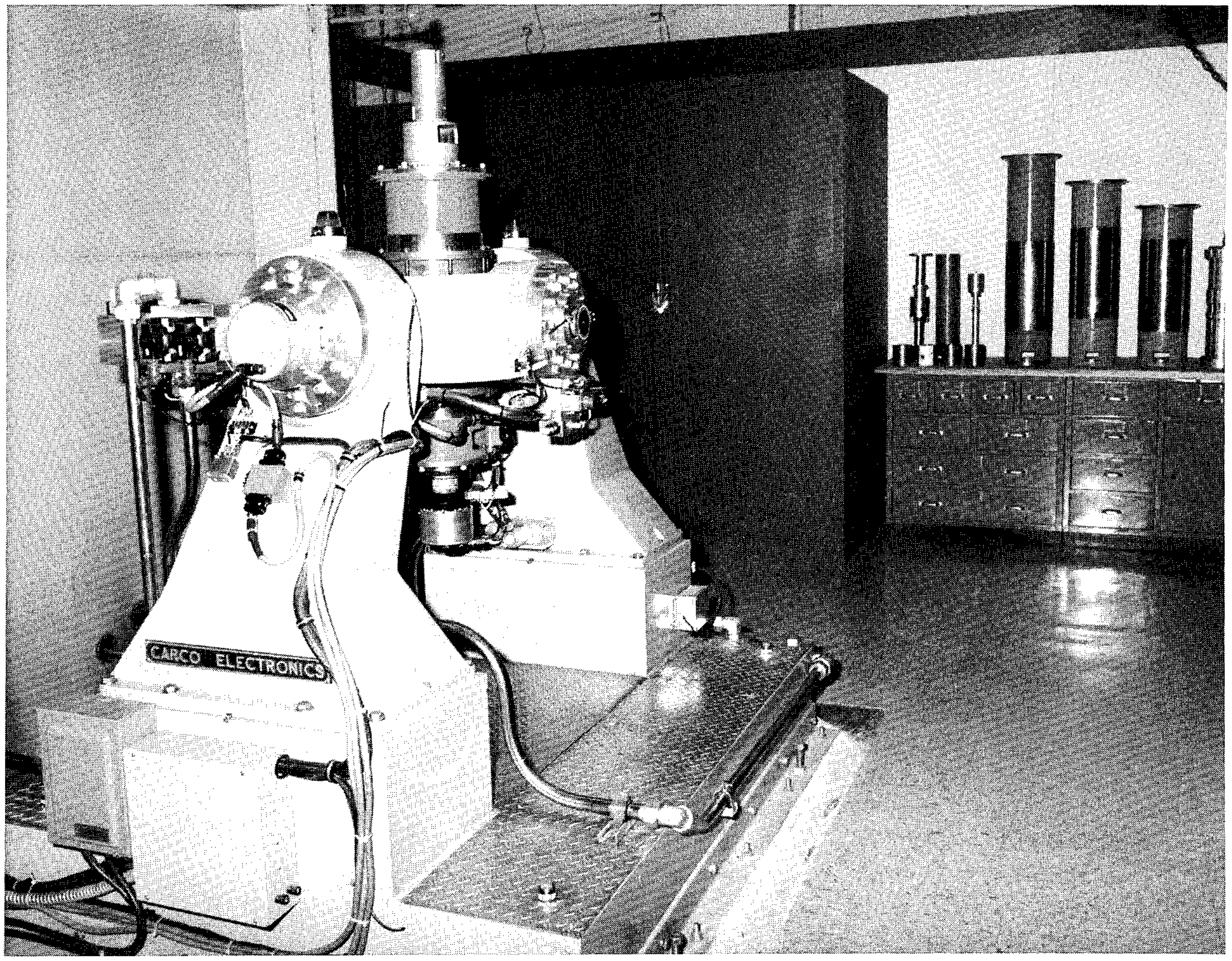
After the experiences with the two major problems of binary and WP-wick rounds, there was a clear realization that the predictive capability was not all that could be desired. Early in the 1980s, it was clear that something better was needed (i.e., an ability to measure the yaw moments at small angles or despin moments at large angles). There was a need for a spinning test fixture with the equivalent of a wind-tunnel balance that could measure the small moments and a fixture that was computer controlled. The latter would help "looking for a needle in a haystack" by allowing the running of a matrix of tests to cover all the conditions of interest. Such a facility would allow the evaluation of payload concepts and would help avoid premature firing of flight hardware until a suitable design appeared to be in hand.[21]

The big-gyro fixture was installed in the early 1980s. In its original version, it could make important measurements (e.g., internal pressures), but the instrumentation was inadequate to make the measurement of the small forces of interest for detecting instability in the rotating environment.[21] We find the facility being utilized in the late 1980s.

"A flight simulator capable of realistic motions for spin-stabilized projectiles was built for the BRL. A 6-HP DC motor provides continuous roll rates in excess of 200 rev/s for payloads as large as 50 kg. The motor is located at the bottom of a long cylindrical tube (the roll-support tube) that is held upright within a conventional gimbal system. A slip ring located at the top of the roll-support tube provides an electrical path for power and data signals to transducers and parts that are on the spinning frame. The payload section utilizes pressure or temperature transducers and accelerometers. Pitch and yaw gimbals are driven hydraulically and have a frequency response of nearly 25 Hz. The orientation and position of all axes are monitored by optical encoders. [A PC with an analog-to-digital board provides analog] signals to drive the gimbals."[1]

"Liquid-filled shell theoretical research provided a firm basis for the calculations of the frequency and damping of inertial waves within a rotating fluid. These waves, in resonance with the shell nutational frequency, account for shell instability. The calculations were validated by a reliable numerical experiment that solved the Navier-Stokes equations. For Reynolds numbers greater than 10,000, the theoretical frequency and damping agree with experimental results to within 2% and 6%, respectively. The numerical experiment data were analyzed using Fourier-transform and digital-filter techniques. The techniques failed at Reynolds numbers of the order of 100, implying that inertial waves do not exist at this low Reynolds number. A method for preprocessing the data was developed and showed that the waves do exist and that the failure was caused by large damping in the waves. Linear theory was used to calculate liquid moments and yaw-growth rates. For solid-body rotation, the Stewartson- Wedemeyer theory succeeds at Reynolds numbers greater than 10,000. Recent gyroscope experiments show a departure of theory from data as Reynolds number decreases: about 100% at Reynolds number of 2,500. The theory was modified to give much better agreement.

"Flight experiments with projectiles carrying viscous-liquid payloads have shown that instabilities marked by rapid yaw growth and spin decay occur under certain conditions. Laboratory experiments with viscous liquids have produced yaw-growth rate measurements. Cylinder aspect ratio, liquid kinematic viscosity, rotation rate, and coning frequency were varied for fully spun-up cylinders with liquids of varying viscosities. The experimental results showed a linear growth in the logarithmic amplitude of motion for precession angles less than 5°. The growth rates varied with the coning frequency of the liquid-solid parts. The The faster the coning motion, the larger the yaw moment. The strongest correlation for amplitude growth rate was the product of Reynolds number and coning frequency. These



The BRL's Large-Gyro Facility.

experimental results for viscous liquids are not consistent with the Stewartson model and require the development of a new theory."[5]

Circa 1988, Hepner developed the necessary instrumentation that allows the moments to be measured in the laboratory under small yaw conditions.[21]

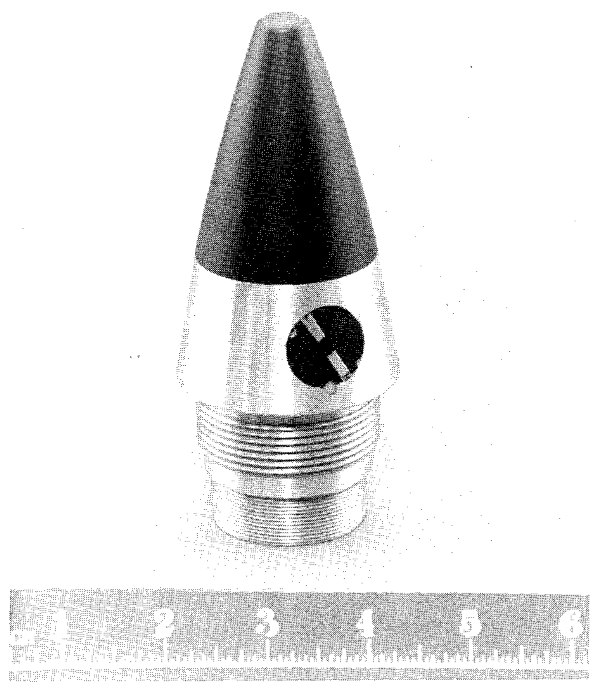
"Modern projectiles do not simply carry bulk-loaded HE. Most carry ICMs such as antipersonnel grenades or antitank mines. These payloads normally are ejected from the base of the projectile over the target area by the fuze/expulsion system. Note that the shell is not exploded. The payloads must be properly keyed to minimize internal payload motions that would be stimulated by the high spin and yaw rates. Also, the sub-munitions cannot be so securely fitted that ejection is impossible or results in damage to the payload. Small amplitude residual payload motions will follow the external yawing motion, but they must be in phase or destabilizing moments will occur. This problem also applies to binary and smoke/ obscurant payloads that typically are liquid. Proper design of these non-rigid payloads is best accomplished using a flight simulator to produce free-flight spin rates and yawing motion in the laboratory under controlled conditions.

"One of the most important primary variables producing destabilizing liquid moments is the liquid pressure. The flight simulator has been used to measure both the amplitude and phase of the pressure. Most theories that predict liquid moment coefficients are linear in nature and apply only at small angles of attack. Hence, one of the important features of experiments is to identify non-linear effects. Another important variable is the Reynolds number, which is the ratio of the centrifugal forces to the viscous forces. This definition is different slightly for pipe flow since the important velocity is the radial velocity, but the basic concepts of boundary layers still apply to rotating liquid flows. However, flight instabilities have been demonstrated over a wide range of Reynolds numbers. For very high Reynolds numbers (>5,000), the response of the pressure (and the liquid moment) has the shape of a *resonance* curve. For lower values of Reynolds number, the response curve is broadened by viscosity such that sharp peaks do not occur, but the magnitude of the destabilizing moments is still dangerously high."[1]

On-Board Instrumentation. Wally Clay, the head of the electronics team, is the quiet guy in the background who has done much of the on-board instrumentation work.[21]

FFAB has done a variety of special in-flight instrumentation tasks. The following from 1980 is typical: "An in-flight instrument to measure fuze-function sequences and times has been developed and applied to specific weapons systems. The instrument uses a strain-gage bridge mounted on the windscreen of the fuze or the projectile ogive. The bridge output is telemetered from projectile to ground; a high-gain amplifier enhances the minute signals. Flight data were obtained from tests of four mechanical time fuzes. The data showed fuze clock rates, fuze events, and the times at which events occurred, thus providing the first such information obtained in flight. Three of the four fuzes flown proved to be probable duds, and further tests are planned."[5]

The workhorse is a BRL fuze-configured yawsonde that has been in use for about 20 years. About 2,700 items have been fired by FFAB alone. The constancy of the yawsonde has allowed FFAB to be unique in the area of high-g instrumentation. Most of the work had been done in artillery rounds where there was lots of space (even in the fuze).[21]



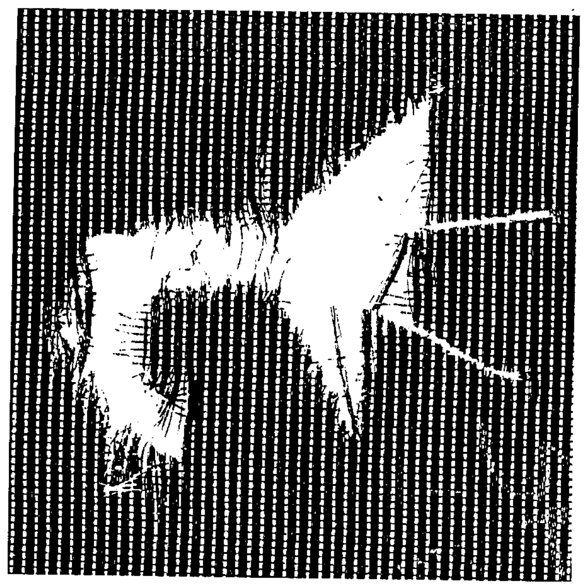
The BRL Fuze-Configured Yawsonde.

"In the past when a projectile was ready for full range testing, a number of projectiles (normally five to a group) were fired, and impact points and times-of-flight were recorded by observers. If a projectile experienced poor flight performance, little was known except that it did not land where the other projectiles impacted. Cameras at the gun insured projectile integrity, but no details were available. Additionally, projectiles not landing in the expected impact area often were not found. Radar instrumentation also has been used during full-range tests. While a radar is designed to measure the trajectory or projectile velocity (and spin can be obtained by special post processing), details of the yawing motion were not available.

"A fuze-configured yawsonde has been designed to measure the yawing motion along the entire trajectory. The yawsonde has two solar cells that are specially masked and oriented to generate a pulse when an *eyeball* is directly aligned with the sun. The phase relation between the time at which one eyeball sees the sun and when the other eyeball sees the sun can be obtained through a static yaw calibration on an optical bench. The roll period of the projectile is the time between pulses from a single eyeball. The yawsonde ... has been developed over the years by engineers at the BRL. Approximately 200 yawsondes [have been] built and tested for various customers by the BRL each year. The yawsonde contains the necessary electronics for obtaining sharp pulses when sunlight illuminates the solar sensors and a telemetry system (battery, transmitter, sub-carrier oscillator, and antenna). No modifications are required of the projectile. The yawsonde simply replaces the standard fuze. The BRL engineers also are responsible for the set up and operation of a ground receiving station for the yawsonde tests. Normally, analog data are recorded and returned to the laboratory for processing and plotting. However, the BRL engineers do have a field processor that is quite efficient, and they are often requested to produce real-time data reductions in the field."[1]

"Generally, a yawsonde requires at least two sensors and a fixture that defines an optical field of view for each sensor. A sensor generates a voltage pulse every time it sees the sun. The signals from both sensors are conditioned, combined, and transmitted to a ground receiving station by a telemeter on the projectile. ... The yawsonde requires that the projectile be spinning in order to measure the solar aspect angle. Since the yawsonde uses the sun and the spin rate of the projectile as a sampling mechanism, the spin rate should be at least 10 times the maximum yaw frequency in order to resolve yaw amplitudes."[24]

Circa 1987, people noticed spin/bending-moment interactions in KE rounds. The variations of the aerodynamic moment with its four-fold symmetry were adequate to interact with the natural bending motion of the long, slender rods to produce truly catastrophic deformations of the round. No one was developing instrumentation to provide good experimental data (other than pictures of the catastrophes). By 1990, Clay and Burdeshaw demonstrated that a complete telemetry system could be placed in the tracer well of a KE round, and spin data became available.[21]



Hole Made by a Deformed KE Projectile. A Damaged Fin Caused Loss of Roll Control.

"There are advanced munitions being developed that could benefit from a yawsonde measurement system on-board to aid in testing during their development cycle. These include HEAT rounds and KE projectiles; KE projectiles are usually long, slender, solid rounds with very small space available for instrumentation. The ... yawsondes ... are too large to use in some advanced munitions. In some cases, the spin-to-yaw rate ratio (steady state) of the projectile is less than 10; so in order to sample the yaw properly, multiple yawsondes must be installed. This compounds the lack of space problem. For this reason, the basic pinhole yawsonde concept was investigated and modified to develop a miniature multiple-sensor pinhole yawsonde that can be used to investigate the yawing and spinning motion of a variety of advanced munition projectiles."[24]

Yawsondes with 3/4-in diameters by 3/4-in lengths that can be stacked in a KE rod or in the probe of a HEAT round to allow measurements at low spin rates have been developed.[21] For example, a four-sensor configuration can provide the resolution needed for measuring the yaw of projectiles with spin-to-yaw rates of 2.5 or more.[24]

Base Bleed. "Development of extended-range artillery systems has been invigorated recently with the introduction of base-burn projectiles. The BRL is deeply involved in the theoretical modeling for these projectiles and the very important associated experimental work.

"When analyzing the drag, or decelerating force, on a projectile in flight, engineers commonly separate it into components. Of these components, base drag frequently accounts for more than one-half of the total. Base drag results from the low pressure associated with the projectile's wake. One method of reducing base drag, and thus extending projectile range, is to raise the pressure in the wake. In the 155mm M864 base-burn projectile, the pressure is increased by the gas from the burning of solid propellant.

"The solid propellant is burned in a chamber located at the base of the projectile. ... The resulting gas is injected into the wake through a hole in the chamber. Although the mass flow (i.e., the amount of gas injected per second) for this powered projectile is much less than that of the conventional rocket-assisted projectile, the effect on range is quite significant, specifically an increase of 25%.

"While the 155mm M864 round uses base-burn successfully for extending its range, the current design was obtained through a *cut and try* method—it was not optimized. Optimization of the design is difficult because there are no complete analytical or numerical models for base-burn systems.

"In an effort to improve the base-burn theoretical models, and then improve current system performance, the BRL has developed a comprehensive experimental and computational program. This program includes CFD studies using state-of-the-art techniques and Cray computers, ground tests of the solid propellant to determine effects of projectile spin and altitude, and radar analysis of the projectile in flight.

"The most substantial benefit to the program, however, would come from in-flight base pressure measurements. This was a very challenging task because non-intrusive, in-flight base pressure measurements had never been made on an actual projectile configuration.

An instrumentation system "was contained in the body of an M864 projectile. Four measurements of pressure were made ... two on the projectile base, one in the propellant chamber, and one on the projectile ogive. Temperature was measured in the propellant chamber, ... and projectile yaw was measured with yawsondes. ... All the measurements were telemetered, via the transmitter, back to a ground receiving station."[25]

The work by Kayser in designing the onboard instrumentation was truly exceptional. He overcame great difficulties in making pressure measurements in an extreme centrifugal field. (It was also necessary to withstand launch pressures.) The temperature measurement was tricky because the sensor can produce extraneous effects due to conduction. However, those temperature measurements were critical since chamber temperature has a profound effect on the drag-reducing performance and is critical to the analysis.[21]

"In order to make pressure measurements in the propellant chamber and at the projectile base, holes of 2.0-mm diameters were drilled in the walls of a standard M864 projectile base assembly, forming paths for pressure in one location to be sensed at another location. ... Each path was made in several segments by drilling holes with split-point drills; sections of the holes were then plugged by welding to provide a leak-free path from the orifice to the transducer.

"Since the base assembly had two halves, it was necessary to form a leak-free path across their threaded joint through careful alignment of the holes and the use of small O-ring seals. The alignment was secured by placing three set screws through the threaded section at circumferential positions between the pressure paths.

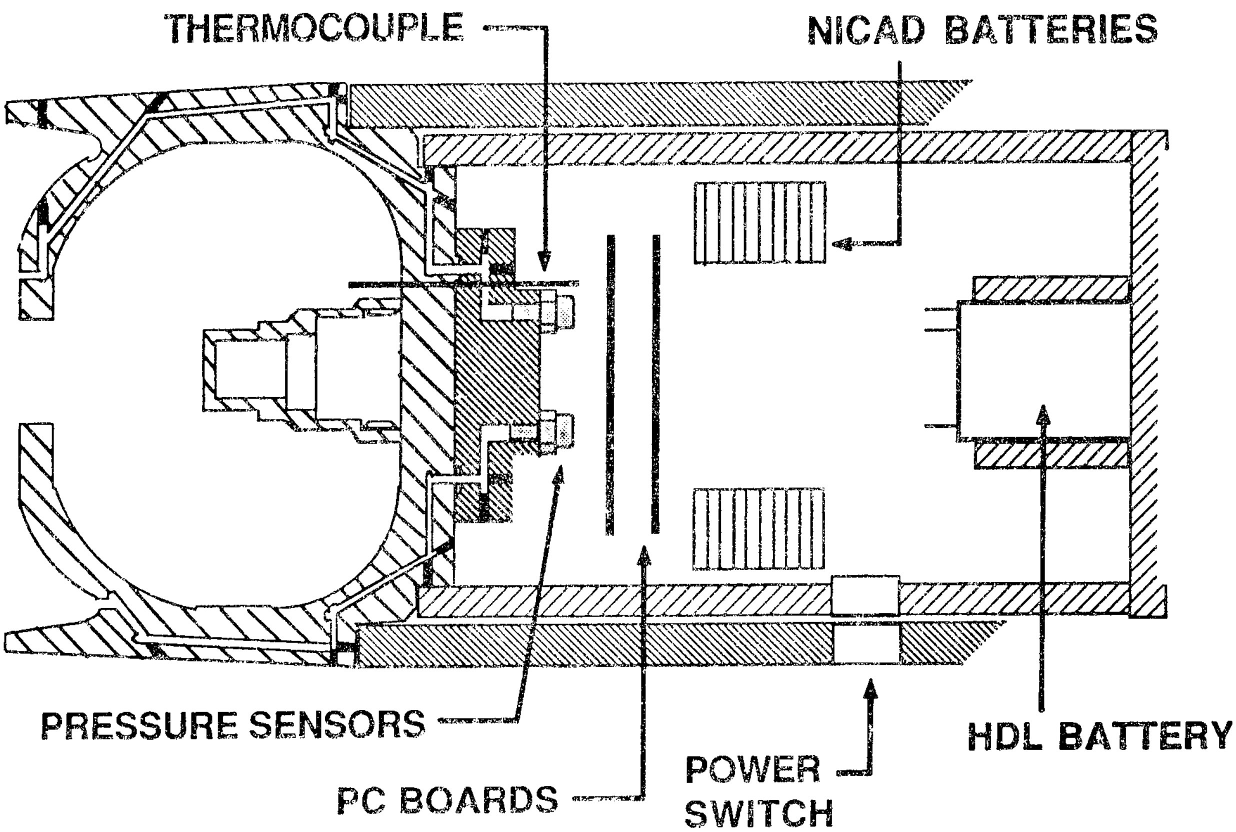
"The pressure transducers used in these experiments were purchased from the Kulite Corporation and are miniature, solid-state semiconductor strain-gage sensors with a four-element bridge circuit. The transducers are rated for 25-psia full scale; however, they are equipped with mechanical stops for an overload protection of 40 times the rated pressure. The transducer sensitivity to acceleration is very low and is quoted to be typically 0.0005% of full scale per g perpendicular to the diaphragm and 0.0001% transverse to the diaphragm.

"A hole was drilled through the transducer fixture and the front wall of the base assembly so that a thermocouple could be inserted into the propellant chamber. A tungsten, tungsten-rhenium thermocouple was used to measure temperature inside the propellant chamber. A slightly non-constant cold junction temperature of approximately 80° F inside the instrumentation canister was considered adequate for the much higher temperatures to be measured."[26]

"In late August 1988, the first instrumented projectile was fired at APG, and all systems performed very well. These first measurements of in-flight temperature and pressure are being used to validate ground test results and to validate CFD calculations. Five more instrumented projectiles will be fired during the first quarter of 1989."[25]

From 1987, we have: "Innovative test procedures were used to measure, for the first time, motor temperature pressure, and duration of burn [of base-bleed motors]. Initial tests have considered ambient temperature and pressure and the effects of high spin rates. The results were of such high quality that the test matrix will be expanded to study the effects of temperature and pressure variations as well as high spin. These data will form the base of propulsion models that can be incorporated into CFD models to understand the details of the base-bleed concept."[12]

And from 1988: "A 155mm M864 base-burn artillery projectile was instrumented with sensors to measure the internal motor pressure and temperature and the external base pressure during flight. These measurements have previously been precluded by technology limitations and represent a unique data base that will be expanded with more flights during FY89. Additionally, two techniques (one using a simple fuze-located RF transmitter and another using doppler-radar data) have been able to determine motor burn-out time. These data and comparisons with firing-table range



155mm M864 Base-Burn Projectile.

tests have provided insight for CFD solutions for this complex problem."[9]

Tank-Training Munitions. The muzzle velocity of KE rounds was so high and the drag so low that it was difficult to find training ranges large enough for safe operation. A rather clever concept for a training round for these KE rounds was conceived. This involved a solid-fuel RAMjet (SFRJ) that burned during the early phase of flight and maintained the proper velocity; when the fuel was spent, the round choked, and a high drag resulted. For 1982, we find: "SFRJ technology has been developed for use as a training round for the 105mm APFSDS penetrators. Full-scale tests demonstrated ignition, thrusting, flight stability, and a ballistic match to the M735 and the M774 penetrators to the maximum desired range, and then fell safely to earth within the limits of the range. Confirmatory firings are underway to validate the low-dispersion characteristics of the munition.[27] This was a good idea, but it was decided to use a flare-stabilized training round instead.[21] The SFRJ story had a happy ending of sorts after all. Mike Nusca was able to translate his computational capability, that was developed for the RAMjet training round, to the analysis of the RAM accelerator.[28] Nusca was able to help in scaling the 37mm UW device to a 105mm system. This was a difficult task since RAMjets do not scale linearly.[21]

In the flare-stabilized training round that the Germans developed, they had included perforations in the flare, which they said were necessary to reduce base pressure and must be canted to control roll. Mermagen and Yalamanchili shot similar rounds without holes and demonstrated adequate ballistic performance. (A trajectory match was only needed for 2,000 m.) ARDEC realized that flutes could be easily milled at the edge of the flare for adequate generation and control of roll.[21] "The Army has recently adopted a flare-stabilized projectile, ... as training ammunition for 105mm tank cannon. ... A series of experiments [was] performed to measure the practical effect of the perforated flare on the overall flight performance of the projectile. No improvement in ballistic match was observed between rounds with solid flares and rounds with perforated flares. Since the perforated flare is expensive to produce, a considerable cost saving (estimated at $60M/year) would accrue if the Army adopted the solid-flare configuration. GE and General Defense Company have submitted PIPs to the Project Manager-Tank Main Armament System (PM-TMAS) on the basis of these experiments. An experimental program to determine the ballistic performance of similar projectiles for the 120mm smooth-bore tank cannon are ongoing at present, with the potential for demonstrating even greater cost savings."[14]

FIRING TABLES

"The primary mission of the Firing Tables Branch (FTB) is the development of firing tables and associated aiming data for all unguided Army land-combat weapon systems. Other responsibilities include the generation of data for fire-control devices and the development of a rational basis for NATO and quadripartite STANAGs involving firing-table elements, theory, and application."[1]

To give some idea of the scope of the operation of FTB, we have listed some of the systems for which they have been responsible:

Infantry and Aircraft Weapons Team

* U.S. infantry small-arms weapons and ammunition
* 30mm munitions for AH-64 (APACHE) helicopter
* 40mm, MK-19 grenade machine gun
* 60mm, 81mm, and 120mm mortar systems
* Aeroballistics of small-caliber munitions.

Tank Weapons and Fire-Control Team

* 25mm, M2, and M3 fighting vehicles
* 105mm, M1, and M60 series tanks
* 120mm, M1A1 Abrams tank
* Ballistic data bases to support field-artillery computers (advanced field artillery tactical data system [AFATDS], battery computer system [BCS], backup computer system [BUCS], etc.)
* Delivery accuracy analysis and data base
* Fire-control software engineering.

Heavy Artillery Weapons Team

* 105mm, M119, M102, and M101 series howitzers
* 155mm gun and howitzer systems
* Artillery projectiles including base-burn and rocket-assisted projectile howitzers
* 155mm, M721 guided projectile (Copperhead)
* Artillery rockets and missiles
* Foreign and special purpose weapon systems
* Ballistic test design and analysis.[29]

Field Computers. "FTB not only produces firing tables; it also provides the data necessary to create computer data bases and to build ballistic-weapon aiming devices. Basic information found in a firing table, such as range and elevation to attain the range, is used to build the weapon aiming devices, but additional information is required to support computer data bases used in field computers.[1]

"There are two basic sets of data for field computers: fire-control inputs (FCIs) and fire-control trajectories (FCTs). FCTs contain the same type of information required in the mathematical trajectory models; namely, aerodynamic coefficients and ballistic performance parameters. FCTs are grouped by propellant charge, and in each group is a set of five trajectories which are used to verify the output of the field computers. The field computers, which contain a program code to compute a trajectory mathematically, use the FCTs to determine a trajectory under current conditions, and the FCTs are used to check the validity of the computation.[1]

"FTB supports three field computers: BCS, BUCS, and the mortar ballistic computer (MBC)."[1]

The branch is trying to make life easier for the developers of field computers. In the past, input for the computers was in the form of paper documents; now things are done in the electronic mode, using tapes or electronic mail, which makes the process easier at both ends of the communication link between the branch and the developers of the computers. Likewise, the new requirement is to develop fire-control packages in the Ada language as modules (sub-routines) to be added directly to the computers with no modification by the contractor; presently each contractor has to write his own sub-routines, and the branch has to help each of them debug his particular system.[30]

As an aside, it is interesting to note that, while hand-held calculators were to completely replace the much older graphical firings tables (GFTs) (which were slide rules), GFTs are again in demand after a hiatus of a number of years.[30]

Trajectory Models. Presently more data gathering is being done in the flight mode (particularly using Doppler radar) than was done in the early days when velocimeters and impact conditions were the main source of data. Yawsondes are not used much, since the branch is mostly concerned with projectiles that fly properly.[30]

The modified point-mass (MPM) model is still the workhorse for trajectory calculations. In the late 1970s, the model was extended to account for rocket-assisted projectiles; thrust data were obtained by Doppler radar. Next in importance to the original work on the point-mass model has been the addition by Lieske and Danberg of base burn.[30]

"An addition to the MPM trajectory model for rocket-assisted projectiles ... models the change in aerodynamic base-drag based on the change in base pressure due to the base-burn motor's ejection of hot gas into the wake of the projectile. The mass-flow rate of the remaining fuel of the base-burn motor is modeled as a function of the instantaneous projectile spin rate and atmospheric air pressure."[31]

"The MPM trajectory model ... is the primary method of trajectory simulation used in the preparation of firing tables. This model requires four types of input data: projectile mass properties, motor characteristics, aerodynamic coefficients, and the performance parameters determined from experimental range testing. This report presents a method of modeling the aerodynamic drag of base-burn projectiles with as much similarity as possible to the approach used for rocket-assisted projectiles. Hawk Doppler radar data for the 155mm, dual-purpose improved conventional munition (DPICM), M864 base-burn projectile have been analyzed and used to verify the modeling approach for a variety of test conditions."[31]

The following is from an *Update* article on base-bleed modeling by Danberg: "Extending the effective range of artillery is a priority objective of U.S. Army R&D. The concept of using base bleed to reduce the projectile's drag (and thus increase the range) is not new. But the idea has only recently been turned into fielded ammunition such as the M864 (DPICM) dual-purpose shell for 155mm howitzer; with base bleed, the maximum range has been increased from 24 to 27 km.[15]

"The Swedish coastal defense forces were the first (1985) to introduce base-bleed projectiles (75 and 120mm) as a way of achieving longer range with their existing artillery systems. Luchaire S. A. of France (LU111), Bofors of Sweden (HEER), and Rheinmetal of Germany (Rh49) all have similar HE shell, and a number of other countries, notably Japan and the Peoples Republic of China are experimenting with base-bleed extended range technology.

"The base-bleed technique involves providing a small solid-propellant grain in a chamber in the projectile's base. The burning of the grain produces combustion [gases] which are discharged at low speed (unlike a rocket motor) into the near wake of the shell. This mass addition to the wake reduces the base drag. Base drag counts for up to half of the total drag of a modern high-performance shell. Reducing the drag produces the longer range and without additional dispersion which is usually associated with rocket propulsion. Despite the number of existing shell designs, detailed analysis of the physical mechanism by which drag reduction is achieved has been inadequately understood. The BRL is a leader in providing new experimental and computational data on the base-bleed mechanism and in developing techniques for predicting the base-bleed shell performance.

"Earlier analysis of base-bleed depended on scale-model wind-tunnel test or flight-test data to deduce the relationship between the mass flow from the gas generator and the base-drag reduction. The development of base-flow CFD techniques by the BRL's LFD has provided a new way of meeting this need. Computational methods of solving the basic equations of high-speed flow in the near wake of a shell with mass addition, developed and applied in LFD by J. Sahu and C. Nietubicz, provided the critical drag reduction data. The added mass stretches the wake and reduces the flow expansion at the base, thereby, increasing the pressure and lowering the drag. The CFD computations have been carried out for the M864 but can be easily extended to other configurations. The modeling does not consider, at this stage, the details of the combustion of the propellant. Computations have been performed for a wide range of propellant mass flow and its temperature and shell speed. These results have been put into the form of correlation equations relating the base-pressure increase with propellant mass flow for use in a model of the shell flight performance.

"A comprehensive solution of the base-bleed shell performance has been developed considering three major elements: (1) gas-generator performance, (2) aerodynamics of the shell with gas injection into the wake, and (3) trajectory simulation.

"The gas-generator performance analysis accounts for solid-propellant grain geometry change with time and uses the burning rate at low pressures obtained by M. Miller and H. Holmes in IBD. LFD laboratory spin-fixture tests of L. Kayser and J. Kuzan were used to define spin effects on the grain-regression rate as well as discharge-orifice effectiveness.

"As already mentioned, the CFD computations were the essential element in determining the breakdown of shell aerodynamic drag into pressure, viscous, and base-drag components. These computations showed that the base pressure increases linearly with injected gas flow and roughly linearly with the gas temperature. However, the effect on base pressure is highly non-linear with respect to projectile Mach number. Since the grain burning rate depends on the base pressure which, in turn, depends on the gas mass flow generated by the grain, the gas generator and external aerodynamics are coupled and must be solved simultaneously. In addition, the base pressure depends on the flight altitude and Mach number which links the trajectory computation to the other elements of the analysis. A numerical solution to the two-dimensional, MPM trajectory equations of R. Lieske provides the final element of the analysis.

"The above computer-simulation technique was originally applied to the M864, and comparison with the extensive flight-test data base developed by FTB provides the data for evaluating its accuracy. The predicted range of the M864 is within 4% of the flight measurements over a wide range of launch conditions. Because of the BRL base-bleed code's ability to model the many design parameters of the system, studies have been performed for ARDEC on (1) new designs, including a long-range version of sense and destroy armor (SADARM), and (2) an extended-range shell for the AFAS cannon that combines both base bleed and rocket assist. Evaluations have been performed for Talley Industries and on Bofors' 155mm HEER.

"Future plans include CFD computations of the near-wake flow with chemical reactions which more correctly model the external burning products of the gas generator.

"Although the current base-bleed modeling code is not sufficiently accurate to provide aiming data, it has already proved to be a valuable tool for studying parametric changes in design of drag-reducing shell. This will lead to a new generation of effective long-range artillery."[15]

International Activities. FTB has a long history of involvement in NATO activities. Bob Lieske, the branch chief, is chairman of the NATO Army Armaments Group, AC/225, Panel 4 (Surface-to-surface artillery), Sub-Panel 2 (Ballistics). Lieske replaced Charles Lebegern who retired in 1985 and who was extremely active in NATO circles.[30]

The MPM model became NATO standard (STANAG 4355) in 1988. As an aside, we note that the model has quite an international appeal. For example, when Murphy (the Chief of LFD) visited China, the MPM model was the one thing that the Chinese most wanted to discuss.[30]

The branch has also assisted in preparing a STANAG for interior-ballistic modeling, which has been ratified and is now in the promulgation stage. This is for a lumped parameter model based on work in IBD. Also, methodology for interchangeability of ammunition is in draft form for a NATO document.[30]

The NATO panel has been very useful for the interchange of ideas and information. For example, it allowed a joint test in Norway of a variety of base-burn projectiles. This test provided a cold-weather test as well as a chance to examine a variety of base-burn concepts.[30]

The branch is now [1992] preparing firing tables for a Japanese base-burn projectile. They have completed the provisional table, and final firings are now being conducted at the Yuma Proving Ground, AZ.[30]

Liquid Propellant (LP) Systems. LP is the system of choice for the new AFAS howitzer that is now [1992] in development.[32] LP raises some interesting issues. For one thing, LP allows continuous zoning, which in turn requires an extension of the ballistic quantities such as form factors, deflection factors, time factors, etc.[33] Also, LP allows time-on-target firing from a single weapon, by firing rounds to the same range with different combinations of angle and muzzle velocity. One of the problems is determining how many rounds are practical and what is an optimal firing schedule. The goal is to have the rounds arrive within a 3-s interval. If truly continuous zoning is possible, 20 rounds can be delivered on target at some ranges within that interval.[30]

Artillery Accuracy Data Base. A data base has been developed based on tests at Fort Sill, OK, and the Marine's test area at Twenty-Nine Palms, CA. The only sizeable data base of its kind (to Lieske's knowledge), it defines various procedures such as the use of GFTs, the use of BCS, the conduct of registration with other rounds, predictive fire, etc.[30]

Tim Kogler and Fran Mirabelle write: "Since 1987, FTB has been accumulating a data base to quantify the delivery accuracy of cannon artillery aimed with the predicted-fire technique as requested by the U.S. Army Field Artillery School (USAFAS). The predicted-fire aiming technique, established by the Gunnery Department at USAFAS, allows immediate target engagement without the expenditure of ammunition for registration or adjustment. Evidence of the U.S. artillery's reliance on the predicted-fire technique came from televised reports of Operation Desert Shield/Storm. News footage showed Army and Marine Corps artillery units firing at Iraqi targets with a technique referred to as *shoot and scoot*. No registrations were conducted from the weapon location used to fire for effect (FFE), thereby minimizing counter-battery fire.

"Historically, artillerymen have successfully engaged enemy targets using tabular firing tables (TFTs), GFTs, and BCS. BCS employs the MPM trajectory model to solve the equations of motion using an extensive aerodynamic and ballistic data base developed and maintained by FTB. Until recently, the accepted aiming technique was known as *registration and transfer*. This technique requires rounds to be fired to a known location to zero or register the weapon system. Miss distances generally occur because of uncertainty in muzzle velocity, meteorological data, and weapon location. Registration corrections are computed on did-hit/should-hit data and subsequently applied to the aiming data for the transfer or FFE missions.

"The current trend in the field-artillery community calls for engaging hostile targets by means of the predicted-fire delivery procedure. A statement contained in a recent addition of *Field Artillery* reaffirms the artilleryman's concern with registration: 'Our doctrine discourages the use of registrations because they expose the battery to counterfire and waste time and ammunition.' The five requirements for accurate first-round FFE are accurate target location, firing-unit location, muzzle-velocity variations (MVVs) from standard, meteorological data, and accurate computational procedures. The MPM trajectory model in BCS provides the soldier with the predicted-fire capability. When the above are available, the predicted-fire delivery technique is utilized; that is, FFE is conducted without a registration.

"In an effort to quantify the predicted-fire accuracy, FTB has coordinated several joint U.S. Army and Marine Corps stockpile-reliability and delivery-accuracy tests with the Naval Weapons Station (NWS), Fallbrook, CA. These quasi-combat tests fulfilled the requirements of both the Navy (stockpile reliability) and the Army (delivery accuracy) with a minimal expenditure of funds. FTB analyzed the test results to quantify the predicted-fire delivery accuracy. The fall-of-shot and radial-miss results have been documented in several BRL memorandum reports. These results also provide the necessary empirical data to statistically validate the cannon-artillery delivery-accuracy model (CADAM) developed by AMSAA and FTB. ... The fit of the CADAM output closely matches the fit of the empirical data indicating agreement between the model and data base.

"In conjunction with the effort to quantify cannon-artillery delivery accuracy, FTB participated in the USAFAS delivery-accuracy improvement analysis that was requested by the Assistant Secretary of the Army for Research, Development, and Acquisition (ASARDA). USAFAS's report indicated that muzzle velocity and meteorological variations are the major contributors to inaccurate artillery fire. Recent FTB accuracy-test results verified the correlation among MVVs, stale/old meteorological data, and large-radial miss distances.

"During the Operation Desert Shield/Storm, FTB answered numerous requests for data and ballistic consultation from the USAFAS. Although most requests centered on the availability of aiming data for developmental items, several inquiries were made concerning field-artillery delivery accuracy. The established accuracy data base for the predicted-fire and registration/transfer delivery techniques and the proven need for proper muzzle-velocity management and frequent [meteorological] data provided a strong foundation for their tactical decisions. As a member of the Artillery Accuracy and Effectiveness Working Group, FTB will continue to address USAFAS's accuracy requirements for existing and future systems."[34]

Some Systems Work. The following are some assorted tasks in which the branch has been involved over the period covered by this volume:

Enhanced Meteorological Message. The branch has been involved in a program to enhance the meteorological message that is used by artillery. The efforts are aimed at extending the altitudes and at including spatial and temporal variations. The concept involves a meteorological management computer to digest data from all sources (all services, etc.) over the battlefield and then to provide updates as they are warranted.[30]

Multiple Launch Rocket System (MLRS). Until recently, the firing data for MLRS had been prepared by the contractor. The BRL is now playing catch-up on MLRS ballistics to be able to support the extended-range version of MLRS.[30]

Fleet Zero. "Another area of expertise in which FTB participates is tank-gun jump. When firing a tank gun, the compensation for jump is one of the main concerns of a tank crew. Jump is defined as all the error sources which cannot be accounted for by the tank main fire-control computer. As a means of quantifying tank-gun jump under the fleet-zero philosophy, several sources of data have been explored. Over the past several years, FTB has maintained a data base which examines jump results from lot acceptance testing (LAT) conducted on 120mm ammunition.

"Even though LAT for tank ammunition is not conducted specially for jump purposes, jump data may be gleaned from the resulting firing records. These results offer an economical (cost free) source of jump data, and since the tests are fired throughout the year, the LAT provides an excellent data base of jump for fleet-zero purposes.

"In addition to the year-round testing, several other parameters associated with the lot acceptance make it a desirable means for the collection of jump information. The sampling of results from a wide variety of lots, the use of several different tank and tube combinations, and the firing of some temperature-conditioned rounds make the jump results obtained from the LAT a useful tool in verifying the established fleet-zero values. Further analysis is conducted with regard to the relative accuracy associated with various zeroing techniques."[1]

From a 1987 report, we find: "A major enhancement to the *fleet-zero* data base for tank gunnery has been accomplished. Tank jump information can now be computed from ammunition LATs due to the development of a new algorithmic technique. The subsequent data reduction and analysis provides the comparisons."[12]

Nuclear Spotter. From 1980, we find: "A special range-firing program was conducted to evaluate projectiles other than the M549A1 as possible registration projectiles for the XM785 nuclear projectile. The program resulted in a special GFT addendum to allow the M483A1 and the M107 projectiles to be used for registration."[5] This was one of the early efforts associated with the accuracy data base previously mentioned.[30]

Copperhead. From 1980: "New firing-table entries and graphical fire-control devices were also developed for the 155mm XM712 Copperhead projectile."[5] Working with Martin Marietta (the system contractor), the BRL developed the firing-table data using the MPM model. This was done first for a good-weather firing table and then later for a target-lock logic (or shaped trajectory) firing table (published 31 December 1990). The latter allowed the fly-out portion to be tailored to account for atmospheric conditions in order to optimize the chance that the seeker could acquire the target.[30]

Training Rounds. From 1987: "It was determined that a non-conical boat-tail despin concept, previously evolved for the 25mm training round, allows small-arms [caliber .50] training in locations normally deemed too small to contain the ammunition. This design affords a maximum range-limiting feature through unstable flight characteristics at ranges beyond those normally associated with training."[12]

Helicopter Fire Control. From 1980: "Fire-control equations were developed for the 2.75-in MK66 rocket with XM261 warhead for use with the Cobra AH-15 helicopter."[5] These calculations used the 6-degree-of-freedom model and considered the 2.75-in rockets and the 20mm and 30mm projectiles. Hal Breaux did the fitting of the trajectory data to produce the equations.[30]

Olympic Shooting Team. On a somewhat lighter note, the following is offered from an *Update* article by Bob McCoy: "Well before the 1992 Olympic competition, the U.S. Shooting Team naturally had its eye on winning. To help achieve this goal, the chairman of the team requested technical assistance from the BRL. Specifically, the team wanted the BRL to determine the effect of wind on the trajectory of the caliber-.22 long-rifle match ammunition used in Olympic competition. The request resulted in a decision to conduct a limited firing program of caliber-.22 match ammunition in the BRL Aerodynamics Range. Determination of the aeroballistic properties of the projectile would then permit accurate assessment of the effect of wind on the trajectory.

"The two commercial brands of caliber-.22 match ammunition in common use by U.S. Olympic shooters are the British Eley Tenex and the German RWS R-50. (No currently manufactured U.S. ammunition is good enough to be competitive, although this will change in the near future.) Most of the BRL spark-photography range firings were conducted using the Eley Tenex ammunition, which is preferred by the majority of our Olympic shooters; a few rounds of the RWS R-50 ammunition were also fired, to verify that the two brands are essentially identical in aeroballistic performance. Two Olympic-grade match rifles—an Anschutz Prone Rifle and a Shilen-barreled Remington 40-X rifle—were loaned to the BRL for the spark-range tests. Two rifles were used in an attempt to determine if different guns produced any significant differences in the observed aeroballistic properties of the Eley Tenex ammunition. These results suggest that the choice of rifle or brand of match ammunition used has an insignificant effect on the wind sensitivity of caliber-.22 long-rifle bullets used in Olympic competition.

"The BRL 6-degree-of-freedom trajectory program was used to determine the effect of wind on the [caliber-].22 long-rifle match bullet at the 50-m range used in Olympic competition. ... As a result of the precise aeroballistic measurements and the technical expertise of the BRL scientists and engineers, U.S. shooters will achieve better scores on windy days during the Olympic shooting events next year in Barcelona, Spain."[35]

To bring things up to date, Lieske provided the following: "In addition to the firing tests and data analysis [described previously], the BRL acted as an aeroballistics consultant to the Federal Cartridge Company of Anoka, MN, who manufacture the Ultra Match ammunition. A few days ago, the joyful news was received that U.S. small-bore shooters won a gold and a silver medal in Barcelona, Spain, with the new Federal ammunition."

FLUID PHYSICS

The special provence of the Fluid Physics Branch is the processes associated with the separation of projectiles from guns. One might say that they provide much of the "L" in "LFD."

Muzzle Blast. From 1980, we find that, new "pressure instrumentation was developed for testing in the near muzzle and far field of gun blast. Weapons including the 66mm light antitank weapon (LAW), the 75mm MC-AAC, and the 155mm M109 were tested for blast using a new microprocessor-controlled, digital data acquisition system. The M109 tests showed coupling between the blast over-pressure pulse and the occurrence of flash at both zone 7 and 8S, but not for lower charges. The possibility of reducing overpressure by elimination of flash is suggested. A blast-mitigation effort included testing of aqueous foam and novel muzzle-brake deflection mechanisms. Both foams and novel brakes produced significant blast attenuation. A new muzzle-blast scaling law was developed from the 20mm cannon data base. This law predicts overpressure, positive-phase duration, and time of arrival. Numerical analyses of blast and sabot discard are being done under contracts with Aerospace Corporation and AVCO. Three-dimensional, finite-element solutions offer the possibility of accurate flow descriptions from realistic muzzle brakes."[5]

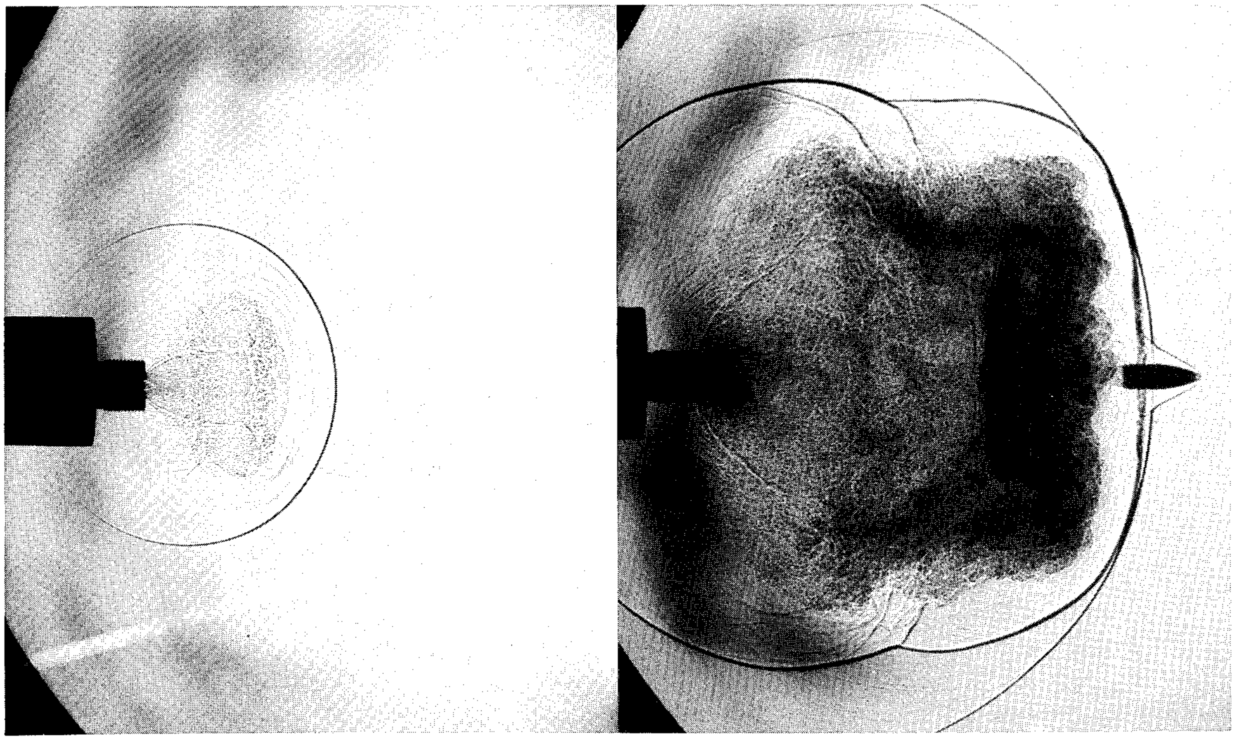
"When the projectile leaves the muzzle, the high-pressure ... propellant gas is free to expand. ... The structure of the muzzle flow is that of an under-expanded, supersonic plume encapsulated within an expanding air blast wave. Both flow features are of concern. The plume drives the blast, is responsible for muzzle flash, must be transited by the projectile, and is modified by the presence of muzzle devices. The air blast propagates to long distances causing noise problems for proving grounds and training areas, giving away friendly gun positions, and possibly damaging surrounding structures or injuring crew. At late times ... the plume begins to collapse back toward the muzzle as the gun tube empties."[1]

"The projectile must fly through the muzzle-flow region. For fin-stabilized rounds, this can be a particular cause for concern since they are designed to be stable in forward flight, but are unstable when flying backwards. In the muzzle plume, the flow velocity reaches twice the projectile velocity and the round effectively flies backwards.

"In studying this problem, it was found that even though the flow velocity could be quite high, the density was very low; therefore, the aerodynamic loads on the projectile peaked within the first caliber of travel as the velocity built-up and then decayed rapidly as the density dropped. ... Integration of the lift force demonstrates that the resultant perturbation is quite low for rounds launched with low initial angles of attack.

"Muzzle-blast loadings can be a problem if ... the muzzle of the weapon comes into close proximity to a sensitive component [for example] the muzzle of the helicopter cannon comes close to the optical window of the fire-control system.

"Using scaling relations for muzzle-blast propagation coupled to a blast-reflection model, it is possible to estimate the overpressure loads upon an aircraft surface. ... The model also permits the effect of muzzle devices to be computed. The model may be used to design a



Muzzle Blast: Precursion (left) and Propellant Gas Flow (right) From a 5.56mm Rifle.

weapon system which will not degrade structural integrity or component functionality.

"Flash can give away the firer's position and cause loss of crew night vision. In addition, it can add a significant amount of energy to the surrounding air leading to a strengthening of the muzzle blast wave. Muzzle flash has long been a problem endemic to cannon. During World War II, all major combatants had programs to attempt a reduction in the occurrence or magnitude of flash. Currently, work has concentrated on providing improved analyses of the coupled chemical and gas-dynamic processes.

"... As the leaked propellant gases exhaust ahead of the projectile, a preflash is possible; however, the main flash is associated with the exhaust of the propellant gasses. These are not fully oxidized and are rich in combustible H and CO which will burn when mixed with air at the proper temperature. This ignition and combustion event is termed *secondary flash*, and its suppression is of prime concern in studies. It is also possible to observe luminosity which is not associated with combustion, but is flow related. The primary flash occurs right at the muzzle as high-temperature particles are expelled. As the flow expands through the plume core, the temperature drops, and luminosity decays in the muzzle glow regime. Once the strong recompression shock or Mach disc is passed, the gases are shock heated to temperatures near the flame temperature, and particulate luminosity and chemistry can proceed.

"The secondary flash process has been analyzed. Models are available to predict the probability of ignition and the influence of muzzle brakes; however, the entire process is not completely understood nor amenable to exact analytic treatment."[1]

A major contribution was made in 1987 when, "the BRL also successfully designed, developed, and demonstrated a noise attenuator for the 25mm cannon on the BFV; previously, no fieldable muffler had ever been developed for such a gun. This attenuator will permit the construction and expansion of Bradley ranges allowing the crews to gain the necessary combat training without restrictions and much greater expenditure. More importantly, the noise attenuator technology developed represents a significant advance in the realm of weapon-signature reduction. Clearly, this was a banner year for the BRL and the BFVs."[12] "With the aid of supercomputer analyses, a muffler was developed for the 25mm cannon on the BFV to reduce noise levels during testing in Europe. The muffler provides blast attenuation without degrading performance. Demonstrations in Germany proved the device was effective, and continued testing of the BFV was approved by the German Government."[9] A more complete discussion of this project is in the section on Field Assistance in Science and Technology (FAST) under System Engineering.

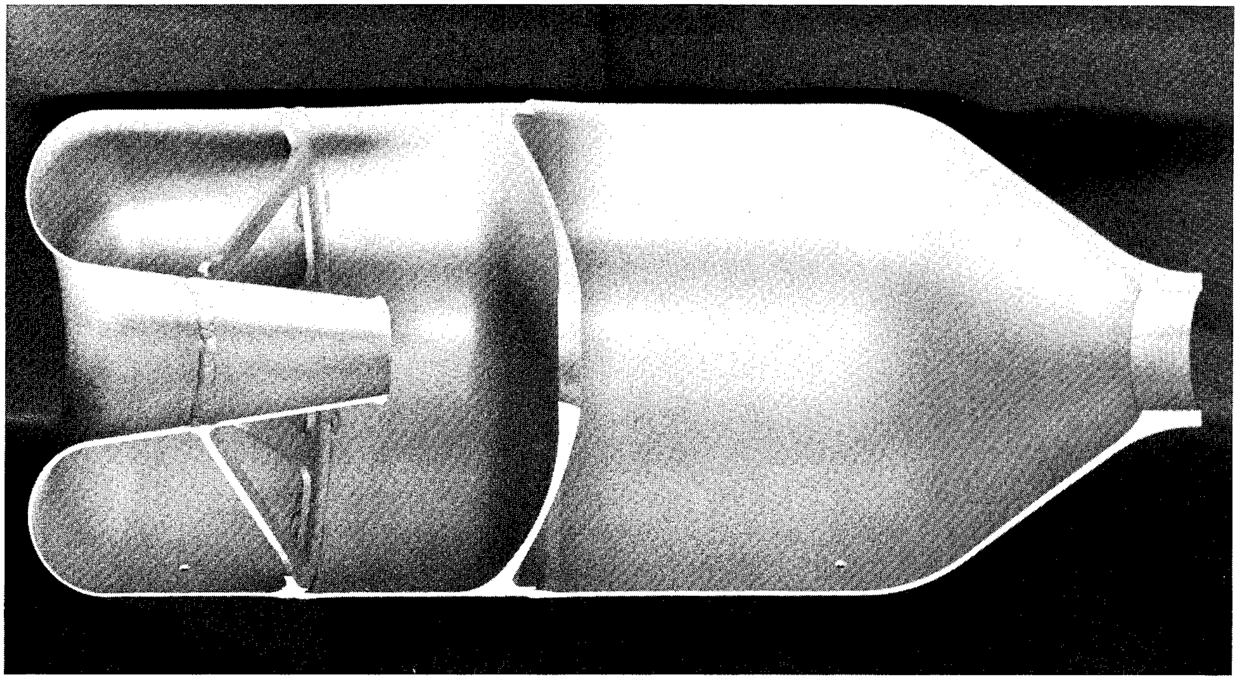
In a related vein, Schmidt et al. have made some simple theoretical/semiempirical calculations on the time, duration, transient peak overpressure, and quasi-static pressure resulting from the entry penetration, jet ballistic shock, and exit penetration of an SCJ. This has considerable application to the survivability of armored vehicles. The results were encouraging, but, to quote Schmidt, "more needs to be done with respect to looking at data and developing the analysis."

Tank-Gun Accuracy. Circa 1985, the BRL's tank-gun accuracy program began. Jim Walbert (then in IBD) had made careful muzzle measurements and impact measurements for a number of 120mm cannon. Some of the expected correlation showed, but some gun-to-gun variation also showed. The tube dynamics were similar from tube to tube, but there were tube-related effects, which turned out to be related to curvature of the gun tube, and these curvature effects turned out to be more observable in KE than in the more tightly fitting HEAT rounds.[36]

The following is taken from an *Update* article by Ed Schmidt, the chief of the branch and leader of the tank-gun accuracy program: "Recognizing that the firepower of modern KE ammunition is maximized only when tanks can achieve hits out to the maximum range at which the ammunition can provide kills, the BRL has established an accuracy program to improve the hit probability of tank-fired munitions. On the modern battlefield, U.S. tanks must win multiple engagements in chaotic, mobile fire fights, hitting small-point targets such as tanks in defilade or even selected vulnerable locations on an opponent. In pursuit of this objective, both ballistic and fire-control technologies are being actively investigated under the program.

"In the area of ballistics, there are two major factors which characterize firing error: occasion-to-occasion variability and round-to-round dispersion. To reduce the first, the BRL has developed a unique experimental capability to measure the details of the launch process. Through the use of instrumentation on the tank, gun tube, and along the projectile trajectory, it is possible to analyze the disturbances associated with each step of the projectile's acceleration down the tube, separation from the gun and sabot, and entry into free flight."[37]

As reported in 1986: "With the decision to implement a fleet-zero calibration policy for the M1A1 tank, it is necessary to insure that the system fires consistently, not only between occasions for a given vehicle, but also across the various tubes and tanks of the fleet. Tests on prototype gun tubes demonstrated that when properly mounted in the recoil system, a 120mm M256 cannon had relatively small

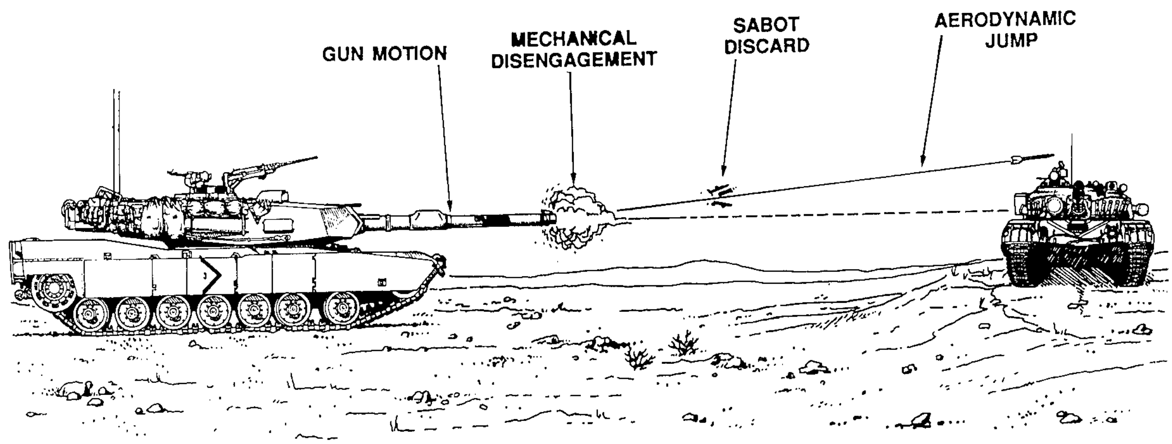


Muffler Designed by the BRL for the Bradley 25mm Cannon.

occasion-to-occasion bias; however, between cannons, there were considerable differences in centers of impact making a fleet-zero calibration impractical. To resolve the sources of cannon-to-cannon differences, the BRL personnel assessed the performance of both the prototype and production M256 cannon fired off an M1A1 tank. The launch perturbations were quantitatively measured and associated with tank motion prior to shot exit, gun tube dynamics, and projectile launch and flight dynamics. The launch data successfully correlated with measured target impact. The data and analysis have provided techniques and insights for improving tank-gun accuracy."[14]

"... Experience has shown that if multiple rounds are fired the strike of the projectile can shift through the group. Investigations at the BRL have shown that much of the shift can be related to thermal distortion of the gun tube due to firing-induced heating. Tube distortion caused by solar heating is well known and has resulted in the installation of heat shields or thermal shrouds on all modern tank cannon. However, the effects of firing-induced heating were not well understood. Tests conducted on a number of different conventional thermal-shroud designs demonstrated that while the influence of solar heating was reduced, thermal distortions under rapid-fire conditions were not adequately handled. By mathematically modeling the heat transfer through the bore and into the shroud, the BRL succeeded in developing an understanding of the process which leads to a new concept for thermal-shroud design. The shroud was fabricated and tested showing an improvement by a factor of two over the best conventional design both in terms of solar and firing-induced thermal distortions."[37]

From 1986: "In order to test thermal shroud performance on tank cannon, both environmental (solar heating and rain) and firing-induced thermal loadings must be



Launch Perturbations to Fin-Stabilized Rounds.

simulated. Based on examination of existing test practices, the BRL developed a new procedure, which provides improved simulation of the battlefield environment. The test procedure was used to examine the relative performance of four different candidate shrouds for the 120mm M256 cannon. To complement the experimental results, the BRL developed a mathematical model describing tube response to both external and internal heat transfer. The model explains the performance variations observed with different shroud concepts and has lead to the design of a unique, integral thermal shroud which has been fabricated and currently awaits test."[14]

And 1988: "The influence of firing-induced thermal distortion on the gun tube and muzzle reference system was defined. For the first time, temperature gradients in the portion of the gun tube contained within the recoil mechanism were measured. The results show gradients associated with the nature of tube mounting. These results are being correlated with other firing data to further reduce round-to-round dispersion."[9]

And finally for 1989: "Research at the BRL has improved tank-gun accuracy by counteracting the sources of projectile dispersion. Experiments at the BRL established a physical basis for a temperature-dependent gun-tube jump and developed a correction. The resulting corrections are expected to reduce this source of error by a factor of three, thus improving gun accuracy by 15%. In addition, the BRL technology resulted in the fabrication by Benet Weapons Laboratories of an integral composite shroud for a tank gun, which was demonstrated to be the best available for reducing thermally induced errors in the M256 cannon.[38]

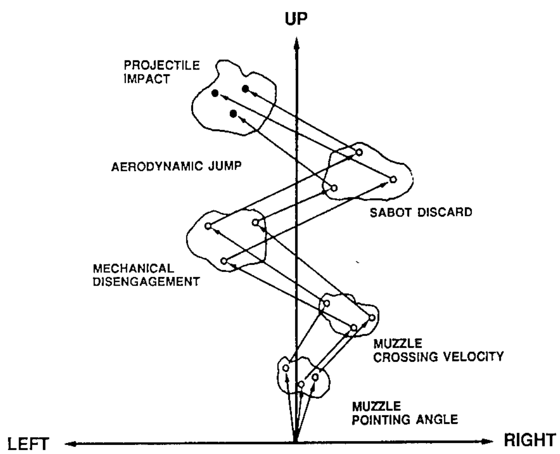
"To reduce round-to-round dispersion, emphasis is being placed on the use of computation rather than experimentation. While this is partially driven by the high cost of gun firing for dispersion measurement, the main advantage of the computer is its ability to expose cause-and-effect relationships which are often missed in the real world. With the development of validated mathematical models, it is possible to investigate how the details of weapon-system design and manufacturing tolerances affect precision. ... Development is underway to model the details of the complete launch process, including the projectile in-bore vibratory motion, separation from the tube, and sabot discard. Only through coupling these models can the projectile trajectory be predicted from shot start through target impact. Application of this capability will permit projectiles and gun systems to be *designed for accuracy*."[37] Eventually Dyna-3D codes were used to predict gun-tube motion.[36,39]

More details of the tank-gun accuracy program are found in an *Update* article by Jon Bornstein: "The increased lethality of modern armor systems has resulted from an evolutionary process in which the BRL has taken an active role. One portion of this effort has been the BRL's examination of projectile-launch dynamics and its impact upon ammunition accuracy. During launch, an extremely short time period of perhaps 20 ms, a number of disturbances act upon the projectile: gun motion or vibration, in-bore projectile balloting motion, and sabot discard. Each in its turn influences the ultimate trajectory of the bullet and its ability to accurately reach a target. This article will examine the experimental techniques used to characterize the motion of tank main guns during firing and the impact of gun dynamics upon ammunition accuracy.

"Ballisticians have been aware of the influence of gun dynamics upon projectile launch for many years. In a seminal BRL report on the subject, Gay and Elder refer to tests conducted in 1899 by C. Cranz in which the lateral vibrations of rifle barrels were photographed. In that work, the connection was first made between the variation of gun-tube vibration with powder charge and corresponding change in point of impact. Later efforts by other investigators extended this correlation to both artillery and direct-fire weapons.[40]

"The antecedent to current BRL experimental efforts was a research program conducted in the late 1950s by Gay and Elder, examining the contribution of gun dynamics to overall fall of shot for ammunition fired from the 90mm T-139 tank main gun. Utilizing state-of-the-art instrumentation and despite significant experimental difficulties, the authors recognized many of the key elements describing the firing dynamics of tank cannon: the lack of any significant turret motion until after the projectile has left the gun; the importance of the *powder pressure couple* brought about by the offset of the gun-tube centerline from the center of gravity of the system in initiating gun motion; the description of the gun as an elastic structural member subject to significant vibration during the projectile in-bore time; and the realization that a major portion of jump may be due to the in-bore balloting motion of the projectile.

"With the passage of time, instrumentation has greatly improved, enhancing the ability of the BRL investigators to quantitatively characterize the motion of modern tank guns during firing. During the mid-1980s, the BRL conducted its first fully instrumented test firings in support of the BRL tank-gun accuracy program, examining the launch dynamics of sub-caliber APFSDS and full-bore HEAT ammunition for both the 105mm-rifled tube of the M1 tank and the 120mm-smooth-bore tube of the M1A1 tank. A strong emphasis was placed upon the accurate determination of gun-tube motion. The result was a complete depiction of tube motion that provided the data base necessary for the verification of gun-dynamics codes developed by both the BRL and contractors. Four separate measurement techniques were utilized: inductive gauges (both eddy-current proximity probes and coils), strain gauges, and optical trackers. The high degree of consistency between results obtained using each of the four techniques provided the



Components of KE-Round Dispersion.

necessary degree of confidence in the accuracy of the measurements. As a result, gun-dynamics measurements, particularly the determination of muzzle motion, have become a routine part of launch dynamic testing for large-caliber ammunition, such as the recently introduced 105mm M900AI APFSDS and 120mm M830A1 multipurpose antitank (MPAT) rounds. [The instrumentation involves] metal rings surrounding the gun tube [which] contain four proximity probes encased within a protective plastic holder to minimize sensor damage during firing. The comparatively small probes, approximately 5 mm in diameter and 25 mm in length, measure the magnitude of the gap between the sensor and the gun. The anticipated lateral motion of the gun tube during projectile in-bore time is exceedingly small (<1 mm), as is the in-bore time itself (<10 ms). Thus, sensors having a linear range of 2 mm and a bandwidth of 10 kHz suffice for this application.

"Instrumentation mounting also plays a non-trivial role in testing. While motion of the gun is very small during projectile in-bore time, the recoiling gun undergoes much larger motion once the projectile exits the muzzle. Only designs which permit the probes to roll with the punch of the gun tube will survive to see a second use. A minimum of three probes is required to determine the lateral gun motion at any location. But for ease of data reduction and redundancy, four probes are normally employed at each location. This permits the complete determination of both tube motion and tube dilation. Differencing the measurements obtained at two tube locations permits the average slope of the tube to be determined.

"Using strain gauges ... to measure the longitudinal bending strain of the gun during firing together with the proximity probes permits a still more detailed examination of gun dynamics to be performed. The substantial tube vibration experienced during the final few milliseconds before the projectile exits the muzzle ... will produce a muzzle-pointing angle at shot exit which differs substantially from the muzzle orientation when the gun was aimed at a target and can have a significant impact upon accuracy.

"The irregular in-bore bullet trajectory ... brought about by this vibration causes lateral forces on the projectile which give rise to in-bore balloting motion. To minimize the in-bore disturbance to a projectile, this trajectory should ideally be a straight line. The dynamically indexed gun-tube concept, proposed by the BRL, sought to utilize the bore curvature normally created by the manufacturing process to compensate for the vibration of the tube and create the straightest possible in-bore trajectory for the projectile."[40]

"As a result of experimental and computer analysis of the dynamics of projectile-gun tube actions and reactions, the BRL was able to deduce the most favorable gun-tube alignment. By modifying the tube-indexing procedure used at Watervliet Arsenal, NY, it was possible to configure cannon assemblies to compensate for firing dynamics. These dynamically indexed tubes are almost twice as accurate as standard tubes. This is perhaps the greatest achievement in tank-gun firing accuracy in the past two decades."[9] This concept of dynamic indexing started out looking good for a few tubes, but later full-scale tests showed less than the hoped-for improvement.[36]

"The steady upward motion of the gun towards the turret ... is due to rotation of the tube about the trunnions. A moment created by the lateral offset between the centerline of the gun tube or center of action for the rearward axial force of the propellant gases acting against the breech, and the center of gravity for the weapon system is primarily responsible for this motion. Recent work at the BRL has focused on minimizing the magnitude of this moment, reducing gun vibration, and thus minimizing in-bore projectile disturbances and improving accuracy."[40] Balancing the breech and support on the front end to reduce torque helped—but not as much as it should have. More work is needed on the effects of recoil.[36]

"Extensive measurements for both 105mm and 120mm tank main guns [have] shown that the natural vibration of the tube, excited by forces on the breech and tube supports due to pressurization of the gun tube, is the dominant factor determining the motion of the forward portion of the gun, including the muzzle-pointing angle-shot exit. Differences in propellant temperature will alter the projectile in-bore time without seriously affecting the tube vibration. Thus, the phase of the vibration at shot exit and the muzzle-pointing angle will differ with propellant temperature. ... Measurements of gun dynamics and target impacts for full-bore 120mm HEAT-target practice (TP) ammunition have shown a good correlation between gun dynamics and fall of shot. Compensation in the fire-control solution for this effect offers another avenue for potential accuracy improvement.

"Gun dynamics influence the accuracy of tank main-gun ammunition in two ways: it moves the muzzle-pointing angle at shot exit away from the original aim point and places lateral forces upon the projectile as it moves down the length of the bore which ultimately causes the round to move away from its intended trajectory. The experimental studies conducted by the BRL have led the way towards a better understanding of gun motion, the modelling of in-bore projectile dynamics, and the minimization of projectile launch disturbances."[40]

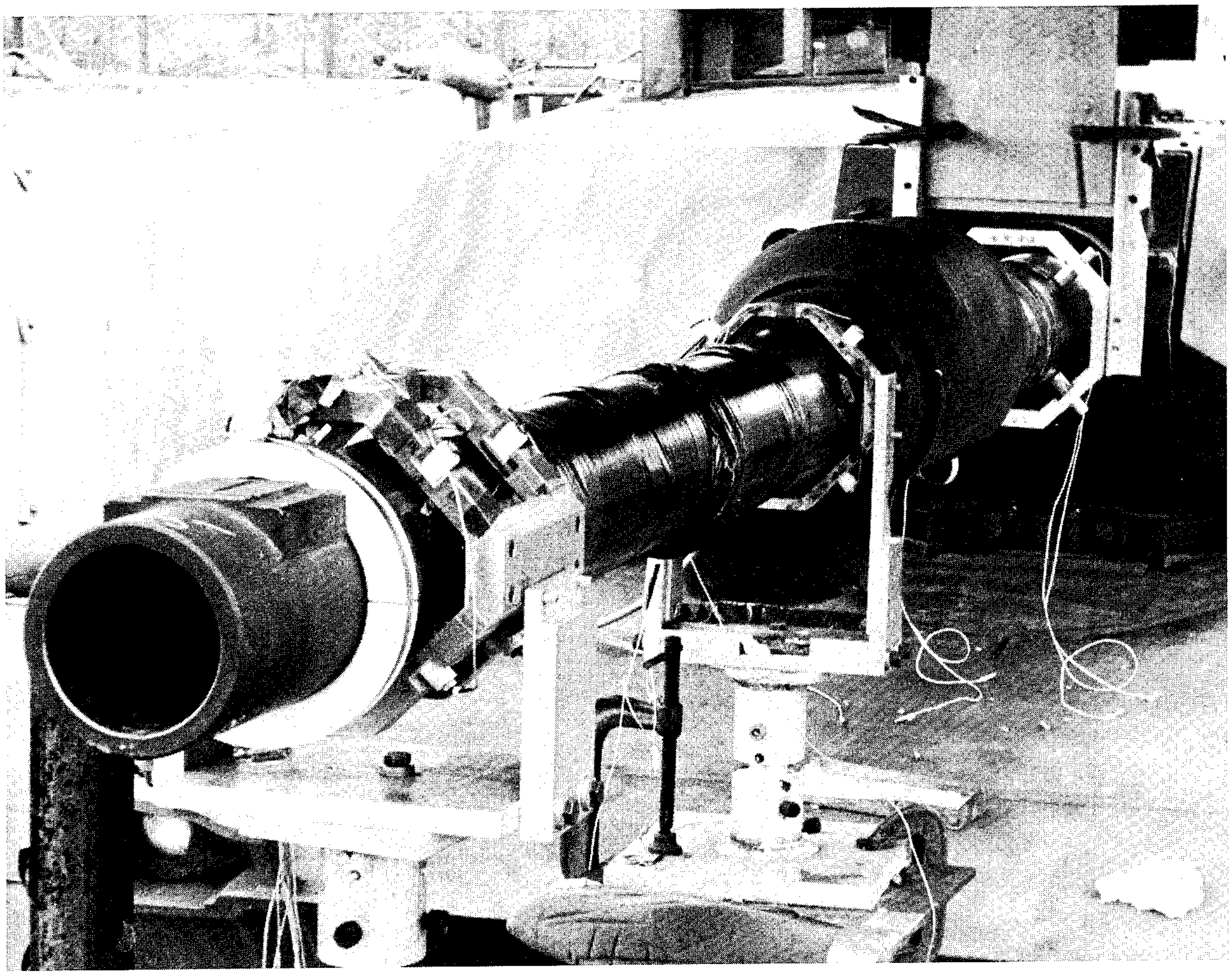
"The BRL has developed an integrated experimental diagnostic technique to aid in the optimization of ammunition performance. State-of-the-art instrumentation is utilized to determine the contributions of gun dynamics, projectile disengagement, and sabot-discard disturbances to ammunition jump and dispersion, thus permitting the engineer to identify the principal sources of disturbance of the projectile during launch and initial phases of free flight. Using information obtained with this tool, the designer can focus on modifications to the projectile design which will optimize performance. The technique has been successfully utilized during the development of 25mm, 105mm, and 120mm ammunition."[13]

The latest effort on tank-gun accuracy is on the use of miss-distance indicators for the correction of fire and to reduce biases.[36]

COMPLEX-PROJECTILE STABILITY

Throughout his career, Charlie Murphy, the Chief of LFD, has been quite active in individual research. During the period of this volume, Murphy has been working on stability problems associated with shell that have moving internal parts and shell that have liquid payloads. He has been particularly successful in developing a unifying understanding that allows laboratory experiments to predict flight behavior.

In 1978, he published a paper[41] on the anomalous behavior of the 8-in atomic shell, the



Fully Instrumented 120mm Gun Mounted on an Abrams M1A1 Tank.

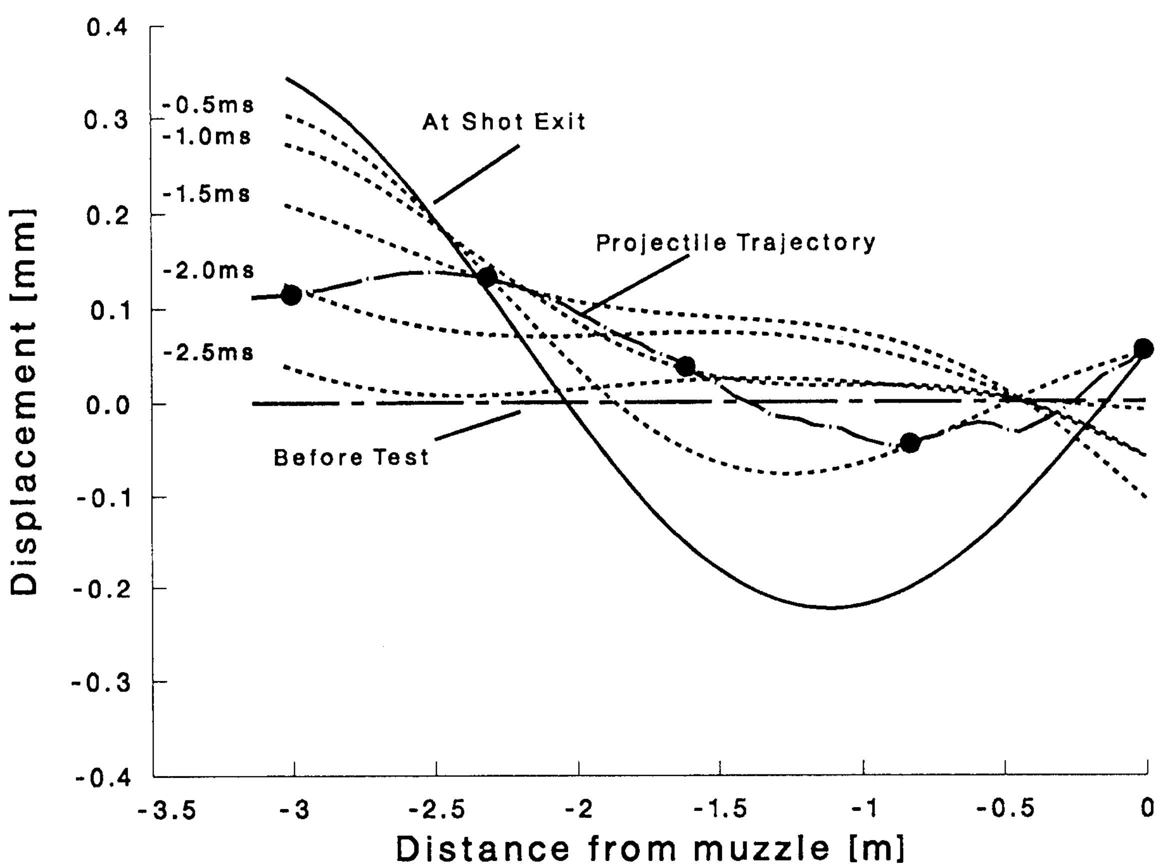
T317, which did not match its spotting round. The source of the trouble was loose-fitting rings that slid on a rod. The motion of the rings and rod interacted with the precession. Murphy found that a *forced gyroscopic* motion was the dominant motion of the rod rings. The solution was to create a self-locking device to keep the rings tight on the rod.[42]

Murphy's work is summarized in the following: "In 1955, an 8-in shell, the T317, showed a strange spin decay coupled with a significant range loss. ... The T347 had the same aerodynamic shape and mass distribution as the T317. ... The T317 had range losses of between 1% and 11% and associated spin losses. The range loss was due to a growth in the high-frequency component of the pitching motion. A quite similar behavior has been observed in recent ballistic range tests of a 20mm projectile with the M505 fuzes, which showed a growth of the high-frequency mode and an unexplained spin decay. Both the M317 projectile and the M505 fuse carried components that could move a small amount during flight.

"These phenomena have been explained by assuming either (1) a forced circular motion of an internal part about the axis of the projectile (hula-hoop motion) or (2) a forced precession of the spin axis of the internal part about the spin axis of the projectile. In both cases, only the Fourier component of the motion at the higher coning frequency of the projectile was considered. Thus, a resonance was considered for which the amplitude of the internal motion was constant.

"The theory predicted a relationship between the growth of the higher frequency mode and the spin decay, and in both cases excellent quantitative agreement was obtained. Therefore, the derived expressions can be used to set tolerances for manufacture of these projectiles. Recently an extension of this theory was used to predict the adverse effect of an interior cantilever beam."[43]

Around 1987, Murphy developed the concept that a despinning moment accompanied a destabilizing side force. This concept furnishes a useful diagnostic for liquid shell and other rounds with possible problems with interior motion. "Observations of instability caused by



Measured Profile of the Axis of a 120mm Gun Tube During Projectile Travel.

a moving payload—liquid or solid—have shown that large angular motions are always accompanied by a large spin-down moment. A simple general relation is derived between the side moment and the spin moment caused by the steady-state motion of any movable payload."[44] The idea is summed up in the equation

$$M_{spin} = - \tan(\alpha)\, M_{side} ,$$

which says that the spin moment is equal to minus the tangent of the coning angle times the side moment.[44] Thus, large angle tests in the laboratory with forced coning motion can be used to predict small-angle instability by looking at the despinning moment. The relation appears to have rather universal application.[42] This relationship was appreciated earlier for the case of liquid shell.[45]

Circa 1987, Murphy also did an analysis of the motion of a projectile with a two-component liquid system.[46] In 1989, he contributed to a summary of the motion of liquid systems: "Four liquid-payload theories—Stewartson (S), Stewartson-Wedemeyer (SW), Kitchens-Gerber-Sedney (KGS), and Hall-Sedney-Gerber (HSG)—are developed within a single unifying framework. Equations are presented that form the basis of interactive computer programs. These programs apply the SW, KGS, and HSG theories not only to their original domain, fully filled cylinders, but to partially filled cylinders, cylinders with a central rod and cylinders containing two liquids. Side-moment coefficients from the relatively simple KGS calculations are shown to be a good approximation to results from the more exact HSG theory."[47]

Finally, in 1988, Murphy identified some special cases of spin-yaw lock-in. In these cases, a non-linear roll moment can lock the spin to the coning motion. This can happen with the motion produced by either a mass asymmetry or an aerodynamic asymmetry. This, in turn, can lead to the typical increase of dispersion associated with roll resonance.[42,48]

NOTES

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3. Discussion with Walt Sturek on 28 July 1992.

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8. C. J. Nietubitz and W. B. Sturek, "Navier-Stokes Code Verification for Projectile Configuration at Supersonic and Transonic Velocities," AIAA Paper No. 88-1995, May 1988.

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15. James E. Danberg, "Computer Modeling of Extended Range Projectiles," *BRL Update*, vol. 3, no. 1, February 1991.

16. See discussion of base bleed in section on firing tables.

17. BRL Program Report - Annual FY91.

18. See Volume I of this history.

19. From the program of the dedication ceremony that was held on 21 October 1982.

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25. CPT John Kuzan, BRL Experiments on Base-Burn Projectiles," *BRL Update*, vol. 1, no. 1, January 1989.

26. L. Kayser and J. Kuzan, "Flight Test for a 155mm Base-Burn Projectile," AIAA Paper No. 80-2208-CP, July–August 1989.

27. BRL Program Accomplishments, FY82, Laboratory of the Year Submission.

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29. FTB, Handout, March 1992.

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32. The solid-propellant option known as UNICHARGE is being considered as a backup at this time [1992].

33. Formerly, these were required for only a small number of discrete muzzle velocities.

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SYSTEM ENGINEERING

Mr. Harry L. Reed, Jr., Chief of SECAD (and Predecessors) From 1967 to 1987. He Received a Bachelor of Science in Mathematics From the Massachusetts Institute of Technology (MIT) and Did Graduate Work at JHU in Physics.

From the late 1960s to 1992, the BRL had a division (or laboratory) that addressed system engineering functions. Prior to the creation of ARRADCOM, it was known as the Concepts Analysis Laboratory, with the creation of ARRADCOM, it became BMD, and it finally acquired the rather cumbersome name of the System Engineering and Concepts Analysis Division (SECAD).

It is important to understand that SECAD did not have a monopoly on system engineering activities in the BRL, nor were its activities confined to system engineering.

The system engineering efforts of SECAD were primarily managed by the Weapon Area Coordinators, a group of team leaders who were concerned with the weapon areas of air-defense systems, armored combat systems, artillery systems, infantry systems, and aircraft systems. The aircraft systems function moved with Don Haskell when he became Chief of the Air Systems Branch (ASB) of VLD because of that branch's special relation with its customer.

As a general proposition, the Weapon Area Coordinators provided several basic functions for the BRL:

1. Interface with the relevant user group to remain abreast of the Army's needs for new weapons, in particular those that might relate to the research program of the BRL.

2. Interpretation of those needs in terms of technical issues by application of system analysis techniques, combat modeling, and sound engineering principles.

3. Interpretation of new technical developments in the BRL into possible weapon opportunities by applying similar techniques. Help to market those ideas to the user communities.

How these functions were actually carried out and the scope of the activities were quite different for each team and will be discussed under the appropriate headings below. For reasons that will be explained later, the infantry team will be discussed under the heading of smart weapons.

A typical example of one class of effort by the Weapon Area Coordinators is the *Propulsion White Paper*[1] that compares a variety of advanced propulsion concepts (solid, liquid, and electromagnetic [EM]) as they might apply to future weapon concepts for air defense, armor, and artillery.

Mr. William H. Mermagen, Sr., Chief of SECAD From 1987 to 1992. He Received a Bachelor's Degree in Physics From Fordham University in 1957 and a Master's Degree From the University of Delaware in 1966.

In addition, the division always had a very active millimeter-wave (MMW) radar group. As part of the reorganization under ARRADCOM, the Applied Mathematics and Science Laboratory became part of BMD, and Don Eccleshall formed an outstanding branch of researchers in advanced technology. The BRL's Director, R. J. Eichelberger, asked Dick Moore to form a probability and statistics branch in SECAD. And finally in the late 1970s, BMD became active in interactive and networked computing, which eventually involved its assuming responsibility (in 1984) for main-frame and networked computing in the BRL. This included the acquisition and operation of the BRL's two Cray supercomputers.

Although the organization of SECAD changed somewhat in the late 1980s, it is still convenient to use the Weapon Area Coordinator's interests for part of the taxonomy as well as sections on advanced techniques, artificial intelligence (AI), probability and statistics, and the most recent efforts in the FAST program. The work on main-frame computers, interactive computing, and networked computing has been addressed in the general BRL section.

ADVANCED TECHNIQUES

In 1977, when the Applied Mathematics and Science Laboratory was combined with the Concepts Analysis Laboratory to form SECAD, Don Eccleshall formed an Applied Physics Branch within SECAD that addressed a variety of advanced physical concepts for weapon systems and advanced experimental techniques for the study of ballistics. In 1987, this branch was transferred to TBD. One of their projects, the synthesis of ceramics, is reported under the section on terminal ballistics; the others are discussed here.

Electromagnetic (EM) Propulsion. The idea of using EM forces to propel a round of ammunition is far from new. Over the years, there has been much speculation and trial-and-error with little avail. The basic problem has been that of finding an energy source that could deliver the millions of kilowatts that are needed for a practical gun system.

Conventional chemical propulsion systems have an upper limit (the escape speed of the gases) to their muzzle velocity. Well before that limit is attained, the process becomes extremely inefficient. On the other hand, theory tells us that electromagnetically propelled systems become more efficient with increasing velocity.

Thus, the idea has remained alive if not very active—that is, until about 1972 when Richard Marshall and John Barber at the Institute of Advanced Studies, Australian National University, Canberra, Australia, had a large homopolar generator that had been acquired for a particle accelerator. The accelerator program had faded. However, since the homopolar generator was available, it was used in conjunction with a shaping network to produce suitable pulses (in the millisecond region) to demonstrate a rail gun with a plasma armature. Ultimately, the group was able to launch a 3-g projectile at 6 km/s. While this was promising, a lot of engineering was needed before one could make this into a practical gun system. For one thing, even though the use of homopolar generators was a major step forward, they were still far too heavy.[2]

A homopolar generator (and the variety of generator concepts that have followed) can be viewed as a very low impedance device that can convert the KE of rotation into electrical energy very rapidly. A rail gun uses two rails and the projectile as the circuit into which the electrical energy is dumped. The EM field tries to expand the circuit and pushes the projectile down the rails. In a plasma-armature system, the projectile itself does not complete the circuit; the plasma arc behind it does. The pressure in the plasma provides the driving force.

Marshall came to Westinghouse which had become interested in marketing homopolar generators. This sparked interest in the United States.[2]

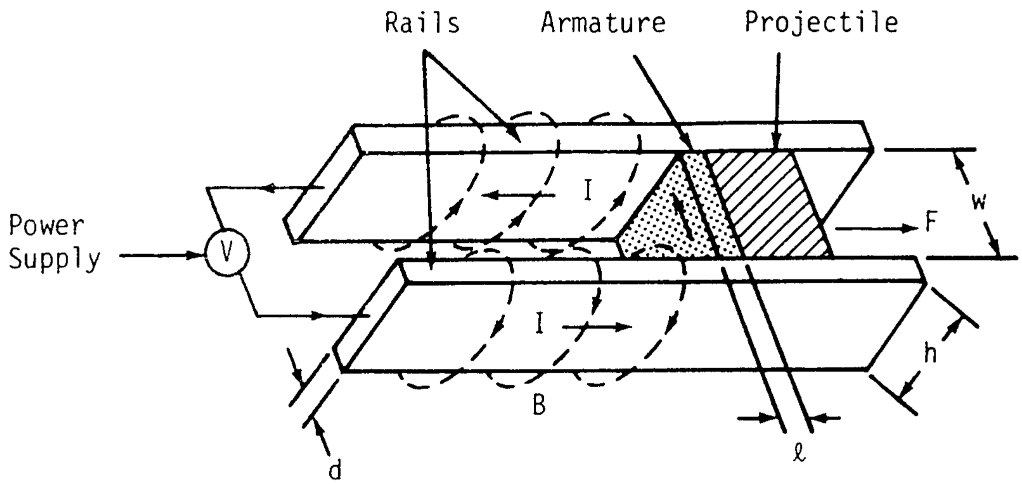
In the late 1970s, John Powell and Jad Batteh developed a theoretical model of plasma armatures. It was the first really good understanding of the processes by which the armature functions, providing a predictive code for plasma properties (degree of ionization, temperature, heat conduction, melting of the walls, etc.). This model has continued to be used and improved upon until the present.[2]

By 1980, a first-principles model was developed which describes the arc dynamics of the dynamic compaction (DC) rail gun with an arc rather than a solid armature. The model has been used to calculate important parameters such as the arc temperature for existing experimental systems and to derive scaling relations for use in evaluating guns that can accelerate projectiles of ordnance interest. ..."[3]

Around 1980, the need arose to create a laboratory facility for studying high-velocity terminal effects. EM propulsion appeared to offer some distinct advantages for such an application: it promised a relatively constant (low peak) acceleration for the launch of experimental payloads, it had no theoretical limit on the velocity attainable, and it appeared to be more easily used for repeated shots than devices such as light-gas guns. Of course, the weight of the system was of no concern for a laboratory device. The BRL and DARPA agreed on a program to develop such a facility using a rail gun that would be driven by a homopolar generator.[2]

About the same time, the LCWSL in ARRADCOM at Picatinny Arsenal became interested in a homopolar system for research in EM propulsion. It was decided that ARRADCOM should have only one such facility, and LCWSL was chosen.[2]

Keith Jamison, in conjunction with Henry Burden and John Powell, developed a laboratory research facility at the BRL to validate predictions made by the plasma-armature codes. Actually, the codes became more of an interpolation device to understand the experimental data which were not measurements of current density at particular points but were some sort of spatial average taken at a particular point from which the density must be inferred (a parameter fitting problem). The experimental and theoretical work enhanced the understanding of EM propulsion immensely.[2]



Schematic of a Rectangular Railgun.

During the 1980s, the BRL developed a unique theoretical and experimental expertise concerning the properties of plasma arcs in both EM and ET guns. Techniques for calculating properties of these plasmas were developed, and approximately 10 computer programs that solved the governing equations were written. Emphasis was placed upon developing calculation techniques that were appropriate under a variety of conditions. In addition to the theoretical work, experimental diagnostic procedures for measuring the characteristics of the arcs were also devised. These experimental techniques were complemented with extensive fitting routines which provided the capability for extracting from the data properties of the arcs that could not be measured directly.

"The developed technology was disseminated to the EM propulsion community through approximately 15 open- literature papers, an equal number of BRL reports, and presentations at all major conferences concerned with the subject. Many of the theoretical computer programs were provided to personnel both at universities and in industry. The theoretical methodology for analyzing the diagnostic data has now been adapted by investigators at the Science Applications International Corporation (SAIC) and has been used by them to analyze experimental work undertaken at the University of Tennessee Space Institute. Maxwell Laboratories has adapted BRL experimental instrumentation and techniques in the design of their new facilities, and data-reduction procedures have been transferred to the Lawrence Livermore National Laboratory. BRL personnel have continuously consulted with research workers in both industry and at universities and have upon occasion worked together on the same project. For example, the BRL and SPARTA Incorporated have undertaken a joint effort to test and analyze rail and insulator erosion. In two instances, doctoral students at the University of Miami and at Georgia Institute of Technology have sought both assistance and advice from the BRL EM propulsion group. Information, in the form of detailed instructions concerning how to carry out certain calculations as well as access to the BRL results, has been provided to those students.

"The principal use of the technology discussed previously has been to examine how the properties of plasma armatures vary with gun size and acceleration characteristics. Various types of EM guns, as well as different types of armatures, are now in competition. Consequently, efforts are underway to develop *end-to-end* models which are capable of assessing the feasibility of different devices for both military and other applications. The behavior of the plasma armature is expected to form an integral part of these models."[4]

Most recently (1992), Alex Zielinski has been working on solid armatures in which the sabot and the armature are the same. He has been designing these armatures for the small-caliber gun program for an automatic cannon for an armored vehicle. Major support is from the Marine Corps and the Electric Armaments Project Office at ARDEC.[2]

Charged Particle-Beam (CPB) Technology. Here we are concerned with beams of relativistic electrons that would produce a shower of gamma rays that would in turn be lethal to personnel, energetic materials, and electronic devices. That such beams could, in fact, be propagated over useful distances through the air has been theoretically predicted and partially verified by experimentation in national programs.

Wide internal pulse spacing (WIPS) has been the propagation mechanism of interest. In this mode, pulses long enough to bore a hole in the atmosphere but short enough to avoid magnetic instability are to be used to create an ionized channel. Actually the creation is a progressive process in which the first pulse goes a limited distance, the next uses that channel and adds to it, and so on. The pulses are spaced closely enough that the previously ionized channel does not cool too much before the next pulse arrives.

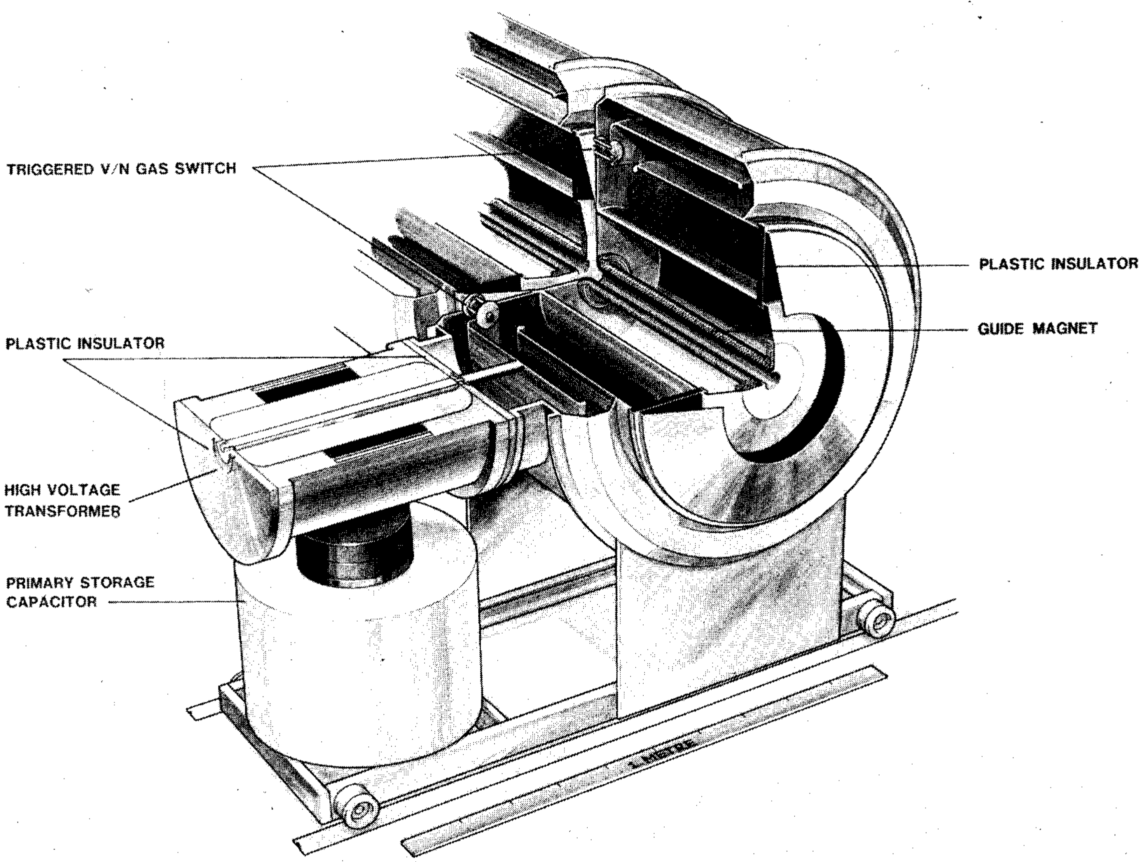
Briefly, the national program started with an Advanced Research Projects Agency program called Seesaw, which ran from 1958 through 1972. Seesaw considered the application of bolts of electrons for ballistic-missile defense. This was followed by the Navy's Chair Heritage program that considered antiship-missile defense. In 1980 to 1982, there was a national program for all three services to look at applications of CPBs.[5,6]

The BRL was the Army's lead laboratory for this effort and considered mine-clearing, air-defense, antiarmor, and urban-warfare applications. In addition, they also considered the design of accelerators that might be practically sized for tactical application.[2]

The BRL was particularly well suited for the task since a number of its scientists and engineers had been members of the Nuclear Defense Laboratory and were nuclear physicists by training. In particular, circa 1977, Judy Temperley and Eccleshall developed a concept for compact accelerator cavities. This concept has been adopted by Sandia National Laboratories (SNL) for applications requiring compact accelerators.[2] "Excellent progress was made using laboratory models to validate the new BRL electron-accelerator cavity concepts with potential for achieving small, lightweight devices required for any tactical Army exploitation of particle beam technology (PBT). The BRL scientists were also able to extend the very general analysis of charged transmission-line cavity structures to include three-line systems."[3]

"They showed that, under the assumption of ideal, lossless lines and switches, and within the approximation of a principal-modes

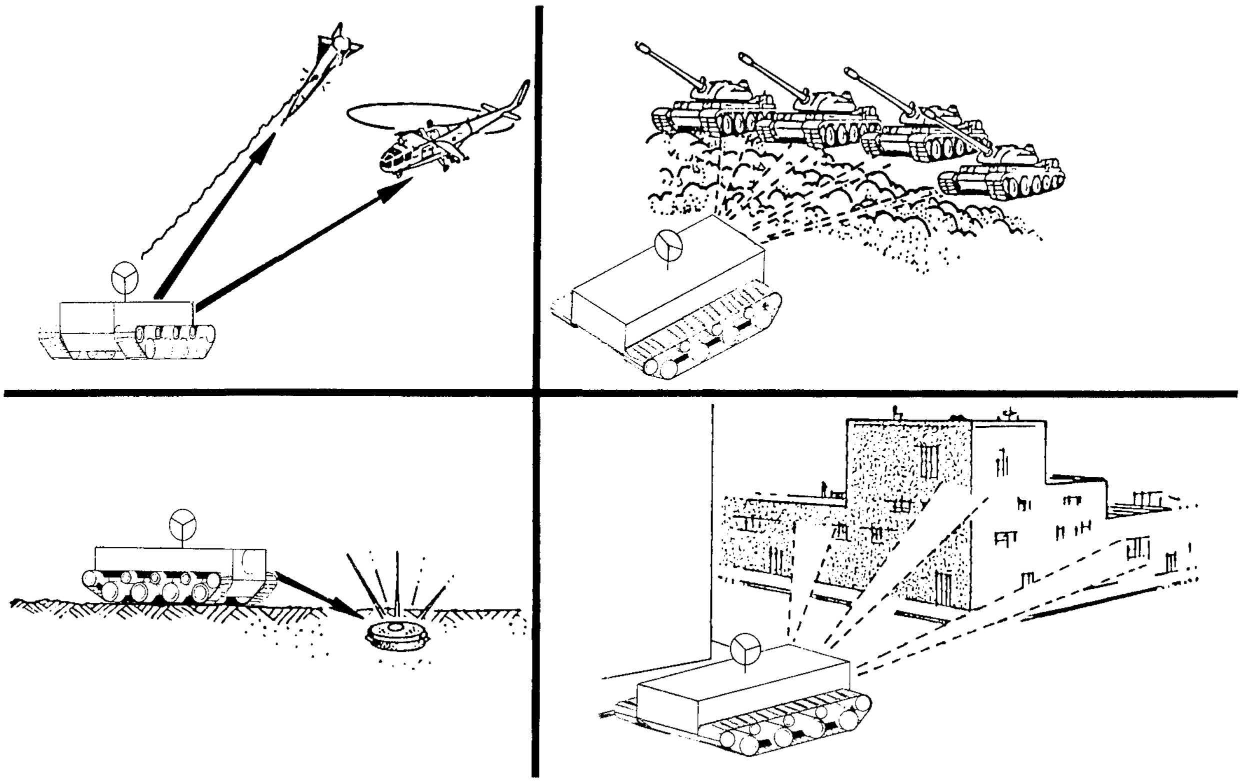
ET2 COMPACT ACCELERATOR



SNL Adopted the BRL's ET2 Cavity for Its Recirculating Linear Accelerator.

analysis, a transmission-line accelerator using asymmetric line pairs can be designed that will accelerate a constant-current beam pulse ... through a constant voltage with a theoretical efficiency of unity. ... In addition, ... a lower-current beam pulse can be circulated through the accelerator several times resulting in a total accelerating voltage several times that of the single-pass case and that, in this case also, total transfer of the stored energy can be achieved."[7]

Experimental verification of the performance of the transmission cavity was done by Clint Hollandsworth.[2] A two-line system was shown to be appropriate for a recirculating accelerator that would be relatively compact. Also, a number of three-line cavity arrangements have been found that may be attractive for efficient acceleration in a single-beam pass. The cavities offer the prime advantage of placing the switch in a region away from the accelerating gap where the electric field can be lower.[8]

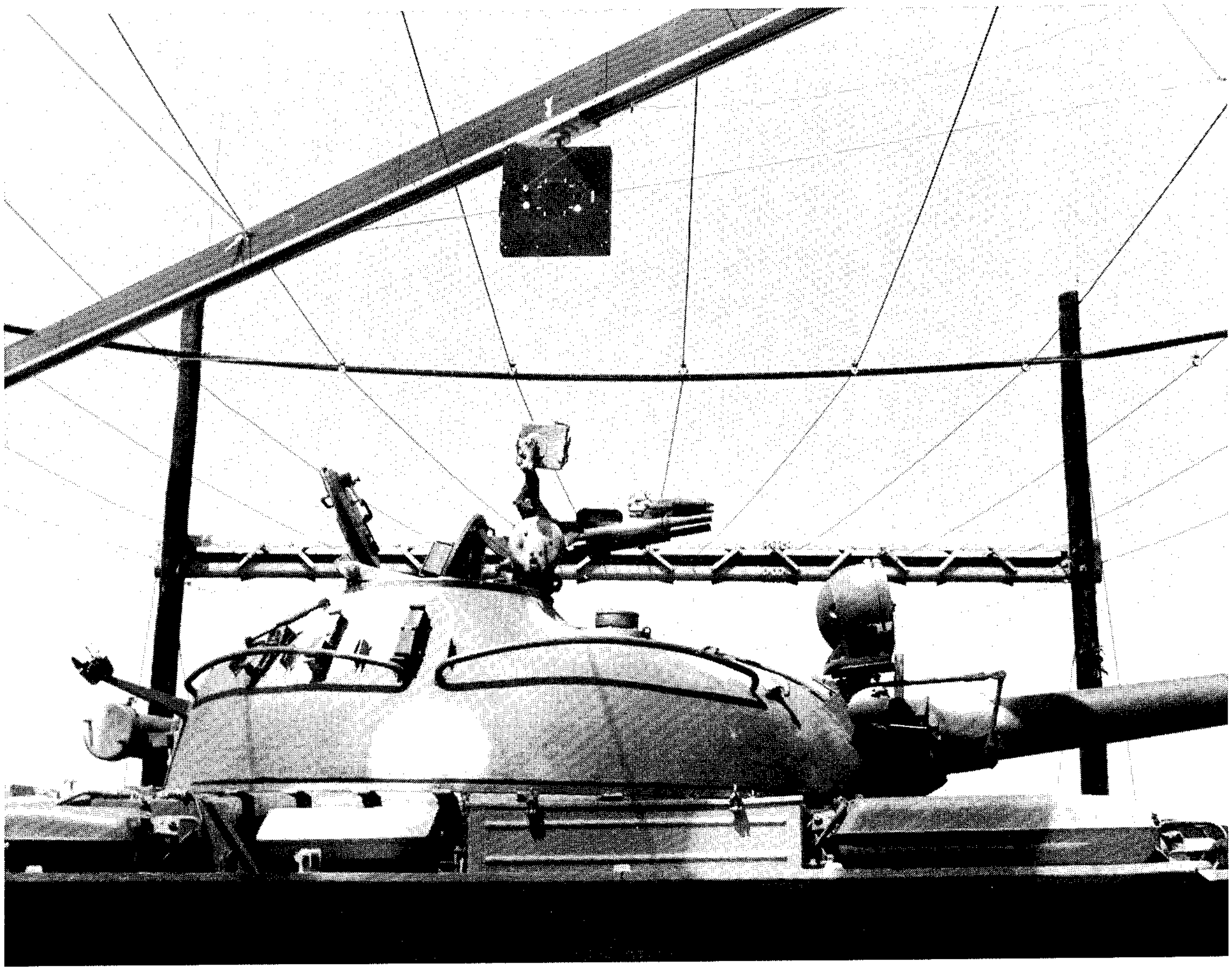


Potential Applications for CPB Technology. BRL Scientists Evaluated the Molecular Applications of CPB Technologies for Use in Military Acquisition Processes.

With in-house and contractor support, they calculated the energetics, estimated lethal mechanisms, considered countermeasures, and sized systems.[2] Unfortunately, the indications were that the technology was far too immature for most applications, and most of BRL's work ended around 1987.[2]

The BRL's role at present (1992) is very limited. Eccleshall and Hollandsworth are consultants on the use of electron beams mainly for countermine applications.[2]

Overhead Magnetic Signatures. "Since 1980, the BRL has actively studied the changes that armored vehicles, particularly foreign tanks, produce in the earth's magnetic field above them. The work was driven by the Army's interest in top-attack munitions. The BRL's effort was two-pronged. The first was the development of a theory and computational methods that describe perturbations to the ambient magnetic field, given the vehicle's basic geometry, overall material properties, geomagnetic location, and orientation. The second was to subject the models to experimental test with actual field measurements of the magnetic fields above Soviet, Chinese, and U.S. vehicles at APG. Essential to these tests was the creation of a one-of-a-kind apparatus designed to map the overhead magnetic fields and its integration into facilities where armor could be precisely located and oriented.



Setup for Measuring the Magnetic Signatures of Vehicles.

"The cuing of top attack munitions has been explored by the Program Evaluation Office (PEO)-Armaments for projectile applications and by the U.S. Army Missile Command (MICOM) and several of its contractors. The data base developed by the BRL served as the main resource for proof-of-principle and exploratory-development efforts in improved fly-over, tube-launched, optically tracked, wire-guided (TOW) antitank missiles and other systems. Paralleling top-attack efforts was a U.S. Army Mobility Equipment Research and Development Center (MERADCOM)/U.S. Army Belvoir Research, Development, and Engineering Center (BRDEC) endeavor to render U.S. armor less susceptible to top attack by removing the vehicles' overhead magnetic signatures. There are two aspects to the problem—the magnetic field due to the locked-in magnetic moments of the tank's steel components, the so-called *perm*; and magnetic moments the earth's field induces in the tank's high-permeability steels. The former may be removed with a one-time application of a strong magnetic field which opposes and ultimately cancels the *perm*. The second requires continuous on-board monitoring and cancellation via a weak magnetic field surrounding the entire tank. Devices for accomplishing these results were incorporated into MERADCOM's vehicle magnetic signature duplicator (VEMASID) effort. The BRL provided MERADCOM and its contractors (primarily Raytheon) both the BRL data base and the BRL portions of the Magnetic Signature Facility. Both were extensively utilized in the design and test phases of the signature reduction effort.

"Close fly-over, top-attack appeared to have considerable antiarmor potential. Sweden has recently fielded a system (BIL) which operates in this mode and has been evaluated for possible U.S. use. Magnetic cuing is an obvious candidate for a multimode product improvement. It is likely that within the foreseeable future, U.S. assets will be subject to magnetically cued top attack. Mitigation via signature reduction is an obvious requirement. The BRL has been instrumental in laying the theoretical, computational, and experimental foundations for the essential overhead magnetic signature data base."[4]

Erosion Studies. Nuclear technology was exploited to develop a tool for erosion analysis. This work started in about 1973. Niiler irradiated plugs of steel, which converted some of the iron 56 near the surface to cobalt 56 which then would decay. By measuring the activity before and after firing, the loss of surface metal could be determined. This thin-layer activation method became a very useful technique for measuring erosion in hard-to-get-places (gun barrels and rocket nozzles).[9]

In about 1980, a soft chrome plating technique[10] developed by the Benet Laboratory preempted interest in erosion work. Now, of course, the high temperatures and reactive products associated with ET chemical propulsion raise erosion questions again.[9]

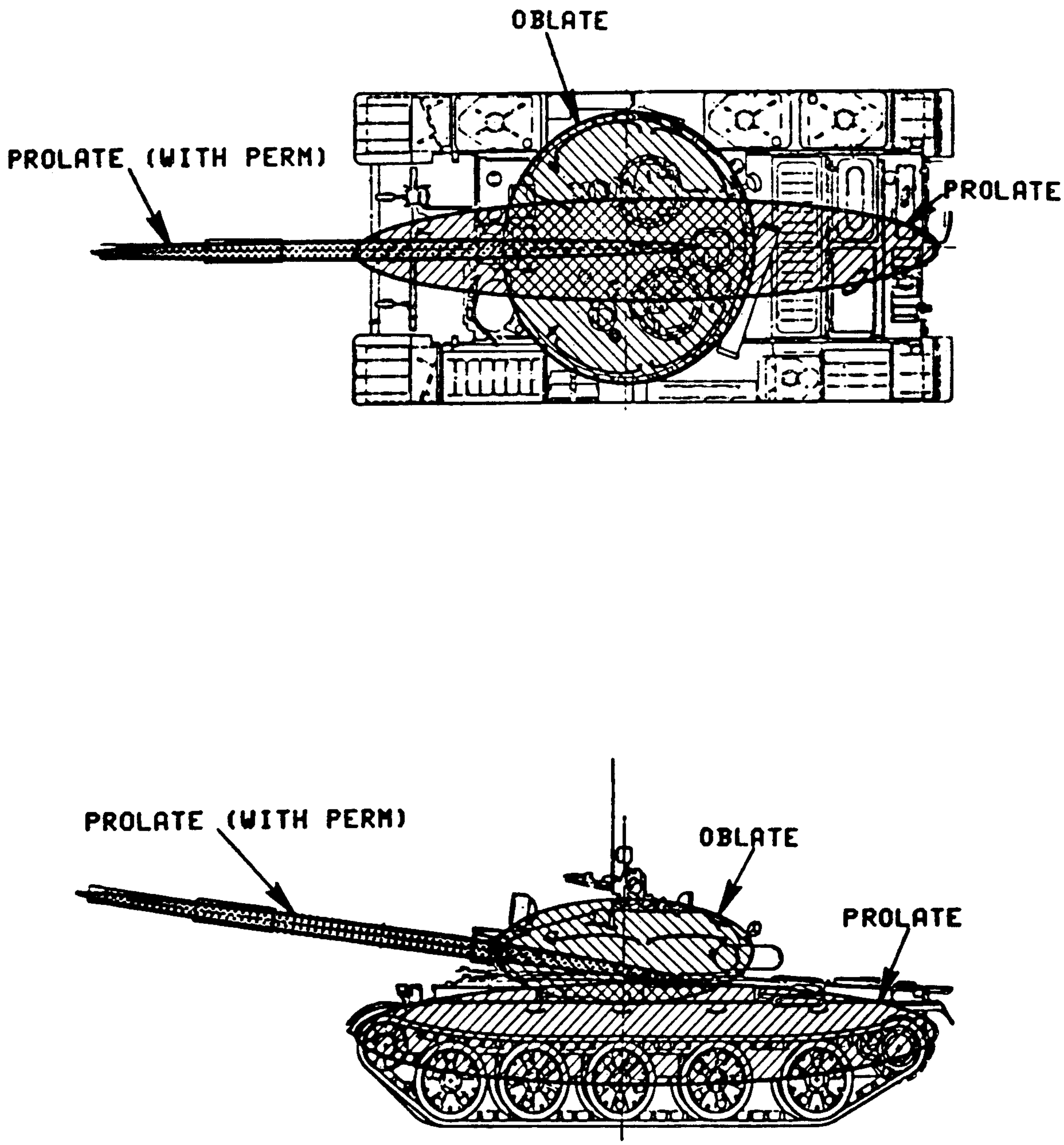
Range Hazards Detection Device. In 1986, George Thompson developed a simple and effective technique for making on-the-spot checks for the presence of heavy-metal dust.[9] "As a spin-off of the BRL's DU test program, BRL researchers have devised a new instrument for rapid, accurate characterization of the composition of aerosol dust clouds. Test firings in the BRL indoor ranges often produced quantities of dust that contained uranium and other elements of medium to high atomic weight in forms that pose serious toxicity hazards. Monitoring practices available at that time were not only expensive but also impaired productivity in order to assure personnel safety. The new device collected dust and droplets from the aerosol and pumped them through a filter tape which was subjected to analysis via real-time X-ray fluorescence. Elemental concentrations as small as 0.1 parts per billion could be read out individually or collectively. The new device has contributed to significant improvements in range testing productivity while, at the same time, maintaining personnel safety. It has the potential to be used in similar problems encountered by mining and industrial concerns."[11]

Radar-Absorbing Coatings. "BRL research has produced a highly effective new type of radar-absorbing coating for protection of military vehicles. The developed durable, thin, lightweight coating provides significant radar attenuation over a broad band of centimeter-wave and MMW frequencies and, thus, a countermeasure to EM sensing munitions."[12]

AIR DEFENSE

The air-defense team was created in the mid-1970s with Larry Puckett as the team leader. The team was mainly concerned with the application of gun systems to air defense and, in particular, with the Army's need for a gun system to replace the aging Vulcan air-defense system.

The BRL evaluated a number of approaches to the problem of a forward-area air-defense system that included hypervelocity KE systems, high-velocity proximity-fuzed systems, and



Magnetic Signature of a Tank Simulated by Three Spheroids.

readily available systems. To be effective, hypervelocity kinetic systems require muzzle velocities on the order of 3,000 m/s, and such systems were not expected to be practical within a reasonable time frame. High-velocity proximity-fuzed rounds with muzzle velocities of the order of 1,500 m/s were highly attractive. This velocity was within the range of existing technology for solid-propellant guns and also appeared to offer an exciting application of bulk-loaded LPG technology. The latter concept lost support when the DARPA demonstrators blew up.[13]

Sergeant York. However, a new system was urgently needed. The Army decided to consider only medium-caliber cannons that already existed. Therefore, the BRL engaged in a series of parametric studies to determine the appropriate caliber for such a system. "In March 1977, the Army published the first version of a requirement for a new division air-defense (DIVAD) gun. By virtue of its experience in systems analysis, involvement in HITVAL (joint Army and USAF test in 1974), and its large data base on air-defense projectiles which were generated in support of a commonality (air-to-ground, ground-to-ground, and ground-to-air) study in 1974, the BRL was in a unique position to assume a major role in the DIVAD development program. The BRL had also conducted a study by this time on the relative effectiveness of 30mm, 35mm, and 40mm rounds in the air-defense role; this included an analysis of both point-detonating and proximity rounds."[14]

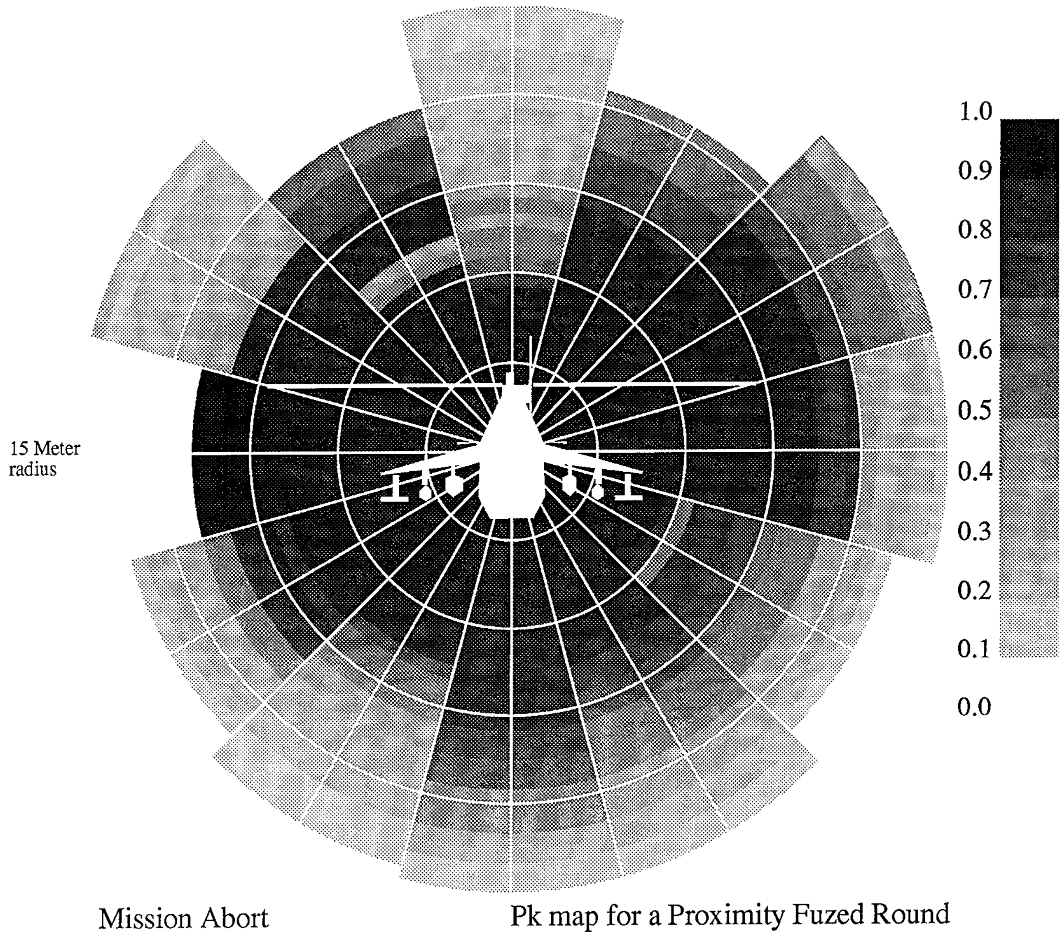
The three major results of this analysis were that the results were quite flat over the calibers considered, the proximity fuze was important (especially for maneuvering targets), and the performance of gun systems and missile systems crossed over at about 1,500 m (guns performed better at shorter ranges; missiles, at longer ranges).

"In the request for proposal (RFP) for the initial phase of the DIVAD program (a competitive-development effort), the BRL contributed a technical annex that instructed the contractors as to what information should be contained in their proposals concerning a technical description of expected system performance. The BRL also developed the technical-evaluation plan for the first DIVAD Source Selection Evaluation Board (SSEB) which convened in July 1977. BRL personnel served as members of the SSEB, including chairmanship of the system-performance and the NATO-interoperability areas. Five contractors submitted proposals in response to the RFP, and the Source Selection Authority selected the 35mm General Dynamics system and the 40mm Ford Aerospace system to proceed into the competitive-development phase of this program. The contractors were free to design their systems and make tradeoffs as they saw fit to meet the firm requirements and desired capabilities of the RFP.

"Proximity-fuzed ammunition was proposed for use in DIVAD, and the PM-DIVAD requested that the BRL coordinate a program among the BRL, HDL, and ARRADCOM to characterize the fuze functioning and projectile lethality for proximity-fuzed rounds. The BRL also had the responsibility of generating the lethality data for the proposed point-detonating rounds against the targets specified in the RFP.

"A deliverable item was a contractor-developed simulation code which would model the total performance of the system throughout the course of an engagement. The BRL was a member of the Government team that guided the contractors in code development, provided them with the required data, and recommended appropriate methodology. The BRL also had the responsibility of adapting the two contractors' models so that they could be run at a Government facility in support of the second SSEB."[14]

Shortly after the first SSEB, Puckett became the assistant to the Director of the BRL, and Judy Temperley became a Weapon Area



Proximity-Fuze Data as Provided by the R-Theta Program.

Coordinator. "The BRL was an active participant in planning the 1980 combined development and operational test (DT/OT). This participation included establishment of test conditions, definition of data requirements and optimum instrumentation, and construction of the test matrix, as well as day-to-day interaction with the test community during actual conduct of the tests to advise in the on-the-spot decision-making process."[14]

"The second DIVAD SSEB convened during DT/OT, and again the BRL developed the technical evaluation plan. BRL personnel served as board members in the area of system performance, NATO interoperability, and tactical suitability, and chaired the first two of these.

"In May 1981, the Source Selection Authority selected the 40mm Ford system to proceed into the maturity phase. BRL personnel continued to serve on related committees including the DIVAD NATO Interoperability Team which was tasked to determine the effects on system performance of the use of the higher-velocity U.S. ammunition in the NATO Bofors L/70 air-defense gun systems."[14] DIVAD was renamed the Sergeant York system.

The Sergeant York project was terminated in August 1985. Circa 1986, the BRL participated in AMC's Air-Defense Team that developed the follow-on to the York system. This was to be a non-developmental item which became the air-defense antitank system (ADATS). The BRL had little involvement with the ADATS missile system.[15]

Smart Rounds. The main problem for air-defense gunfire is to reduce the prediction error in the future position of the target. The actual prediction process is limited by the inherent random nature of target maneuvers. Reduction in the time of flight of the bullet helps by reducing how far the target can travel. Alternatively, increasing the footprint of the round allows larger open-loop errors to be tolerated.

Smart rounds offer a way to increase this footprint, and an effort to analyze their application to air defense was initiated around 1983. While the results were encouraging, there was little interest in developing a new gun system for air defense.

However, there was a considerable concern over the antitank guided-missile (ATGM) threat posed by attack helicopters, and the use of the tank's main armament for self-defense against these helicopters appeared quite practical. After all, the tank has a good fire-control system, the tank gun has high muzzle energy, the round is large, and the helicopters have limited maneuver capability. Circa 1985, the BRL considered the basic KE rounds, proximity-fuze HE rounds, and smart rounds to counter the helicopter ATGM threat.[15]

The use of proximity rounds was particularly appealing, since the tank already carried a multipurpose HE round, and such a round appeared to be quite capable against the helicopters. ATGM-delivering helicopters represent a growing threat to armored combat vehicles. The Army has been considering a concept in which an existing 105mm howitzer projectile would be coupled with a Navy-developed proximity fuze, resulting in a round which could be fired from the M1 tank in self defense against helicopter targets. To enable the Army to assess the viability of this proposal, the BRL developed simulation methodology. The behavior of the projectile was modeled, and its performance against a number of realistic helicopter trajectories was analyzed. The results indicate that, against non-stationary targets, the round would enhance the tank's capability.

This effort resulted in the proximity-fuze development for the 120mm M830A1 round for the Abrams tank, which has a shorter time of flight than its predecessor.[15,16]

ARMORED SYSTEMS

The Weapon Area Coordinator for Armored Systems was somewhat unique in the extent to which his efforts were related to the on-going efforts of the BRL. The armor/antiarmor business was a very major function of the BRL, and, for the period from the early 1970s until about 1986, he provided considerable coordination with customers in that arena and handled large amounts of customer money.

Abrams Tank. Don Menne was the first Weapon Area Coordinator. The position was created in 1973 by the director of the BRL to act as coordinator for armor for the development of the Abrams tank. (In June 1973, contracts for the M1 competition were awarded to General Motors and Chrysler. Prototypes were to be delivered in 1976.)[17] He was to see that the two competing contractors incorporated the BRL special armor into their designs properly, making sure that the basic armor concepts were properly adapted to cover a real vehicle with corners, holes, etc. He held the position until he became the Chief of the Vulnerability Methodology Branch. Larry Johnson suceeded him and held the position until 1987 when he became the Director of the Benet Laboratory.

We have more to say about the armor for the Abrams tank in the section on terminal ballistics.

Silver Bullet. In 1974, a number of the BRL laboratory chiefs attended a meeting in Washington at which the forthcoming Tripartite tests were discussed. Those tests, to be held in September 1975 at Shoeburyness, east of London, and at Kirkcudbright in Scotland, were to compete the U.S. 105mm XM735 KE tank round against the German 120mm and the British 110mm.[17] The attitude at the meeting was that the 105mm round would lose to its larger competitors.

However, the BRL concluded that the technology should exist to make the XM735 a winner and that everything possible should be done to demonstrate this in the competition. R. J. Eichelberger agreed to bankroll the effort, and the Silver Bullet Project was formed. A working group was set up that consisted of Bruce Burns, Bill Gillich, Len MacAllister, Art Thrailkill, and Harry Reed (chairman).

The group did the analysis and created concepts for KE rounds that could defeat the NATO Triple Heavy Target. While the context of a total round had to be considered (propulsion, sabot, flight configuration), the emphasis was on finding a penetrator that could be part of a practical 105mm round fired from the M68 cannon.

Essentially over the Christmas holidays, Gillich and Bloore made arrangements with the Y12 Plant at Oak Ridge, TN, to make the experimental tungsten and DU penetrators. This turned out to be an extremely valuable arrangement that gave very rapid response for the experimental efforts.

The first efforts focused on tungsten penetrators that were sheathed in steel. This approach was chosen because it was similar to the XM735 and modification of the XM735 seemed to be the best way to get to an early demonstration of a complete round. Also conventional wisdom said that the steel sheath would help keep the round together as it penetrated the complex target.

This first effort was a success. Several improvements were found for the tungsten penetrator: swaging, using more alloying material (10% rather than a few) and a longer penetrator. These were incorporated in the XM735, and it did, indeed, win the competition, but that is ahead of our story.

The group also determined that the steel sheath was more of a detriment than a help and a tungsten penetrator was inferior to a DU penetrator in its ability to remain intact as it penetrated a complex target. This led to the demonstration of a monolithic DU penetrator using a DU alloy with 0.75% titanium.

The Silver Bullet Group disbanded in 1975, and transferred the technology to the PEO-Armaments. The tungsten core went into the improved XM735 and the DU penetrator into a series of rounds for the 105mm and later Tripartite tests and the 120mm M829A2.

We leave the rest of the story for the section on terminal ballistics.

Line-of-Sight Antitank (LOSAT). In 1985, the BRL was asked to look at the concept for a high-velocity missile system that was proposed by LTV. The concept looked quite promising, especially with a large KE penetrator as recommended by Larry Johnson. The system appeared to offer a weapon that was quite robust, and the BRL encouraged its development with AMC, the Ninth Infantry Division, DA, and MICOM. In 1992, the system was under development as the LOSAT system.

Precision Aim Technique (PAT). PAT was originally conceived as a way to stabilize gunfire from helicopters. However, the technique seemed to have more application to cannon fire from tanks and infantry fighting vehicles, and that application was pursued. The effort was transferred to IBD, and the work is reported under the discussion of that division.

Tank Wars. Tank Wars I was created by Fred Bunn in the early 1980s to provide a tool that could assess the combat worth of detailed engineering changes in armored combat vehicles. It is an M-on-N combat model that can handle small homogeneous armored units. It is an event-sequenced model that has a statistical terrain sub-model and considers detailed descriptions of detection, firing, and killing processes. The friendly force is allowed to reorganize itself after each of a sequence of engagements to provide a representation of sustained combat.

Tank Wars has been distributed to numerous U.S. Government, foreign government, and private organizations.

Bunn has updated the model. "The Sustained Combat Model is a computer simulation of sequential engagements between mechanized combatants; one side of which is not resupplied. It has been routinely used at various military installations and by Government contractors for evaluating the combat effectiveness of tanks and other fighting vehicles. The systems being evaluated (usually U.S. systems) defend against one or more waves of attackers without resupply, or, on the attack, engage one or more defended positions without being resupplied.

"Each engagement is simulated in detail. The critical events in such an engagement include search, detection, selection, acquisition, firing, impact, damage, target disengagement, and reengagement. Interwoven with these events are motion events and intervisibility events. If desired, the program will print an event history for detailed study.

"The model includes three types of engagement scenarios, two generic armaments, three categories of functional losses, and two types of false targets. The three scenarios are attack, defense, and a meeting engagement. Guns fire KE or HEAT rounds while missiles may be guided-to-impact or fire-and-forget systems. Systems may fire while moving or may halt to fire. In either case, they may suffer loss of mobility, firepower, or both and may be catastrophically killed. In addition to the weapon systems being evaluated, there may be a number of active or passive decoys, and there are generally some false targets in the scenario."[18]

Fire Control. For some time, the BRL had been concerned about the limited performance of the original M1 tank's fire-control system against maneuvering targets. "Tracking tests were conducted with the M1A1 tank against simulated maneuvering targets. The results demonstrated unequivocally that predictions concerning the performance of the driven-reticle fire control system against such targets are correct. The BRL is being funded further to test and implement fire control modifications."[19]

The following is taken from an *Update* article by John Groff who developed a fix for the Abrams tank. "Since development and fielding of the M1 Abrams tank in the mid-1970s, the vehicle has experienced difficulties in successfully engaging maneuvering or evasive targets. In the early 1980s, Government field tests and analytical work isolated the problem to the gunner's primary sight (GPS) and azimuth turret drive and specifically the manner in which they were mechanized and linked together. After identifying the problem in 1982, the BRL proposed a design modification intended to greatly improve the tank's performance against these types of targets.

"In the current M1 Abrams and newer M1A1, the problem lies in the gunner's azimuth sighting system being slaved to the gun. The target lead solution is simultaneously fed into the weapon and into the sight. In the case of the weapon, the lead solution is processed through a network which reverses the direction of rotation. The net effect is that the gunner's reticle rotates in one direction and the weapon rotates in the opposite direction. At steady state, the rotation for the sight and weapon servo are equal in amount but opposite in direction. The mechanization is further complicated by the fact that the gunner's sight is physically locked to the weapon and moves with it. If everything functions properly, the gunner's reticle appears to remain on the target. For maneuvering targets, the lead solution needs to be updated frequently, which creates performance problems for the two servos, since the sight servo and the weapon servo have different response characteristics.

"The proposed BRL design modification reduces the mismatch between the two servos. This is accomplished by a relatively simple analog signal modification which now utilizes the residual error between the commanded ballistic computer lead solution and the actual weapon lead offset as an input to the azimuth weapon drive. Effectively, the weapon system attempts to null out this error. The overall effect is to increase the responsiveness of the weapon turret drive and reduce phase lag between the weapon and sight servos. In addition, the analog signal decoupling of sight from the gun also permits elimination of present ballistic computer software that contributes substantial time delays into the azimuth lead solutions.

"Analytical studies at the BRL indicated more than a 50% reduction on both weapon-pointing and gunner-tracking errors against either ground or airborne evasive targets. In addition, target servicing or firing opportunity increased by over 50% for the decoupled design over the present driven reticle system."[20]

Tests of the decoupled concept were successful, but the decision was made to use a gun-director system for the M1A2. This is a more complete (and more expensive) solution to the problem than Groff's and justifies his analysis that showed the need for a new approach. We might also note that one reason for looking at a decoupled-reticle concept was an earlier reluctance to invest in the more expensive gun-director approach.

Composites for Armor. "The MTL, Watertown, MA, in an effort to demonstrate the applicability of armor composites to combat vehicle structures, contracted with FMC Corp. for a reinforced plastic turret for the M2/M3 BFV (1984–87). It proved to be ballistically comparable, with a reduction in behind-armor debris (BAD), and was 16.5% lighter than the production turrets (BFVA1). MTL then contracted with FMC Corp. for a reinforced composite infantry fighting vehicle (CIFV) hull (1986–91) which demonstrated the viability of composites for a 30-ton vehicle and resulted in a weight savings of 25%.

"In 1992, the BRL decided that the promise of composites, as evidenced by the MTL/FMC Corp. success noted previously, justified a greatly enhanced effort in developing the tools to evaluate this new technology. The survivability of composite vehicle structures to likely ballistic and blast threats had to be determined. The composite-hull technology program was initiated by Barbara Moore to provide experimentation and algorithm development for medium-caliber (30mm) KE rounds, SCJs, EFP simulators, and the blast effects associated with artillery rounds and mines against composites and ceramic composite laminates. The algorithms will be delivered to VLD for incorporation into vulnerability codes and implementation in subsequent analyses. An engineering analysis was also included in this program which will determine the areas of research that were being neglected if composites become serious contenders for major structures in armored vehicles.

"Close coordination with other LABCOM laboratories and the research, development, and engineering center (RDEC) community was undertaken to ensure that researchers were aware of related efforts (structures; ballistics; nuclear effects; signatures; nuclear, biological, and chemical [NBC]; etc.), that appropriate composites technologies were being considered where relevant, and that contractual work undertaken by the RDECs could be evaluated."[21]

ARTIFICIAL INTELLIGENCE (AI)

Fire Advisor (FA). As part of its work in artillery fire control, the BRL became interested in the application of ES technology to the process of fire-support planning. NRL had developed a fire-support planning ES called Battle for the Marines. In 1983, the BRL acquired the Battle from the Navy. Initially, Paul Broome installed Battle at the BRL.

Later, Rich Kaste took Battle as a point of departure and developed a fire-support planning program for Army use. "FA is an exploratory-development project for fire-support management, with dynamic fire planning and traceable recommendations for tactical fire (TACFIRE) control in support of a maneuver brigade. It is an AI program (currently running on a Texas Instruments [TI] Explorer Computer) that is partially based on an NRL fire-planning program called Battle.[22]

"Among other things, FA provides optimal fire plans for a set of target arrays with consideration of both present resources, supply capabilities, and the need to be able to provide support against future targets. As with such ES programs, it provides alternative recommendations with rankings and with reasons for the particular choices. We emphasize that it is to be considered as an aid to decisions not a decision maker—the user being able to accept or reject the recommendations in whole or in part.

"While it is highly experimental, FA represents a potentially valuable tool for use in the complex, split-second decision environment of the battlefield. And the computing capacity should certainly fit in a HMMWV with plenty of room left over."[22]

FA was successfully demonstrated in 1989 as part of the Smart Weapon Systems (SWS) LABCOM Cooperative Program that is discussed in the section on smart munitions.

Air-Land Battle Management (ALBM). In the mid-1980s, DARPA asked SECAD to be the technical agent for the DA/DARPA ALBM initiative. This program was to develop AI tools for use in supporting decision processes at the corps and the division levels.

After an intensive evaluation process, the contract to develop ALBM was awarded to the Lockheed Corporation in December 1986.

"ALBM was to develop battle-planning decision aids to assist high-level battlefield commanders. ALBM, an applied-research program in AI, was sponsored by the BRL, DARPA, and the Communications-Electronics Command (CECOM).[23]

"First and foremost, ALBM was meant to be a planning tool for reducing the planning cycle at high echelons with no sacrifice of quality, allowing increased planning time and preparation at lower echelons; those echelons and units which actually engage the enemy in combat. Current Army doctrine at the corps level shows a 72-hour area of influence; that is, that time the commander needs to fight the current battle. In essence, this is the time required by the corps commander to do his planning. Each succeeding subordinate unit below corps has roughly one third to one half of the planning time of its superior unit available for planning and preparation. Viewed on a 24-hour corps planning cycle, a division would have 12 hours of planning time, a brigade 6, a battalion 3, and a company 1 hour. These times are ideal and seldom realized at the echelons below corps. Additionally, there is really never quite enough time to do planning. It should also be noted that units at and below brigade do not have planning staffs per se.

"The steps of the planning process themselves consist of (1) generating courses of action, (2) evaluating courses of action, (3) selecting a course of action for implementation, (4) preparing and executing orders, and (5) monitoring the situation (assessing the execution of the orders).

"To implement the planning process described above, ALBM developed a prototype system called FORCES. ... FORCES contain three loosely coupled, cooperative expert (knowledge-based) systems. They demonstrate cooperative planning between levels of command (at corps and division), and between elements of the Sigma Star (maneuver and fire support). ES are the corps maneuver system (MOVES-C), the division maneuver system (MOVES-D), and the corps fire-support system (FIRES-C) for use by the fire-support coordinator.

"Each of the knowledge-based systems in FORCES, that is MOVES-C, FIRES-C, and MOVES-D, [is] expected to be able to operate independently of [the others], if necessary distributively and cooperatively. Their interaction is meant to mimic the interactions among staff officers in a Tactical Operations Center (TOC).

"In order to implement FORCES, a customized development tool, STAR, will be constructed. STAR will provide the basis for FORCES, being both a knowledge-engineering tool and a communications tool. New FORCES nodes will be able to be created and linked to existing FORCES nodes through STAR."[24]

"ALBM runs on a set of networked workstations. Each workstation consists of a Symbolic Lisp Machine, containing several ES,and a Silicon Graphics Machine containing terrain information plus friendly and enemy troop information. For example, the corps-level maneuver workstation, called MOVES-C, consists of ES with appropriate knowledge of corps-level maneuver planning, plus terrain data and knowledge bases.

"The computer terminals are linked together; presently [1989] one is programmed using the Training and Doctrine Command (TRADOC) Common Teaching Scenario, which is Europe based and Army approved. This terminal provides the decision-making choices. The other terminal shows color map displays and plays out the red-blue attack scenario. Given a proposed threat, mission, and commanders' guidance, the ALBM system generates from one to eight courses of action, including positioning of maneuver and fire-support battalions. Each course of action is evaluated by the ES tool called the Heuristic Combat Evaluator. Evaluation involves battle simulation, and the outcomes are quantified to show the results of alternatives. The recommended course of action is presented to the corps, or division, planner as a doctrinally sound solution, which can serve as a start-point for his further analysis. ALBM can then be used to generate the operations order from the chosen course of action, including several variants, in 2 hours vs. 12 hours when done manually.

"Expertise for the system comes from instructors at the Command and General Staff College, Fort Leavenworth, KS; the Field Artillery School, Fort Sill, OK; and the Intelligence School and Center, Fort Hauchuca, AZ. The system was designed by a contractor team led by the Lockheed Austin Division which includes the Advanced Decision Systems (ADS), Titan, BBN, and Intellicorp. Fire support at division is being performed by GE. ALBM software sites exist at the above schools and at the BRL and CECOM."[23]

At the end of 1988, DARPA added some additional tasks to include an intelligence node (Lockheed and ADS), divisional fire support (GE), and a Red ALBM for the Soviet equivalent of a corps (Lockheed, SAIC, and ADS).[25]

By 1989, the project had done a good job on fire planning at corps level and a pretty good job on maneuver planning at corps level. Division-level maneuver planning was only done *stand alone*, i.e., the system could create a valid plan for a division but it was never demonstrated whether a number of divisions could iterate their plans with corps. By middle-end of 1990, the main effort was completed; all the program objectives were met.[25]

By 1991, integration had been accomplished among the intelligence system, Red ALBM, corps maneuver, corps fire support, division maneuver, and division fire support. The ALBM project has transitioned in late 1990 to an advanced technology transition demonstrator (ATTD) at CECOM, which is in progress (1992).[25]

The ALBM program has developed many tools, some of which are still useful including: the Procedural Reasoning System developed by SRI and modified by ADS and the war gamer, Heurista Combat Evaluator, developed by BDM, ADS, and the soldiers at Fort Leavenworth, KS.[25]

ARTILLERY

The Artillery Team was originally organized with Orrin Kaste as its Weapon Area Coordinator. Barry Reichard became the area coordinator in 1985. The team had several major interests. For one thing, there were innumerable issues on new rounds, new charges, new fuzes, etc., that had to be coordinated with the BRL. There were efforts on advanced weapon concepts. Finally, there was a considerable interest in artillery as a large-scale weapon system which came to dominate the efforts of the team.

The concern for the large-scale system came from studies that showed that the main drivers for modern artillery were its survivability in a counter-battery environment and its ability to cope with moving targets. Its survivability appeared to be strongly related to its ability to change position rapidly while still maintaining its ability to shoot accurately and to keep control of its assets. The ability to cope with moving targets in a fluid battlefield appeared to be related to its having suitably smart munitions and a fire-control system that could respond fast enough to allow the targets to be engaged in a timely and effective manner (within the limited footprints of the smart munitions).

"In 1979, the BRL chaired and coordinated a working party involving a number of agencies to provide system analysis in support of the enhanced self-propelled artillery weapon system (ESPAWS). Much of the work centered around conceptual 155mm direct support systems capable of performing on-board technical fire control, pointing the tube automatically, and firing 18 conventional rounds (or 6 guided rounds) in less than 2 min. After firing such a 2-min burst, the howitzer moves to a new firing position. Simulations of two such battalions showed very favorable results, but when the analyses were extended to the case of seven battalions in support of an armored division, the results were most disappointing at first. However, after the allocation rules were changed, the results were very impressive—pointing up the need to consider artillery in a full-force context with the rules of its application considered as part of a total artillery weapon system. The final results of the study showed that gun-and-run tactics could reduce losses to counter-battery fire dramatically, that fire-and-forget munitions could produce armored vehicle kills by several fold while reducing the number of rounds correspondingly, and that fire control must be highly responsive and tailored to the effective utilization of the division assets."[26]

This study shaped the efforts of the Artillery Team. Since the Infantry Team became heavily involved with smart munitions per se, the Artillery Team focused its interest on issues related to the fire-control issue.

Modeling. Although much of the modeling by the team eventually involved the use of interactive computing, there was also a need for more conventional models. For example, Ed Stauch from AMSAA participated in the previously mentioned study and provided the modifications to the Artillery Fire-Support Model (AFSM) that were needed to look at alternative fire-control concepts.

Austere Field Artillery Concepts Effectiveness (AFACE). There was also a need for models tailored to the needs of the team. "An AFACE model was developed by Alan Downs during FY75–76 in response to a need for a model that could quantify issues such as the efficacy of increased range, the effects of massing fire, and the relative merits of various approaches to achieving improved technical performance of artillery weapons.

"In 1987, AFACE-2 was created. AFACE-2 represents an engagement between two forces, each containing armored units, ATGMs, artillery, and USAF support. During the engagement, one side attempts a breakthrough with its reserve armor, and the other side counters that assault. AFACE-2 has been used in a number of studies, including a study of the effects of smoke, a study of various options for countering an unfavorable (Red) artillery imbalance, the Army/USAF NATO fire-support requirements study (1979), and the ESPAWS study."[26]

Fire-Control Simulation (FCS). "To assess results obtained in the artillery control environment (ACE) program [see respective section] in a larger tactical organization and to address other areas of interest, the BRL undertook development of an analytical tool called the BRL message-processing model (BRLMPM) (Hirschberg 1983). BRLMPM is a time-based simulation capable of processing all the messages generated by the field artillery in support of a maneuver brigade for any period up to 24 hours. It is a heavily input-driven FORTRAN computer code that traces, step by step, the flow of digital messages through the artillery communication network and tracks net and unit busyness and throughput. A number of studies were conducted with BRLMPM (Downs and Hirschberg 1982; Downs 1985, 1987). In 1982–83, it was used as an analysis tool by the AFATDS modeling working group that was established by the Office of the Project Manager-Field Artillery Tactical Data System (OPM-FATDS) to examine and evaluate the methodological tools available to address various issues with the developmental AFATDS. Although BRLMPM was used to establish a baseline case, its inability to handle the link-switching and message routing required in AFATDS studies demonstrated that a stronger analytical tool was needed. BRLMPM was therefore shelved, and thought was devoted to the types of tools that would be needed to address fighting-level command and control (C2) concepts of the future. This marks the beginning of the BRL FCS concept.

"ACE developers turned their expertise toward the application of both military and computer science techniques to develop abstractions of military concepts that can be referenced and processed by state-of-the-art computers and associated procedures by which information can be distributed on the battlefield. This effort was initiated as part of the CECOM/DARPA funded Army/DARPA Distributed Communications and Processing Experiment (ADDCOMPE) effort and evolved into what the BRL calls the Information

Distribution Technology (IDT) (Chamberlain 1990). The FCS was never a part of the IDT effort, but it was planned that the FCS should be able to support IDT activities. Since IDT was being developed around a very small number of nodes, it [was] desirable to know the implications of applying the emerging techniques to a reasonable slice of the battlefield. In order to address those problems deemed most crucial to IDT, FCS was developed to encompass a wide variety of technical and tactical situations.

"FCS was designed so that various segments of the simulation can be easily replaced whereas others will remain fixed. Those segments that will routinely be replaced represent basic input data (e.g., net, unit, and transmitter information) and those variables that specify the conditions under which the simulation will be run (e.g., the mission-initiation window and the number of missions of specified type to be used to drive the simulation). The conditional variables are primarily stored in the various sub-elements of FCS.

"FCS was employed in 1992 in its first formal exercise, a study [of AFATDS by Downs and Joel]."[27]

Variable-Resolution Terrain Model. While this effort was not part of the artillery effort, it does fit into the modeling category: so we treat it here.

Joe Wald and Carolyn Patterson have created a variable-resolution terrain model that depends strongly on the concepts of self-similarity and minimum-desired resolution. While the key feature of the approach is the concept of self-similarity, "this idealization can be relaxed for practical applications. For example, it may be argued that, at least for certain terrain types, smaller hills erode faster than larger ones. If that is the case, one can introduce a scale-dependent decay factor that smooths out the smaller hills and fills in the smaller valleys.

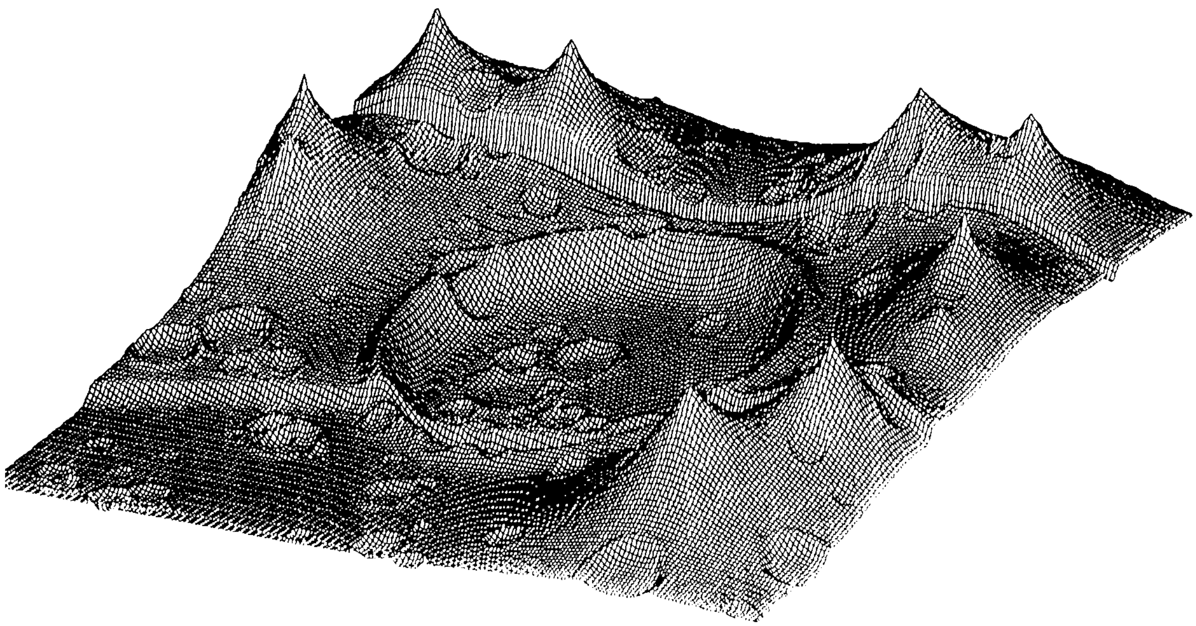
"The variable-resolution terrain model ... was developed under the umbrella of the nested system of battlefield simulation models (NSOM). The NSOM is conceived as a fully integrated, fully automated set of event-sequenced, Monte Carlo, combined-arms computer simulations, each of which models the battlefield at a distinct command level. The key feature of the NSOM is the *time history injection process*, which links simulations at adjacent command levels by providing the commander at the higher-command level with the ability to interact, during the execution of the higher-level simulation, with the dynamically unfolding lower-level battle.

"At the higher-command levels, terrain is used in the modeling of such features as the positioning of large formations of troops, selecting approximate locations for observation posts, and the estimation of likely avenues of approach of large enemy formations. For these purposes, a relatively low resolution is required.

"At the lower-command levels, terrain is used in the modeling of such features as the positioning of individual weapon systems, the creation of overlapping fields of fire for small units, and the calculation of lines of sight in the (short-range) direct-fire battle. For these purposes, higher resolution is necessary.

"In the NSOM, we need the ability to model a large battlefield at low resolution and still retain the option of looking at smaller portions of the battlefield, as necessary, at higher resolution. Hence, the development of a variable-resolution terrain model is essential."[28]

Extended Range. "Circa 1978, the BRL was involved in a couple of contractual efforts with the Space Research Corporation on new ammunition concepts for the 8-in howitzer. These included the [full-bore] extended-range XM762 projectile and the saboted M708 projectile."[26] The latter was to demonstrate the feasibility and practicality of achieving extended



A Sample From the Variable-Resolution Terrain Model, Cratered Landscape.

range by adding a sabot to an existing 155mm projectile.[29]

"In the case of the XM762 round, low drag was to be obtained through the use of a tangent-ogive body, a long boat tail, and a discarding non-metallic rotating band. While the discarding attribute of the rotating band was itself discarded at the request of the user, the glass-filled rotating bands provided full spin and good-to-excellent obturation over all charges and from -65 to +145° F. Also, the original concept called for a discarding section of the boat tail to ensure adequate stability at the lower zones; this concept was also abandoned in favor of a shorter fixed boat tail with a concomitant loss of 5% in maximum range capability."[26] This projectile concept, which used a nubbed full ogive, was ultimately developed and used as an extended-range 155mm round by the Dutch artillery.[29,36]

"The saboted round for the 8-in howitzer used the developmental XM708E2 155mm projectile. The forward sabot consisted of a four-piece aluminum ring that was retained by a stainless-steel bore-riding band. The rear sabot consisted of four aluminum sections that were retained by the copper rotating band. Firing tests were very successful, validating the basic concept and demonstrating a 40% increase in range over that achieved by the standard M106 8-in projectile fired at the same maximum chamber pressure."[26]

Human Engineering Laboratory Battery Artillery Test (HELBAT). There has been a sequence of HELBATs over the years. These were joint user and developer exercises that took quick looks at procedures and new concepts in technology for artillery. They were jointly chaired by the Director of HEL and the Director of Combat Developments at Fort Sill, OK. The BRL was very active in providing technical support for HELBATs (especially numbers 6, 7, and 8) and was represented on the HELBAT executive committee and working group. HELBAT 7 in 1979 and HELBAT 8 in 1981 were instrumental in introducing new fire-control concepts to howitzers and to the artillery system in general. Interest was so broad in these exercises that "during this general time frame, the BRL was also serving as the National Leader of The Technical Cooperation Program (TTCP) [action group] WAG-4 (1975–78) and follow-on WAG-6 (1979–82), the purpose of which was to address artillery total-system issues and to involve the other TTCP countries [Canada, the United Kingdom (UK), and Australia] in HELBATs 7 and 8."[30]

In 1977, the Field Artillery School expressed interest in the exploration of possibilities for integrating and automating the laying and fire-control systems in the field-artillery battery. Harry Reed chaired a working group to assemble an experimental howitzer system (battery-level automated-system technology [BLAST] program) that could be tested in HELBAT 7 as the number-one priority concept area. Two M109 155mm self-propelled howitzer test beds (HTBs) were developed: one by ARRADCOM using the Canadian gun alignment and control system (GACS) and one by industry and the HELBAT team featuring an inertial-based system for aiming, referencing, and positioning. The demonstration of the latter HTB in HELBAT 7 marked the first time that inertial navigation had been used successfully for howitzer fire control in live-fire, operational tests. This in turn led directly to the howitzer extended life program (HELP) and to the fire-control concepts embodied in the new Paladin howitzer.[26,29,36]

During HELBAT 7, Barry Reichard and Sam Chamberlain[31] were responsible for evaluating and guiding improvements to the fire-support team's (FIST) digital-message device (DMD). Later, the BRL led an effort to reprogram FIST DMD to perform on-board howitzer fire direction. In HELBAT 8, this was demonstrated along with an improved HTB to become the first autonomous howitzer used in field operations.[29,36]

"HELBAT 8 was the first HELBAT to include artillery fire-support control (FSC) as a primary issue. The BRL's primary effort was to spearhead the planning and control of the FSC part of HELBAT 8. The BRL developed a 300-page document that showed the flow of digital-message traffic."[32] This document showed all the messages that would flow back and forth through the artillery network during the conduct of typical missions such as the conduct of observed fire. This was the first time that these details had actually been laid out in this form, which led to a new appreciation for the complexity of the functions.

Artillery Control Environment (ACE). Circa 1980, it was found that the students in computer science at JHU had developed a multiplayer war game called *Search* for interactive computers. Any number of players could log onto the computer and use their terminals as display panels for their space ships. They engaged in mutual combat using the graphics on their terminals for their fire-control displays. *Search* ran on the UNIX computer (the BMD-70) in SECAD, and it seemed reasonable that the terminals could just as well be representing pieces of digital equipment in the artillery C2 network and that the computer could be managing fire missions rather than a war in space. The computer could be part of the communication network and supply the driving scenario and also surrogate players—reasonably smart programs that could perform the functions of missing players well enough that the system should not notice the difference. Finally, with proper interfacing, real military terminals and computers such as BCS could be integrated into the system. Thus was born ACE.

"Through simulation, tactical-equipment availability problems can be avoided; *what if* changes can easily be incorporated and evaluated; and training spin-offs are possible. Through the accommodation of actual equipment, the time-consuming development of simulator programs can be avoided; hybrid mixes of actual and simulated conceptual equipment are possible; and automated scenario-loaded testing can be performed."[26]

To allow military hardware to be used with ACE, Mark Kregel created computer modems called bit boxes "to interface the frequency-shift-keying protocol such as used in the Army's TACFIRE network with the RS232 protocol as used in commercial computer equipment. The bit boxes were a best seller. They made experimentation with military communication equipment much easier since commercial computer equipment could be included for monitoring, for running the experiment, and for providing surrogate nodes. The BRL could not keep up with the demand for bit boxes and for their support; so Magnavox picked up the item and produced a commercial version, which remains quite popular."[26]

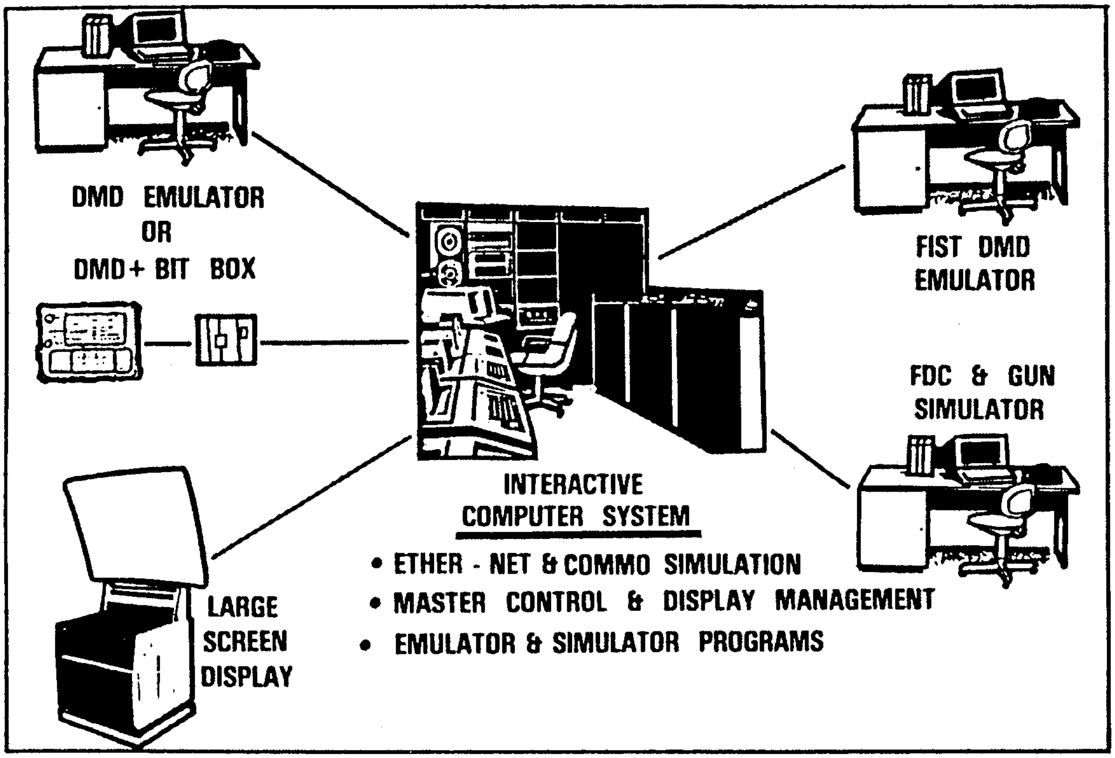
A command-post experimental facility was created in HEL that included mock-ups of various artillery fire-control nodes such as the FIST vehicle. ACE was used as the backbone of the facility—HEL supplied the computer hardware and the BRL supplied the software. "In 1983, the first experiment in the facility was a FIST experiment in which a number of FISTs were buttoned up in their (simulated) vehicle and fed electronic messages via ACE to their DMDs. The ability of the teams to perform in periods of varying intensity of message traffic was monitored and evaluated statistically. The experiment also identified seven key problems for which Magnavox incorporated software modifications in the production of FIST DMD."[32]

The Artillery School at Fort Sill, OK, supplied a number of FIST crews for this experiment. When the Commanding General (CG) of Fort Sill saw the ACE facility, he asked the BRL to help him replicate it at Fort Sill for training. The BRL helped transfer the technology, and "it is being exploited at Fort Sill for training."[30]

In 1983, the Army conducted a test of the FIST concept at Fort Riley, KS. ACE was the only available means to monitor the digital-message traffic, and so it was used for that. In addition, the BRL was asked to develop a statistical design for the experiment. Jill Smith developed that design, went to the field to implement it, and coordinated the use of ACE. "The local ACE facility was used to analyze the data from a massive field test (FIST Force Development, Training, and Evaluation II) of the artillery digital C2 system that was held at Fort Riley in 1983. Note that bit boxes and recorders were used on site to gather the actual digital data from the radio network for later replay in ACE. Total-mission message traffic was aggregated, and time lines, etc., could be inferred. In addition, several major TACFIRE software problems were identified, and detailed recommendations were provided to the FATDS Software Support Group."[32]

The data base that resulted from the ACE analysis of the Fort Riley experiment was the first such available and proved invaluable in studies of artillery C2. "Other highly significant research achievements by the BRL include the design of a new, automated method of monitoring and analyzing TACFIRE direction system performance. This unique capability for generating TACFIRE data bases for subsequent message recovery and analysis is the most extensive anywhere for C2 and AI research in battlefield management."[12]

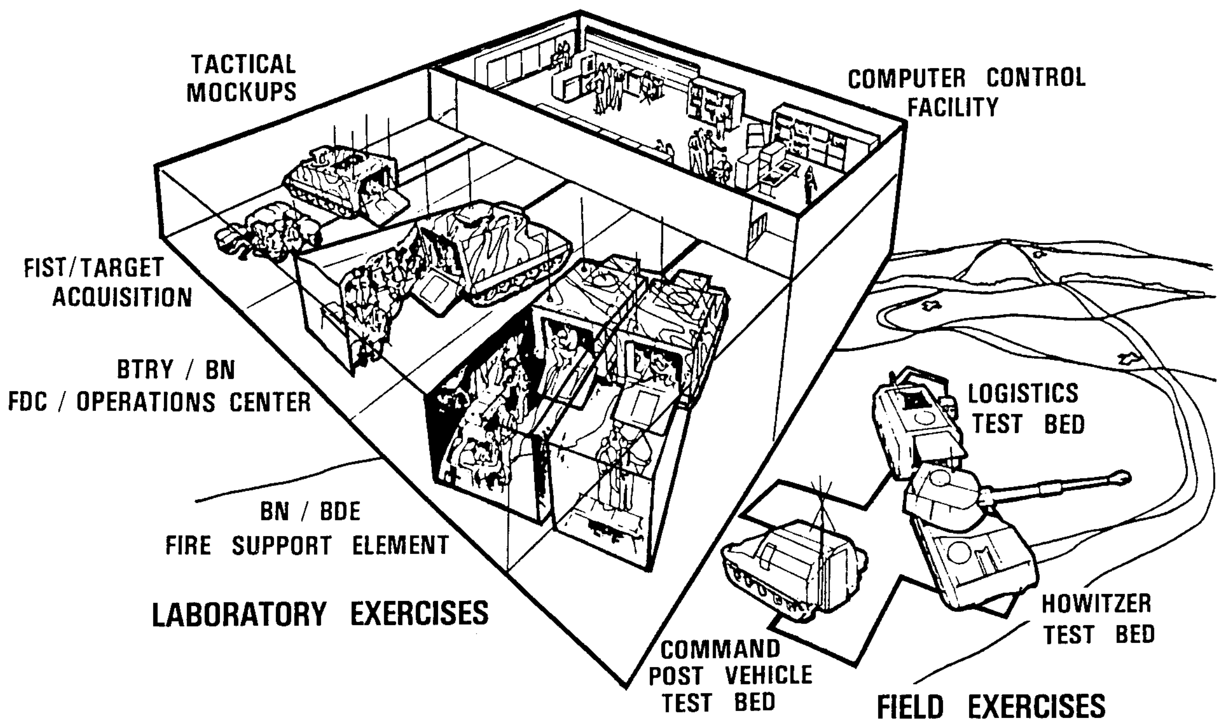
In 1985, the BRL "used ACE to exercise battalion fire-support officers to develop statistical data in two areas: network utilization of the fire-direction center (FDC) to



ACE FSC Simulator Technology.

howitzer-crew links and decision data associated with the allocation and distribution of artillery. The latter data were used in research programs to combine ES technology and other programming techniques to enhance the performance of the artillery network and in particular the fire-direction officer's (FDO) performance."[32]

"This experiment was designed to investigate two separate areas simultaneously but independently: TACFIRE-direction decisions by the FDO and communications between BCS and simulated howitzers. For this experiment, a real tactical BCS was used; a commercial automatic data-processing device was programmed for the FDO terminal; and a special bit box was built to interface the gun side of the BCS to the commercial computer. The commercial computer simulated: target-acquisition nodes, battalion FDC, and multiple howitzer units. The operators for the experiment were seven officers provided by Fort Sill. The factors for the FDO portion of the test included: the FDO, target type and size, ammo basic load, and control, i.e., adjust fire (AF) or FFE. The factors for the BCS portion included: number of howitzers, number of simultaneous missions, and control (ratio of AF to FFE missions). We learned that FDO decisions were only weakly tied to the factors we chose, i.e., it is a lot more complex than we thought, and we continue to work with PM-FATDS and Fort Sill on this allocation-and-distribution-of-fire (ADF) problem. We collected valuable information on net utilization at the battery level which is critically important to making decisions on autonomous howitzers and AFATDS



HELBAT/ACE FSC Research Facility.

development and networking. We also provided an extensive report on alternative network architectures for Fort Sill to consider; this included supporting data provided by exercising BRLMPM to depict total-system operation. These data were much appreciated by Fort Sill communications folks because up to this time there were very little hard data available."[30]

As a result of the last experiment, "two important data bases were collected: (1) the first definitive statistical data base on baseline battery FDC-to-gun digital operations to document existing net loading and (2) an experimentally controlled data base on ADF decisions to provide the knowledge necessary to explore ADF decision-aid development. The latter data base was supplemented by administering a comprehensive questionnaire that provided a wealth of important data for the BRL, USAFAS, and the AFATDS contractor."[11]

While the specific ACE program faded away in the late 1980s, HEL is using (1992) ACE derivatives in conjunction with experiments on a howitzer test bed. The computers in the laboratory have radio contact with the test bed which can be actually firing rounds on the firing range.

Also, the BRL has used (1992) some of the hardware (bit boxes) and software to study communication protocols,[33] and some of the experience with ACE has evolved into other efforts in artillery C2 as discussed in the next section.

COMMAND AND CONTROL (C2)

Here we see ACE and other work in SECAD on networked computing coming together toward work on artillery C2 and on C2 as a research area.

Information Distribution Technology (IDT). In the early 1980s, AMC became interested in a larger version of the HELBAT exercises. An AMC thrust program demonstration was conceived that would allow new technology thrusts to be examined by large field experiments. After much effort in AMC, including much by the BRL, the program collapsed under its own weight; the resources required for such experimentation were just too great.

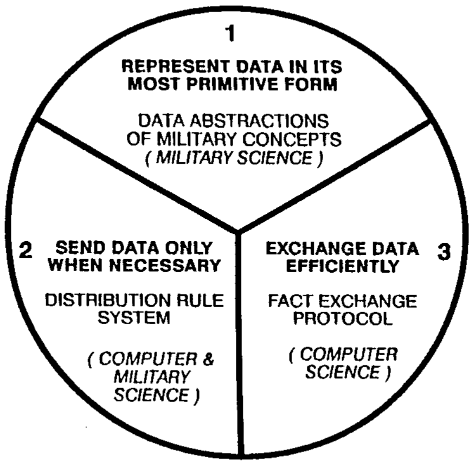
However, "One good thing that came out of the thrust program was the BRL's involvement in ADDCOMPE. The AMC Thrust Manager ... asked the BRL to submit a C2 concept, and that was the beginning of what we now call IDT. The official purpose of ADDCOMPE was [to] establish a joint program of research, development, experimentation, and evaluation to explore concepts for enhancing tactical C2 performance and survivability." The products of the program were to go into a XVIII Airborne Corps test bed.[30]

The BRL's objective in ADDCOMPE was to "Investigate and develop innovative computer-science concepts for highly flexible communications-efficient distribution of tactical information. We agreed to demonstrate and evaluate the potential of these new concepts through dynamic fire-support management applications at the fighting level (brigade and below). The initial IDT concepts were conceived by Sam Chamberlain, Mike Muuss, and Joe Pistritto. The basic idea was to abstract military concepts into *facts* (terse terms that computers can manipulate) and to use a free-form fact base and a modified TCP/IP data gram protocol to send data. A major selling point was also to return some voice-type communications features to the data-distribution world; these advertised features were: (1) overhear or eavesdropping, i.e., use all the information broadcast on the net that you need even if not addressed to you; (2) multicast without repeated transmissions, i.e., send to more than one address with surety, i.e., with acknowledgements from each addressee; and (3) receive only or radio silence, i.e., the ability to receive information without sending even acknowledgements with a bulk acknowledgement after you come out of radio silence. The final key feature was capability profiles (CAPS), which defined the node or workstation capability and interfaces (and later data-distribution rules to automatically distribute information to the levels designated by the commander); this was like a fighting unit's software standard operating procedure."[30]

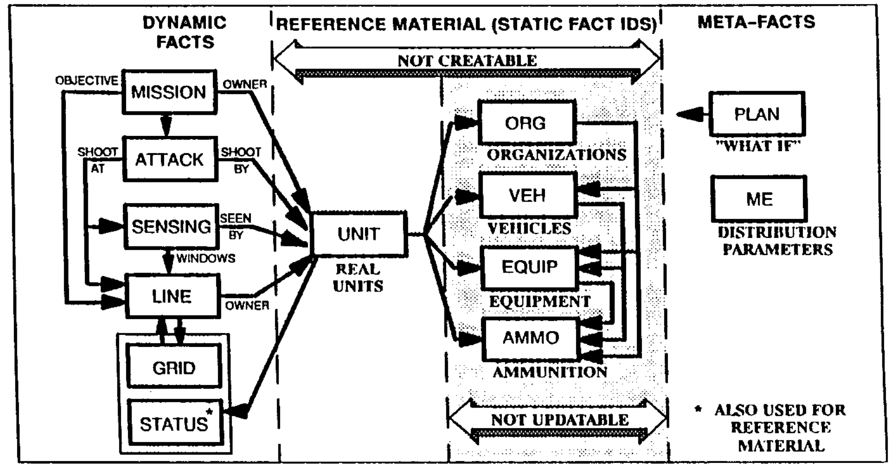
Although the ADDCOMPE project was terminated, the work on IDT continued under Chamberlain's leadership. "The primary goal of the IDT project was to develop tactical computer and communications network technology to support *fighting level* commanders and soldiers who must contend with highly dynamic, unpredictable, and hostile combat environments. Current tactical C2 systems have two key shortcomings: (1) the information is not in a form that computers can readily manipulate, and (2) with the use of inefficient information exchange techniques and protocols, information often exceeds the maximum bandwidth available on VHF-FM and HF-AM radios required by lower-echelon units.

"The IDT approach to data distribution incorporates several new concepts in an effort to explore techniques that provide more flexibility and survivability to the information distribution function in C2 systems. Flexibility is enhanced via a free-form distributed fact base (DFB) and CAPS that embody the standard operating procedures for the communications between nodes. Survivability is enhanced through minimizing electronic emanations by: transmitting only significant information (as

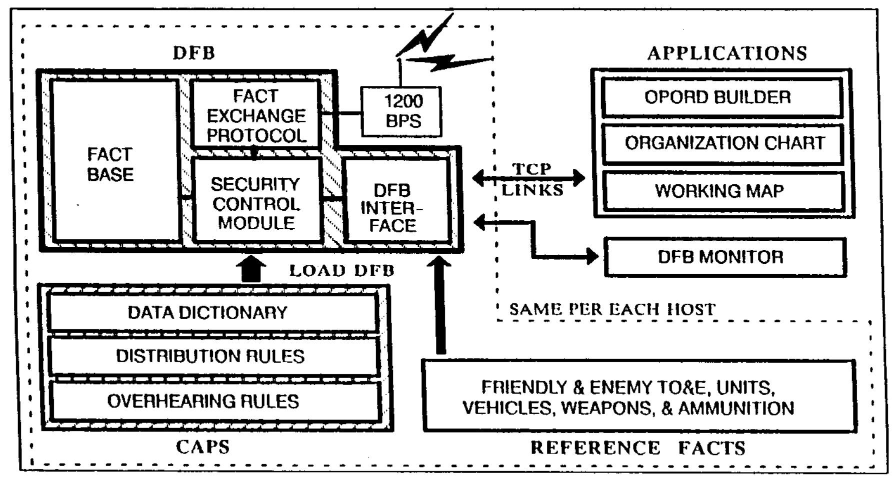
BRL INFORMATION DISTRIBUTION TECHNOLOGY RESEARCH



A BASIC APPROACH TO REALISTIC TACTICAL INFORMATION EXCHANGE



CANONICAL LIST OF FACT TYPES



SOFTWARE ARCHITECTURE OF PROTOTYPE SYSTEM

IDT.

determined by the commander), transmitting information in its most terse form, taking advantage of overheard information, providing a *radio silence* mode of operation, and using multicast transmissions when possible.

"An experimental prototype information-distribution system (IDS) was successfully implemented and demonstrated during the SWS demonstration [see next section] in September 1989. During this time, IDS was used to integrate several sophisticated application programs over standard Army FM radios: the HDL information processor (IP), the Electronic Technology and Devices Laboratory (ETDL) commander's intelligent display (CID), the HEL smart-howitzer automated management system and the BRL FA system."[34]

After it was demonstrated in the SWS LABCOM Cooperative Program, the IDT was briefed to a variety of offices with responsibility for programs that involve C2. The response was uniformly enthusiastic and encouraging, and IDT is finding its way into a number of programs, which include: command, control, communications, computers, and intelligence (C4I) for the Warrior; the Army tactical C2 system; the Joint Theater Missile Defense Program Office; and the advanced field-artillery tactical-data system.[35]

After surveying all on-going C2 efforts, the Architecture and Integration Division (J6I) in the Joint Chiefs of Staff "has recognized IDT as the only new basic Army C2 technology concept work that offers hope for future interoperability." J6I resulted from the advent of major joint service and international C2 interoperability problems encountered in Operation Desert Shield/Storm, and C4I for the Warrior is their mission.[36]

A "major tactical computer-science accomplishment was the completion of a general translation program to convert existing bit-oriented messages into a data kernel representation common to all battlefield functional areas. A general demonstration suite of software was transferred to CECOM on 8 May 1992 to provide an ever-ready IDT demonstration at Fort Monmouth, NJ. This demonstration highlights the translation program and the track reporting capabilities of working map as well as providing a general overview of IDT concepts. Research was also conducted into the possibility of *teaching* a compression algorithm the general properties of large numbers of messages and the algorithm then being able to *remember* these properties and compress/uncompress individual messages.[29,36]

The "AFATDS design scheme now relies heavily on several concepts and technologies developed in the IDT program, e.g., exchange of information in the form of data base (fact)operations and automated data distribution based on rules."[29,36]

Apropos of AFATDS, Ginny Kaste has completed a "project to evaluate AFATDS communications performance over just combat net radios (CNR) since the [newly emerging] digital radios will not be fielded in time for AFATDS fielding. This also provided an opportunity to develop much needed statistically sound baseline data on CNR. The experiment, designed to allow statistical analysis of several critical factors on throughput and delay using a 4-node set-up, was conducted in the August–September 1991 time frame. This marked the first use of the research facility for the experiment and FCS for analysis over an entire AFATDS brigade C2 network. ... A unique sidebar is that the logical data base technique was extended as a new approach to and greatly eased the job of collecting and analyzing large volumes of network data."[29,36]

IDT also applies to air defense. In 1991, "the BRL demonstrated the use of low-bandwidth radios to support air-defense operations of a TOC in a realistic scenario. Air-track reports producing a coherent 144-track picture were reduced from the previously required 90,122 reports to just 5,277 reports." This represented a compression of the data by 94%.[37] Then from 1992, "IDT air-defense applications were demonstrated in the BRL-HEL cooperative Human Engineering Laboratory Counter Air Program (HELCAP) showing a remarkable 96% reduction in air-defense message traffic during an 83-min aviation air-defense scenario."[29,36]

Mathematical Research. In addition to work in AI, a group in SECAD has been conducting research in mathematical topics associated with Army problems. The following items are typical:

Reduced Delay Methods for Channel Sharing. "In an attempt to increase throughputs and reduce delays, the scientific community has developed, simulated, and analyzed a great number of protocols. All of these work on one of two principles: (1) reduce the probability of collision (collision avoidance); and (2) grant priority of channel use to nodes which sent colliding packets (collision resolution). Each of these is based upon sensing collision, implementing some algorithm for delaying transmission of subsequent packets, then retransmitting the colliding packets in a prescribed order and with specified delays.

"In 1985, Massey and Mathys had shown, in principle, how to use error-control coding to extract information from packets in collision without retransmitting anything.

"In a cooperative effort, Brint Cooper (SECAD) and Brian L. Hughes (Professor of Electrical and Computer Engineering, JHU) have addressed this problem with the following results: (1) derived the capacity of the multiple user channel (T active users out of a population of M > T); and (2) developed a family of linear codes that permit unique decoding of up to T colliding packets on the real adder (multiple user) channel; (These codes achieve the capacity of that channel.)"[38]

Groebner Bases and Algebraic Coding Theory. "The foundation of successful distributed systems lies in a complete understanding of the noisy channels from which the nets are built. Accordingly, Cooper's research includes studies of these channels and of coding/decoding methods for managing the data-transmission errors which channel noise and interference induce. Of special interest is an algebraic system which has implications for codes which may be developed in the distant future, exploiting some mathematics, which is receiving much attention in related communities.

"So far, his investigations have revealed a number of interesting parallels between present (non-coding) applications of Groebner bases and possible uses in algebraic coding and decoding. His first result was to discover a technique for constructing shortened cyclic codes of any length (useful in many applications of formatted data communications) using Groebner basis methods. The significance of this result is the ease with which these methods can generalize existing results in coding.

"More significant is his recent work on the direct decoding of Bose-Chaudhuri-Hocquenghem (BCH) error-control codes. Existing decoders for this powerful code family solve a system of non-linear algebraic equations by an indirect method which involves some searching techniques. He has formulated this decoding problem in a more direct manner using Groebner basis techniques. He has solved a few small decoding problems, showing that the technique works, and demonstrated the existence of a *single-step* decoder. The possible impact includes the development of simpler, lower-power decoders for codes presently used on high-performance Army digital links. The significance of this work has received international recognition as evidenced by invited presentations at universities in the UK, by papers at two international conferences during 1990, and by publication in an international journal in 1991."[38]

Soft-Decision Decoding of Iterated Error-Correcting Codes. "Driving the error probability to zero requires very long codes. Unfortunately, the information rates of most known families of codes also move toward zero with increasing codeword length. The design of codes and decoding algorithms with low-error probability and non-zero information rate remains largely an unsolved problem.

"In one successful approach published by Cooper in 1978, very long codes were constructed with arbitrarily small decoding-error probabilities and with non-zero rates of information transmission.

"Cooper has shown that rank decoding provides coding gains of 2–4 dB. This represents the amount by which the transmitter power must be increased to achieve the same error probability without decoding. While other code/decoder combinations have achieved 6 dB or more, they do so at the expense of severe decoder complexity, resulting in more complicated, less maintainable equipment that may require more battery power than simpler techniques.

"He has completed a survey of the important soft-decision decoding techniques from which promising ones are being selected for the decoding of the improved iterated codes. Recently, he has discovered that a class of efficient codes, the self-orthogonal-array codes, has properties which permit their decoding by a modified rank-decoding algorithm."[38]

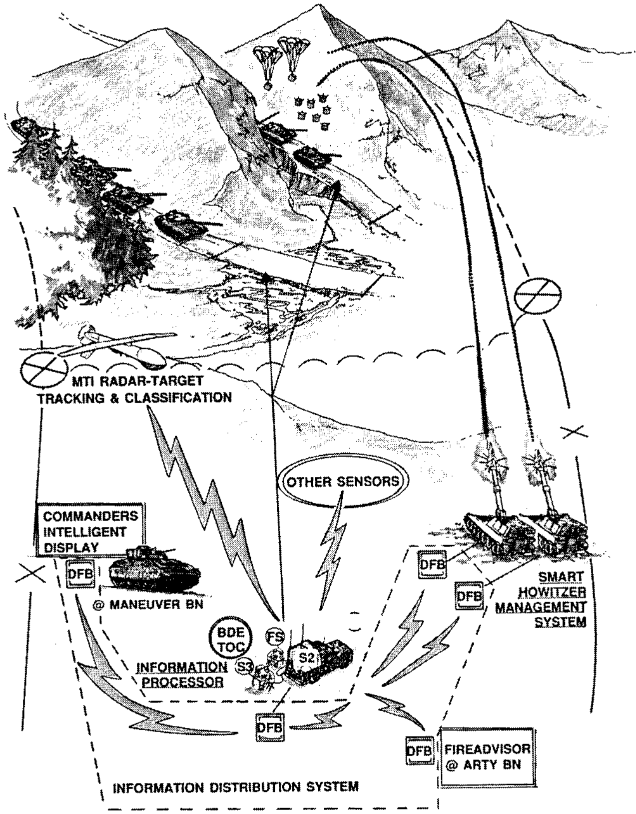
TACFIRE Error Control. Having examined "the results of the BRL/HEL ACE, Cooper concluded that improvements were needed in TACFIRE's error-control performance. He developed an error-control scheme that can be used without disturbing the existing system. His method uses a non-binary Reed-Solomon code which treats each detected character error as an erasure in an abstract non-binary channel which transmits symbols in the non-binary code. This code corrects many such symbol erasures, thus improving the probability of correct message reception from noisy channels. Improvement in the message rejection rate by several orders of magnitude was demonstrated with only a 31% increase in the volume of symbols transmitted. This compares quite favorably with a 100% increase in traffic volume each time a message must be fully retransmitted."[38]

The Theory of Chaos. The theory of chaotic behavior in physical systems is of considerable interest in the understanding of phenomena such as turbulence that are in turn related to ballistics. "In 1983, 1984, and 1985, SECAD participated in the U.S Army Summer Faculty Research and Engineering Program. Walter Egerland [SECAD] collaborated successfully with N. Bhatia of the University of Maryland - Baltimore County (UMBC). The results of their joint work were presented at three Army conferences and published in several papers in the open literature. The research was directed at the mathematical foundations of the theory of chaos. In particular, new criteria for chaos and refinements of Sarkovskii's Theorem were established."[39]

Smart Weapon Systems (SWS) Program. The BRL created and coordinated the SWS LABCOM Cooperative Program. The following has been extracted from a report by Rogers and Ellis:[40]

"The SWS program, which was demonstrated in September 1989, presented a futuristic concept that used emerging technology to give the brigade commanders the ability to shape the future battle by attacking enemy forces prior to their arrival at the battle's forward edge. The program looked at the total delivery system from acquiring targets to delivering munitions and applied innovative technology and operational concepts to improve the effectiveness of conventional and small-footprint smart munitions, such as SADARM. The program showcased several key technologies under development within

SMART WEAPONS SYSTEMS LABCOM COOPERATIVE PROGRAM



GOALS

- SHOW HOW TO ATTACK MOVING TARGETS BEYOND FORWARD OBSERVER RANGE
- USE DIGITIZED TERRAIN, WEATHER, etc.; TO REDUCE TARGET LOCATION ERRORS; PROVIDE CURRENT TARGET TRACKS & PREDICTED TRACKS (WINDOWS FOR ATTACK)
- HOWITZER MANAGEMENT TO IMPROVE RESPONSIVENESS, FLEXIBILITY, AND SURVIVABILITY
- FIRE SUPPORT DECISION AID FOR EMPLOYMENT OF SMART AND CONVENTIONAL MUNITIONS
- EFFECTIVELY DISTRIBUTE INFORMATION REQUIRED TO CONDUCT RESPONSIVE AND ACCURATE FIRE MISSIONS
- PROVIDE STATUS INFORMATION FOR MANEUVER COMMANDERS

SWS LABCOM Program.

LABCOM and demonstrated how they could be integrated into a system. Each component of the system is a *stand-alone* program that could be employed with existing or proposed weapon systems. It is important to keep in mind that the SWS program demonstrated new concepts and technologies rather than a particular system.

"The basic thrust of the SWS program was to explore a smart-systems approach to the problem of reducing target-location errors so that smaller footprint smart munitions and conventional munitions could be effectively employed against a moving target array.

"Goals of the program included:

1. Show how to attack moving targets beyond forward-observer range.

2. Use digitized terrain to reduce target-location errors; provide current target tracks and predicted tracks (windows for attack).

3. Improve responsiveness, flexibility, and survivability of howitzer delivery systems.

4. Demonstrate a fire-support decision aid for employment of smart and conventional munitions.

5. Effectively distribute information required to conduct responsive and accurate fire missions.

6. Display status information for maneuver-battalion commanders.

7. Model the system; conduct analyses—address allocation of direct and indirect fires.

"The BRL was responsible for development of IDS, which addressed goal 5, and FA, which addressed goal 4.

"HDL was responsible for development of the mini-moving target indicator (MTI) surveillance radar for unmanned aerial vehicles (UAV), which addressed goal 1, and IP, which addressed goal 2.

"HEL was responsible for development of the smart-howitzer management system (SHAMS) and the human-factors howitzer test bed (HFHTB), which addressed goal 3. HFHTB was not a part of the SWS-program demonstration.

"ETDL was responsible for development of CID, which addressed goal 6.

"Results of the September demonstration were:

1. All system components were successfully integrated into a coherent system using the IDS. The IDS distributed data over high bandwidth data links within the simulated brigade TOC and via low bandwidth VHF-FM radio (PRC-77s) between all other nodes.

2. The timely processing of moving vehicle sensings from the simulated MTI radar into targets for future engagement was demonstrated in TOC using IP.

3. Decision aids were used to assist *war fighters* in near-realtime planning—IP by the S2 and S3 in TOC; FA by the fire-support officer in TOC; SHAMS by howitzer section chiefs; CID at battalion command level.

4. One concept of effectively attacking moving targets beyond typical forward observer ranges was demonstrated.

5. The utility of influencing the future battle by attacking forces prior to their arrival at the battle's forward edge was illustrated through the demonstration and a force-on-force evaluation using the

combined-arms and support-task-force evaluation model (CASTFOREM).

"As a result, the IDS concepts are currently being considered by CECOM for a low-echelon C2 system (battalion and below C2 - B2C2), by the Balanced Technology Initiatives program for the battalion targeting system, and by Magnavox Corporation for AFATDS."[40]

FIELD ASSISTANCE

The BRL's contribution to the AMC-FAST program is a fine example of its ability to apply its technology to real Army problems and its willingness to respond quickly and effectively. The following is extracted from an *Update* article by Johnson and McCoy on the FAST program and an *Update* article by Fansler and Lyon on their work on a silencer for the Bradley vehicle. The latter even involved "supercomputer analysis."[19]

"The mission of the AMC-FAST program is to provide senior Army commanders with modest scientific and technical staffs to implement quick-reaction solutions to technical field problems and to demonstrate the solutions in the field environment. AMC-FAST seeks to improve communications between R&D communities and the operational forces.

"The nucleus of AMC-FAST is the field team. Each field team consists of a science advisor and a technical advisor positioned within major Army units, worldwide, with the responsibility for advising major army and corps commanders. Advisors are selected from AMC laboratories for nominal 2-year tours, serve at the invitation of the host commanders, and represent all AMC laboratories during the assignment. The on-site advisors initiate FAST projects from facts gathered or problems observed in the field. Each project must formulate and evaluate a solution concept, accelerate new technology, enhance the capability of deployed systems, provide studies or analytical support unique to the AMC R&D community, or evaluate the capability of non-developmental items or systems.

"FAST projects are implemented through dedicated points of contact at each AMC laboratory or center. Commonly referred to as reaction-cell officers, these points of contact provide a direct link between the AMC-FAST advisors and the research, development, and testing communities. Each reaction-cell officer assumes full responsibility for acquiring a solution to the field problem through research, the application of engineering principles, or trial and error experimentation.

"Once a laboratory solution has been found, the reaction-cell officer assumes the additional responsibility of demonstrating that solution in the field. When possible, the solution is demonstrated in the actual environment in which the problem was detected. Following a successful demonstration, the solution is transitioned to a PM's office for implementation and production.

"The BRL has been an active participant in the AMC-FAST program since its inception. Several of the projects with which the BRL has been involved independently or as a co-participant with other laboratories have been transitioned or successfully demonstrated. A synopsis of these projects follows."[41]

Improved Limp-Home Capability for the Abrams Tank. "The BRL's interaction with AMC-FAST began in December 1985 when the science advisor to the Commander in Chief, U.S. Army Europe (USAREUR), requested the BRL to investigate a quick, easy, and inexpensive fix to a mobility problem observed with the M1 tank.

"During the operation of the Abrams tank, transient loss of electrical power or erroneous sensor readings precipitated a high occurrence of transmission malfunctions or engine protective mode conditions. These protective modes were designed to prevent damage to the engine. In one protective mode, PM-III, the engine power is reduced to the point where the vehicle is virtually immobile. Once PM-III is activated, it is often impossible to recover normal operations.

"According to CPT (P) Curtis McCoy, the BRL AMC-FAST cell-reaction officer, hostile fire might precipitate a high occurrence of PM-III transmission malfunctions. However, protection of the engine and transmission in combat becomes a moot point. The value of a concept that protects the power train during peacetime must be weighed against the danger to the tank's crew during combat.

"An informal ad hoc consortium consisting of representatives from the BRL, HEL, AMSAA, and the U.S. Army Ordnance Center and School (USAOC&S) were formed with the goal of developing an improved limp-home capability for the M1 tank. Constraints placed on the fix required it to be simple, cheap, easily installed, amenable to training, and capable of being protected against frivolous peacetime use.

"Lessons learned from several interactive concepts led to the final development of a Shift Hand-Activated Fuel Transmission System (SHAFTS). SHAFTS provided a purely manual solution to the Abrams tank's problem including manual activation of the transmission should PM-III be incurred in a hostile environment.

"Subsequent to a successful demonstration of the SHAFTS concept, a technology transfer was made to the U.S. Army Tank-Automotive Command (TACOM)."[41] SHAFTS was fielded in 1991.[42]

Bradley Live-Fire Automated Scoring Tool (BLAST). "BLAST, a high-impact BRL-developed software package, automates the scoring and analysis of BFV gunnery tables. Bradley gunnery tables are used to develop and to test the proficiency of Bradley-crew gunnery techniques. Each gunnery table simulates a series of engagements expected in a typical battlefield scenario. Within each table, the training unit is evaluated on its ability to recognize, to acquire, to hit, and to kill enemy targets. Threat considerations include tactical deployment of enemy weapon systems at realistic distances from the BFV and choosing the best weapon system to defeat the designated target. The objective of the Bradley gunnery program is to attain and sustain Bradley-crew gunnery proficiency through proper use of the Bradley's fire-control system and engagement techniques.

"Bradley crews progress from the basic to the intermediate and advanced levels of gunnery. BLAST automates Tables V–VIII of the intermediate level. Of these, Table VIII is the most important; crews must earn a qualifying score on Table VIII before advancing to the highest level of gunnery. Tables V, VI, and VII are used to train and to prepare crews for the Table VIII trials.

"Prior to the development of BLAST, crew scores were calculated manually by Bradley crew evaluators (BCE). SSG (P) Dennis Kelham, the BRL Bradley master gunner, describes the manual scoring process as complex, labor intensive, and frequently reflecting errors arising from poorly written score sheets. Unit commanders wishing to pinpoint the strengths and weaknesses of their crews were forced to wade through stacks of illegible score sheets. If the reports were desired at the battalion level, it became virtually impossible to complete the summary report before the next gunnery exercise had begun. Corrective training was difficult to implement; gunnery problems could not be identified. Bradley crews carried their mistakes and poor engagement techniques from one gunnery exercise to the next.

"SSG (P) Kelham's transfer from a field unit in Germany to the BRL provided the spark for BLAST. One of his first observations at the BRL was that scientists and engineers used computers rather than pencils to obtain results.

He soon convinced his superiors that automation of the Bradley gunnery tables would be a significant benefit to infantry troops in the field. Working closely with Geoffrey Sauerborn, a BRL mathematician, SSG (P) Kelham helped to quickly make BLAST become a reality.

"Designed to work on International Business Machines (IBM)-compatible PCs, the program requires a minimum of 640K memory and one floppy-disk drive.

"BLAST provides positive feedback to Bradley crews, through instantaneous printouts of scores, before the troops leave the training range. Low-scoring tasks are immediately identified. Summary reports pinpoint the unit's strengths and weaknesses. BLAST even recommends corrective training for the weak areas. Lessons are learned before the gunnery exercise is forgotten.

"Less time and ammunition is needed for gunnery exercises because the troops are able to correct their problems faster. Unit summaries, from the platoon to the corps level, become available to the commander within minutes after the completion of the gunnery exercise. Command decisions for corrective training can be based on objective, unbiased facts rather than on intuition."[41]

The BRL transferred BLAST to the U.S. Army Infantry School during December 1989. BLAST is being distributed Army-wide and is in use in major training sites (Fort Hood, TX; Graffenwoehr, Germany; and the National Training Center [NTC] at Fort Irwin, CA). The Abrams Tank Live-Fire Automated Scoring Tool (ATLAST) for Tables IV–VIII was transitioned to Fort Knox, KY, in May 1992.[42]

Foot-Operated Switch. "The current method of changing magnification of the GPS within the Ml/M1A1 from 3X (wide angle) to 10X (telescopic) and back, requires the gunner to remove a hand from the power-control handles. This action results in a momentary imbalance of the control handles and a potential loss of visual contact with the intended target. During 1987, a request was made to the BRL and HEL to develop an electrically operated magnification selector that would permit the M1 gunner to change magnification without disengaging from the tracking process.

"A proof-of-principle, electrically operated magnification switch that could be easily retrofitted to the GPS was conceived and developed. The system consists of a foot switch for shifting magnification, a solenoid box to operate the existing lever under electrical control, a control box, and an intercom switch. The system is powered through an auxiliary jack from available 24-V DC power. Installation of the system can be accomplished in 1 hour. Over-ride capability is provided to the commander during selection of the GPS magnification; manual over-ride is always available to the gunner in the event of system failure.

"The foot-operated, 3X/10X magnification system was successfully demonstrated in USAREUR in May 1988."[41]

25mm M242 Cannon Muffler System. "A group from the village of Dalhedra, which adjoins the U.S. Army training area at Wildflecken, Germany, obtained evidence that the projected noise from a proposed expanded range would violate local noise exposure laws. An injunction was obtained preventing the construction or expansion of range facilities for the BFV. In order to construct new range facilities or expand existing range facilities, it would be necessary to reduce the level of gun noise emanating from the ranges. Several alternatives for reducing the noise level were explored including earthen berms, autobahn noise barriers, and carport-like structures. Each of these options was expensive, permitted stationary firing only, and failed to reduce the noise to the desired level.

"Dr. Kevin Fansler, a BRL scientist, was requested by the AMC-FAST advisor to develop a 25mm muffler system that could be used in the Wildflecken training area."[41] "The device would have to reduce the noise by at least 10 dB to the sides and rear of the Bradley Fighting Vehicle System (BFVS). Furthermore, it must be durable, reliable, safe, and exhibit the same performance characteristics as the standard brake it replaces. These requirements put severe constraints on the weight of the muffler, as a scaled-up version of a rifle silencer would weigh well over 100 pounds. The BFVs cannot tolerate that much weight on the muzzle.

"The prototypes were developed by using mathematical models that predicted noise attenuation as a function of muffler volume, among other parameters. In order to evaluate and tune the prototypes with configurable baffles, the Aerodynamics-Range Blast Chamber of the BRL was used to obtain near-field muzzle-blast measurements, while other ranges were used to obtain far-field measurements.

The BRL-Developed Muffler on the Bradley Vehicle.

"Pressure transducers were also utilized to obtain internal muffler pressures. Gages in each chamber supplied investigators with valuable data that would later be applied to structural analysis. After the experimental and theoretical evaluations, and with consideration of manufacturability, durability, and safety, it was concluded that the optimum design would incorporate a large-diameter expansion chamber followed by a smaller diameter-baffled cylinder which would maximize noise attenuation while requiring a minimal volume.

"With the design established, a search was conducted for the most suitable construction material. Among the materials considered were high-strength steels, titanium alloys, and metal matrix and carbon composites. Experimental evaluations led to the selection of high-strength stainless steel because it possessed many good qualities such as machinability, high-temperature performance, and corrosion resistance.

"The prototype muffler, ... allows the propellant gases to expand freely at first, reducing the high transient pressures to a level where they can be contained without a massive structure. The baffled sections then promote energy extraction from the gases through both heat transfer and viscous effects. The most effective configuration attenuated the gun blast noise an average of 12 dB A-SEL to the sides and 19 dB A-SEL to the rear, which exceeds the USAREUR requirement of 10 dB A-SEL, and provides a dramatic demonstration of noise reduction.

"After the noise attenuation demonstration tests, a performance, durability, and safety test was conducted that evaluated the muffler in the most severe training scenarios. The muffler met or exceeded all requirements, and this muffler weighs only 13.5 lb."[43]

Subsequent to several iterations of a muffler design, a final proof-of-principle demonstration was conducted in Germany, and the BRL-developed barrel muffler system was then transitioned to ARDEC.[42]

Bradley Improved Gun-Gas Removal System (BIGGRS). "During developmental testing of the 25mm muffler system for the BFV, excess levels of carbon monoxide were measured within the vehicle. To correct this problem, BIGGRS was developed by SSG (P) Kelham and Dave Lyon, an engineer in the BRL's LFD. Subsequent testing revealed that the carbon-monoxide levels within the BFV were reduced when BIGGRS was used and that BIGGRS appeared to have the potential to reduce the carbon monoxide levels within non-muffler BFV scenarios.

"A subsequent BRL briefing to the Bradley PM led to the establishment of a formal test program to evaluate the effectiveness of BIGGRS, and other potential BFV modifications, in reducing toxic-fume concentrations during firing of the Bradley weapon system.

"The results of the test program led to a BRL recommendation to the Bradley PM for a BFV modification that will significantly reduce the toxic-fumes hazard to Bradley crew members. According to SSG (P) Kelham, "BIGGRS did not emerge as the best vehicle modification; however, it pointed us in the right direction."[41]

BIGGRS evolved into the Bradley dual fan which was tested by the BRL and will be incorporated in the A2 series of Bradley vehicles.[42]

Improved Abrams Firing Circuit. "Experimental tests performed with the Abrams tank revealed that the manual back-up firing circuit would not function if turret power were lost. The chief scientist, USAREUR, requested that a fix for the problem be developed through the AMC-FAST program. The BRL, in association with HEL, the PM-Abrams Tank, and the USAOC&S, proposed a quick-fix, low-cost solution to the problem using tools and supplemental parts from the current inventory. Supplemental cables and connectors were used to bypass the turret network box, which, if damaged, would cause failure of the firing circuit.

"The improved firing circuit was successfully demonstrated in Germany and transitioned to TACOM in FY89."[41] The improved firing circuit was scheduled to be on the M1A2 version of the Abrams tank.[42]

Combat-Vehicle Marker System. "Assistance was requested by the USAREUR science advisor from the BRL, HEL, and the Night Vision Laboratory, Fort Belvoir, VA, in the development of a range-safety/passage-of-lines marker system for tracked vehicles. The system was needed to improve the existing range-safety flag concept that was virtually useless in darkness and which required the signaler to be physically exposed during the signaling process. A need for a thermal beacon was later identified as a requirement for recognizing manned vehicles on the training ranges in Germany. The combined laboratories produced a light system which enabled the vehicle's crew to illuminate, individually or in combination, red, amber, or green lights located on the rear turret.

"The lights are controlled from within the turret; their intensity may be varied according to the prevailing need or tactical situation. The combat-vehicle marker system was demonstrated in Germany in February 1989 and transitioned to TACOM for production and implementation during May 1989."[41]

Improved Gun-Mount Recoil-Exercise Kit. "A request from the AMC-FAST science advisor to the CG, 21st Theater Army Area Command (TAACOM) was made to the BRL and HEL to investigate the current method used to exercise the cannons of M60 and M1 tanks stored at the Prepositioned Overseas Materiel Configured to Unit Sets (POMCUS) sites. The current procedure requires a six-man team to perform recoil exercise on a single tank. The team must install batteries, fuel and power up the vehicle, move the vehicle outside of the storage area, and perform the exercise with a 5-ton wrecker. Subsequent to the exercise, the process must be reversed before the vehicle is returned to its storage position. The Abrams tank's requirement that the process be made on each stored vehicle semiannually makes the process very time consuming and expensive.

"The BRL and HEL collaborated with Benet Weapons Laboratory to find a solution to the problem. In February 1989, the first manually operated prototype recoil-exercise kit was demonstrated. A demonstration of an electrically operated system soon followed. However, the manual-operation capability was retained for use in the event of power failure.

"Testing of the prototypes was accomplished in Germany during October 1989 at three different sites. During the first test, a 3-man crew from the BRL and Benet exercised a 58-tank battalion in 4 hours and 36 min. A 3-man German work crew exercised a 58-tank battalion at the same site in 3 hours and 50 min. At a second site, a German work crew exercised 58 tanks in 3 hours and 30 min. In contrast, the wrecker method used at most POMCUS units required the use of 6 men for 5 days to exercise the 58 tanks."[41]

Twelve copies of the recoil-exerciser kit were fielded (as of 1992).[42]

Field Assistance in Science and Technology (FAST) Jr. Program. The AMC-FAST Jr. program is designed to provide junior-level (GS 9–13) scientists and engineers with field experience for periods of from 2 to 8 weeks. At present (June 1992), the BRL has two participants at Graffenwoehr, Germany; one in Japan; and two at Fort Lewis, WA.[42]

PROBABILITY AND STATISTICS

In 1978, R. J. Eichelberger asked Dick Moore to form a branch that would "hang out a statistics shingle." The branch was created to provide consultation and support to the BRL in particular and to be available as needed to the rest of the defense community. It also was to develop statistical tools that would address the special needs of the ballistics community.[44]

The most significant statistical problem for the BRL was related to the fact that many of their experiments and tests were very expensive and difficult to conduct. Thus, the number of samples was often extremely limited. This caused the branch to emphasize areas such as small-sample theory and non-parametric statistics. It also took them into research into analytic techniques to combine numbers of past tests to extract data.[44]

In the early 1980s, Moore developed a sequential probability ratio test that is used to accept large-caliber high-velocity tank ammunition. The procedure is very efficient and has saved millions of dollars over the years in reduced sample size.[44]

The branch has provided statistical support to CRDEC since 1984. The branch designed experiments, analyzed data, and prepared reports on a large number of projects including chemical-agent resistant coatings, gas masks, agent-detection paper, chemical-detection kits, and sperm mortality.[44]

The tank-gun accuracy program was active through the 1980s and 1990s. Thomas and David Webb provided statistical support in the planning of experiments and the analysis of data. Among other things, they supported the efforts to determine the best way to *zero* (calibrate) tank cannon. The goal was to determine a *fleet zero* or a computer correction factor (CCF) that could be applied to the bore sight. In addition, the branch developed techniques for obtaining the parameters for the CCF.[44]

In 1981, Bill Baker and Malcolm Taylor used order statistics to solve a problem involving the determination of time windows for firing impulses in a warhead's fuzing system. Then they developed a computer program that provides the probability of a warhead's fuzing as a function of the parameters that characterize the detonators.[44]

In 1981, Jill Smith and Thomas developed testing procedures for the evaluating of sympathetic detonations in an ammunition store if one round detonates. TBD used these procedures several times, and they were shown to result in a drastic reduction of sample sizes over other techniques.[44]

Smith, Ann Brodeen, Jock Grynovicki, and Wendy Winner provided statistical support to ACE studies conducted by the Artillery Team, created the statistical design for the FIST tests at Fort Riley, KS, in 1983, and analyzed the data therefrom.[44]

In 1985, Baker and Taylor developed a non-parametric statistical approach to the validation of computer simulation models. This is a way to assess empirical data to provide a certain level of confidence in the statistical significance of the output of the models. The technique can address problems such as, "How sensitive is the model to various parts of the data base?" or "Is the model using the right grid size?"[44]

If a piece of equipment has a requirement to operate for N miles, a conventional acceptance test would be to test M items to see if each met that requirement. In 1985, Linda Crawford, Thomas, and Moore developed sampling plans for durability testing beyond requirements. In this approach, each item would be driven beyond the requirement (> N miles) to obtain more data from each test and thus reduce number of tests and test items required.[44]

Dick Moore moved to the BRL's front office in 1985 and retired a year later. Jerry Thomas became the new branch chief.[44]

In 1986, Smith, Brodeen, and Winner provided statistical support to the Artillery Team's efforts in the ADDCOMPE program.[44]

One aspect of consultation is to provide the customer with tools that he can use for himself. To provide a user-friendly system of statistical tools, the branch used ES technology. A non-parametric data analysis (expert) consultation system [NONPARE], was developed in 1987 at the BRL. NONPARE is an intelligent interface to a body of statistical software. It acts as a guide, instructor, and interpreter to the user. The system is currently in feasibility prototype but is anticipated to be available for limited release during FY88. The system utilizes Genie, a robust generic inference-engine ES shell developed at the BRL. Many non-parametric statistical procedures are applicable to small-data sets, and they are the only confirmatory procedures which can be used for data collected on a nominal or ordinal scale of measurement. The system is intended for a user with a limited statistical background—perhaps an introductory course in statistics 4–5 years ago—although provisions to accommodate a more advanced user will be included.

An idea of the breadth of the consultative services can be gained from this report for 1987: In-house statistics expertise enables the BRL to serve as the Army's lead laboratory in Statistical Consulting. The BRL personnel acted as statistical consultants during FY87 to AMC Headquarters, LABCOM, CRDEC, HEL, AMSAA, TECOM, the Combat Systems Test Activity (CSTA), as well as the BRL. The program of highest visibility during FY87 for which the BRL served as AMC's statistical expert was the Vice Presidential Feasibility Demonstration Program to evaluate methanol as an alternative fuel.

The Vice Presidential initiative was a study to consider the feasibility of using methanol in Government vehicles as an emergency measure in the event of a major gasoline shortage. Jerry Thomas created the statistical design of the demonstration, and Bob Umholtz analyzed the data that were collected. The result showed that the use of methanol was feasible, but that methanol is half as efficient as gasoline (although it is a cleaner fuel).[44]

In 1988, the production line for the Abrams tank was about to be turned off due to the lack of a procedure for the testing of its armor. Thomas, Robert Umholtz, and Baker proposed a procedure that is still in use [1992].[44] "The BRL developed an acceptance plan to test armor packages. Because of the tremendous cost of the armor packages and the testing procedure, extremely small sample sizes are dictated. A new procedure was devised using chain sampling to test both the structural integrity and depth of penetration."[19]

A more esoteric tool was developed in 1989 by Barry Bodt and Taylor in a (multivariate) random number generator that uses actual data-base information in a non-parametric manner. The procedure was accepted for inclusion in the *International Mathematics and Statistics Library*.[44]

Linda Moss designed and analyzed experiments to evaluate the effectiveness of the modifications to the Bradley vehicle for reducing the concentration of toxic fumes in the crew compartment during firing. This was part of the Bradley improved gun-gas-removal-system effort in the AMC-FAST program (see respective section).[44]

As a part of a 1992 study on the use of fuel-air explosives (FAE) for the breaching of mine fields, John Sullivan, Thomas, and Moss developed techniques of computing the probability of clearing based on FAE tests against mines.[44]

The branch has been actively involved in the planning and analysis of the results of the Congressionally mandated live-fire testing (LFT). The results of LFT on the Abrams tank were statistically compared with the results simulated by the Stochastic Quantitative Analysis of System Hierarchies (SQuASH)[45] model.[44]

SMART MUNITIONS[46,47]

We cover the operations of two groups under the heading of smart munitions: the Infantry Weapons Team that originally was created by Bob Gschwind and later led by Harry Rogers, and the MMW Team that was led by Dick McGee. Eventually, both those groups were incorporated in the Weapon Systems Technology Branch (WSTB).

The Infantry Weapons Team was formed in the mid-1970s and, at the outset, asked itself what was the pressing problem for infantry weapons. The answer seemed to be that the development of modern armor had thwarted infantry weapons such as the TOW missile that attacked tanks from the front with shaped charge (SC) warheads. If weapons were to be found that could defeat modern tanks and still be light enough for infantry use, they would have to use some finesse and attack from some other direction than the well-protected front of the tank. Top-attack smart munitions seemed to be an exciting possibility; so the team dedicated itself to looking at infantry weapons for the attack of armor and focused on the application of smart munitions.

The MMW Team started up around 1960 and has conducted seminal work in MMW radiometry, propagation, techniques, and devices.[48]

System Studies. The team considered the total functioning of the smart weapon. That would typically include both the open-loop portion with errors associated with launch and flight of the projectile; the detection process with scan pattern, decision logic, target signature, and error signals; and the warhead functioning, pattern of hits on the target, and associated probabilities of kill (PK).[49]

Two systems have been of particular interest over the years: smart target activated fire and forget (STAFF) and SADARM.

STAFF is a flat-trajectory round that uses its rolling motion to scan the ground with a side-looking detector. As it flies over the target, an EFP is fired down on the top of the target. Presently (1992), the main application being considered for STAFF is in a 120mm tank round.

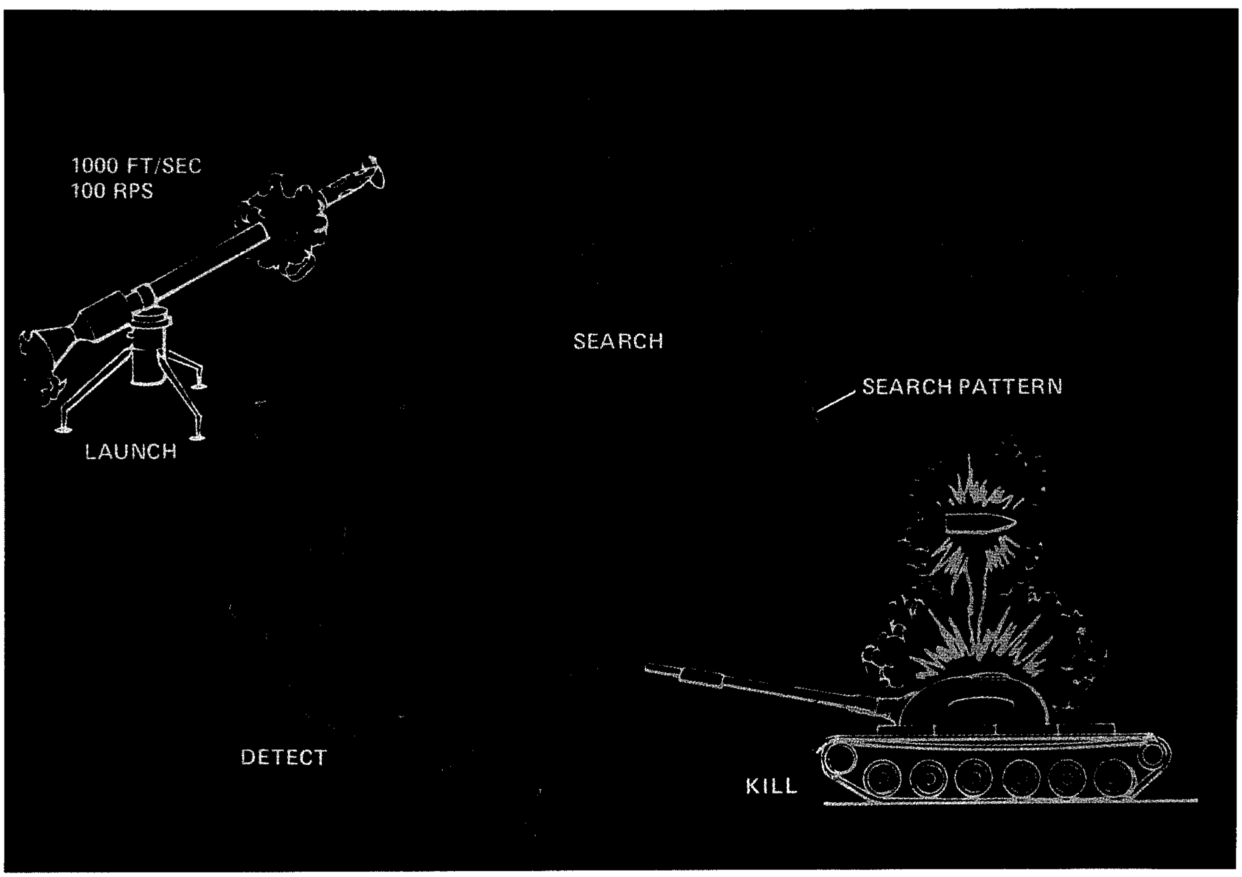
SADARM is an artillery concept in which a round carries a number of sublets to the vicinity of the target, at which point the sublets are dispersed. They fall to earth on parachutes and conically scan the ground during their descent. As a target is detected, the sublet fires an EFP down onto the target. SADARM is also currently under development for the 155mm howitzer and MLRS—principally with a counter-battery role.

While neither SADARM nor STAFF was conceived in the BRL, the Infantry Team has played a continuing role over almost two decades in the analysis and refinement of the concepts—this includes system details such as signature data, decisions algorithms for the EFP, EFP performance, and countermeasures. The analyses were carried out with excruciating detail that included the following of the footprint of the scanner over detailed descriptions of the target and background.

In addition, the team considered various concepts for guided and smart mortar rounds and for wide-area mines (WAMs) to include the Wide-Area, Side-Penetrating Mine (WASPM) and WAM, which is currently (1992) in development.

For 1987, we find in-Government expertise and technology assessment *tools* were provided industry, USAF, and Army commodity commands such as the Armament, Munition, and Chemical Command (AMCCOM) and MICOM. Specifically, the BRL (1) identified critical STAFF-projectile sensing problems and developed improved signal-processing algorithms for detection and aiming that were accepted by PMs and contractors; (2) provided alternate prioritized solutions to STAFF (shoot over friendly forces) fratricide problem; (3) *fine-tuned* the BRL SADARM-performance model to new field data, added a high-resolution target module, and transferred the model for ARDEC use; (4) transferred extended-range antiarmor-munition (ERAM) performance model to ARDEC for evaluating candidate WAM smart munitions; and (5) served as sole, in-Government technical expert in estimating the performance of USAF sensor-fuzed weapon (SKEET) and predicting a sensor problem, later confirmed by Government-directed tests.

Circa 1988, the group "upgraded the STAFF engineering model to reflect latest system changes and documented changes needed to avoid fratricide and upgraded the SADARM engineering model to incorporate changes needed according to Chicken-Little data [Joint Technical Coordinating Group/Munitions Effectiveness (JTCG/ME) target data]—this model will be used by PEO Armaments to continue engineering development of SADARM."[50]



Typical Elements Considered in the Analysis of a Smart Weapon.

The group also began a new project to develop engineering simulations of the next-generation MMW/IR sensors. "High- resolution, modular, generic end-to-end system engineering models are being developed to simulate SWS concepts from launch to terminal effects. With the advent of tank-launched SWS such as STAFF and X-Rod, the interaction of the projectile and sensor system is critical since the sensor is *strapped down* to it. Trajectory models were matured and EFP warhead simulations were added to compute probable impact locations. A detailed study of a generic family of spinning STAFF-type rounds was completed. It was found that a number of conditions would cause serious degradation of performance emphasizing the importance of total-system engineering. Some aspects of the fin-stabilized STAFF, now being developed, and [guided KE] X-Rod type projectiles were also studied. The coupling and integration of a radar-sensor model integrated with target and background signatures was investigated with emphasis on tracking and pointing errors. The effort progressed from simple point targets with a *cookie-cutter* beam to high-resolution targets and background signatures with full polarimetric mono-pulse beam functions. Results showed that ultimate tracking performance is closely coupled with tracking and guidance-and-control algorithms, target-to-clutter ratio, clutter spatial resolution, as well as tracking errors. It was found that simplistic assumptions are misleading and that engineering models are needed to investigate parametric interactions. A radar-sensor model was completed to the point of integrating an IR-sensor model to it. To simplify arduous calculations and reduce run time, a glint model is being analyzed. The active-protection system (APS) sensor model was modified to allow 10 sensor systems each with 10 sensors. A noise routine was added to simulate errors in range, azimuth, and elevation. Routines were added to predict impact and intercept locations as well as time to intercept and impact."[51]

Detailed signature data are a concern for evaluating detection and for determining where, if at all, the destructive mechanism will impact the target; so for the early 1990s we find: "In the area of high-resolution prediction modeling, the physically reasonable IR-signature model (PRISM) was modified to predict the non-operating IR signatures of a red threat target over a diurnal period. After resolving some problems, results compared well with measurements. Development of computer-aided design (CAD) routines for generating mensuration data inputs for PRISM were completed, and efforts to add a gun-tube firing model are underway. X-window capability was developed to interactively compare predicted and measured signatures and time-lapse animation."[51] PRISM evolved from an IR-signature model for the M60 tank that was developed by Jim Rapp, circa 1960.

Methods have been developed "for predicting the radiative heat exchange within the engine compartment of armored vehicles and the development of BRL-CAD tools for interrogating target-geometry descriptions to extract data needed for inputs to vehicle signature-prediction models such as PRISM. Various engine-compartment radiation models were developed and have been incorporated as options in PRISM. PRISM was then used to generate IR signatures of an operating T62 tank, and predictions using the various options were compared to determine their relative effectiveness. The investigation demonstrated the importance of proper modeling of the radiative heating of engine armor by engine-exhaust components, which had been ignored in earlier versions of PRISM.

"For modeling IR signatures of diverse complex backgrounds, finite impulse response (FIR)-based models have now been selected for research emphasis since background scenes having both random and structured properties may be simulated more easily in SWS engineering models. [A research contract] with Vanderbilt has produced: a FIR model coded in

C for use on the BRL's computers; a simple model for characterizing temporal variations over a diurnal cycle; an analysis of the effects of FIR filter size and window shapes on the quality of synthetic IR-background scenes; and further investigations into the generation of scene textures using different filter-excitation methods. The FIR models for various background scene elements will provide the fundamental components for compound scenes for top-attack sensor performance analyses."[29,36]

Millimeter Wave (MMW) Technology. The BRL's effort in MMW technology has had a number of aspects that include leadership roles in the development of advanced devices, the measurement of atmospheric propagation, the support of system applications, and the measurement of spatially detailed target signatures.

Millimeter Wave (MMW) Devices. In 1976, the BRL had 94-GHz and 140-GHz IMPATT-diode tracking radars built. These were used for tracking and multipath tests in support of beam-rider and other system concepts and for false-target studies. By 1977, the feasibility of 94- and 140-GHz beam-rider concepts had been demonstrated.[52]

In 1978, the BRL received a quasi-optical mixer from Hughes Aircraft Co. for a 217-GHz radar. This was the first device of its kind at this frequency. By 1978, a pulsed IMPATT radar at 217 GHz was made operational.[52]

Highly reliable and lightweight solid-state devices such as these have made weapon concepts at these frequencies practical.

Date	Investigators	Frequency GHz	Atmospheric Condition
1966	Kammerer, Richard	140	Fog
1973	Richard, Kammerer	10, 35, 70, 95	Rain
1975	Richard, Kammerer, Reitz	140	Fog, Rain, Snow
1976	Bauerle, Knox, Wallace	140	Rain, Fog, Smoke, Dust
1977	Bauerle, Knox, Reitz, Wallace	95, 140	Smoke, Dust
1977	Bauerle, Knox	35, 95, 140	Smoke, Dust
1978	Knox	35, 95, 140	Smoke, Dust
1979–80	Bauerle	217	Rain, Water Vapor
1981	Bauerle, Knox, Wallace	35, 95, 140, 217	Snow
1981–82	Bauerle, Knox, Wallace	35, 95, 140, 217	Snow

The BRL Measurement Programs of Atmospheric Propagation.

Propagation Studies. "Since 1960, the BRL has been investigating the interactions of MMWs with the near-earth environment. The following is a list of BRL measurement programs that measured atmospheric phenomena:[53]

An important series of tests [was] conducted on the effects of snow. These were called Snow I (in January–February 1981) and Snow II (in January–February 1982). As usual, the BRL provided instrumentation for these tests. "Results of the Snow IA experiment at Burlington, VT, pertaining to the BRL propagation tests were provided to the Cold Regions Research and Engineering Center (CRREL) for inclusion in the final report. This was a four-frequency (35, 95, 140, 217 GHz) propagation experiment. The BRL also provided technical and logistical support for SADARM flight tests at Snow 1A. The BRL provided snow reflectivity data to SADARM contractors to be input to the design of the signal-processing algorithms to assure proper operation in snow-covered terrain."[52]

"The BRL had in 1988 six radars available for such experiments. The five MMW radars were all superhetrodyne-pulsed radars with non-coherent pulsed IMPATT transmitters. The X-band radar used a low-power traveling-wave tube (TWT) amplifier and was fully coherent. All the instrumentation required for reducing the data was contained in a single trailer."[53]

System-Related Efforts. Over the period of this history, the BRL has supported many system programs with propagation data, signature data, and consultative services. The following from FY87 is typical: "Various DOD-unique, experimental MMW instrumentation setups were developed or adapted and used to (1) investigate basic remote sensing phenomenologies such as the forward-scattering coefficients of terrain features through atmospheric turbulence and the attenuation and backscatter from experimental man-made obscurants; (2) evaluate the signature-reduction qualities of various radar-absorbing coatings; and (3) develop calibrated high-resolution MMW signatures of 22 targets for the official USAF/Army data base."[54]

In some instances, this has involved the actual development of component concepts for munitions. In 1979, for example, an improved sensor for SADARM was designed, developed, and fabricated at the BRL. The sensor uses a cross-polarized stepped-frequency FM-CW homodyne radar. It provides simultaneous passive backscatter amplitude and range diminution profile outputs and is electronic warfare (EW) hard.[52]

Similarly, from 1991 we have: "The BRL conceived and began patent application for a new concept for a low-cost frequency-scanning radiometer without expensive gimbaled elements for passive detection and cuing for active guidance. ... identified a niche in Army needs to service targets in the 3–8-km range. A new [work package] was proposed to use this new sensor concept to develop a conceptual smart munition to solve this problem and serve as a vehicle to proof the BRL technology-based work."[51]

X-Rod is a guided KE round to be fired from a tank cannon. There were two competing concepts for the X-Rod program. One of these concepts was the computer-aided trajectory (CAT).

Signature Measurement. One advantage of MMWs is that they can be used in scale-model experiments to simulate the effects of longer waves. This has been exploited by the group since the 1970s, and many customers have been provided with this service. In some instances, quite inexpensive plastic models could be plated with a very thin layer of gold (a service provided by NASA) and then used in place of very expensive machined models. The amount of gold involved was insignificant, but the models did occasionally bring wry comments about *gold plating* from visitors. The plastic-model approach was particularly convenient if a commercial plastic-model kit were available (these usually proved to be quite accurate models).

Smart munitions sense their targets at close range, and their functioning and effectiveness is determined by the detailed structure of the targets' signatures. This means that the MMW signatures of targets must be characterized by much more than just the conventional radar cross section. Specialized instrumentation is needed to make the appropriate measurements.

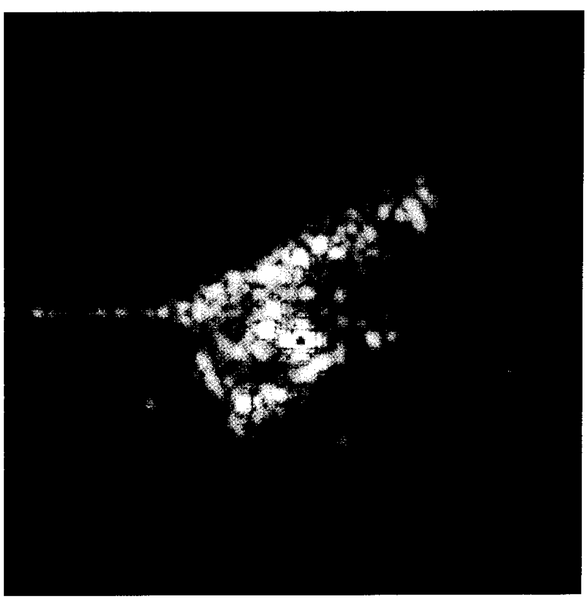
In the late 1980s, the BRL began the development of advanced MMW instrumentation and joined with CSTA in the development of a range facility. "The development of unique state-of-art raster-scan MMW imaging instrumentation and the BRL/CSTA collaborative development of a target-signature range opened the door to significant accomplishments: (1) the development of surrogate-target technology and more importantly the ability to certify same will hopefully permit the first smart munition (SADARM) to surmount the last hurdle to production—realistic FSD testing; made many MMW-signature measurements for several versions of several developmental surrogate targets and reported on same to the PM's office and many other DA organizations; developed and documented IR-predictive gun-tube model to provide engineering data for surrogate gun-tube heater development; (2) made many critical signature measurements through the year in almost on-call fashion [for many customers]; about 10 unique targets were measured, and about 20 high-resolution signature data bases were developed that can be used in the BRL mission work. Several of these vehicles were only available for short exploitation windows. The Low-Observable Technology Activity [now Applications] (LOTA) highly praised the BRL for its timely capability and expertise to both measure and analyze low-observable technology concepts; (3) also developed [a] new measurement technique for characterizing radar-obscuring clouds which will be used by TECOM and CRDEC for FSD testing of self-protection grenades for combat vehicles; and (4) also developed and delivered a MMW scatterometer for the Corps of Engineers (COE) Waterways Experiment Station (WES) and their Balanced Technology Initiative work in smart-weapon operation environment."[35]

"One of the most outstanding WSTB accomplishments was the completion of the in-house development of 35-GHz inverse synthetic aperture radar (ISAR) imaging capability including radar, sophisticated fast-Fourier-transformation data processing and instant-analysis software, and range facility–the first such in-house capability in DOD. This new ISAR capability was used to make high-range resolution signature measurements (full, camouflaged, and defilade) as critical [Government-furnished] data for the recently initiated full-scale STAFF development. A second SADARM surrogate target (on M48 chassis) was measured and certified. All the high-resolution signature data from the past 2 years were organized into a data base, and X-window-based image-analysis tools were developed to display and analyze this data base. Preparations continued for new 140-GHz multipath measurements at MICOM. A new vertically moving target was constructed, and the 140-GHz radar (a former world first) was repaired. Also, took delivery of the world's first indium-phosphide solid-state Gunn-diode oscillator as part of our collaborative effort with ETDL. A new agreement with CSTA LOTA was established for the development of new, permanent 35- and 95-GHz instrumentation, which was designed and fabricated by us this year, for Range 8 and for training of CSTA personnel (which we have been doing) to routinely operate this signature measurement range."[51]

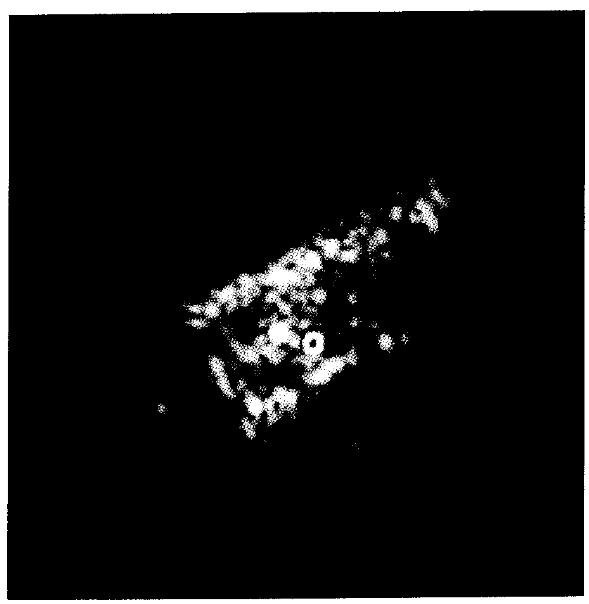
"The 35-GHz ISAR ... imaging capability ... was improved to exceed current industry standards in quality and to support varied signature-measurement needs and is now truly an outstanding DOD asset. Using sophisticated software developed by the Remote Sensing Team (RST) [work by George Hartwig], one can reduce measurements in the field to construct polar radar cross-section (RCS) signatures and range profiles."[29,36]

Surrogate Howitzer Target. This project by Bruce Wallace is a fine example of a combination of experiment, theory, computer modeling, and the building of hardware. "For most SADARM sensor tests conducted prior to engineering and manufacturing development (EMD), U.S. Army M109 howitzers were used as substitutes for the threat vehicles. The Department of the Army Headquarters (HQDA), however, mandated that smart munition testing could no longer use unmodified U.S. vehicles as targets but instead must use actual threat vehicles, or if they were unobtainable, use U.S. vehicles that have been modified and verified to conform to threat-vehicle signatures. To satisfy near-term testing needs, Mr. Wallace proposed the development of a quick-fix surrogate target kit that could be added to an M109. The approach was limited by the level of knowledge of the salient features of the threat vehicle, the 2S3 howitzer. The information that was available was a good definition of the exterior dimensions and some limited estimates of the thickness of the armor. This limited the signature that could be recreated to active and passive MMW and an approximation of the IR solar load.

"The design approach was first to verify a radar-scattering computer simulation of the M109 with experimental MMW-radar imagery. Mr. Wallace led a group from VLD to develop, use, and verify this computer simulation which was a special adaptation of their solid-body geometry lighting model and the BRL multidevice graphics editor (MGED). After the results of the computer simulation were made to agree with the experimental data, the simulation was run using a computer model of the 2S3 as the target. Modifications were then made to the computer description of the M109 to make its simulated radar image agree with that of the 2S3. Scaled line drawings of the modifications were then provided to the BRL welding shop and used to construct the surrogate target kit.



35-GHz ISAR of an Armored Vehicle Without Clutter Suppression.



35-GHz ISAR of an Armored Vehicle With Clutter Suppression.

"The kit that was produced weighed about 6,500 lb and could be attached to the M109 without any structural modifications or welding. The kit was shipped to Fort Grayling, MI, for SADARM sensor testing in March 1988. These sensors tests were conducted in a winter environment, and sensor testing continued throughout the summer at Fort Drum, NY; Yuma Proving Ground, AZ; and Fort Hauchuca, AZ."[55]

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TERMINAL BALLISTICS

For the period covered by this volume of the BRL's history, the work of the Terminal Ballistics Division (TBD) has been dominated by the escalating armor and antiarmor technologies.

Mr. Richard Vitali, Chief of TBD From 1976 to 1982 and VLD From 1982 to 1985. He Received a Bachelor of Science in Physics From the St. Lawrence University and Was a Visiting Fellow at the Sloan School at MIT. From 1985 to 1992, He Was the Director of the Corporate Laboratories for LABCOM.

Mr. Donald F. Menne was Chief of TBD From 1982 to 1985 and Then Chief of VLD Until 1986. His Picture Is in the Section on VLD.

In the period prior to 1977, TBD had followed up on British developments in modern armor to create an improved version that was the basis of the armor for the M1 Abrams tank.

Dr. Clarence W. (Wes) Kitchens, Chief of TBD From 1985 to 1992. He Received a Bachelor of Science and Master of Science in Engineering Mechanics From the Virginia Polytechnic Institute and State University and a Doctorate in Engineering Mechanics From North Carolina State University.

When Dr. Kitchens Was Detailed to Be Director of the ARL Transition Office, in June 1992, Dr. Walter F. (Rick) Morrison Became the Acting Chief of TBD.

An interesting account of the development of the Abrams tank is contained in Kelly's book.[1] Since then, the effort has been on improving the armor for the Abrams and for other fighting vehicles as well as trying to anticipate armor developments in other countries.

Concerns for antiarmor developments increased in 1976 when the British announced their intentions to sell tanks with advanced armor to Iran. This and other developments around the world increased the concern for improving the capabilities of KE rounds for the 105mm and the 120mm cannons used on the M1 and for developing improved warheads for ATGMs and smart munitions.

Modern armors come in various types and combinations, the performance of weapons against them is not easily characterized, and an improvement against one threat might be counterproductive against another. The research, development, and testing of armor and antiarmor systems requires considerable scientific, engineering, and testing facilities. Thus, there is a great benefit in both economy of resources and in synergism for TBD to play a leading role in armor development, antiarmor development, and in threat assessment.

But there has been a downside to this multiple role. Some perceive the process of working on the threat and on the counterthreat as potentially incestuous. The people in the BRL have worked hard to avoid this problem; their contributions to U.S. armored systems and antiarmor systems have given the U.S. Army a capability second to none. Kelly calls the Abrams tank the "King of the Killing Zone" for good reason.[1]

ARMOR MECHANICS

As one would expect, the work on armor in the BRL for the period 1977–1992 was largely devoted to the upgrading of the protection for the M1 Abrams tank and the M2/M3 BFV.

The basic armor for the M1 was a major accomplishment for the BRL in the earlier part of the 1970s with the original basic design, the guiding of the competing contractors in the realization of the armor concept, and working with the winning contractor to mature the design. The basic M1 was fielded early in 1980. Kelly's book[1] gives an interesting account of the trials and tribulations in developing the Abrams tank.

"In the 1960s and the 1970s, the BRL became more heavily involved in armor R&D. Rapid development of new, more effective SC and KE penetrators threatened MBT survival. Ammunition in the 1960s was capable of penetrating unprecedented thicknesses of steel, far more steel than could be incorporated in armor protection. Efforts concentrated on novel concepts to replace monolithic armor steel. These concepts were directed towards the MBT-70 and its follow-on, the XM803. In the 1970s, research focused on the successor to the M60 tank, the M1 Abrams, because the planned successor, the XM803, was viewed as too costly by Congress. The armor systems incorporated in the Abrams were a matter of considerable importance to contemporary MBT development. While the exact composition of the M1 armor is not available for public disclosure, suffice it to say that the armor gives unprecedented protection against antitank rounds—both KE and SC. The M1 Abrams armors are considered a revolutionary development in protection systems."[2]

As good as the M1 was, the world was marching on with newer armors and with more powerful weapons. Clearly, as others in the world became more familiar with advanced armors, they would not only adopt the protection but would also work to develop weapons to defeat that armor. It is doubtful that any event had a more stimulating effect on the U.S. armor community than the 1976 announcement by the UK of the agreement to sell Challenger tanks to Iran.[1,3] All the armor community had to see was the effect that announcement had on the U.S. weapon community.

"As Abrams production nears completion, the Army has embarked on development of a new class of vehicles in support of the armored-systems modernization program. The first vehicle being developed is the heavy chassis vehicle; i.e., the next generation MBT. Rapid advancement in KE and SC capabilities will tax current armor designs. No longer can the armor technologist rely on a single armor element to defeat a threat spectrum. New armor technologies are required, posing new challenges to BRL armor technologists."[2]

An important part of the process of developing new systems is the understanding of the competition; so the BRL has been involved in the exploitation and analysis of threat armor leading to improved understanding of threat systems.[4]

In 1981, the BRL established the Armor Mechanics Branch, with Bill Gillich as its chief, to support the Army's armor-development initiative.[4] Also in that year, two advanced-development armor programs (6.3a) were created to develop advanced passive armors for the upgrade of the Abrams and for the development of RA for future tank systems.[4]

Finally, we note that both the Armor Mechanics Branch and the Penetration Mechanics Branch are involved in developing a fundamental understanding of the penetration process. The following items from 1980 are typical:

"The modeling of material response in the terminal ballistic environment is critical to all research activities [previously] discussed. The current program is focusing on advanced failure models, improved models of plastic flow and non-destructive testing of components. Singular success in the modeling of adiabatic shear at very high strain rates has been achieved by quantifying the phenomenology of plugging failure. Adiabatic shear is the dominant failure mechanism in many materials loaded at high strain rates, and these modeling results are being incorporated in two- and three-dimensional penetration calculations to simulate plugging and fragmentation failure of targets.

"A more realistic plastic constitutive relation has been incorporated in the BRL structural response codes to permit better treatment of strain-hardening materials and hysteresis effects. More accurate predictions of buckling/plastic failure should be achieved when this model is validated. In the non-destructive testing area, a significant advance was made with the demonstration that acoustic emission could be correlated with localized microstructural failure sites by fast Fourier transforms of the acoustic-emission spectrum."[5]

Heavy Armor Development. Before the M1 was fielded, the BRL was embarking on a program of improvements for its armor. The most notable was the use of DU in the armor package. However, we should also note that there were also other significant improvements in special armor particularly against the SC threat.

In 1977, the BRL team patented an armor concept (secrecy order) that was developed for the M1A1 tanks. Also in 1977, the concept of obtaining potential armor improvements through the use of high-density materials was confirmed at quarter scale, but it was not confirmed at full scale until 5 years hence. There was early development work on frontal armors for the M1 system using the newly discovered technology. Major improvements were achieved as spin-off for fabrication of armor packages in early production M1 vehicles. KE backpacks were part of the new armor development.[4]

The design hand-off for the improved M1 (IPM1) armor packages was in 1979;[4] the IPM1 packages did not involve the use of DU.[3]

As a reference point, note that the basic M1 tank was fielded in January 1980.[3]

In 1980, "[An] upper glacis design [was] developed and demonstrated, although not adopted."[4] "The armor program, geared to the defeat of advanced threat penetrators, produced some outstanding successes. There was a successful full-scale demonstration of an alternate and extremely effective defeat mechanism for KE penetrators, ... "[5]

"Development work begins [in 1982] on *heavy armor* at full scale."[4] "The BRL achieved an extraordinary success in an urgent, high-risk armor development program for future fighting vehicles. Test results confirmed performance of prototype armor, which provides protection from threat antiarmor munitions of the next decade."[6]

"Front module designs [were] completed, and production-implementation plans [were] affirmed [in 1984].[4] "In armor technology, the BRL achieved two important technology advances. The first was the development and demonstration of an improved integrated armor for the 1990s; ... "[7] This eventually became known as the M1A1 Heavy.[3]

The IPM1 was fielded in December 1984. This tank still used the 105mm gun. In August 1985, the basic M1A1 was fielded with its 120mm gun.

In 1986, the Vice Chief of Staff of the Army (VCSA) made the "production decision for [the] high-density-material armor package for [the] M1A1."[4] The M1A1 Heavy was fielded in October 1988 with its DU armor.[3]

"While the fielding of the M1 provided a quantum jump in MBT protection, the threat continued to escalate. Larger, more effective unitary SCs, tandem SCs, high-density KE penetrators (both DU and tungsten) entered the battlefield. Research at the BRL continued to address these threats and provided increased levels of protection for the Abrams MBT. The unique design of the Abrams allowed BRL armor technologists to develop and propose product improvements for the armor packages. Consequently, variants of the Abrams include upgraded armor systems consistent with original weight and space constraints. This has resulted in the fielding of the IPM1, M1A1, and most recently, the M1A1 Heavy Armor tank. The M1A1 Heavy Armor tank includes a revolutionary armor system incorporating DU as a component providing unprecedented SC and KE protection."[2]

The armor/antiarmor game continues, and, in 1989, we find "design modification adopted to *heavy armor* for the M1A1 to address escalating battlefield threats/potential threats."[4]

Then there were efforts toward armor for the next version, the M1A2. "Armor technology advances have been examined to improve the survivability of the heavy forces modernization and M1 Block II vehicles. DARPA/Army/Marine Corps armor/antiarmor program contractors and the best of the international armor producing companies have had competitive armor designs evaluated by an independent assessment group. A BRL hull armor design has been developed and demonstrated which provides 35% more KE protection and 25% more SC protection than the present M1A1 hull armor; this armor is under consideration for a vehicle-upgrade program."[8] With the demise of the Soviet threat, the M1A2 armor upgrades in the form of applique armor serve only as baseline technology for potential applications.[3]

The 1988 armor dialogue between the United States and the UK was the forerunner of the creation of a US/UK MOU on armor technology that was signed in 1990.[4]

The BRL's Cray-2 was accredited for special-access program (SAP) computing in 1990, and supercomputing on SAP armor technology began in earnest for the study of mechanisms and additional improvements to advanced armor technology.[4]

The "potential for further improvements to *heavy armor* technology [was] identified and demonstrated" in 1991.[4]

"The BRL has a long history of research into effective SC and KE penetrator countermeasures for use on U.S. armored vehicles. This interest includes active, reactive, and passive armors. During Operation Desert Shield/Storm, we constantly heard reports lauding the Abrams MBTs: the M1, IPM1, M1A1, and the M1A1 heavy armor—the best the world has to offer. The BRLer's view this with great pride. The armors protecting these vehicles were developed here. But with this pride came trepidation. Intelligence information could only give a best guess the threats these vehicles would see. Were the designs robust enough to handle the unexpected, the unanticipated? Did we translate our research into well-engineered armor packages? The successful, decisive head-to-head tank victories by U.S. armored forces in Iraq and Kuwait answered these questions."[2]

In a somewhat more futuristic vein, a "program [began] for the development of electromagnetic-armor (EM-A) technology; [but] funding shortfalls interrupted after 18 months." However, in 1991, the technology program for EM-A was resumed with the identification of possible KE as well as SC defeat mechanisms. Incidentally, the SC defeat mechanism was proposed by Harris Walker of the BRL in 1973. In 1992, the "EM-A ranges [are] under construction. EM-A modeling work and computational simulations continue."[4]

Reactive Armor (RA). In its basic form, RA involves two metal plates that sandwich a sheet of explosive. The explosive is initiated by the penetration, and the metal plates are propelled obliquely against the penetrator. The BRL is the U.S. leader in RA technology for the defeat of SC and KE threats.[4]

There were considerations for application of passive and reactive appliques to the M60 tank in 1980:[3] "The armor program, geared to the defeat of advanced threat penetrators, produced some outstanding successes ... and the development of techniques for effective applique armors. The development of the latter has possibilities for up-armoring fighting vehicles that are in the current inventory, as well as those in the development cycle."[5]

The efforts got a nudge in June 1982 when Israeli tanks were observed with reactive applique.[3,9] The advanced-development program, D221, started with emphasis on RA in February 1982. "Development and testing of RA has demonstrated structural integrity and the ability to provide protection from multiple hits. Full-scale tests have demonstrated protection levels at least two times greater than M1 type armor of equal weight."[6] This was for the KE and SC threat.[3]

The go-ahead for the design of reactive appliques for the M60 tank was given in February 1983, it was turned over to TACOM in September, and full-scale engineering development (FSED) began in July of 1984.[9] "In armor technology, the BRL achieved two important technology advances. ... The second, in the area of retrofit armor applique, was the development of a unique attachment system with an improved design superior to any known in the world. This design has been accepted by the Project Manager (PM) [for the M60 tank]."[7] The RA tiles for the M60A3 tank that were the products of research, development, and design by the BRL were used in Operation Desert Shield/Storm by the Marines.[4]

RA was also a part of the M1A2 program. "The latest Abrams variant, the M1A2, currently undergoing final development is also a beneficiary of BRL armor research. Continued threat escalation necessitated enhanced protection. As early as 1957, BRL researchers were searching for new defeat mechanisms. This led to RA, a combination of spaced armor and explosives. This armor showed considerably greater resistance to SC penetration than any previous armors. The first and only U.S.-fielded recipient of this technology is the Marine Corps M60 MBT, [which gave] another stellar performer in

M60A3 Tank With RA Applique—As Used by the Marines in Operation Desert Shield/Storm.

Southwest Asia. Continued research over the years led to the RA appliques designed for the M1A2 design."[2]

"An improved explosive was also developed for RA which solves a number of sensitivity problems, including sympathetic detonation between armor elements and multiple impact sensitivity ... "[10] This material uses very finely ground RDX in a binder (heavy on the binder).[3] The BRL and DuPont performed a joint unfunded study to examine applications of LF-2 in RA designs. Hugh Denny was the BRL project engineer, and Dr. Martin Wagner was the DuPont researcher.

"In addition, both a means for improving the performance of RA against SCJs and a new model for the interaction of KE rods and RA front plates were developed [by the BRL]."[10]

Some advanced ideas for RA include the development of pill armor leading to prototype armors for increased protection of roof and frontal armors.[4] This involves non-parallel-plate RA that will withstand multiple hits.[3]

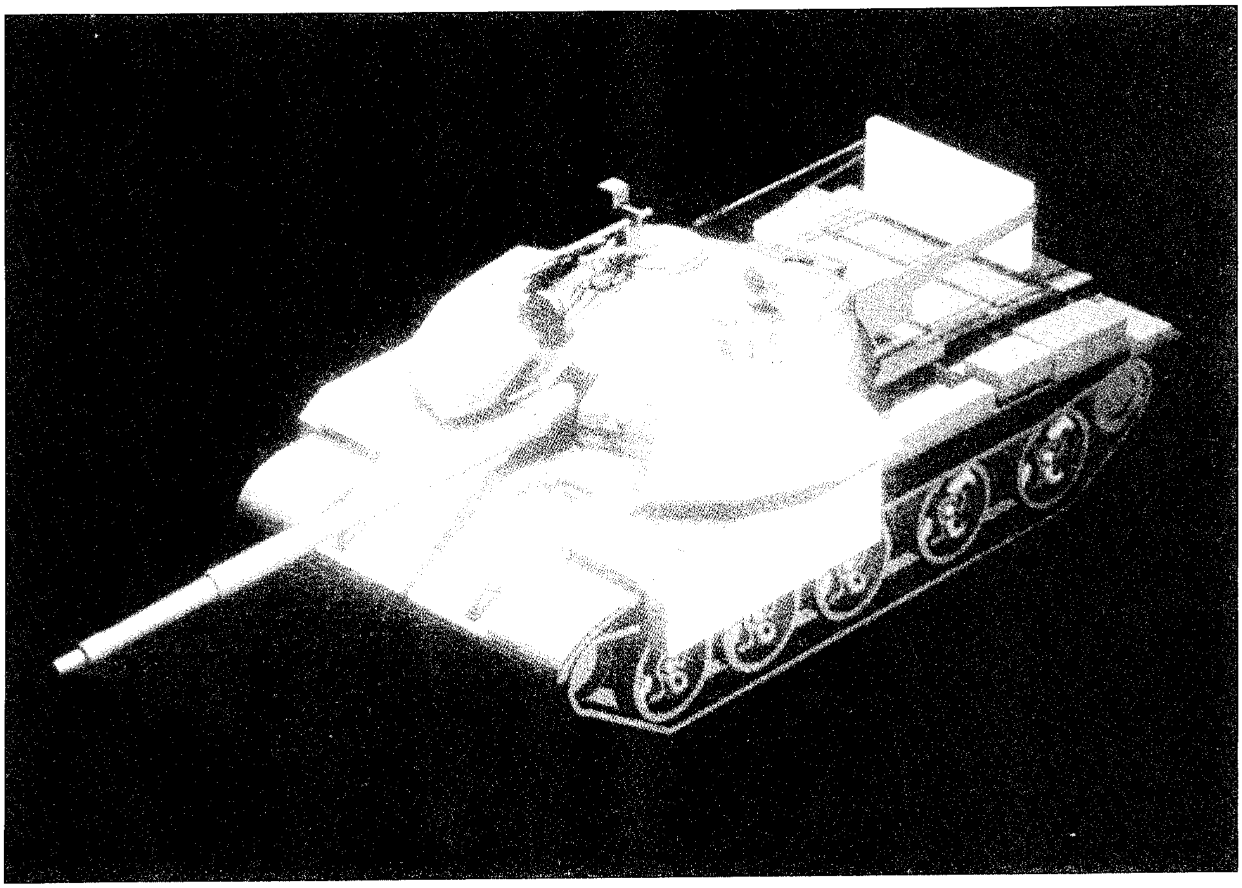
There is also concern for troop safety in the neighborhood of the vehicle, which has led to the development of the initial-confinement technique for full-scale RA. This concept of integral armor keeps the plates from being projected from the vehicle.[4]

Reactive Applique Armor Package Developed for the M1A2 Tank.

"During Operation Desert Shield/Storm, and at the request of the U.S. Army Foreign Science and Technology Center (FSTC), the BRL conducted a rapid ballistic evaluation of an Iraqi T-55 tank that had been upgraded with a passive applique. The results were provided to U.S. forces prior to the ground war."[11]

According to Hugh Denny: "As U.S. forces began the ground phase of the liberation of Kuwait, they did so with an enhanced understanding of an armor technology used by the Iraqis, thanks to [the] efforts of BRL engineers and technicians. This key information was disseminated to troops on the ground by the U.S. intelligence community based upon the result of a rapid material exploitation effort by the BRL's TBD. Adding this knowledge to the confidence in their own equipment was a successful combination for American troops.[12]

"The genesis of this program was the Battle of Khafji in late January 1991. In the aftermath of that short offensive action, U.S. and Allied Forces captured a number of Iraqi armored vehicles. One of these was a Soviet T-55 tank with an armor upgrade package put on by the Iraqis. This design consists of a series of external armor appliques mounted on the T-55 to provide enhanced protection along the hull glacis, the turret front, the hull sides, and the turret rear. It was critically important to determine just how much armor protection was



BRL-CAD Model of an Iraqi T-55 Tank With Applique Armor.

provided by this armor array and to assess how it functioned against U.S. munitions.

"Although this design had been displayed previously at the Baghdad Arms Show in 1988, no actual detailed examination had been possible. The capture of this vehicle provided a windfall opportunity to evaluate an unknown armor threat against U.S. weapons by U.S. experts and provide results to our forces before further ground contact with the Iraqi Army occurred. ...

"Aware of the benefit for U.S. forces of timely materiel-evaluation effort, intelligence personnel in the Kuwait Theater of Operations (KTO) rushed actual components of the Iraqi armor package to the BRL. A team of engineers, scientists, and technicians was quickly formed to analyze this foreign equipment. The program methodology selected to examine the Iraqi armor had three phases. First, TBD made a detailed inspection of the armor appliques to include disassembly, measurement, material property testing, and photographs of internal components. Next, an intensive ballistic testing phase was undertaken that evaluated the armor components against a variety of U.S. munitions. This test program included the use of BRL-produced surrogates of the Iraqi applique that used on-hand materials of a closely similar type and size. In addition, portions of the captured items were mounted on an actual T-55 tank and evaluated in the same way as the surrogates were. In the last phase of this program, the ballistic test results were provided to VLD for their use in performing a detailed vulnerability analysis of the Iraqi equipment.

"... The result of this foreign materiel exploitation did not lead to any design changes in U.S. equipment. Although exact insights cannot be disclosed here, the BRL assessment gave our forces a better understanding of this new Iraqi threat. The BRL team was proud that their efforts increased the confidence levels of U.S. armored units on the eve of the ground war. That this detailed evaluation was completed in less than 2 weeks was also a significant accomplishment of which everyone could be equally proud. A rapid expert evaluation of this nature that directly impacts on the outcome of history-making events is but another chapter in the long and successful story of Federal Government laboratories like the BRL."[12]

Composite Laminate Armor. The very hard ceramic materials have become an important ingredient in many recipes for modern armor. The BRL has played a leading role in this technology.[13]

The BRL's accomplishments in this area include:

1. The development of a nationally used ballistic-ceramic screening technique with MTL.[4]
2. The development of Tandem Ceramic-Armor Technology with MTL, which improved armor performance (Patent Pending).[4]
3. The development of a structure to enhance performance of free-standing ceramics (Patent Pending).[4]
4. Initial leadership in research into cumulative damage mechanisms in ceramics.[4]
5. Research leading to improved understanding of SC penetration into glass materials.[4]

In 1987, the advanced survivability test bed (ASTB)[14] was the first vehicle to undergo LFT with a ceramic armor. The first round was stopped; the second round was not. Since then, there have been tests with more satisfactory results.[3]

Eight unfunded study agreements have been implemented with U.S. and foreign industry to leverage funding and take advantage of industry expertise.[4] These were related to materials (e.g., ceramics) and other technology issues. The arrangements facilitate the sharing of information between industry and Government.[3]

Armor for Light Vehicles. "As armor research continued at the BRL, other vehicles became recipients of new protective measures. RA appliques were developed for the BFV to enhance SC protection for the hull glacis, sides, and the turret front. Technological breakthroughs included explosive isolation techniques which eliminated blast damage to the Bradley's aluminum hull. The BRL appliques are being used as a benchmark in non-developmental-item procurement for the vehicle.[2]

"Light-armored vehicles are also recipients of passive-armor technology. The BRL has developed compact ceramic laminate and metallic-spaced armors to defeat small to medium-caliber KE threats. Both technologies are more effective than monolithic steel. The composite ceramic laminates defeat KE threats by nature of their high hardness which shatters projectiles on impact. Spaced metal armors, on the other hand, are designed to put asymmetric loads on penetrators, causing them to tumble, shatter, and be easily defeated by the light-vehicle structures."[2]

The BRL has a patent pending on methods of implementing effective RA on light-combat vehicles like the BFVS and the armored gun system (AGS).[4]

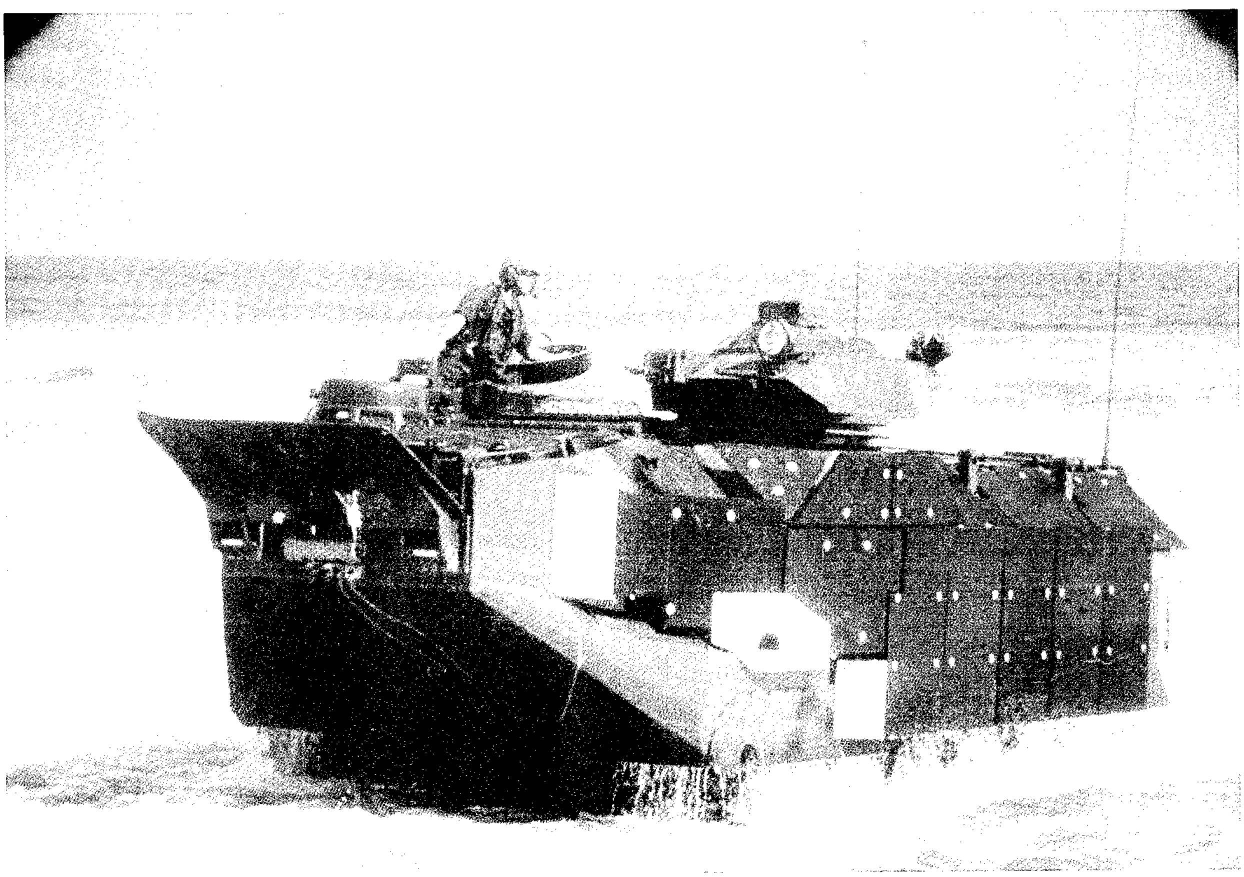
In September 1985, the BRL demonstrated reactive frontal armor for the Bradley; in March 1986, modules were provided for the Bradley high-survivability vehicle; and, in April 1986, the Bradley reactive side-armor design was completed. "Armor-technology advances have been demonstrated and transitioned into engineering development with efficiencies several times that of rolled homogeneous armor (RHA). In the late 1960s, it was thought impossible to develop tank armor to defeat SC warheads. Today, armor technology has supplied applique armor to protect infantry fighting vehicles from moderate SC and [medium-caliber] KE threats. ... After the successful demonstration, the BRL participated in the accelerated development of the Bradley high-survivability technical data package (TDP) required to meet a May 1988 production cut-in. Continued improvements in armor protection are expected with the discovery in the BRL's tech-base armor programs of more efficient, versatile warhead defeat mechanisms. For instance, several developments in tank armors for the defeat of large-caliber weapons have been brought to the point where exploitation can produce substantial gains in protection."[10] The program was separate from the ASTB.[3]

Armor for the BFV.

"There was a multidisciplinary effort by the BRL to provide enhancements for the BFVs. The survivability of the BFVs and crew to SC attack was addressed. Two means of hardening, RA and exterior stowage of munitions, have the potential of structurally damaging the BFV. The results of a study involving extensive hydrocode calculations performed on a BRL supercomputer and conducted to characterize the detonation loads from RA tiles and the TOW-2 missile, coupled with parallel tests using the new BRL ballistic pendulum, have initiated the development of lighter and structurally harder aluminum RA containers and buffering technology to protect against *close-in* blast."[10]

The BRL also performed research, development and design of the P900 appliques for the Marines' light vehicle, LVT7, which the Marine Corps used in Operation Desert Shield/Storm. The application of P900 to the bustle and skirt of the BFV and the Marines' light assault vehicle (LAV)-25 was investigated. A cast P900 was developed, and a patent was granted.[4]

Targets and Testing. The test of weapons against modern U.S. armors is far from simple. Not only is there a plethora of types, but there is often tight security on the details of the configurations. This calls for a set of standard targets and testing procedures that are representative and practical. The BRL is the



P900 Armor Applique Package on the Marines' LVT7.

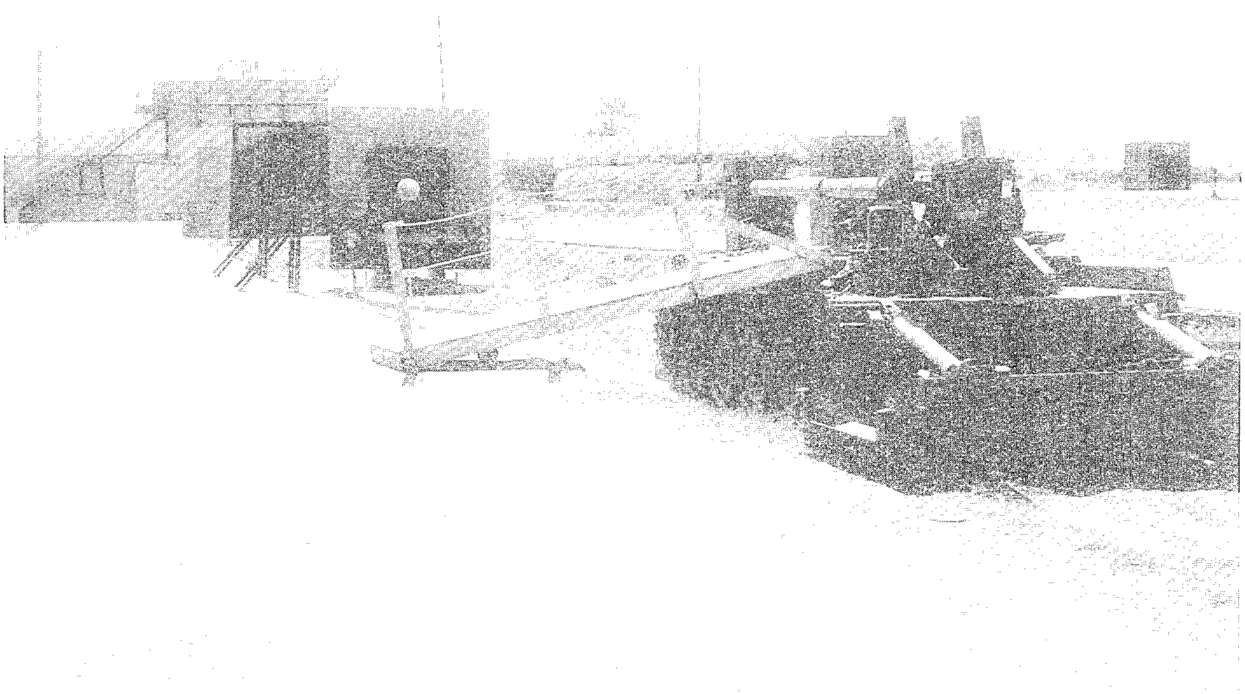
U.S. leader on the national development of range targets. The BRL has also developed medium- and large-caliber threat surrogates of foreign armor developments based on intelligence assessment.[4]

International Aspects. In the international arena, the BRL is the U.S. leader in the Senior National Representatives (SNR) Target Group on the development of range and reference targets for antiarmor munition evaluation.[4] The group is "charged with developing the armor threat for the next generation penetrators. Experts from the BRL have been active participants both in bench-level negotiations with our allies (UK, France, Germany) and in the design and testing of threat-simulating *range targets*, which will soon [this was 1980] be approved by the SNRs for future weapon development."[5]

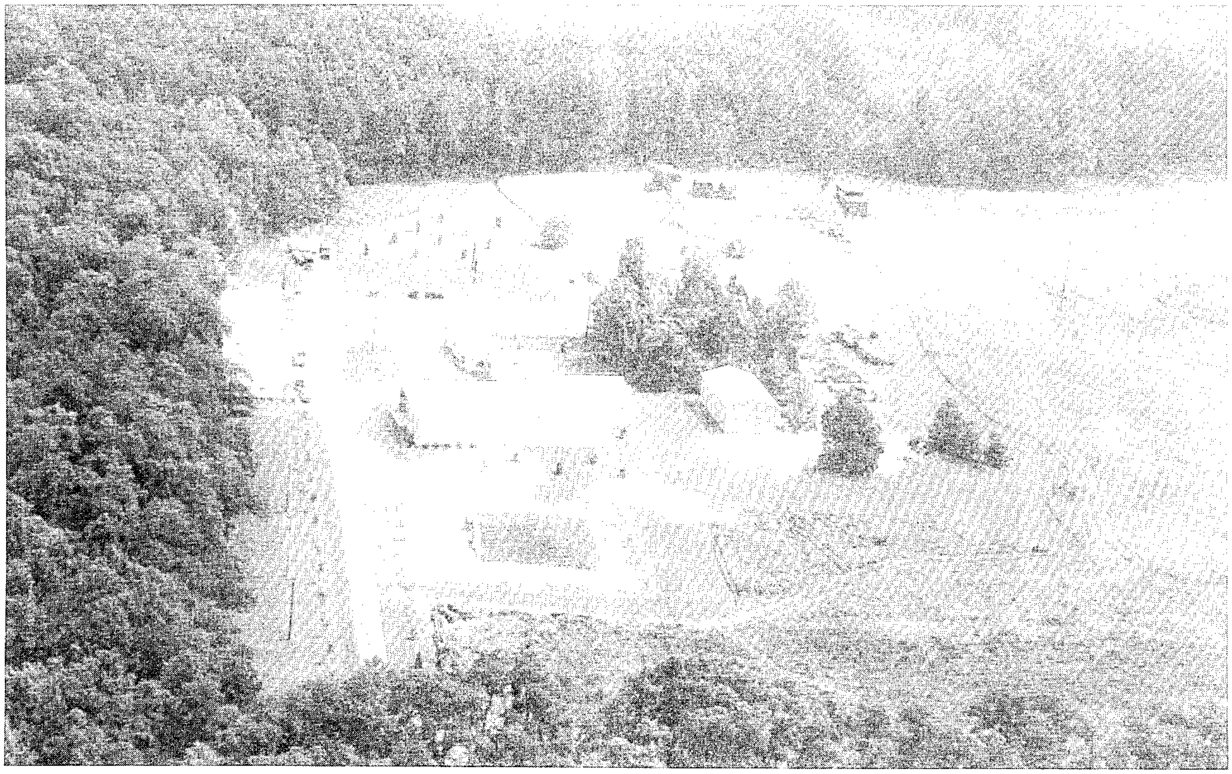
Armor Test Facilities. The two major facilities are a KE test range (Range 14) and a SC range (Range 7).[15]

Range 14 is the *father* of all enclosed KE test ranges. There are two sites:

1. A large-caliber site in which KE rounds can be fired from guns with bore diameters up through 7 in. Flight measurements of velocity, yaw, and pitch are made with 450-kV flash X-rays. Target penetrator interaction is measured with 1-MeV X-rays.



Range R14—For Testing Armor Against KE Threats.



Range 7—For Testing Armor Against SC Threats.

2. A small-caliber site for scale-model testing of armors. It is equipped to handle up through 26mm bore laboratory guns. It is capable of handling small SCs and RA.

Range 7 is the SC munitions test facility, which includes four active sites to study warhead defeat:

1. RA site - limited to 7-in-diameter warheads.
2. Large-scale site - no warhead limit.
3. Horizontal X-ray site - limited to 7-in warheads, 450-kV X-ray equipment.
4. Framing-camera site - limited to 3.2-in precision SCs.
5. New horizontal X-ray site with 1-MeV X-ray equipment.
6. EM-A site.

BLAST DYNAMICS

Armor Mechanics Team. Fred Gregory and the team have been studying the interaction of blast with structures. This includes developing ways to design doors and layouts to minimize effects in the crew compartment of an event in the ammunition compartments of combat vehicles. This has involved a great deal of analysis and tests.[16]

To make measurements in a compartment under blast conditions requires special instrumentation. Gages had to be developed that could survive the environment since conventional gages experienced plastic flow. Stanford Research Institute has developed gages under contract, but more remains to be done.[16]

There are computational problems of describing the equations of state for explosive products. A model due to Jones, Wilkens, and Lee is the one commonly used. It was developed for direct driving of metal by explosives and is probably good for only a few volume expansions. Again, much work remains to be done.[16]

After Richard Lottero heard a conversation of Dr. Richard Dick (University of Maryland) on the use of explosives in oil drilling, he struck a deal for the BRL to use Dick's experimental data and for Dick to use the BRL's hydrocodes. Good data on the accuracy of the hydrocodes were developed from this collaboration.[16]

As a note, defining a proper equation of state for deforming metal is a long-standing problem.[16]

The team's efforts have been directed toward:

1. "Ammunition compartments for the BFV.
2. "Survivability issues related to on-board stowage of ammunition on the BFV.
3. "Design and test of armor modules for the armored-system modernization Block-III tank.
4. "RA effects on hull structures for the BFV.
5. "Ballistic loads on armor module attachments and hull for the armored systems modernization (ASM) Block-III tank."[17]

Fluid Dynamics. Lottero and Richard Pearson have been working on RA blast loading on the BFV, and Pearson has "conducted experiments which demonstrated the synergistic effect of nuclear blast and thermal loading on aircraft-type targets.

"Through in-house work and research contracts, Opalka, Pearson, and Schraml developed much of the enabling technology for the nation's largest nuclear blast and thermal simulator."[17] See the section later that specifically deals with that subject.

"After shut-down of the BRL wind tunnels, Mr. Opalka made the transition from experimental to CFD with the development of the BLOP code, describing the blast-loading of targets, and the BRL-Q1D code, describing the simulated flow field of decaying blast waves in variable area shock tunnels.

"Hisley took part in an In-House Laboratory Independent Research (ILIR) project which involved the design, experimentation, and reporting of a fluidic-analog model for the mechanisms leading to defeat of projectiles by modern armors. The Army R&D Achievement Award was given in 1984 for this work." [Hisley] also "planned and conducted computational research investigations in the areas of blast dynamic phenomena, applied mathematics, and CFD. Intensive research resulted in the development and implementation of two modern codes, Blast2D and Blast3D, for solving shock-wave and target-interaction problems of interest to the Army."[17]

Field Experiment Team. Bud Raley and the team have "developed better shock isolation devices to isolate equipment from blast effects. This includes isolators for electronic racks inside shelters and isolation of rate gyroscopes from local shock/vibration loads so that noise-free whole-body motions of vehicles can be accurately determined during overturning."[17]

They have "developed kits for mobile electric generators that enhance their survivability to blast effects, outriggers to prevent overturning, and a miniature device called a battlebox that supplies electrical power to only essential generator functions. The battlebox bypasses normal controls thereby allowing the generator to function when normal controls are destroyed by conventional or nuclear arms. This technology has been transitioned to BRDEC and the Project Manager - Mobile Electric Power (PM-MEP)."[17]

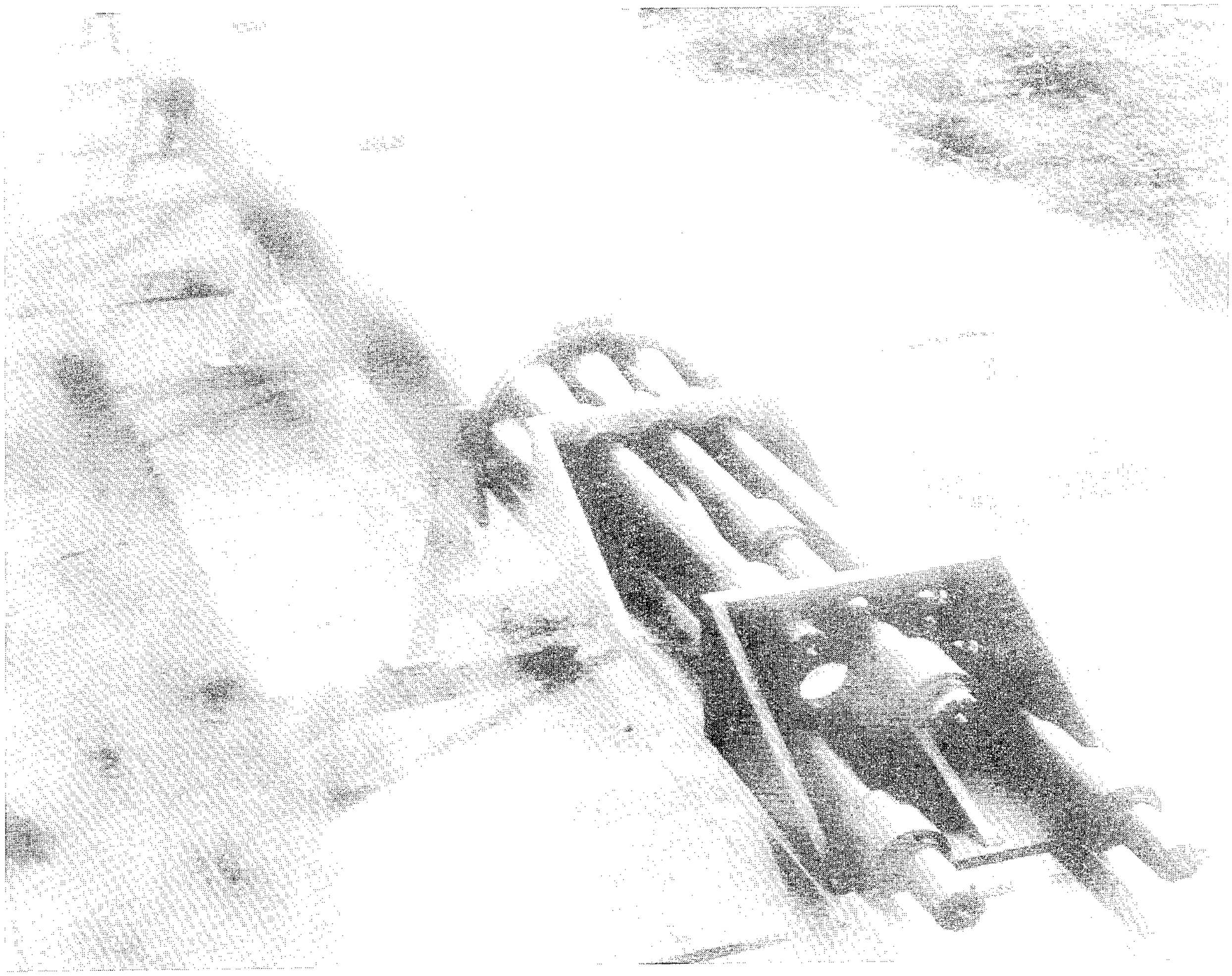
Structural Mechanics Team. Joe Santiago and the team conducted a thermal/blast synergy study for HDL in 1982–1989. "The purpose of the study was to demonstrate that in predicting nuclear vulnerability of structures, the effects of the thermal radiation and the blast wave cannot be treated separately, but that there is a significant increase in vulnerability due to synergistic effects. For this purpose, tests were performed in the 8-ft shock tube on thin cylindrical aluminum-shell specimens for the response to blast only, thermal only, and combined thermal/blast. These tests proved that synergistic effects were indeed significant enough not to be ignored. Counterpart finite-element calculations were performed to verify these results, and demonstrated that with sufficient care, especially in modeling thermal buckling, the finite-element method could simulate the synergistic behavior. The impact of this work was a new awareness in the nuclear-vulnerability community of combined thermal/blast effects.

"In mid-1986, Congress became concerned about the combat performance and, in particular, the survivability of the BFV. The [team] was asked to assess the Bradley's vulnerability to blast and explore means of hardening. One concern was the detonation of stowed munitions, and there were proposals for increasing survivability by relocating munitions. The [team] investigated one proposal to stow TOW missiles externally on the rear-side glacis, but this concept was rejected when our analysis showed that the detonation of the rocket motor by small-arms fire caused excessive damage to the armor. Also investigated was the fratricidal damage to the engine hatch cover from the detonation of RA modules. Here recommendations for hardening were made that contributed to a redesigned hatch cover.

"Most recently, [the team has] begun work on the problem of predicting shock damage to critical components on armored vehicles due to blast and impact from hostile munitions. At present, we are adopting the German (IABG) methodology of detailed calculations of the local weapon/target interaction to generated loading functions, which are inserted into a finite-element model of the entire vehicle to predict the shock-response spectra at critical locations. However, we are also looking into other numerical means of accomplishing these analyses. In particular, we are investigating some more fundamental questions concerning the validity of decoupling loading from response, and the assumptions underlying the shock response spectrum method of analysis. We are also planning for extensive modal testing of select armored personnel carriers (APCs) this summer to verify and improve the counterpart finite-element models of these vehicles.

"It is expected that the techniques and methodology developed by this study will ultimately enable the vulnerability community to assess loss in combat capability due to shock damage and develop means of hardening against such damage."[17]

Large-Blast/Thermal Simulator (LB/TS). The French built a blast simulator at the Centre d'Etudes de Gramat at Gramat, France, which began operation in 1981. That year, there also was a meeting at Cahors, France, of the Military Applications of Blast Simulation (MABS-7). The United States has been involved with France under a U.S./French Data Exchange Agreement on Nuclear Weapons Effects.[16]



ARL Working Scale Model of the French Large-Blast Simulator (LBS).

The French facility is a very large-scale shock tube with seven large driver tubes. Its semicircular cross section is 67 m^2.[16]

In the mid-1970s, Julius Meszaros and others wanted to spin away from the International Symposium of Shock Tubes and Waves (it contained Eastern Block Countries, etc.). MABS was created as largely a NATO group.[16] They saw the value of initiating the development of a facility to simulate nuclear air blast. The French facility resulted with the design starting in the mid-1970s and construction starting in 1978. While Meszaros left the BRL for HDL in 1978, his interest continued.[16]

However, the French facility is too small for proper testing of large items such as tanks and for studying their overturning. Wall effects and blockage are problems, and the flow is inadequate for a complete drag history.[16]

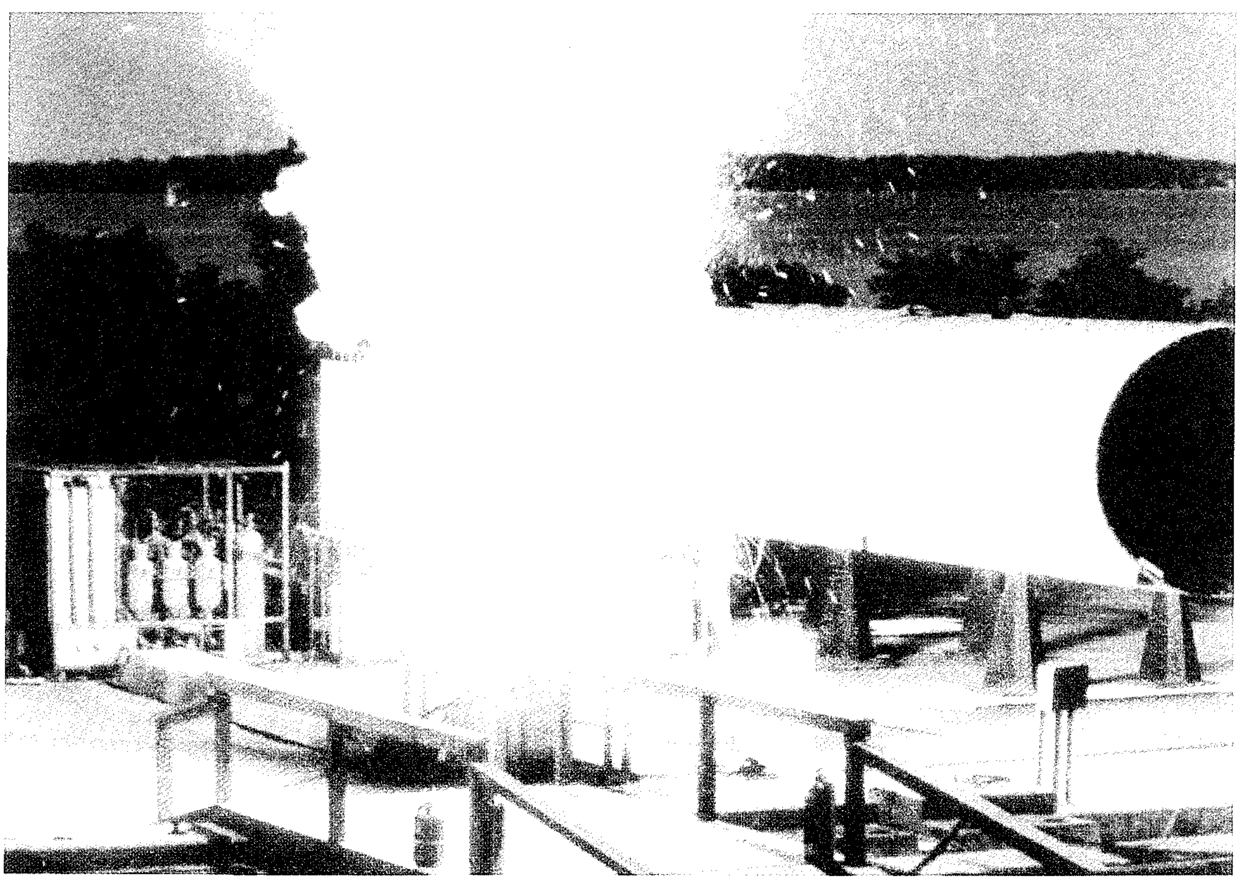
At the time when the BRL entered ARRADCOM, the work in this area was done in the Target Loading and Response Branch with Jack Huffington as the chief. The BRL did not have a direct role in nuclear effects but was in a supporting role.[16]

The BRL participated in the large-scale HE tests in Canada and at the White Sands Missile Range, NM. They developed instrumentation and predicted phenomenology. These shots started with 500 tons of HE per shot and have gone to as much as 5,000 tons of HE per shot.[16]

It is very expensive to do these HE tests, and even they never achieved the total integrated pressure associated with tactical nuclear weapons. Note that the definition of weapons considered as tactical has grown to about 600-kt max.[16]

The French were participating in the HE tests and saw a need for a more controlled environment, more frequent and cheaper testing, and with larger dynamic and integrated dynamic pressure (total impulse); so they took the lead in developing the device. MABS-7 was held largely to show off this facility.[16]

While a breakthrough, the French facility's operating envelope was not the same (pulse shape) as that of a weapon. The device was not heated which affected the later phase of the dynamic pressure pulse. It could not cover the large range of yields, and (as previously noted) it was too small for many tests.[16]



The Thermal-Radiation Source at the BRL—An Aluminum-Powder/Liquid-Oxygen Torch.

BRL/HDL (Meszaros, John Keefer, and Noel Ethridge) initiated the building of a larger facility with better pulse fidelity.[16]

Lottero became involved by about 1983 in defining the parameters of the facility (e.g., the 167-m^2 cross section), and Pearson became PM. A nine-driver setup with heating was selected. The device will be a couple of hundred meters long with elaborate shutters to control the rarefaction wave. The maximum thrust will be about 26–27 million pounds, which is about three-and-one-half Saturn-V rockets. It will have a steel test section to withstand the 2,700 K flame. This will be an LB/TS, while the French device is only an LBS. The flame will use powered aluminum and liquid oxygen. Liquid nitrogen will be boiled to 700 K with a pebble-bed heater; the diaphragms will burst, and away we go.[16]

Originally, the operating envelope was planned to be roughly 2–35 psi pressure and 1–600 kt.* Presently, concrete is being poured for the reaction mass, and some structure is being fabricated. The facility will be in operation at the White Sands Missile Range by 1995.[16]

The following is from an *Update* article by Pearson: "To ensure that fielded Army weapon systems can survive and operate on a combined nuclear/conventional battlefield, the Army has a team of Government, industry, and academic experts working to develop a facility which will provide nuclear-blast and thermal-survivability testing capability.

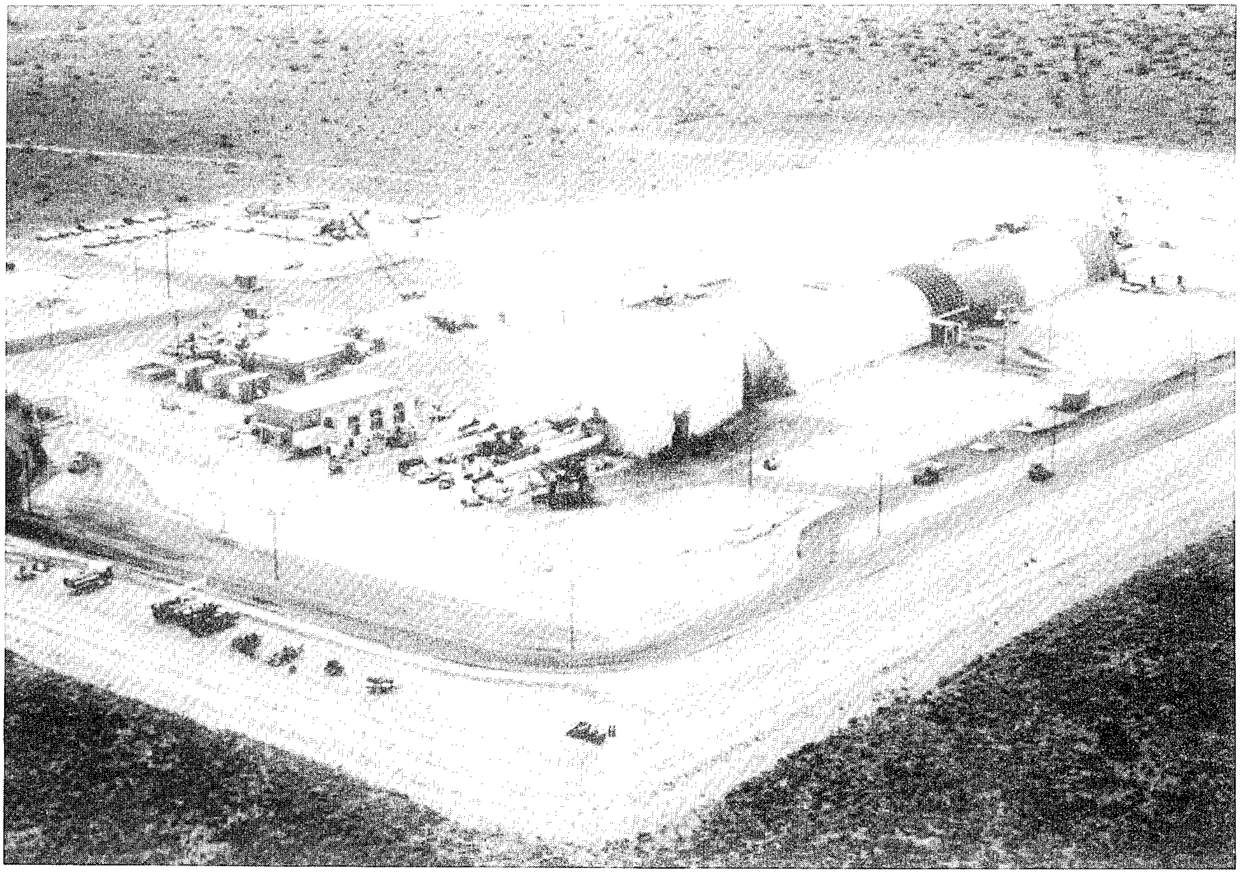
"The development of this facility was precipitated by the need to comply with Army regulations which require new weapon systems to demonstrate specific levels of nuclear survivability and, further, mandate the hardening of systems against prompt radiation, electromagnetic pulse (EMP), and blast and thermal radiation. Presently, the United States lacks the ability to test military vehicles to the full range of nuclear blast and thermal effects required by the Army. To solve this problem, the BRL is working with DNA and HDL to develop the $65 million LB/TS.

"The BRL has played a key role in the LB/TS R&D program which developed the technology that makes the LB/TS possible. The BRL initially identified the need for a simulator like the LB/TS and defined its required operating range. The simulator requirements defined the basic size and geometry of the simulator. The LB/TS R&D program determined the fundamental flow pattern in the blast portion of the simulator, and, from that knowledge, the basic dimensions of the facility. Working with DNA and SAIC, the BRL helped develop the thermal radiation source (TRS) units that form the basis for the thermal simulation capability.

"The facility is being designed for DNA by the COE. The LB/TS is currently in the final design stage with the start of construction scheduled FY91. Construction is currently scheduled for completion in FY93. A 1-year facility characterization and shakedown period is scheduled after the end of construction with testing of military equipment to start in FY94.

"The new facility will be located at the White Sands Missile Range in New Mexico and will be operated by the U.S. Army Nuclear Effects Directorate (NED) of TECOM. A large number of Army systems currently have air-blast testing requirements. Prime candidates for early testing in the LB/TS are communication systems like the joint surveillance and target-acquisition system and the single-channel objective tactical terminal. Other candidates for early testing are combat

*Computational parametric studies were carried out by Opalka.



The U.S. LB/TS Under Construction.

systems like the NBC reconnaissance system, MLRS, BFV, the heavy assault bridge, and prototype vehicles for the armored-systems modernization program.

"More recently, the LB/TS program began work to prototype the major sub-systems used in the LB/TS design. The BRL has managed the development of the facility's unique high-pressure, high-temperature gas supply system by its contractor, Sparta, Inc. The system, based on cryogenic pumps and pebble-bed thermal-storage devices, makes it possible to rapidly deliver the very large amounts of heated gas required to operate the LB/TS. The BRL, working with Applied Research Associates (ARA), the University of Toronto, and the New Mexico Engineering Research Institute (NMERI) has also developed a large computer-controlled flow-metering device termed an active refraction-wave eliminator (RWE). The active RWE controls the flow exiting the simulator, maintaining the proper test environment inside. Without the active RWE, it would be impractical to achieve the relatively long test durations required in the LB/TS. Work continues with large-scale experimental models of the gas-supply system, flow-initiation system, active RWE, and thermal-radiation simulators.

"The large-scale models will be used to test control systems, predictive computational models, and advanced simulation techniques.

The BRL is improving predictive models of the facility using supercomputers and advanced computational algorithms.

"The BRL is currently acting as a technical consultant to DNA, COE, and their contractor, R. M. Parsons, Inc., on the LB/TS design. The improved predictive models developed recently are being used to update the facility's operating envelope estimate to reflect ongoing design changes. The BRL continues to play a significant role in helping to develop a technically sound, safe, and cost effective facility."[18]

EXPLOSIVE EFFECTS

Bob Frey, the Chief of the Explosive Effects Branch, prepared the following list of branch accomplishments for the period 1977–1992:[19]

1. Improved the present ammunition-compartment technology, to include the following:
   a. Antifratricide devices for the M1/M1A1.
   b. Evaluation of the response of ammunition items in the M1/M1A1 ammunition compartment and advice to the PM on the acceptability of storing the ammunition in the M1/M1A1.
   c. Improved understanding of how/why sympathetic detonation occurs in compartments.
2. Basic RA technology including initiation techniques, analytical models, and improved explosives for RA.
3. An improved knowledge of the response of solid-gun propellants to SCJs and KE penetrators, including the following:
   a. Improved experimental techniques for evaluating the response of propellants to SCJ impacts.
   b. An analytical relation which relates the blast output from a propellant charge to the parameters of the attacking jet.
   c. An extensive data base on the pressures developed in ammunition compartments as a function of free volume, vent area, and jet parameters.
4. Techniques for extinguishing propellant fires.
5. Evaluations of the fuel-fire problem on armored vehicles, including the following:
   a. Alternates to halon (powders) for extinguishing engine-compartment fires.
   b. Advice to vehicle designers on the best techniques to minimize the occurrence of fuel fires after penetrating impacts.
6. Basic understanding of ignition mechanisms in solid explosives to include ignition by shear and ignition as a result of cavity collapse in energetic materials.
7. Improved understanding of the several mechanisms by which SCJs can initiate solid explosives, to include the initiation of RAs by jets.
8. Techniques for preventing sympathetic detonation in stored ammunition, to include:

a. *Sand grid* walls for eliminating truck-to-truck propagation in ammunition-handling areas.

b. Storage racks for 105mm and 120mm tank ammunition.

c. Storage rack for 4.2-in mortar rounds.

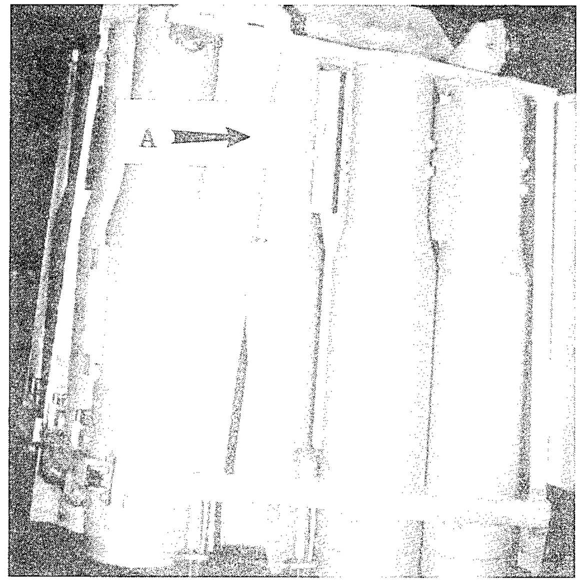
9. Alternative configuration for the BFV (the ASTB) which reduced vulnerability by changing ammunition storage arrangements.

Compartmentation. While the ammunition compartments of tanks cannot stand up to all rounds going off at once, the prevention of total sympathetic detonation takes surprisingly little effort.[20]

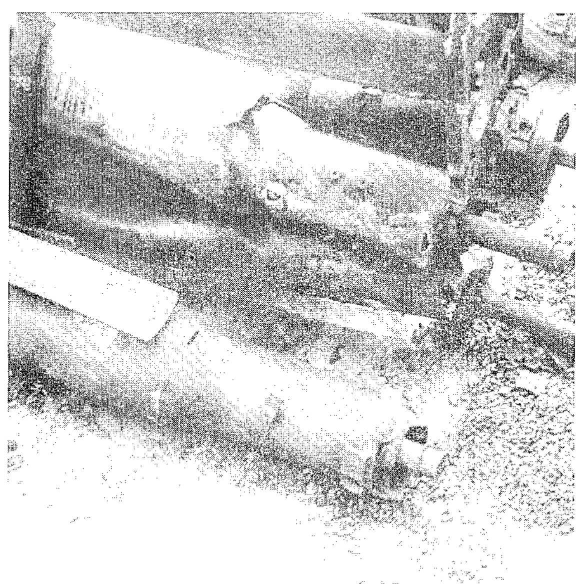
Warheads. Circa 1976, the BRL learned some very fundamental things. The conventional wisdom was that fragments from the donor shock-initiate the receptor. While this is true for a one-on-one situation with no fratricide measures, in a real compartment there are processes that take milliseconds rather than microseconds. The strength of the confinement around the event has a big influence. The presence of the propellant (and the pressure from its burning) is also important in propagation from warhead to warhead.[20]

Antifratricide bars in the M1 and M1A1 tanks were designed by the branch. The trick is to leave some space, and to keep contact with the rounds to prevent a growth of velocity in the bar. Both experimental and analytic studies were made for the design of the fratricide bar. The bars must not add significant extra confinement. To provide minimum transfer of energy through the bar, it is made from plastic and steel.[20]

The relative sensitivity of various explosives is different with and without bars and with and without shock. The without-shock mechanism



Antifratricide Bars (Labeled "A") in a 120mm Ammunition Rack in the M1A1 Tank.

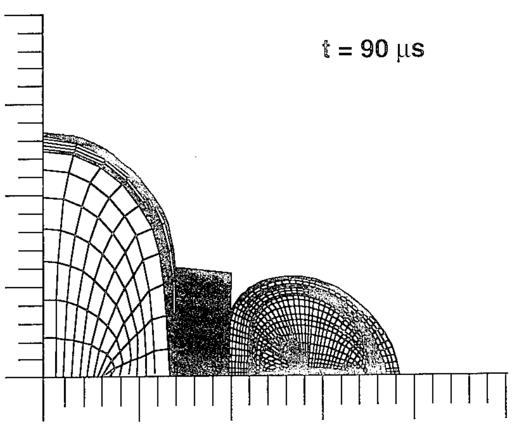


The Antifratricide Bars Prevented Fratricide in This Test.

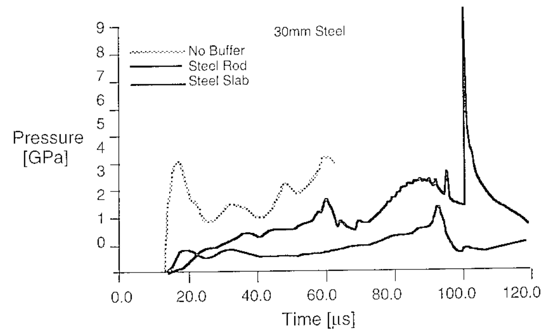
is not clear but it might be related to crushing.[20]

The BRL also learned that there is a minimum free volume that is needed for the gases to expand—and a minimum venting. Circa 1977, Stansbury and Budka developed a model to treat propellant burn in a compartment. This was refined by Battelle, Columbus, OH, to make an ammunition-compartment model that could be used in conjunction with data (sort of an interpolation model) to make venting calculations, but it does not treat explosive burn. The model treats propellant burns; it does not treat explosive reactions.

Propellants. In the mid- to late 1970s, Ned Prenatt was involved in noting that a propellant event could be more devastating than an HE event. That is, the burning of all the propellant is often worse than the detonation of one HE round. Propellant became an important consideration.[20]



Donor Charge on Left,
Antifratricide Bar in Center,
Acceptor Charge on Right.



Pressure History in the Acceptor
for No Measure (Dashed),
for a Steel Rod (Line),
and for a Steel Slab (Dotted).

Circa 1979, John Majerus made some firings against propellants with SCJs at 8–10 km/s and with hypervelocity fragments at 3–5 km/s using a launcher developed by John Kineke in the 1960s. The propellant bed reacted violently, but it did not detonate.[20]

In the late 1980s and early 1990s, Jerry Watson showed that there are at least two mechanisms by which gun propellants react to jets:[20]

1. Violent deflagration - Watson determined that the violence (as measured by the blast energy) correlates strongly with the energy deposited by the jet in the propellant. This gives VLD a tool to go from SC to SC and to consider the effects of armor, etc.[20]

2. Shock-propagated reaction - This is not necessarily a detonation, but the

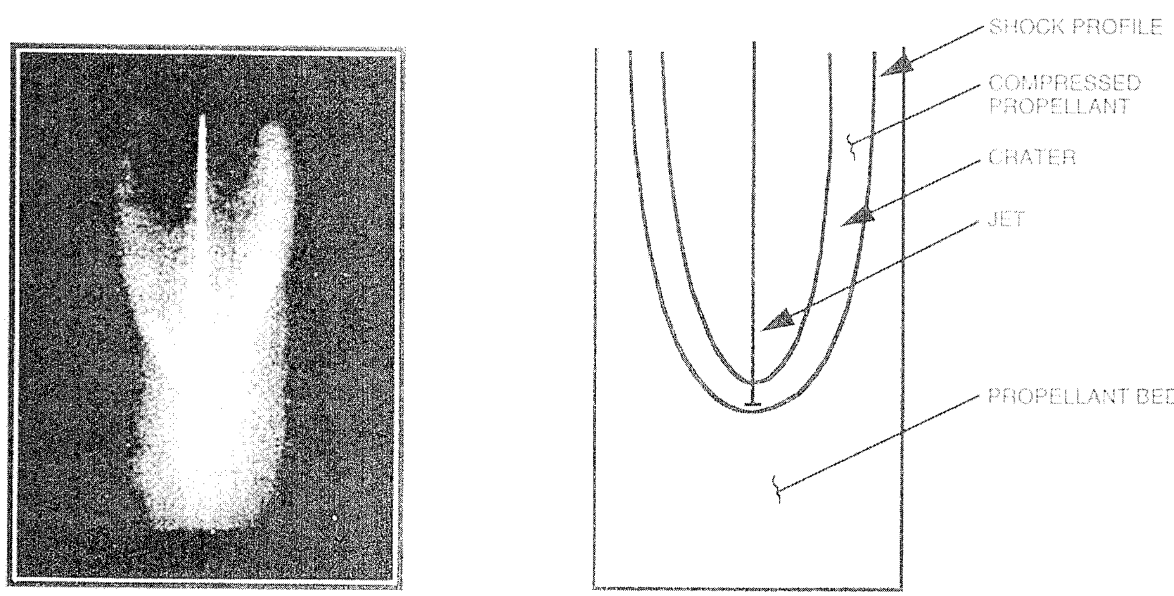
consequences are much worse than a violent deflagration.

There are practical implications to the choice of propellants to avoid (or minimize) the occurrence of the mechanisms. Certain propellants are more sensitive to type 1; others are more sensitive to type 2.[20]

"A neat trick emerged to assess propellant reactions—the time-honored ballistic pendulum. It is simple, gives reproducible results, and is uniquely satisfactory." The propellant is mounted on the pendulum, and the swing of the pendulum is a measure of the violence of the reaction.[20]

There have been numerous experiments with instrumented compartments to measure pressure as a function of time. This is not easy; the environment is severe, dirty, and non-homogeneous (measurements must be made in several places). With special chambers, the researchers can vary the threat, the free volume, the venting, etc. This makes a powerful design tool.[20]

From 1986, we have: "Mass detonation of 25mm ammunition can be lethal to troops and fighting vehicles, such as the Bradley. In the current container configuration, 25mm HE ammunition is mass detonated. However, the BRL has demonstrated that by changing the storage configuration of the ammunition, mass detonation can be prevented. Prototype testing in FY86 points towards the development of space-efficient designs that weigh no more than the current packaging."[10]



X-Ray of a Type 1 Propellant Response.

And from 1991: "An empirical model for the response of gun propellants to SCJs has been developed. With limited experimental data, the model makes it possible to predict the response of gun propellants as a function of jet velocity, jet diameter, standoff from the attacking warhead to the propellant, and jet path length in the propellant. This information is required for the development of a model of ammunition compartment response."[11]

At this point [1992], the concern is to understand the issues associated with the storage of LPs. LP has unique properties, and the work has just begun.[20]

Explosives. In the late 1970s, with a definitive report in 1979, the branch went through a series of impact studies and experiments on Composition-B. Violent (but not detonation) reactions were demonstrated that were equivalent in many applications to detonation (e.g., in an antimissile role for the defeat of an incoming warhead). However, a non-detonation reaction is not adequate to destroy a proper compartment (it will not sympathetically propagate in a properly designed compartment).[20]

SC Initiation of LP.

There has been continuing work on aspects of ignition, especially cavity collapse, which was "known for aeons, but the mechanisms were not clear." There are three hypotheses:[20]

1. Adiabatic heating of gas inside the cavity.[20]

2. Shock focusing by the cavity.[20]

3. Visco-plastic work on the surface of the cavity.[20]

In the early 1980s, Frey did a theoretical study with a model in which all three of these mechanisms were possible. With this model, he could look at conditions that favored each mechanism (things such as size of cavity, strength of the material, viscosity, fast or slow initiation, etc.), and he found the following:[20]

1. Adiabatic heating was favored for large cavities (> 1 mm) with compression but no shock.[20]

2. Shock focusing was favored for large cavities with shock stimulus.[20]

3. Visco-plastic work was favored for small cavities with shock stimulus.[20]

This spawned follow-on research to find ways to recrystallize RDX to make very small cavities (too small for the visco-plastic effect), in which case all processes are turned off. The problem is still being worked.[20]

Starting around 1980, they looked at shear banding. A theoretical (computational) model was developed that showed that explosives could be initiated by spontaneous shear bands. This could occur in less than a microsecond. The model included heat transfer, thermal softening, and temperature-dependent viscosity. Follow-up experiments were conducted to look at shear sensitivity of a variety of explosives. These showed the following:[20]

1. Shear sensitivity is quite different from shock sensitivity.[20]

2. Some initiation events were shear related; some were shock related.[20]

For 1980, we have: "Substantial progress has been made in several aspects of terminal ballistics. The work in explosives and munition sensitivity is a striking example. A complete analysis of shear banding in explosives has resulted in a model which relates local temperature to sliding velocity and pressure. From this model with ignition temperature as a fixed parameter, it has been demonstrated that there is a pressure threshold below which the probability of initiation is very small for all sliding velocities. This modeling observation will be incorporated in exploratory development efforts by impact testing confined HE where confinement has been designed to rupture above or below the identified threshold pressure. A marked reduction in probability of detonation should be obtained for the different confinement designs. In the future, it should be possible to use this probability information to reduce the vulnerability of cased explosive to fragment impact."[5]

From 1986: "Most members of the scientific community studying explosives and propellants are familiar with shock initiation as a means of causing a munition to detonate. Work at the BRL has clearly demonstrated that shear-initiation mechanisms can be very important as well. It was shown that catastrophic shear causes local temperature excursions which can cause initiation of the explosive. Most important, it was shown that the nature of the dependence of viscosity upon temperature and pressure is critical. For example, energetic polymers used as binders can be sensitizing, due to their high viscosities at high pressures. Failure to recognize this led one of the other service laboratories to formulate a propellant, using an energetic polymer binder that was extremely sensitive to shear, although it had good shock resistance."[10]

The following report from 1987 discusses some of the techniques that were considered for desensitizing explosives.

"There were several very promising developments in the continuing quest for explosives which are insensitive to inadvertent initiation while still functioning well in their normal mode. Patents have been filed or written for the first three techniques noted.

"Flame Suppressing Explosives - This is of considerable significance in that its primary purpose is to protect RA from incendiary attack. Adding radical scavengers to explosives appears to quench the ensuing deflagration which results from the *hot spot* caused by the attack."[10] This significantly reduced burning created by small-arms impacts that did not detonate the explosive, and was due to Warren Hillstrom.[20]

"Emulsified Explosives - A composite explosive (AMATOL and EAK) was chosen, and world leaders in emulsification technology [were] consulted in an investigation into the techniques of emulsifying explosives. It was discovered that both emulsions and microemulsions are possible using ammonium lauryl sulfate with EAK and mineral oil. Emulsification causes a reduction in the liquid-droplet size, and thus greater intimacy of ingredients. This leads to a reduction in the sensitivity to low-level hazard shocks while maintaining performance; the liquid droplets are frozen into the solid-state so that crystal growth is inhibited. Such emulsification should make this composite explosive much more acceptable to the Army mission."[10] Although the theory was encouraging, an advantage was never demonstrated.[20]

We should note that, for different compositions, the relative sensitivities as functions of the four combinations of buffered and unbuffered, and shear and shock are quite variable.[20]

Fire Extinguishing. From about 1983 to 1988, Tony Finnerty was interested in the impacts of spall particles on propellants. He demonstrated techniques for preventing (by very early quenching) and extinguishing fires in propellants.[20]

One concept for preventing fires involved a water jacket around the round, which prevents the fire from spreading among the propellant grains. This even works against an SCJ which drags water along. The Army was not willing to take the weight and volume penalties; so the concept is on the shelf. Another concept that used sheet explosive to drive water into the ammunition compartment was developed to extinguish fires. It too is on the shelf.[20]

Finnerty has become the Army's expert on fuel fires and on the use of halon, the use of which is now precluded due to problems with the ozone layer. He has put together a list of *do's and don'ts* to minimize fuel-fire problems that finds considerable use by vehicle designers—this considers all aspects including placement. He has shown that (despite conventional wisdom) SCs and EFPs can start diesel-fuel fires.[20]

He has also demonstrated that a mixture of bicarbonate of soda and alumina in a liner can extinguish a fuel fire. Both ingredients act as a heat sink, and the generation of CO_2 from the soda is also endothermic. This latter concept is being pursued for the new AFAS howitzer.[20]

Quickload Program. Phil Howe conducted a study on the protection of artillery rounds in the early 1980s.[20] "Small-scale experiments with pipe bombs simulating 155mm artillery shell demonstrated that, in addition to the well known shock, blast and fragment hazards associated with detonation of a single round of ammunition, multiple-round detonations generated severe fragment mass focussing, rather similar to linear-SC jetting. In detonations of full-scale artillery shell, this jetting is sufficiently severe to perforate approximately 10 cm of armor plate. The BRL has developed shielding techniques which essentially eliminate the jetting and can be applied to single or multiple-pallet units of separate-loading projectiles. These shielding techniques prevent detonation of a two-pallet unit of 155mm shell (for example) within approximately 600 mm of another two-pallet unit which has been detonated deliberately. Thus, the size of an explosion within an arbitrarily large array of shielded units of projectiles can be limited to one unit. The shields are relatively light-weight, less than 20% of the total unit weight, and can be made from inexpensive, commercially available materials. The shields have been tested and demonstrated to work, as part of the Safe Transport of Munitions (STROM) program. In addition to potential applications in transport of munitions, the techniques appear to have high potential payoffs for use in tactical storage areas, where mass detonations can cause complete loss of ammunition stores and where close proximity to built-up areas prevents compliance with safety regulations—using current storage techniques."[5]

The following is from an *Update* article by Jerry Watson: "An important element in the U.S. policy on maintaining a posture of military readiness is ammunition storage and availability. The state of readiness, and thus, ammunition storage is a matter of concern in many areas of the world today. Frequently, ammunition is stored in an ammunition holding area (AHA) situated close to combat zones. These AHAs are congested with much of the ammunition being stored on trucks or in other vehicles in tank parks. The high density of explosive ordnance, coupled with a state of international tension, creates concern for the safety of all involved. The Department of

Defense Explosive Safety Board (DDESB) has established standards for explosive storage based upon the quantity and type, but in many instances these facilities cannot comply. The scarcity of land, the encroachment of the civilian populations, and the operational and readiness requirements of these facilities have forced many of them to use waivers to operate. Since these facilities cannot comply with the normal standards, there is the possibility of a catastrophic event with significant loss of life among both military personnel and civilian populations.

"TBD of the BRL has been working with the Project Manager-Ammunition Logistics (PM-AMMOLOG) and other DOD agencies as a team in a program called Quickload aimed at resolving these kinds of storage problems. This program is directed at providing solutions to ammunition storage problems which are simple, are cheap, and avoid the necessity of major construction. Originally, the program was directed at providing interim solutions for the storage of ammunition but has evolved into a program whose solutions may be used indefinitely. The solutions are not considered to be waivers.

"The approach is to use the most recent knowledge of explosive-propagation mechanisms and mitigation techniques to develop solutions to minimize the hazards. By changing the storage arrangement or suggesting barrier techniques to limit the amount of explosive which will detonate, many potentially catastrophic situations can be reduced in severity or brought into compliance with the standards. In many cases, this means that the solution becomes ammunition-specific and can only be used for certain ordnance items based on its explosiveness (sensitivity). To ensure that the technique is properly accomplished, a TDP is generated for each application after it has been proven by test. This TDP is approved by the DDESB along with the site plans whenever it is used.

"The Quickload program has generated several TDPs which have been approved and are available for use. A typical example of the kinds of solutions developed is a storage facility which can be put into tank parks or maintenance areas for downloading the tanks for maintenance. This particular facility requires a 75-ft safety radius and can hold the entire basic load from the tank. It only requires 1% of the land area [used for] conventional magazine storage. The storage rack is built from the shipping cans used to ship the ammunition while the fragment barriers are constructed from light-gauge sheet metal, angle iron, and chain-link fence. The fragment barriers are sand filled. In addition, there are several variations to the design which give the user some flexibility for his particular application based upon the availability of skilled labors (welders) and materials. These variations include the use of pipe and pipe clamps or welded angle iron, ground-embedded posts or half-height walls instead of triangular wall bracing, and the use of 2-ft-diameter corrugated pipe in the construction of the fragment barriers. This rack was designed to store 120mm ammunition, but there is also a similar design for storing 105mm ammunition. Since all 105mm ammunition is not shipped in metal shipping containers, there is a third design which uses a simple metal sleeve and the cardboard packaging material to hold the ammunition in the rack and to prevent sympathetic detonations from occurring.

"In addition to these TDPs, the Quickload program has generated solutions for several other situations. TDPs exist for two other storage racks which minimize the explosion size by preventing sympathetic detonations. They are for TOW missiles and 4.2-in mortars. A TDP also exists for controlling the size of the maximum credible event from loads of TNT-filled artillery rounds by load arrangements and plastic side shields to prevent truck-to-truck propagation. For other artillery ammunition, concrete or sand-filled barriers have been recommended. The Quickload program continues to investigate ammunition storage problems and is now looking at controlling the response in larger stock piles of ammunition of up to 25,000 lb."[21]

PENETRATION MECHANICS

Bill de Rosset listed the following items as the accomplishments of the Penetration Mechanics Branch for the period covered by this report:[22]

1. Application of CAD/CAM to projectile development.

2. Transfer of projectile technology (M900E1 and M829A1) to ARDEC.

3. Presented paper on segmented rods at 1981 International Ballistics Symposium which sparked a decade of research in this area; branch has successfully flown full-scale extending segmented rod at 1.76 km/s.

4. Identified the source for the difference in performance between DU and tungsten, which has established a new way of looking at penetration mechanics and analyzing terminal ballistic experiments.

5. Developed eroding slideline routines which allowed Lagrangian codes to be applied to high-deformation problems without rezoning; vigorously pursued use of supercomputers for penetration mechanics problems.

6. Developed and maintained state-of-the-art large-caliber enclosed test-firing site (Range 9) which is the model for two subsequent ranges (Super Box and the facility at Gramat, France).

7. Significantly increased hypervelocity-KE-penetrator data base, especially with advanced armor targets; also, exploitation of computational mechanics to provide insight into experimental results; in-depth analysis of optimum penetrator velocity (report by de Rosset, to be published).

The first item on CAD/CAM is particularly interesting from a general point of view. It again emphasizes the extent to which interactive computing has become a way of life in the BRL.

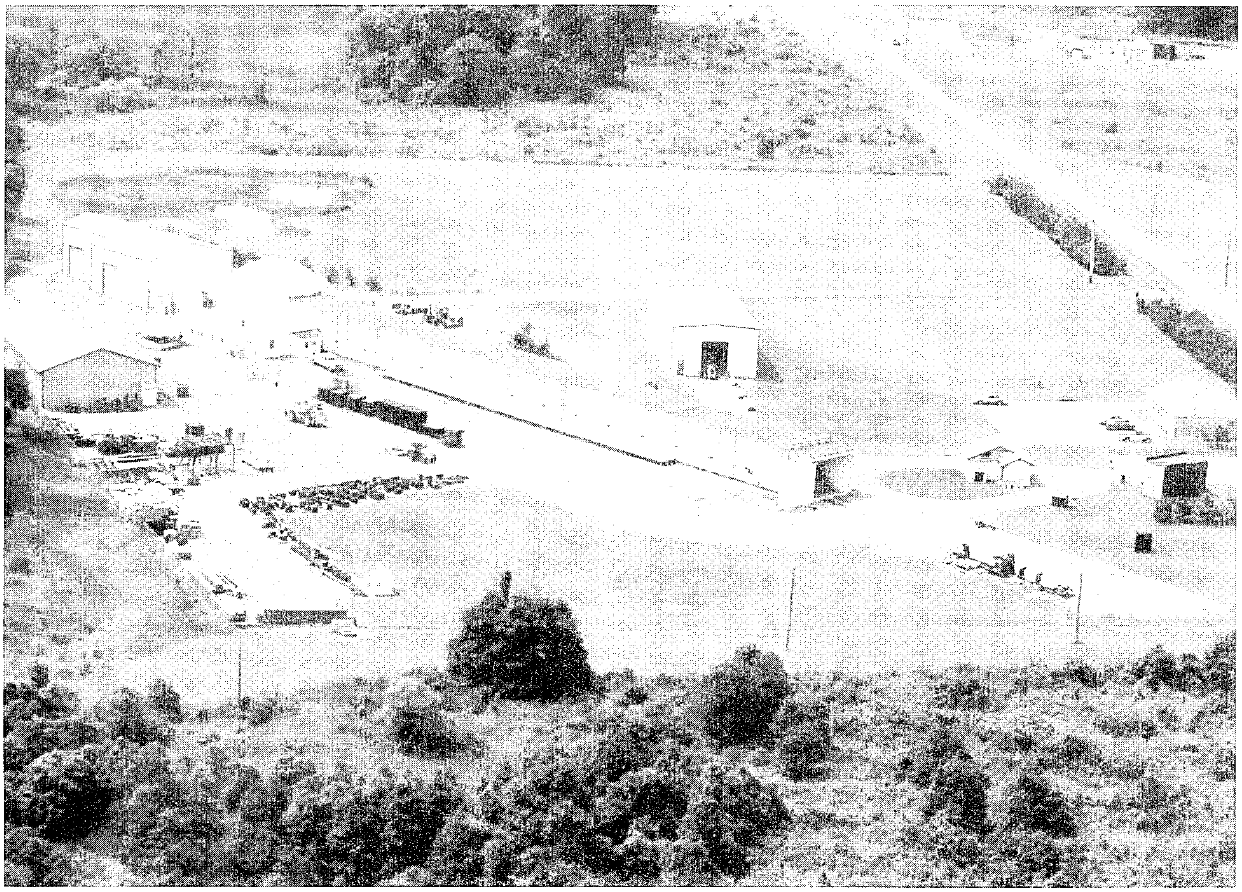
Rounds for the M1. The first version of the M1 tank used the 105mm M68 gun from the M60 tank. In the mid-1970s, the XM735 KE round was being developed for that gun. This round was an APFSDS round, which was essentially a long core of tungsten metal in a steel sheath.

As noted in the section on System Engineering, the XM735 seemed doomed to failure in a trilateral test in 1975. The BRL mounted the Silver Bullet project (also discussed in that section), which produced a much better core for the XM735 and also demonstrated a DU unitary penetrator. The DU was alloyed with 0.75% titanium.

Over the next few years, there were three sets of trilateral tests. In the first in 1975, the new tungsten XM735 round performed splendidly and out-performed the larger competing weapons. The 105mm system continued to perform extremely well throughout the remaining tests with the introduction in the 1978 tests of the M833, which used the DU penetrator derived from the Silver Bullet.

Essentially, the U.S. plan was to continue to use the 105mm system until a suitable new gun system could be developed. This relatively leisurely course was based on assessments of the state of development of armor outside the United States and the UK and on the performance of the 105mm DU round.

In June 1976, the UK announced that it had agreed to sell Challenger tanks with



Range 9—Enclosed Large-Caliber Firing Range for Experimental Research With KE Ammunition, Warheads, and Armor.

advanced armor to Iran.[1] This announcement, plus other growing concerns about the growth of armor technology in the rest of the world, caused the U.S. plan to be changed, and the German 120mm was selected as an upgrade (the M1A1) for the M1.[1]

The monolithic DU core known as the SB 60-24 (a derivative of the Silver Bullet exercise) became the basis for the development of a number of KE rounds that included the M833 for the 105mm and the M829 round for the 120mm gun.[23]

The 105mm gun was not abandoned. There were many M60 tanks and M1 tanks with that weapon. We find for 1982: "Advances in KE-munition technology provided a design for a low-development-risk penetrator with substantially upgraded performance that allows the 105mm tank armament to remain a viable complement to the 120mm tank armament."[6]

From 1984, we find: "In research applied to projectile performance, the BRL had two accomplishments with far-reaching effects for munitions lethality. First, a new BRL-designed long-rod KE penetrator, fired from a 120mm gun, set a new armor perforation record. This achievement provided the foundation for the 120mm XM907 KE-technology demonstration program Honey Bee, as well as the 105mm

XM900 advanced KE round, which is now in advanced development. These accomplishments will extend the effective lifetime of the M1 and M1A1 armaments. The second accomplishment is the incorporation of rate dependency in the formulation of the theory of plasticity, which provides a new scientific basis for refined sabot designs to reduce mass and increase muzzle velocity of antitank KE munitions."[7]

In 1984, AEI was created. This was a crash program to demonstrate a variety of technologies and approaches for tank rounds to defeat advanced threats. The mainstay of the program was the BRL's development of a complete (propulsion, sabot, and flight body) high-performance KE round for the 120mm gun. In 1986, the design for the M829A1 was handed to Picatinny Arsenal, and the round was fielded in 1989.[23]

Wes Kitchens has written an interesting *Update* article on the development of KE ammunition. It not only discusses the terminal ballistics aspects, but also the equally important efforts on propulsion and sabots.[24]

"The BRL has a long and successful history of developing advanced penetrator, sabot, and propelling-charge technology for KE ammunition and transitioning it to ARDEC, PM-TMAS, and industry. Many new component technologies have been developed in the BRL tech base programs and then demonstrated in prototype hardware. After the benefit of these technologies was demonstrated, they were successfully transitioned to ARDEC for further development and fielding, working closely with PM-TMAS and industry. The two most recent examples of fielded KE rounds incorporating the BRL-developed technologies are the 105mm M900 and the 120mm M829A1. These rounds were fielded in Operation Desert Shield/Storm with our fleet of M1 and M1A1 tanks and proved to be highly effective in defeating the Iraqi tank fleet.

"The initial design for the 120mm M829A1 was produced by the BRL early in the AEI program by scaling up the 105mm Honey Bee design developed by the BRL as part of our D223 program. The availability of this proven technology permitted the Army to shorten the normal ammunition development cycle by 2–3 years and introduce an interim high-performance 120mm round, prior to the development and type classification of the [M829A2]. This example helps illustrate why laboratories are valuable to the Army and how they can contribute to the materiel development process.

"A description of the BRL's recent contributions to penetrator, sabot, and propelling charge technology follows.

"*Penetrator Technology.* The long-rod penetrator has been universally accepted as the primary way of defeating tank armor. Pioneering BRL research led to the establishment of a family of DU long-rod, KE penetrators which have now been fielded in a number of tank rounds. The BRL research optimized the metallurgical characteristics of the material and length and diameter of the rod, controlled its launch and flight dynamics to achieve the required impact attitude, and demonstrated the superior lethality of such penetrators. Penetrators directly based on the BRL technology can be found in the 105mm M833 and M900 and the 120mm M829, M829A1, and M829E2 (still in development) [now the M829A2]. The BRL design influence is also present in the recently developed M919, 25mm KE ammunition.

"*Sabot Technology.* The BRL has forged a position of world leadership in the design of advanced, lightweight sabots. This technology is essential in order to provide maximum muzzle velocity to KE ammunition. The sabot is needed for in-bore structural support of the long-rod penetrator; however, the sabot represents parasitic weight since it is discarded once the projectile leaves the gun. Since approximately 1 lb of propellant is needed for every pound of in-bore projectile weight, the weight of the sabot needs to be minimized so that the propellant energy may be more fully employed to accelerate the penetrator. The BRL research led directly to the development of the lightweight double-ramp sabot design being fielded today in U.S. KE ammunition. Sabots based on the BRL designs are found in the 105mm M900, the 120mm M829, M829A1, and the [M829A2], and the 25mm M919.

"*Propelling Charge Design.* The design of modern propelling charges for tank cannon requires that energy in the propellant be maximized to increase muzzle velocity, while at the same time propellant vulnerability must be minimized to assure crew safety. These demands pose seemingly conflicting requirements. Through its HELOVA tech base program, the BRL succeeded in meeting these requirements for the 105mm M900 round. The BRL's charge design permitted the round to meet stringent specifications with regard to launch mass and velocity. With the 120mm M829A1, the host-vehicle design was sufficiently different to permit a successful application of JA2 propellant; however, in order to maximize muzzle energy, the BRL designed an improved grain geometry (19 perforations, hexagonal shaped).

"It seems clear that the Army has been the beneficiary of the close cooperation that has occurred between the BRL, ARDEC, and PM-TMAS. The BRL has been able to initiate high-risk tech base programs, unencumbered by the constraints of existing engineering development programs, to produce significant technology advances, like the double-ramp sabot, the BRL #10 advanced DU penetrator, and HELOVA propellant. The availability of these component technologies at the BRL shortened the development cycle for KE ammunition and permitted the Army to field ammunition with performance second-to-none. The BRL is proud to have played a major role in this process."[24]

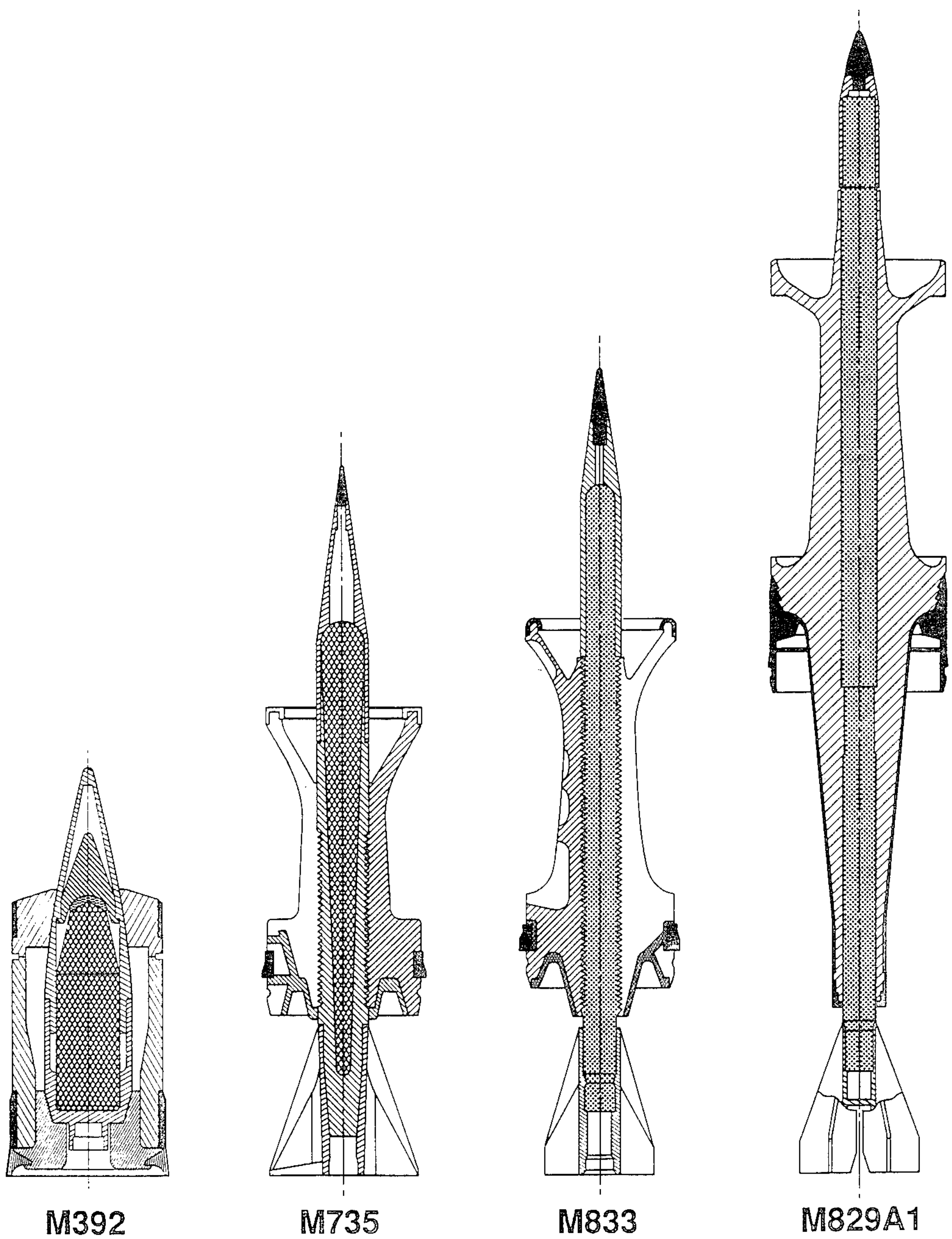
Hypervelocity. In 1987–88, the BRL became interested in hypervelocity, where by hypervelocity we mean velocities between about 2 and 3 km/s for application to antiarmor KE rounds.[23,25] A seminal paper on segmented penetrators written by Val Kucher and presented by de Rosset at the 1981 International Ballistics Symposium in Orlando, FL, had sparked people's interest in the area.[23]

In 1986, the LTV Corporation proposed a concept based on Kucher's and de Rosset's work, and the BRL worked with them in the period 1987–89. One of the outcomes of investigations into the properties of penetration at these velocities was the observation that there appeared to be a benefit to making a long rod into a series of properly space segments. The total penetration of this array was greater than that of the single, long rod. Segmented rods seem to be particularly good at high velocity.[23]

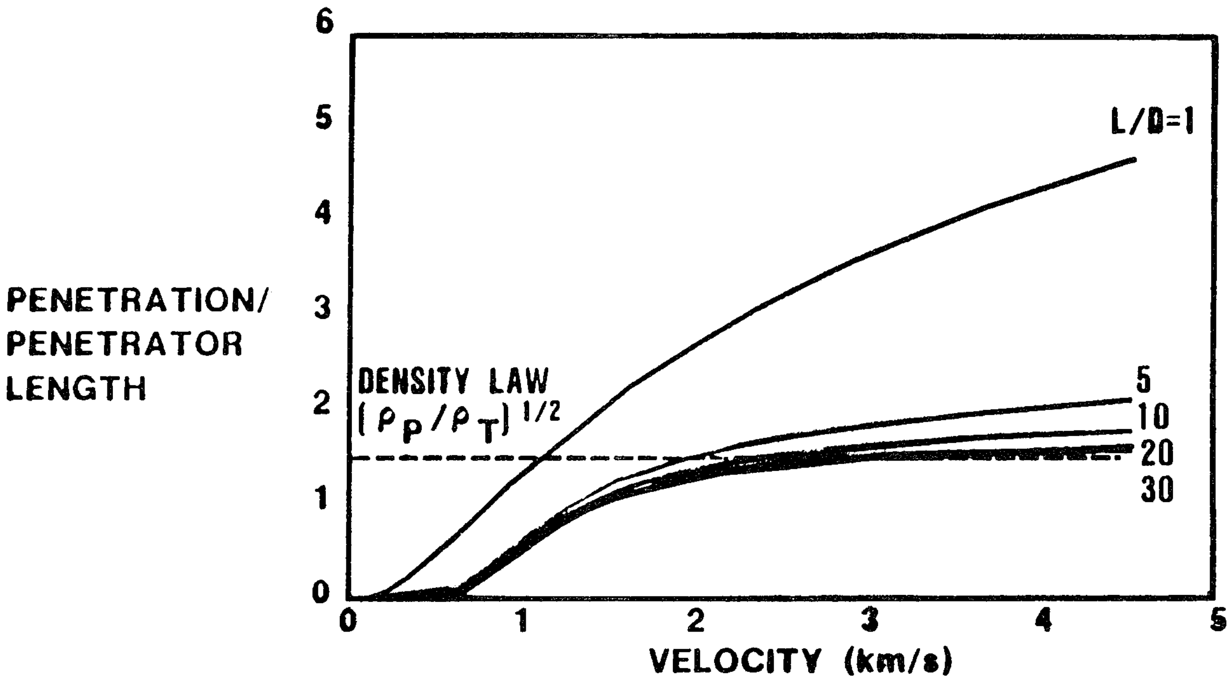
In the period from 1988, the BRL has been conducting a scale-model program aimed at defining design parameters for segmented rod systems—velocity, size, spacing, etc.[23]

From 1988, we find: "The purpose of the BRL program is to assess benefits gained at very high velocities and to help guide the design of hypervelocity projectiles for guns and missiles. Experiments and supercomputer analyses are providing the knowledge critical to the decisions on the future use of EM guns."[26]

The following is from an *Update* article by de Rosset: "The BRL has completed the first year of research into the penetration mechanics of long rods at impact velocities above 2 km/s. Previous interest in this velocity regime came in the 1960s when the United States was concerned about high-velocity impact of meteorites on its space vehicles. Now the interest is being generated by the possibility of achieving very high projectile velocities using new electric-gun technologies under development. The purpose of the BRL program is to assess what benefits will be gained at



KE Penetrator Development.

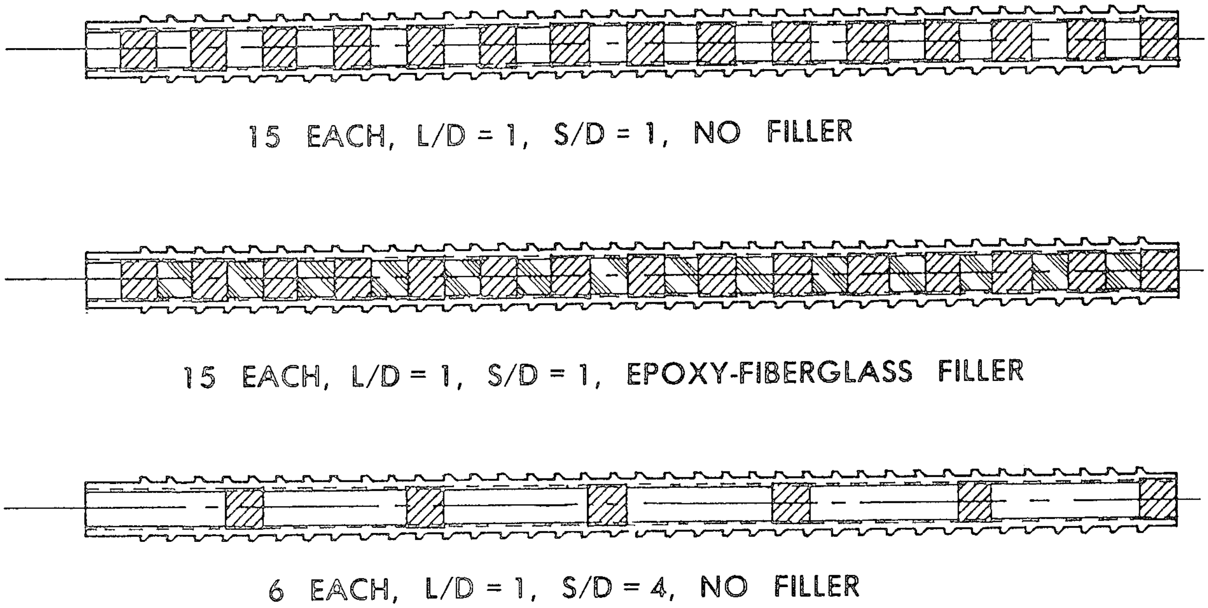


Terminal Ballistic Behavior of Low L/D Penetrators—As Compared to High L/D Penetrators—Is the Basis for Optimism About Segmented Penetrators.

these very high velocities from a terminal ballistics viewpoint, and to help guide the design of hypervelocity projectiles. The BRL program is cosponsored by ARDEC.

"*Program Components.* The BRL program is divided into four major parts: full-scale tests, model-scale tests, computer calculations, and coordination with electric-gun firing programs. The original test matrix proposed for both the model and full-scale tests called for the use of three armor technologies: monolithic RHA, ceramic-laminate armor, and RA. Over 60 model-scale tests have been completed against these armor technologies at the Arnold Engineering and Development Center (AEDC). Three penetrator geometries (L/D ratios of 15, 20, and 30) for monolithic penetrators and four different designs of segmented rods have been examined in tests against both monolithic steel and RA.

"*Test and Results.* As a result of this program, the data base has been extended to higher velocities and higher aspect ratio rods; and previously existing engineering models have



Segmented Penetrator Designs—As Fired at the AEDC, Arnold Air Force Base, TN.

been extended and validated for penetration into [RHA]. From the segmented rod tests, we have concluded that this concept is critically dependent on the engineering details of the rod design, and can significantly affect the performance of the rod. The supercomputer calculations have been especially helpful in deducing the effects of the test designs on the penetration performance, and the results of the tests against RA are being used to refine existing performance predictions in this area. As productive as the first year has been, there is still a great deal of work that needs to be done; e.g., a successfully segmented hypervelocity munition design is not yet available. Tests are planned to study target-perforation effects at high velocity and to extend our data base to other types of RAs. We also plan to examine, in FY89, a wider variety of segmented-rod designs and establish their performance against ceramic-laminate targets. The end result will be a broad Army data base upon which credible performance/ prediction models can be established, leading to a better understanding of high-velocity penetration phenomenology. This work will provide a firm foundation for helping assess the benefits of electric guns in antiarmor applications."[27]

De Rosset also wrote an *Update* article on an international symposium on segmented penetrators that was held in 1989. "An international symposium on segmented penetrator technology was held at the BRL on April 25–27. The purpose of the symposium was to enhance communication among the research agencies studying segmented penetrators and to provide a forum for discussing technical issues.[28]

"Segmented penetrators are being investigated for antiarmor use because of their tactical potential when fired at very high velocity, such as 3 km/s, from electrical energy guns.

"Participation of both foreign and domestic industries and governments gave the symposium a wide perspective. Papers were presented by representatives of France, the Federal Republic of Germany, the UK, and the United States. Topics discussed included experimental results of model-scale tests, analysis and theory, computer modeling, and full-scale concepts.

"The BRL presented seven talks, including a joint paper with the LTV Corporation describing full-scale segmented penetrator performance. Contractors working on the DARPA/Army/Marine armor/antiarmor program contributed a number of papers and the French-German ISL presented two papers. Generally, it was agreed that segmented penetrators offered some improvement in performance over monolithic penetrators as their velocity increased. The data presented indicated that the minimum segment spacing for a segmented rod would be about 2.5 segment diameters in order that the maximum benefit be gained when impacting RHA targets. There was general agreement that the way in which segmented rod data are normalized can be confusing or misleading; attempts should be made in the future to present data which have not been normalized but are given in absolute terms. Test results for *infinite* spacing of segmented rods indicated that each segment contributed equally to the penetration process. However, in a real system, the first, last, and intermediate segments will probably penetrate different amounts in the target. It was also apparent that performance could be increased if the segmented penetrator could be launched in a compact state and then extended in flight, preferably close to the target just prior to impact. In order to better estimate potential benefits, it was recommended that first order calculations should be performed to determine the magnitude of the launch and flight penalties associated with an extending segmented penetrator."[28]

We find the following report from 1991: "Segmented rod projectile. A full-scale segmented rod has been designed, fabricated, and tested in order to assess the benefits and engineering burdens associated with segmented penetrator technology. The five-segment penetrator was successfully launched in a compact configuration at 1,760 m/s and was fully extended in flight. Future work is aimed at muzzle velocities in excess of 2 km/s and terminal ballistic experiments which will demonstrate the effectiveness of full-scale segmented rods."[11]

And finally, de Rosset has written the following *Update* article on the BRL's Hypervelocity Experimental Facility:[29] "The Army is vigorously pursuing the research and engineering of new launch systems such as EM and ET guns, which hold the promise of firing at high velocities not efficiently achievable with today's conventional powder-gun technology. While much work has been done on developing the launch system itself, relatively little work has been carried out to determine what type of projectile can best exploit the higher velocities. With this in mind, the BRL began several years ago to develop an experimental facility capable of conducting research into hypervelocity penetration mechanics. The facility has been in operation over a year, and it already contributed to our basic understanding of penetration phenomenology at high velocity.

"The launch device consists of a 50mm bore powder gun with a 1,600 cm^3 volume chamber. One of the problems with high-velocity launch with a powder gun is the great deal of erosion of the gun tube, which occurs almost entirely near the breech. This leads to poor sealing of the projectile with the barrel, resulting in gas blow-by during launch. A unique feature of the launch device is the wear section of the tube located near the breech. This portion of the gun tube is removable to allow a replacement piece to be inserted when the wear section has reached its useful life.

"A great deal of research has been conducted on the proper propellant formulation needed to achieve high velocity with this particular launch device. It was found early in the development of the launch device that the standard propellants used in model-scale ranges were inadequate. Consequently, we have propellant custom made for us by the Radford Army Ammunition Plant. Work continues today to improve upon the propellant formulation and web size to achieve even higher velocities. To date, we have launched a package of 100 g at a velocity of 2.8 km/s. Heavier packages can be launched at somewhat lower velocities.

"Another capability which has recently been added to this launch device is the ability to launch high-aspect ratio rods at high velocity. In the past, we have used standard base-pusher sabots for launching long rods. There is a maximum acceleration allowable for this type of sabot, above which the rear of the rod is plastically deformed. A new type of single-ramp sabot has been developed for this launch device which relies strictly on the internal gun pressure to develop the necessary high-traction forces on the rod by sabot function alone. No grooves need be machined into the penetrator as are usually found with a traction sabot, an important point for model-scale rods. The entire rod is supported by the sabot. The maximum acceleration is now determined primarily by the properties of the sabot material, allowing much higher velocity launches.

"For the most part, the launch device is used for firing model-scale penetrators. However, some of the work carried out with it has actually been with full-scale penetrators. An example of this is the research conducted on segment impact at high velocity. Here, single segments with a diameter of 25mm were fired into RHA. This is about the same segment diameter as would be used in a large-caliber gun. The work showed that, contrary to some prevailing opinion, the normalized penetration for low-aspect-ratio segments does not increase without bound as the segment-aspect ratio is decreased. Rather, there appears to be a maximum in the normalized penetration for a segment-aspect ratio of one eighth. This information provides projectile designers necessary guidelines for the geometry of segments to be contained in segmented rods of the future.

"The hypervelocity-launch system provides the BRL with an in-house capability to explore promptly major issues and to exploit benefits of high-velocity penetrators. It will provide the BRL the capability of maintaining and extending its leadership in advanced ballistics technology."[29]

Tungsten vs. Depleted Uranium (DU). There is a strong desire to be able to use either tungsten or DU in KE penetrators for a variety of reasons. However, since the Silver Bullet effort, it has been clear that DU has a distinct superiority due to its ability to hold together through the penetration process.

Thus, it was of considerable interest that Magness has been able to shed some light on the reasons for the difference between tungsten and DU and to offer a solution. "Once you understand the processes, you can really do something."[23] To be sure that tungsten can deform properly, one must consider the thermo-mechanical properties at high rates of strain. Tungsten alloy is really a matrix of another material with grains of tungsten imbedded therein, and the properties of the matrix are extremely important; it must shear adiabatically. One prefers locally catastrophic behavior in which local melting and plastic deformation work to get the material out of the way. The material must be strong for launch and for penetration up to a point. In the process, a better understanding of DU was also obtained. The principles have been established for making a suitable tungsten penetrator, but the practice is not yet practical. Nevertheless, with more understanding of the micro-structure, people have a better idea of how things happen, what to look for, and how to make them work better.[23]

The work was reported in 1989: "Pathfinding the BRL research has produced a fundamentally new understanding of the reasons for the 10% and higher performance differences observed between DU and tungsten alloy KE penetrators. As a result, we have identified new tungsten-alloy development approaches which may permit the Army to narrow this performance gap and provide a viable penetrator material alternative to DU. Theoretical and experimental research has been conducted that quantifies the terminal ballistic performance of monolithic and segmented penetrators at velocities of 2–4 km/s against steel, ceramic, and RAs. This research has provided new insights into the performance potential and limitations of hypervelocity antiarmor projectiles being designed for use with future electric-energy guns."[8]

Bruchey has done some work on the importance of grain orientation in tungsten. This may also offer hope for the future, but again much research is needed.[23] "Three different tungsten single-crystal orientations were used to make up sample long-rod penetrators for comparison with DU rods. Analyses showed that tungsten penetration of RHA can match that of typical material at ordnance velocities. A system to launch half-scale KE DU rods at 2.5 km/s has been developed. Further DU/tungsten comparisons will be made in this hypervelocity regime to investigate convergence or divergence of penetration capabilities."[30]

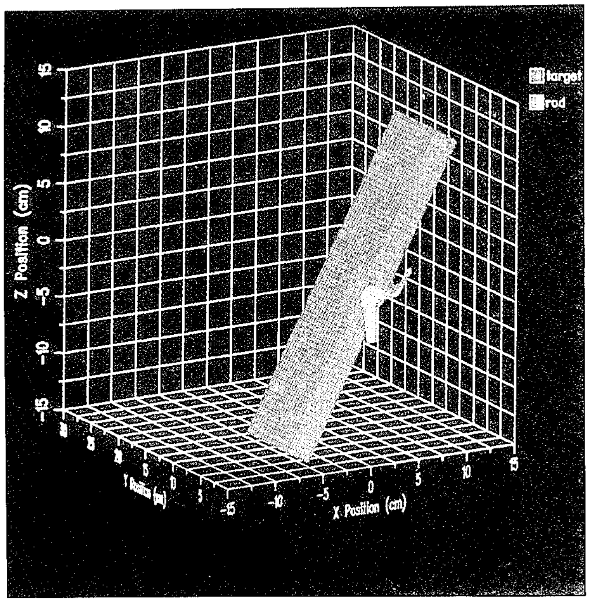
Theory. As pointed out in the section on armor, computational tools are extremely valuable in gaining an understanding of the penetration process. While the BRL's CYBER computer was very useful, the ballisticians looked longingly at the Cray computers at the DOE laboratories and at NASA. However, the people at the BRL were able to use those computers and were able to leverage major programs from those agencies when the supercomputers finally arrived at the BRL.

From 1980, we have: "The modeling of material response in the terminal ballistic environment is critical to all research activities previously discussed. The current program is focusing on advanced failure models, improved models of plastic flow, and non-destructive testing of components. Singular success in the modeling of adiabatic shear at very high strain rates has been achieved by qualifying the phenomenology of plugging failure. Adiabatic shear is the dominant failure mechanism in many materials loaded at high strain rates, and these modeling results are being incorporated in two- and three-dimensional penetration calculations to simulate plugging and fragmentation failure of targets."[5]

Also from 1980: "A more realistic plastic constitutive relation has been incorporated in the BRL structural-response codes to permit better treatment of strain hardening of materials and hysteresis effects. More accurate predictions of buckling/plastic failure should be achieved when this model is validated. In the non-destructive testing area, a significant advance was made with the demonstration that acoustic emission could be correlated with localized microstructural failure sites by fast Fourier transform of the acoustic-emission spectrum."[5]

From 1984: "[The BRL] developed models of plastic flow and fracture during impact and penetration of armor which permit, by varying material properties, computer-aided penetrator design optimization."[7]

The Cray X-MP arrived at the BRL in December 1986, and the Cray-2 in June 1987. They figure into the following: "In the area of



Three-Dimensional Model of Penetration.

KE penetrator/target impact simulations, for example, two-dimensional plane strain calculations were the norm and the accuracy of wave propagation was hampered considerably. This fiscal year, as part of an investigation into segmented rod phenomenology, computations were accomplished for a potential segmented rod; these calculations demonstrated that spacing between the segments is crucial to its performance. Warhead design simulation techniques were able to effect rational improvements of warhead performance, e.g., the Family of Scatterable Mines (FASCAM), and are expected to have an even greater effect on future designs of complex non-axisymmetric EFPs. In the modeling of sympathetic-detonation situations, arrays of explosives can now be considered for modeling; previously only a donor and acceptor could be included. In the area of CFD this fiscal year, the BRL was able to address irregular [projectile] base configurations of current Army interest."[10]

By 1988, the Cray-2 is becoming important: Penetration/Armor Mechanics - The enormous potential of supercomputing on the Cray-2 has begun to pay off at the BRL. The very complex three-dimensional, dynamic problem of advanced armor/penetrator interaction can be run simulating conditions in their most realistic form. Results have already altered designs and planned tests—to include the hypervelocity penetration program.

Finally, we repeat two of the major accomplishments submitted by de Rosset:

"[We] developed eroding slideline routines which allowed Lagrangian codes to be applied to high-deformation problems without rezoning; [we] vigorously pursued use of supercomputers for penetration-mechanics problems.

"[There has been a] significant increase to the hypervelocity KE-penetrator data base, especially with advanced armor targets; also, an exploitation of computational mechanics to provide insight into experimental results; in-depth analysis of optimum penetrator velocity."[22]

ENGINEERING PHYSICS

The Engineering Physics Branch was in SECAD until 1987 under the direction of Don Eccleshall; so much of its work is reported under advanced projects in SECAD. They then moved to TBD, Eccleshall became the Principal Scientist in TBD, and Andy Niiler became the branch chief. The work on self-propagating high-temperature synthesis (SHS) is particularly related to terminal ballistics and was a joint project with TBD even when the branch was in SECAD.

Synthesis of Ceramics. "Faced with having to pay more than $50/lb for high-performance ceramic materials such as titanium diboride (TiB_2) and titanium carbide (TiC) for armor applications, the BRL began experimenting with a novel method of fabricating these ceramics at potentially much lower cost. This method combines SHS and explosive-compaction procedures and has succeeded in making full-density TiB_2 and TiC.[31]

Circa 1981, R. J. Eichelberger read a compendium of Soviet research in SHS that had been put together by SPC. The BRL had been working on explosive compaction, which required heating of the ceramic powder, but this was at best a very awkward and tricky process, and little success was obtained. Eichelberger postulated that the BRL might be able to make a ceramic sponge by SHS and compress it explosively while it is still hot.[32]

Don Eccleshall and Bill Henshaw made the SHS reaction work for a number of materials (including TiC) and made some rods of 50% density.[32]

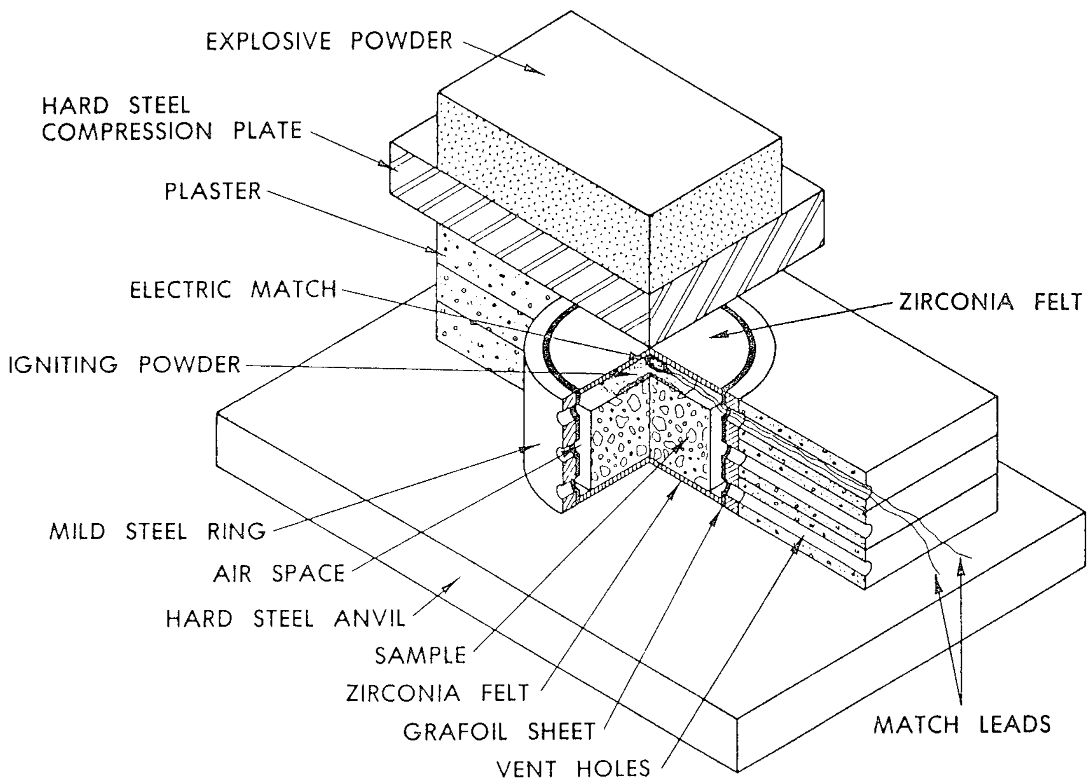
Circa 1982, Eccleshall, Andy Niiler, and Gerry Moss got together to work the problem of combining the processes of SHS and explosive compaction. At first, this did not go too far since the original idea was to put the material in steel confinement, which proved to be too much of a heat loss. This made ignition difficult and caused cracking due to too rapid cooling.[32]

Circa 1985–86, the people came up with the idea of using wall board for insulation.[33] They also replaced expensive and unreliable Army matches with toy-rocket matches, which were cheap, less violent, and more reliable. In-house work stopped in 1990.[32]

"This SHS process involves combustion synthesis reactions between elemental powders, reactions which are characterized by high exothermicities, reaction temperatures of about 3,000° C, and self-sustaining reactions lasting a few seconds. In the BRL method, the constituent titanium and boron or carbon powders are mixed and compressed into a compact which is then placed inside a reaction fixture. The compact is ignited with an electric match, and, once the whole sample has been synthesized and is still at a high temperature (about 2,500° C), it is consolidated to full density by pressure from the detonation of an HE. The experimental program consisted of investigating the effects of the amount of HE; the composition and purity of the precursor powders; the degree of mixing of the powders; the design of the containment fixture; and the lateral dimension scaling on final product density, hardness, and microstructure. Significant effects were found for each of the variables. ... "[31]

"... The current, best SHS produced TiB_2 has density, hardness, and ballistic performance of a par with hot-pressed TiB_2. The current best TiC samples's microhardness is better than the hot-pressed TiC, but it has not yet been subjected to ballistic tests. Another very exciting possibility with SHS-produced ceramics is the ability to tailor the product composition. ... A variation of 33% in the product hardness can be achieved. The best achievable hardness exceeds that of the hot-pressed material."[31]

From 1987, we have: "Shock Processing of SHS Armor Materials. A cost-effective, energy-efficient process for fabricating monolithic ceramic materials for armor applications has been developed. This process combines SHS of ceramics with explosive compaction to produce nearly fully dense (> 98% theoretical max) titanium carbide and titanium diboride. The continuing systematic evaluation of experimental parameters such as reaction-containment geometry, materials, compaction-wave timing and conditioning, materials options, and ballistic testing is expected to lead to an optimized experimental configuration which will result in a new, low-cost armor-ceramics processing method. Present estimates are that this SHS/explosive compaction method may bring the cost below \$10/lb as compared with \$40–\$70/lb for the present commercial titanium diboride. Basic research on SHS reaction has also led to the development of a computational model which can be used to predict many useful characteristics of a reacting sample. Experimental measurements of



SHS Reaction / Compaction Fixture.

parameters such as thermal diffusivity of powder compacts, reaction velocities, and temperatures have been instrumental in validating the model as well as guiding the explosive-compaction procedures."[10]

Samples were available for ballistic testing in 1988: "A cost-effective, energy-efficient process for fabricating monolithic ceramic materials for armor applications, developed in previous years, has been exploited to produce samples appropriate for ballistic testing. This process is expected to reduce the cost of titanium diboride production from the present $50/lb to about $15/lb, a major processing cost reduction which may allow large-scale use of this ceramic by the Army."[26]

The process was transferred to industry in 1991: "A BRL-developed and patented technique for the use of explosive compaction in the fabrication of ceramics has been transferred to three manufacturers. These companies will examine the potential for economically mass producing low-porosity, monolithic ceramic materials for use in ballistic applications."[11] A contract was let with Ceracon, Inc., to look at non-explosive compaction technique called DC (thus SHS/DC). The first phase demonstrated basic feasibility; the second phase will address the commercial feasibility.[32]

"The BRL SHS/DC process and associated research has been reported to the scientific community through more than three-dozen unclassified publications and presentations to government, academic, and professional societies. The BRL personnel have actively participated in six SHS-related workshops and seminars in this country and abroad. Individual visits to and from academic laboratories including the University of California - San Diego (UCSD), New Mexico Tech, the State University of New York at Buffalo (SUNY), and Georgia Tech have spawned cooperative programs where the BRL's unique DC capability has been applied to SHS materials developed at these institutions. Through DARPA-, ARO-, and Small Business Innovative Research (SBIR)-funded programs, the BRL SHS/DC technology has been extensively transferred to industry and researchers at UCSD and New Mexico Tech for further investigation and process scaleup."[34]

Infrared (IR) Tracker. The group was somewhat versatile and occasionally even became involved in IR technology, as in 1991: "A proof-of-concept passive sensor for tracking incoming KE munitions has been devised. Taking advantage of the surface heating, the tracker collects IR from the incoming projectile. Two thousand measurements of projectile position were made each second. Tracking was carried out at ranges up to 25 m with accuracies of better than a few tenths of a degree."[11]

WARHEAD MECHANICS

Drew Dietrich is the Chief of the Warhead Mechanics Branch whose work over the period was mostly dedicated to SC warheads and EFP warheads.

It seems worthwhile to go back to trace some of the origins of the EFP warhead concept.

In 1963, Merendino, Regan, and Kronman wrote: "A method of isolating the tip of an SCJ is described. The tip, thus isolated, provides a massive pellet for research in the field of hypervelocity impact. ... SC scaling laws predict that pellets in the order of hundreds of grams can be ejected at equivalent velocities."[35] While not a true EFP warhead, it did involve a pellet rather than a jet.

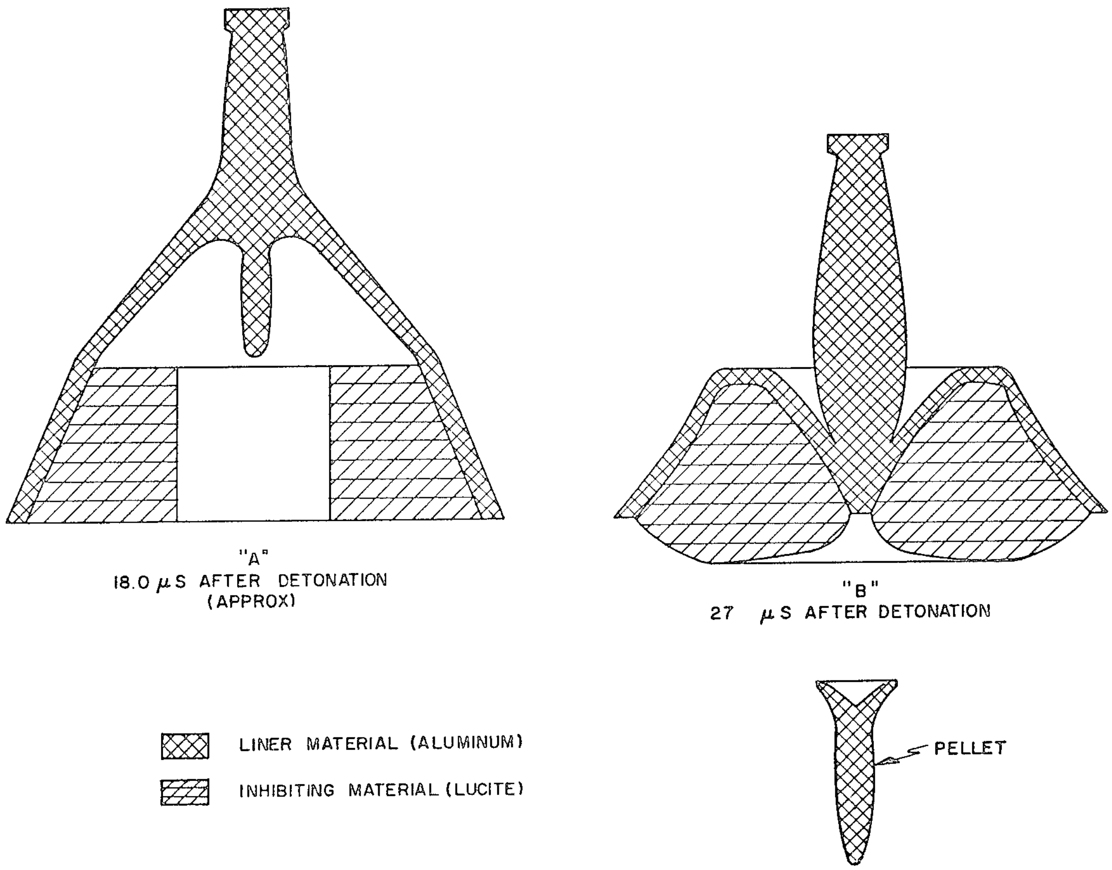
Somewhat later, Kronman developed a ballistic-disk warhead for the Navy, which was originally used for explosive-ordnance disposal by remotely knocking the fuze off the munition to be destroyed. This led to the idea of a warhead that was originally called a self-forging fragment warhead—later renamed EFP by William Reinecke of AVCO/TEXTRON.[36]

As another interesting aside on top-attack warheads, Kronman also did some work for the USAF on a cookie-cutter warhead that used an annular SC to get limited penetration but a large-hole diameter with a large amount of spall.[37] While the device was also not an EFP, the application was essentially that of a top-attack device.

Warhead Developments. The branch has been involved in the development of a number of warheads for Army systems. These include the following:

Tube-Launched, Optically Tracked, Wire-Guided (TOW) Warheads. For the entire period covered by this volume, the branch has worked on warheads for the TOW ATGM. These include the following:

1. An improved unitary warhead for ITOW. This is a form-and-fit replacement to the original TOW warhead.

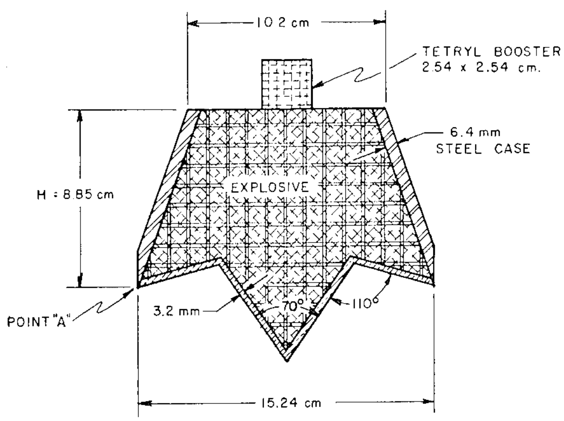


Kronman's Hypervelocity-Pellet Warhead.

2. A full-diameter unitary warhead for TOW II.
3. A tandem configuration for TOW IIA.
4. A fly-over EFP warhead for TOW IIB.[36]

M830A1 HEAT Round. This concept for a multipurpose HEAT round for the 120mm tank gun was developed and proven at the BRL. It was transferred to industry and type classified in a very short time. The idea is to concentrate on the probability of hit for moving targets to include helicopters, since gun-fired HEAT rounds are not the main tank killers. This unique round is a 120mm, sub-caliber, saboted, direct-fire, HE round. Improved muzzle velocity and low drag reduce the time of flight. The round has an impact and a proximity fuze, and it has both fragmentation and SC effects for general applications.[36]

"As an example of an appropriate tech base customer effort, this program funded by PM-TMAS led to the successful demonstration of an advanced, multipurpose-antitank round.



Cookie-Cutter Warhead.

After a competitive shoot-off against two other candidates, the BRL design and development was selected for FSED."[26]

Javelin. For the Javelin (a developmental medium antiarmor weapon system to replace the Dragon), the BRL developed the precursor charge for the tandem warhead. The system is planned for development in 1993.[11,30,36]

Materials for Warheads. Fred Grace listed the three following issues as significant in the work of the branch:

1. Refinement of metallurgy for liners.

2. High-density materials for liners.

3. Refinements in explosive properties.[36]

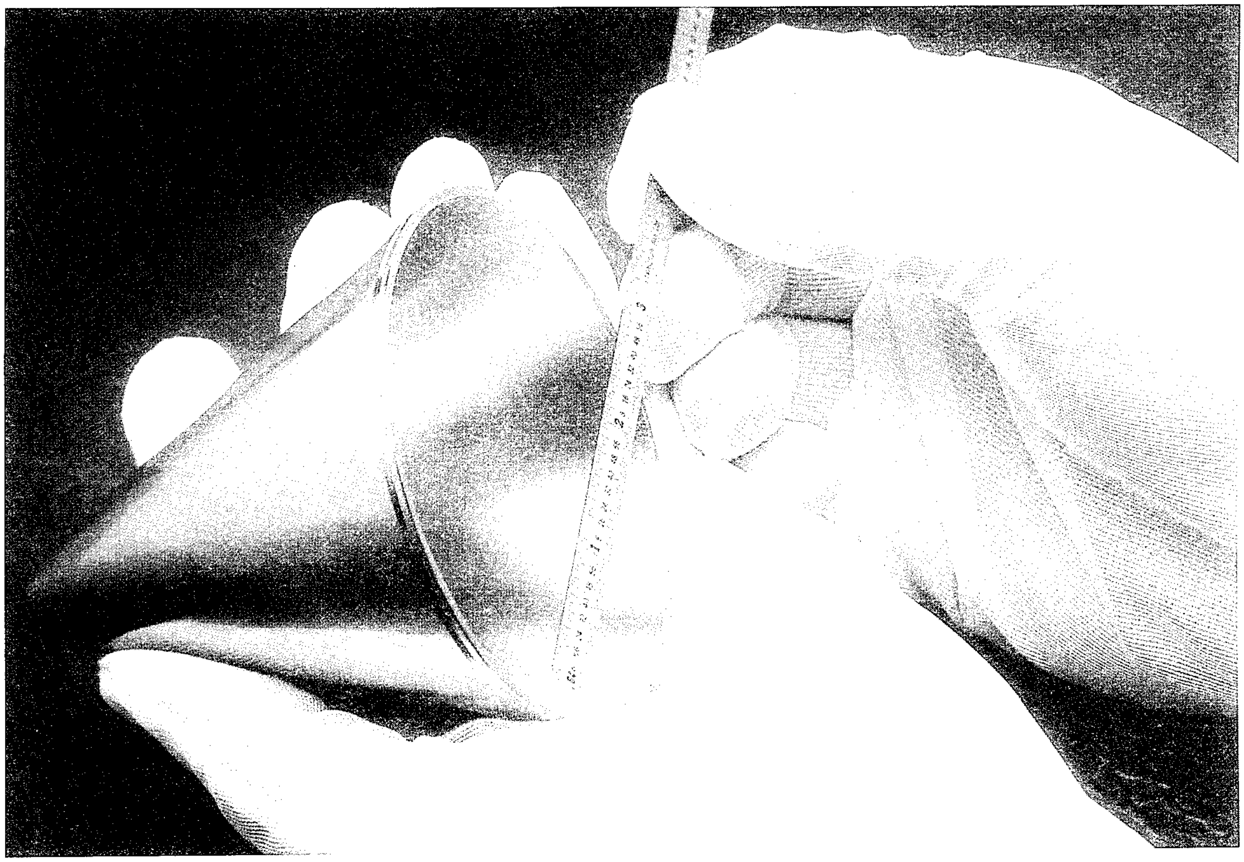
In 1982, we find: "New materials and designs developed by the BRL, with input from DOE laboratories, have demonstrated a 25% increase in penetration over fielded [SC] warheads in the same size and weight envelopes (and technology has potential for another 25% increase). This provides a new capability in the roles of Rattler, the TOW series, and third-generation ATGMs."[6] These were not fielded.[36]

And in 1984: "Research in SC liners has resulted in a 10–15% increase in penetration for the ITOW and TOW II warheads. Exploitation of liner materials with uniform hardness properties produced these gains, and has resulted in new manufacturing specifications for these weapons. Subsequent experiments with amorphous metal liners actually produced SCJs of twice this length, promising even more significant penetration gains."[7] The first part has to do with grain size; the second part involves the use of amorphous copper in spherical charges.[36]

Studies in the early 1980s refined the understanding of the effects of grain size in copper liners. The improvements in copper metallurgy has resulted in improvements in warheads for Hellfire and TOW.[7,36]

Molybdenum has shown promise, as reported for 1989: "Research demonstrated the copper-like ductility in molybdenum jets that were designed for a top velocity of 12 km/s with a potential 20–30% increase in RHA penetration compared to that for copper jets. Other advancements included evaluation of the performance of tungsten SC liners fabricated by hot-forming and hot-forging techniques and the completion of OCTOL/ECX comparison for fine-grained 81mm SC liners."[8] This concept is being strongly considered for application.[36]

From 1990, we find: "CFD techniques were used to model and optimize a SC munition using a molybdenum liner. A polycarbonate wave-shaper was used to produce the maximum theoretical jet velocity. Demonstration prototypes of the SC concept were fabricated and tested. Experimentally observed jet-tip velocities came within a few percent of the theoretical prediction. Baseline designs and performance specifications have been sent to two Project Manager's Offices (PMOs) for product improvement exploitation."[30]



Amorphous Copper Liner.

And from 1991: "A conical SC liner fabricated from molybdenum has been designed, fabricated, and demonstrated to produce a jet velocity 25% higher than that from a copper liner. Molybdenum's high-mass density and excellent ductility make it an attractive candidate for SC warheads to defeat some types of advanced armors. This technology has been transitioned to the Javelin and Hellfire systems. The Army and Navy (Naval Surface Weapons [now Warfare] Center - White Oak Laboratory [NSWC-WOL], the BRL, the Missile Research, Development, and Engineering Center [MIRDEC], and ARDEC) are planning a joint effort for the further development of the manufacturing technology for this class of materials."[11]

Concepts. The BRL has made important contributions in tandem warheads, including work as long ago as the early 1950s. Tandem warheads pose difficult problems. There is "no such thing as a generic tandem warhead." For a unitary, the characteristic time is 50–100 μs; for a tandem, it is more of the order of 1 ms. This causes much more concern about the relation of the arrival of the jets and other warhead parameters such as size, speed, and other parts.[36]

From 1986, we find: "One approach for defeating contemporary and multi-element advanced threat armors is based on the tandem-warhead concept. The tandem-warhead package consists of two SC warheads which are fired independently near the target utilizing a delay time. However, recent intelligence assessments indicate that the more sophisticated future threat armors will defeat fielded tandem-warhead ATGMs. Both larger warheads and greater time delays will be required. In FY86, the BRL demonstrated that delay times between detonation of the tandem pair could be increased by a factor of four over previously demonstrated concepts. This advance involved the development of blast-isolation techniques to protect the second charge from blast effects of the first charge within missile length constraints. This accomplishment represents a critical technical milestone in the BRL's 6.3a combat-vehicle antiarmor demonstration program, as previously demonstrated time delays were inadequate against the evolving threat."[10]

And a year later: "A single warhead is easily defeated by a reactive-sandwich package fronting typical armor. Tandem warheads, theoretically, should enable the second warhead to have a clear path to the armor which it can readily defeat, given the sacrifice of the first warhead to defeating the reactive sandwich first encountered. Tandem-warhead systems were designed, fabricated, and assembled into a realistic missile configuration, and statically tested. The results were highly successful and represent first-time defeats of advanced armors. The systems also had to fit into realistic missile envelopes; even with definite constraints in length, diameter, spacing and mass, and the necessity to include a blast shield between the warheads, short, L/D warheads (~1.1) were designed and shown to be good performers, a most promising development."[8]

Computational Situation. In the mid-1970s, the BRL became involved in technology that came from the DOE labs and worked with them to exploit new concepts. While these initial concepts themselves have not created production warheads, that work has greatly enhanced the understanding of SC processes and technology. The concepts themselves are still the subjects of research. This work created a demand for computation, which, when coupled with the availability of software, contributed significantly to the demand for supercomputers in the BRL.[36]

In the 1960s, the DOE laboratories were using codes that were of interest in studying the penetration processes. While the gridding was coarse, and the material properties were simplistic, the codes were interesting especially for hypervelocity impacts. R. J. Eichelberger created a new enthusiasm, dragging people together and lecturing on the importance of modeling continuum-mechanical processes. By 1965, the codes were computing on a frequent basis using essential fluid properties (no strength). By 1975, the BRL was using hydrocodes with elastic/plastic properties, and everyone in the warhead business found it necessary and appropriate to use these techniques to some extent.[36]

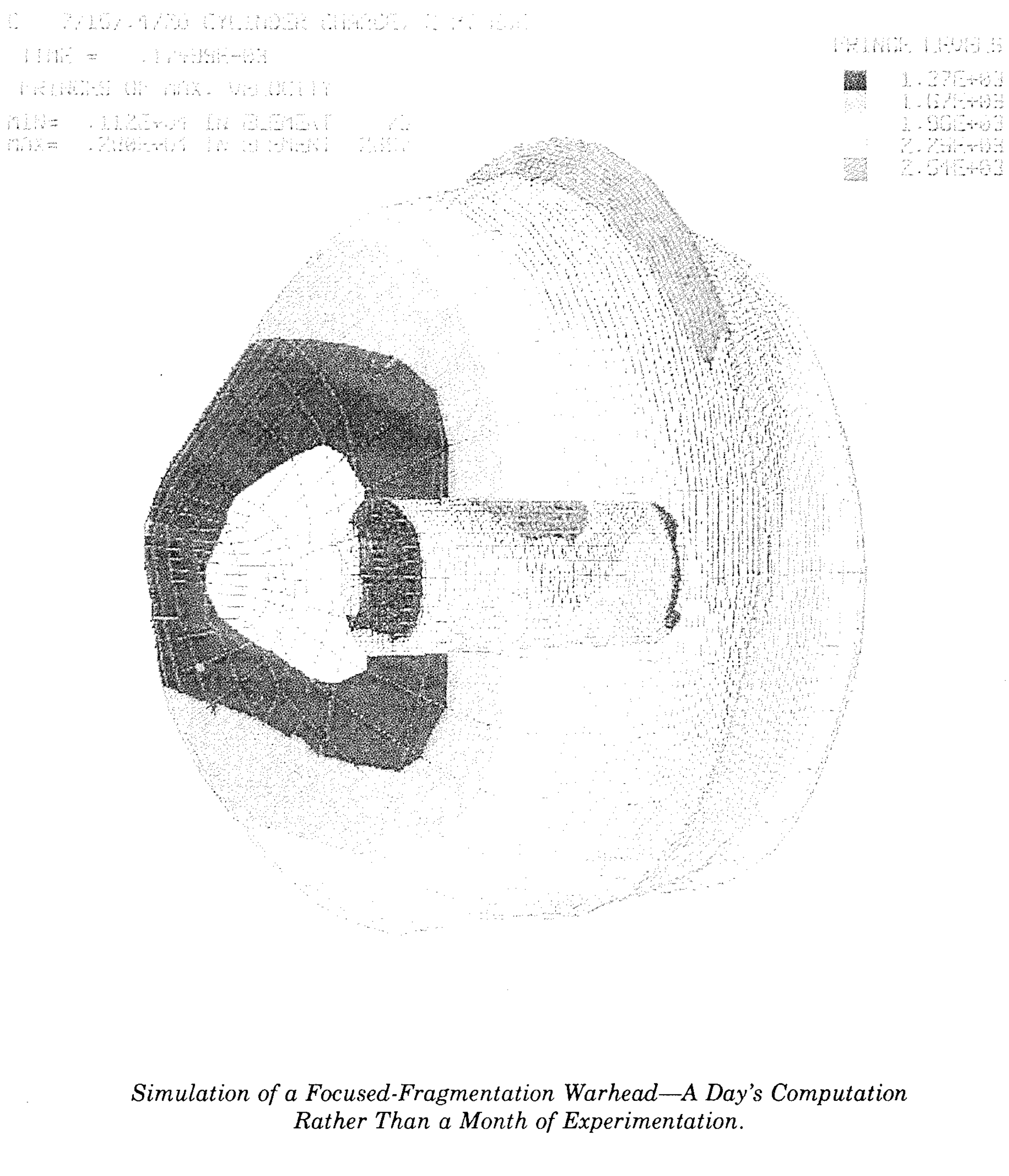
At first, Lagrangian codes were in favor because of their ability to track material boundaries. They have given way to some extent to Eulerian codes since the supercomputers can now use extremely small grid size; so the Eulerian codes can also track boundaries accurately. Eulerian codes are now at the cutting edge of computations for SC design and analysis. They can calculate for complicated flow problems and find good solutions at least for the initial conditions of jet formation. There is general recognition that computers are powerful tools, but not an end-all. There is still a need for experiment and for phenomenological models. This is especially the case when and if fracture is involved. Material properties are not always well represented, and there is a relation to chaos theory in the way that small changes can grow. But now we can iterate on the computer and then build to test, rather than iterate many times in hardware.[36]

Supercomputer Warhead Design. Glenn Randers-Pehrson has written the following

An SC Firing at Range 7A.

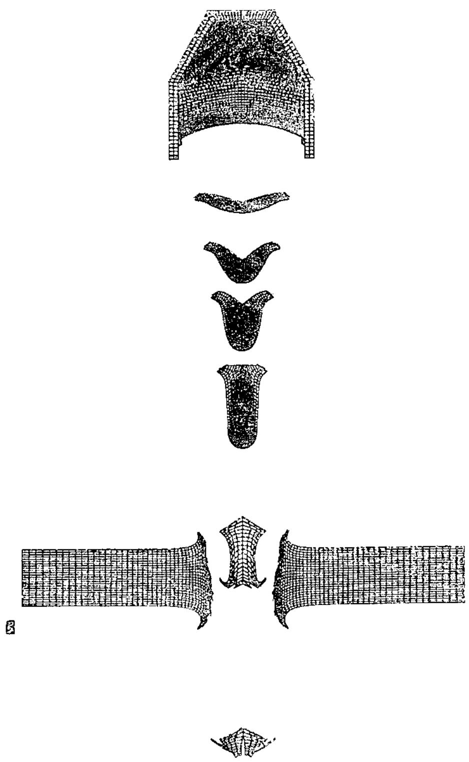
Update article: "Because warhead development poses some difficult problems for the designer, the BRL turns to its supercomputer resources to approach these problems. Analysis of experiments is difficult because, when a warhead's HE charge detonates, it deforms the metal parts under extremely high pressures and strain rates unlike those obtainable in a laboratory. After an experimental test shot, there is generally little or nothing left to examine, except for a hole in some armor plate. Some modern targets are completely destroyed in the test. Data consist mainly of X-ray shadowgraphs, which are sometimes difficult to interpret.

"Using special computer codes (hydrocodes) mainly provided by DOE and converted by the BRL to run on its Cray-2 and X-MP supercomputers and on its IRIS graphics workstations, the munitions designer is able to model the warhead detonation and deformation process, and the interaction of the lethal mechanism with a target. During recent years, the ability of hydrocodes to reproduce the real-world behavior of warheads has gradually and significantly improved. Since about 1977, they have been an essential part of the design process for the EFP warhead, such as that used in the SADARM sub-munition and other top-attack systems.



Simulation of a Focused-Fragmentation Warhead—A Day's Computation Rather Than a Month of Experimentation.

"SGJ formation is an even more difficult problem than EFP formation, due to the much more severe deformation of the metal. But there are some new codes under development which show great promise in treating the SC jetting process. These include new accurate Eulerian codes and Arbitrary Lagrangian/Eulerian (ALE) codes; the present



DYNA-2D Axisymmetric Simulation of an EFP.

codes have answered important questions for warhead designers, such as evaluation of proposed designs for the blast shield between the warheads of a tandem SC system.

"The BRL is supporting ARDEC in its use of these codes for designing EFP warheads and evaluating contractor's warheads. The BRL is also providing advice and assistance to several contractors and other Government agencies' contractors that are using the codes to design EFPs for SADARM, Antiarmor Weapon System-Medium (AAWS-M), and other top-attack antiarmor systems. It would not have been possible to design effective warheads for these systems without the use of hydrocodes. The codes are also useful for assessing vendors claims about proposed systems. This was recently done by the BRL in the course of assisting the Navy in a source-selection evaluation.

"Some problems are still intractable for the current hydrocodes. For example, the material models currently do not treat fracture very well, and fracture is important in the analysis of fragmentation warheads and SCJ breakup. It is only because good EFP designs do not fracture that the codes have been able to treat them so successfully; i.e., the EFP slug stays in one piece after it is formed. The codes are able to detect that breakup is going to occur, but do not do a good job of modeling post-breakup behavior. When modeling EFPs, it is enough to know that fracture is going to occur. *Good* designs that do not come apart can be modeled accurately with the codes. Work in progress at the BRL and at DOE is directed toward improving the constitutive models used in the codes.

"Even today, the hydrocodes must be used with care when making predictions about designs that are significantly different from known designs. They are best used to predict trends, to interpolate between known designs, and to help understand experimental data. When used properly, the codes make a significant reduction in the number of iterations of *cut-and-shoot* design methodology.

"Savings in time and money spent using instrumented experimental test shots vs. computer-generated development and testing are impressive, the former costing several thousand dollars and taking several months, and the latter achieving results on the Cray-2 in a few minutes for less than $100 worth of computer time and half a day's labor. Hydrocodes have become an essential part of the warhead design process. They have made possible an entire class of munitions, the top-attack antiarmor systems."[38]

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VULNERABILITY/LETHALITY

As noted in Volume II of this history, the BRL has been the Army's lead laboratory for vulnerability and survivability matters officially since 1971 and practically since 1945. For the period from 1977, this mission has been carried out in the Vulnerability/Lethality Division (VLD)[1] of the BRL.

VLD has provided vulnerability and lethality information on both U.S. and foreign materiel to all having a valid need for such information. The various annual reports and other such documents listed in the references

Mr. Donald F. Menne, Chief of TBD From 1982 to 1985 and Chief of VLD From 1985 to 1986. He Received a Bachelor of Science in Mechanical Engineering From Bradley University and Did Graduate Study at the University of Delaware and at MIT.

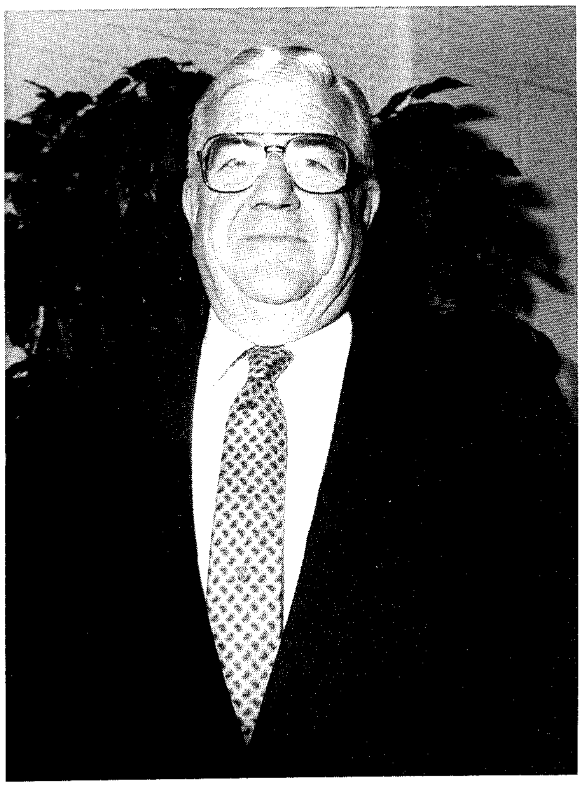
Mr. Alvin J. Hoffman, Chief (and Founder) of VLD from 1970 to 1981, Received a Bachelor's Degree in Mechanical Engineering From the University of Pittsburgh and a Master's Degree in Mechanical Engineering From the University of Delaware.

attest to the yearly magnitude of this effort. To get a flavor of this magnitude, consider FY88, "As a result of advances in computer-aided analyses during the past year, the BRL has provided vulnerability/lethality estimates for more than 6,000 weapon/target combinations. A prodigious accomplishment in this time of manpower reductions! Major studies supported include the following: Granite Class, AAWS-M, Hellfire, Hellfire DAP, TOW, Future Infantry Fighting Vehicle (FIFV), MLRS-Terminally Guided Weapon (TGW), SIMATS Patriot, Stinger, Antitactical Missile System, Volcano, Forward Area Air Defense System (FAADS), aircraft survivability equipment, Aircraft Modular Armor Program Antijamming System, T800 engine, light helicopter - experimental (LH-X), and Abrams Tank System."[2]

In addition to specific information for specific Army projects, VLD has prepared a number of compendia for broad categories of weapons against broad categories of targets. These have been affectionately known as *the Red Book, the Peach Book,* etc. The data in these compendia have been extremely important to those who conduct war-game analyses for the Army.

VLD has been in considerable demand by weapon designers and developers for consultation on lethality and survivability issues, and has become heavily involved in the Congressionally mandated live-fire testing (LFT) of the late 1980s and early 1990s.

Finally, the mission includes responsibility for the development and dissemination of



Mr. David L. Rigotti, Chief of VLD From 1986 to 1989. He Received a Bachelor of Science in Chemical Engineering From Michigan Technological University and Did Graduate Studies at the University of Delaware and at the Georgia Institute of Technology.

When Mr. Rigotti Retired in February of 1989, Mr. John (Jake) R. Jacobson Served as Acting Chief Until December 1990.

Dr. Paul H. Deitz, Chief of VLD From 1990 to 1992. He Received a Bachelor of Arts in Physics From Gettysburg College and a Master's and Doctorate in Electrical Engineering From the University of Washington in Seattle.

vulnerability and lethality methodology to accommodate new weapons and new threats.

To some extent, VLD has been a victim of its own success. The continuing demand for specific data to support high-priority programs has made the allocation of resources to work on improved methodology difficult, and the need to relate the results of new methodology with the huge inventory of data already developed makes the introduction of new methodology tricky and possibly can require considerable computation just to update the existing data base.

Despite these difficulties, in the last decade and a half, VLD has made considerable advances in their methodology, which have been driven by the demands of major advances in weapon and armor technologies, the exigencies of LFT, and the computer revolution.

GROUND SYSTEMS

Vulnerability Methodology Developments. Tanks and other armored combat vehicles have dominated the efforts on the vulnerability analysis of ground vehicles. Over the years, the workhorse methodology for the analysis of such systems has been based on what is known as the compartment model and is generically called the Vulnerability Analysis Methodology Program (VAMP).[3] VAMP is a very empirical model.

The thrusts of methodology improvements have been:

1. to facilitate the description of targets and threats with user-friendly graphics, more efficient ray tracing, and computer-assisted scanning and data-reduction techniques;

2. to consider the lethality mechanisms in more detail by the use of point-burst methodology, better representation of component vulnerability, better penetration models, and new correlations functions for VAMP;

3. to create more meaningful and sounder measures of effectiveness by the introduction of degraded states (DS);

4. to make the analyses stochastic; and

5. to make the methodology more accessible to the users and to provide better audit trails.

The Compartment Model. The compartment model uses a methodology that follows a penetrator through the target (e.g., a tank). It determines if external components such as running gear are damaged. If the crew or engine compartment is entered, the model estimates the probability of a functional kill (mobility [M], firepower [F], or catastrophic [K]) based on the parameters of the penetration (e.g., the size of the exit hole at the intrusion). This correlation function accounts for damage by spall from the penetration as well as by the residual penetrator. Finally, the penetrator is followed through the compartment to see if ammunition or fuel is struck to determine the probability of a K-Kill from fire or an explosion.[4]

The correlations between the penetration parameters and the damage were based largely on a series of tests that had been conducted in the late 1950s at the Canadian Army Research and Development Establishment (CARDE) on complete tanks. It was only recently that LFTs provided significant new full-scale data for the correlations.[4]

The original compartment computer programs were written by Howard Ege as four versions that covered the combinations of tanks and APCs being attacked by SC rounds and by KE rounds. The four programs were merged, updated, and documented by the Computer Science Corporation into the program named VAMP.[3] This included the shotline generator

GIFT of 1975 vintage.[5] While the VAMP documentation was useful, Ege's decks were still used for production until about 1986 when the code had to be redone for more modern computers.[4]

In the late 1970s and early 1980s, the advances in armor and in SC and KE threats made penetration modeling somewhat frantic. There was a strong need for TBD's participation on a day-by-day basis. Robert Jameson and Konrad Frank were appointed on essentially a full-time basis to help meet the heavy demands. The issue was the need for the consideration of a large number of cases rather than concentrating on limiting conditions. The main goal of the terminal ballistician was to determine the levels at which the penetrator can breach the armor or the level at which the armor can defeat the penetrator. The details of under and over-penetration were of less concern. On the other hand, these details were just what define the level of kills for the vulnerability analyst.[4]

Around 1980, canted and high-yaw SC warheads also became a matter of concern and were a major challenge for the penetration models. The situation is currently (1992) much better, but there are still problems as newer concepts for missiles and for protection continue to emerge.

The M1 Abrams tank was a case in point. Its modern armor and configuration bore little resemblance with the tanks tested at CARDE, nor did the modern rounds against which it must defend itself resemble those tested. To develop suitable correlation data, Robert Kirby made the assumption that the internal components had similar vulnerability as those in the CARDE targets except for the compartmented ammunition. Data from the firing tests of the M1's ammunition compartments were folded into the CARDE data to provide modified correlations that could be used to model the M1 with VAMP.[4]

Also around 1983, Kirby made some other modifications to the algorithm for SC correlations. Firings against modern armor configurations showed that BAD was much less than was implicit in the CARDE compartment model; so an adjustment was indicated. The CARDE model relates the various kill categories (M, F, and K) directly to exit-hole diameter (d). In looking at other data acquired in the CARDE trials, Kirby was able to relate kill to the number of spall fragments that could penetrate at least 1/16 in of armor. He was also able to relate d^2v to that number of spall fragments and thus d^2v to the kill probabilities. This correlation was combined by using the survivor rule with an observed relation between the residual-penetration capability of the jet and PK for the main penetrator in the compartment.[4]

The Vulnerability Methodology Team (VMT). As noted above, VAMP is very empirically related to full-scale firings. Since funds were inadequate to support a continuing full-scale series of experiments on modern tanks and since the ability to look at conceptual systems also implied the need for the ability to do ab initio analyses, there was a general feeling in the mid-1970s that a new approach to vulnerability analysis was needed.

As an example of the type of problem that was encountered, we can consider the request by TRADOC for an analysis of the Swedish S-tank in 1975. The S-tank had no turret and nothing that really qualified as a crew compartment; so the basic premise of the compartment model was inappropriate. James Rapp was selected to head a team to develop an analysis of the S-tank.[6] He elected to use the Armored Vehicle Vulnerability Analysis Model (AVVAM).[7] AVVAM was a point-burst model that had the unique advantage of being available with an author (Don Haskell) who was willing to support the S-tank endeavor.

Rapp and his team had to put together an entire methodology—the geometric model of the tank, the estimates of damage to the components, and the relation between component damage and levels of kill (called a damage assessment list [DAL]). This was all accomplished in about 6 months, but unfortunately there was no way to relate the results to analyses of other vehicles that had been done by VAMP. So the effort became a very valuable learning experience on the process of conducting a point-burst analysis of a total tank, and that experience was not lost.

In 1977, the Director of the BRL commissioned an ad hoc team under the leadership of Donald Menne to look at vulnerability methodology and to recommend a program of methodology development. Rapp was a very active member of that team. The team completed its report, "Lethality/ Vulnerability Methodology and Database Update,"[8] which has come to be called the *Yellow Book* in August 1977. The report encouraged the development of point-burst methodology and the development of a data base (e.g., on BAD) to support that methodology. It also raised questions about the nature of the kill criteria and the need for a stochastic approach (see the sections on DS and on SQuASH later).[9]

The team was then chartered and assigned to the director's office in May 1978 to execute the program called for in the *Yellow Book*. VMT worked on its agenda until January 1980 when it became the Vulnerability Methodology Branch of VLD and continued the development of methodology until the present time (1992).

John Suckling has submitted the following reminiscence of his experiences with the VMT: "When Don Menne yanked me out of TBD (circa 1977) to become a charter member of the VMT, he assigned to me the task of sorting out the muddle of terminal effects. A cursory examination of the state of things revealed the following:

"The major potential damage mechanisms produced by both KE bullets and SCJs on armored vehicles seemed to be those of the main penetrator/jet and the debris cloud appearing behind a perforated armor:

1. Penetration models for SCs were fairly well off for conventional armors.

2. Penetration models for KE were less well off, but the DeMarre equations worked fairly well, and a lot of data existed for fashionable situations.

3. Some behind-armor investigations had been done for SC, and Merendino and DiPersio et al. had generated some data.

4. The biggest gap was BAD for KE; that is where we chose to press on TBD for support. Its a long story, but despite the cooperation of John Kineke and Tony Ricchiazzi, we were not able to get much data from them.

"Shortly after I got to VMT, Bob Shnidman was given to us; he just had 6-months experience in SCs in TBD, so he became the SC expert. With the initial blessing of the Hafers [Tom and Ann], Bob and I tried to work out the knotty problem of how to collect BAD: after considerable gnashing of teeth, we decided that *direct lethality* of BAD towards components was the way to go (remember that the Hafer Vulnerability Analysis for Surface Targets (VAST)-QD was a rudimentary direct-lethality code). The above conclusion was not arrived at overnight, but came from my participation in several Key Technical Area tasks for TTCP-WTP-1 on BAD data collection techniques for KE plus a NATO panel on behind-armor effects, as well as Shnidman's later work in TTCP along the same line for SCs.

"The availability of the data and resultant models went a long way towards making SQuASH possible. One of the key differences between the conventional VAST and

Shnidman's and my spectrum of vulnerability codes was that direct lethality path—VAST used fragment mass and speed in its BAD model. We believed that:

1. Masses and speeds are VERY hard to come by (a long story, which we would be glad to expand upon).

2. Mass and speed is not sufficient to specify a fragment's ability to perforate or to inflict damage."[10]

Rapp left the branch in 1983, having written a report on the subject of deficiencies in the measures of vulnerability being used by the BRL.[11] That report seems to have been somewhat of a catalyst for the efforts in the late 1980s and early 1990s to overhaul the metrics used in modern vulnerability analyses.

Point-Burst Models. Point-burst models are similar to compartment models up to the point at which the penetrator breaches a compartment. At that point, the various point-burst models use some characterization of the spall's cone of fragments and relate this to damage of the components in the compartment—rather than use the correlation functions of VAMP. They then must relate that damage to functional kills by way of a DAL.

While the aforementioned AVVAM was an early point-burst model, it did not gain general acceptance as a production model.

Falcon Research and Denver Research Institute (DRI) had created an external point-burst model for artillery (VAREA). Tom Hafer used the shotlines and penetration of compartment models and considered the burst points to be inside the compartments (rather than external as in VAREA). The model was called the spall-handling universal threat evaluator (SHUTE). SHUTE calculates the subtended angle of the various components with respect to the burst point of the spall and thus estimates the probability of being hit by fragments.[12]

There was also a point-burst model SLAVE in which debris was represented as a cone. Components were placed in categories as to vulnerability to spall and/or main penetrator, and those in the spall cone had probabilities of being killed by the spall.[4]

VAREA and SHUTE were further cleaned up by Tom and Ann Hafer with help from Watervliet Arsenal, NY, and from the Computer Science Corporation to create the model called VAST. In VAST, when a spall-producing armor component is encountered along the shotline, spall rays are traced from the spall burst point through the target to all the target-critical components.[13]

As VAMP is BRL's prototypical compartment model; so VAST is its prototypical point-burst model for ground vehicles. VAST is quite computationally intensive; VAMP is less demanding on computation but relies heavily on full-scale determination of the damage-correlation functions. Thus, a very reasonable paradigm has developed that calls for the use of a large amount of small-scale experimentation to develop the BAD and component-damage data, which can then be fed into VAST for limited runs to develop new correlation functions for compartment damage. These derived functions can then be used in VAMP for large-scale production of vulnerability analyses.[12]

That paradigm is indeed sound, and it has been used to good effect on a limited basis, but VAST has proven to have a vast appetite for data. To quote Kirby, "It is one thing to have a VAST code; it is another to have the data to allow it to run."[4] Still much remained to be done on gathering data on BAD, component damage, and DALs. In time, Keith Myers, the Director of AMSAA, supported the idea of off-line testing for BAD as part of the LFT process, and this has produced large amounts of data.[4]

Circa 1980, EFPs with their attractive long-standoff capability and application to top attack emerged as an exceeding important subject for lethality analyses. EFPs depended to a large measure on back-face failure for penetration, which resulted in new distributions of mass and velocity from those of previous penetrators. This implied that the existing correlation functions of VAMP were inappropriate for EFPs, and therefore VAST was viewed as the more appropriate model. However, it also implied that new BAD data would be needed for EFPs. MICOM provided funding to fire EFPs against real targets. A BAD model for EFP penetration was presented to the American Defense Preparedness Association conference on smart munitions that was held at Fort Belvoir, VA, circa 1983.[4]

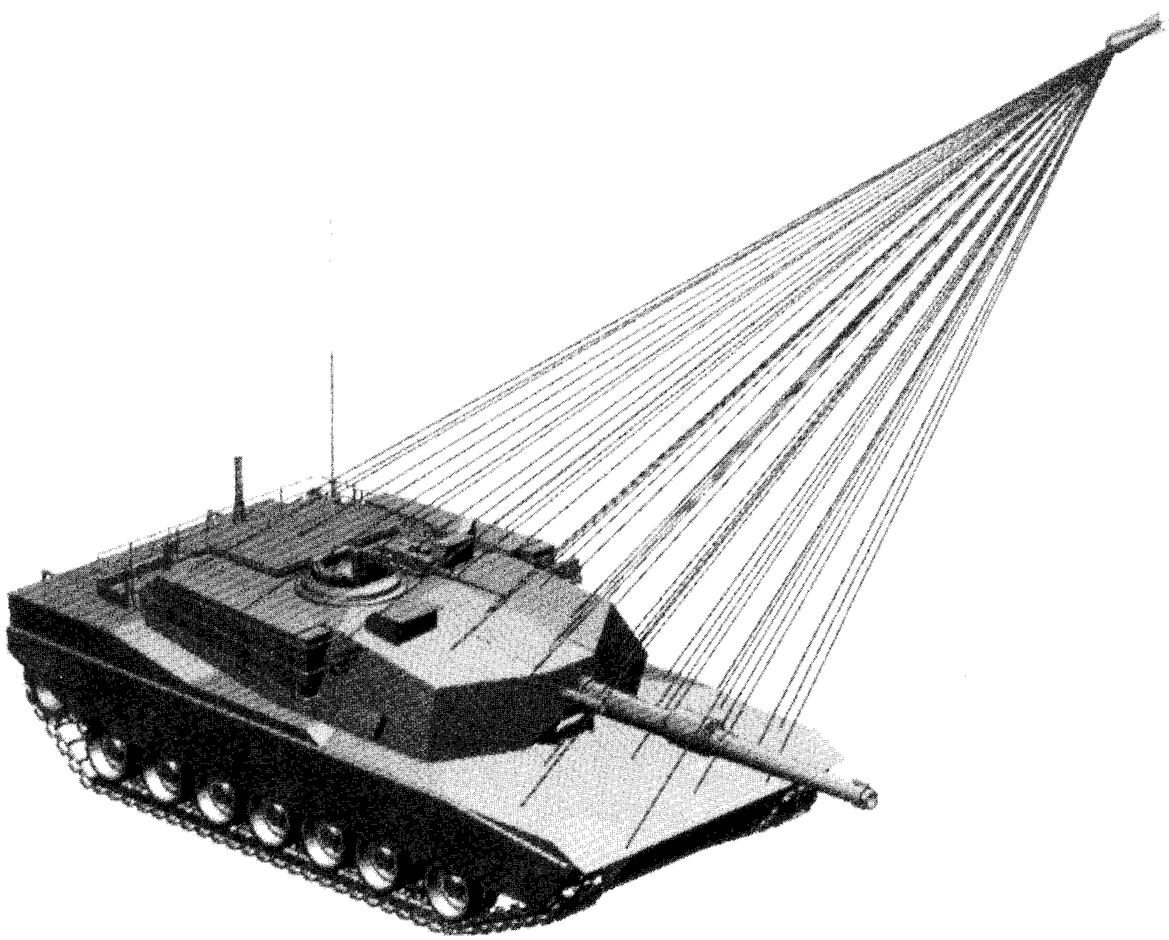
Circa 1982, Larry Losie was concerned with the EFPs that were employed in the STAFF and SADARM weapon systems. He used a point-burst analysis to develop generic PKs for EFPs based on four or five different EFP designs, which were fired at armor plate for BAD and M48 tanks for component damage.[12]

There has also been an attempt to develop improved models of component damage. This includes the work of Robert Shnidman in 1988 that is related to earlier (1984) work on EFPs by Michael Saccucci, Linda Crawford, and Shnidman. Shnidman's approach is to use direct correlation of the observed data from witness-plate firings with component damage rather than to use intermediate variables. To quote Shnidman, "Currently for a variety of experimental reasons, the most widely used technique to obtain behind-armor data is to place a series of metallic witness plates behind the armor, shoot at the armor, and measure the size and location of the fragment produced holes in the plates. Fragment mass and velocity are then inferred from the hole data, and analytical mass and velocity distributions are constructed therefrom for insertion into vehicle-kill prediction codes. Difficulties and inaccuracies arise from this procedure both during the inference of the fragment mass and speeds and construction of the distributions. Among the reasons for these problems are the wide variety of fragment shapes and impact orientations and coarse resolution of the witness arrays for measuring fragment penetration. We present an alternate approach of utilizing the witness-plate array data that deals directly with the penetration and hole size producing capability of the fragments. This approach will be shown to be more accurate and suffer from [fewer] problems. We also present a technique for modeling the hole size, penetration capability, and positional data for individual shots using a maximum-likelihood procedure; show how to model the behavior of the distribution as a function of shot conditions; and, finally, describe how to use the distributions in vehicle vulnerability codes."[14]

VAST has been used to evaluate revised correlations that have been developed for VAMP from LFTs of ATGMs and 30mm KE threats against the BFV.[12]

Since VAST deals specifically with components, it is also quite useful for developing the vulnerable areas of components for use in the sustainability prediction for Army spare components required for combat (SPARC).[9]

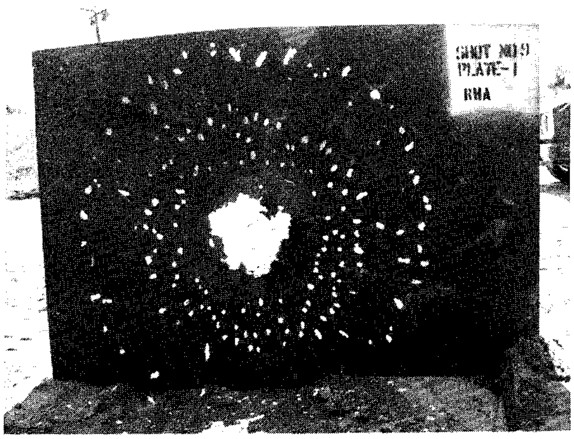
While much of the glamour of the vulnerability analysis of ground vehicles is associated with the attack of armored vehicles by SC and KE threats, artillery is still a significant threat to armored and unarmored systems. To provide a tool for the consideration of the effect of conventional artillery, Bob Schumacher developed a single-shot burst model called the Stochastic Processor for Artillery Effectiveness (SPRAE), which was running in 1991 and in full use in 1992. SPRAE traces fragments from the burst point to the target stochastically. The target description can be entered interactively, and the model can be interrogated for the results of each burst.[9]



The SPRAE Model.

Now (1992) it is becoming apparent that computer power makes it possible to consider a large array of sub-targets (vehicles, vans, radars, etc.) and to assess the functional degradation of the complex (as a command post, a missile site, etc.) resulting from an artillery attack. Since there is no conceptual difference between the geometric description of an individual target and of a set of individual targets in SPRAE, it could be used directly to develop the damage information. The Army Unit Resiliency Analysis (AURA) model (discussed later) could then be used to develop the degradation of the complex's function.[9]

One of the problems with VAST (and SQuASH) was the fact that the gathering of spall data from witness-plate firings was very labor intensive. In FY88, "The BRL developed an automatic witness-plate analyzer, which provides the vulnerability analyst with accurate measurement and inspection capability of holes in witness plates used in BAD testing. The manual approach would require as much as 20 man-hours to analyze one plate whereas the present system requires approximately 20 min and does it more accurately."[2]



Typical Witness Plate.

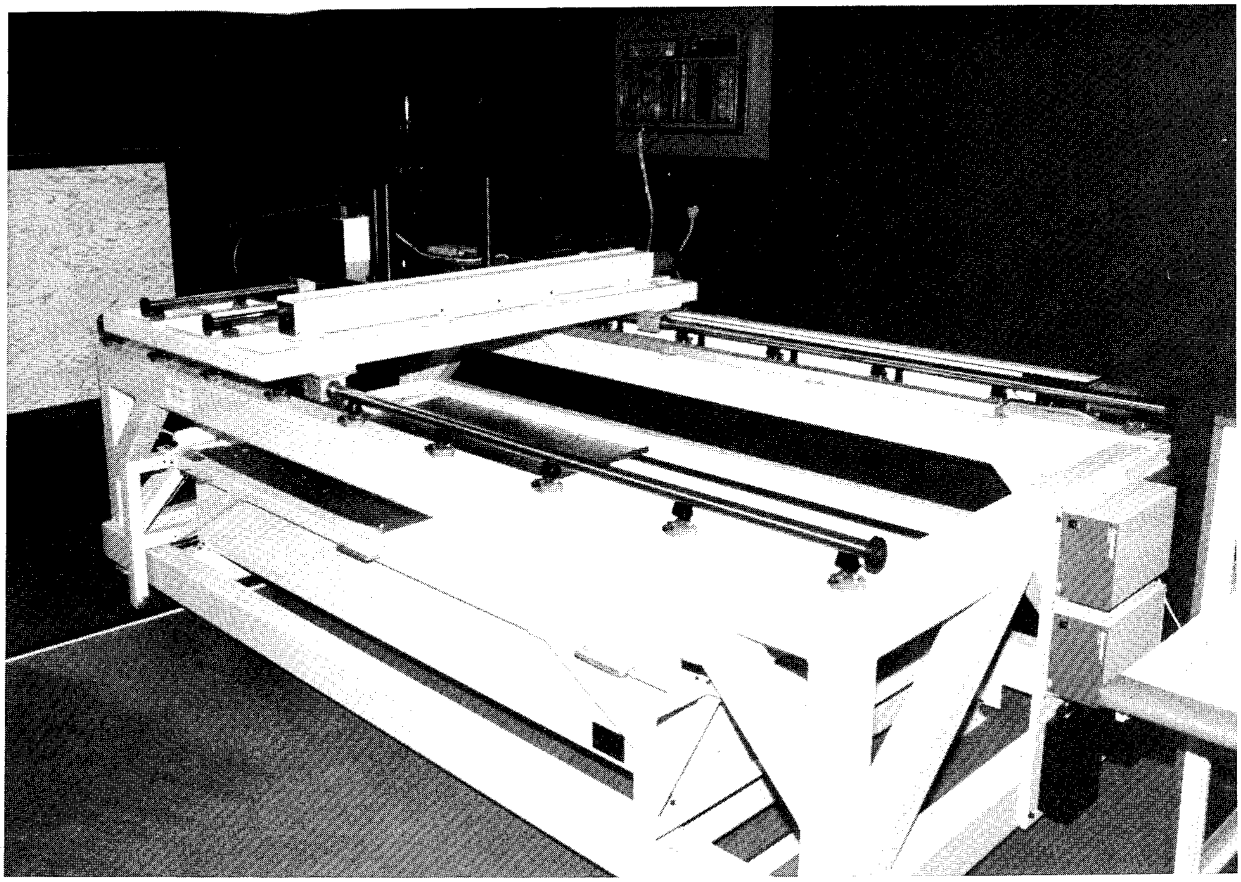
This was also the subject of an *Update*[15] article that describes the process as follows: "The BAD environment is characterized experimentally by placing packs of 4-ft X 4-ft or 4-ft X 8-ft thin steel plates behind armor plate arrays replicating specific vehicle armor sections. Holes created in the witness plates by the ejecta from the armor and pieces of the attacking penetrator are located, counted, and measured to determine the quantity, sizes, speeds, and spatial distribution of the lethal debris. In a typical experiment, a tank-fired projectile created 5,011 identifiable individual particles which made 6,084 holes in the five plates of the witness pack. Traditionally, plates such as these were *read* manually, an expensive, time-consuming, and error-prone process. In this example, 56 man-hours were required to read the five plates and enter the measurements into a computer data base.

"The scanner setup read this same pack and entered the data into the data base in 2 hours, requiring only 6 man-hours of operator time for setup and operation. In a current 132-shot test program, a savings of 3,800 man-hours is anticipated using the scanner.

"The heart of the scanner system is a video camera mounted on a mechanical stage above the back-lighted perforated witness plate. A computer controls the movement of the camera as it traverses the length and width of the plate scanning and digitizing the plate in 4.4-in X 6.0-in segments. Each digitized image, which emphasizes the fragment holes that contrast with the background because of the back-lighting, is stored in the computer for later analysis. Once installed, a 4-ft X 8-ft plate can be scanned in less than 10 min."[15]

Another important step toward an analytic point-burst methodology was made in FY91. "An analytic component-kill estimation methodology has been developed. It uses highly detailed geometric information, accurate numeric integration techniques, and the direct lethality characterization of the behind-armor-environment threat description. A prototype computer code has been implemented that can handle multifunctional components. This effort is the most significant update of component kill estimation methodology in the past two decades."[16]

Stochastic Quantitative Analysis of System Hierachies (SQuASH). Both VAMP and VAST, as well as related models, are expected value models. That is, they calculate the probability that a given event (e.g., an M-Kill) occurs for a given encounter, but they give no information on the variability of that event. The component damage in VAST is similar in that a set of expected values of damage for the components is available, but no data are given on the variability of those values, nor are any data given on the correlations of damage among the components.



The BRL's Automatic Witness-Plate Analyzer.

This limitation of VAMP and VAST became acute when LFT became popular in the mid-1980s. Those tests produced data on the specific damage to the target system for each of a relatively small number of full-scale shots. Further, the tests did not give direct data on the classical measures of effectiveness of M- and F-Kills—K-Kills were directly observable.

What appeared to be needed was a model that would predict the probabilities that various sets of components (component-damage vectors) would be damaged by a given encounter with the threat. The model that emerged to satisfy this need was SQuASH. There is no direct evidence that this formidable name's acronym is related to Paul Deitz's interest in the game of the same name. As reported for FY86, "The BRL has reconfigured significantly a point-burst (component level) vulnerability model in order to support the many live-fire programs (e.g., M2/3, M1, M113). Previously, damage calculations were deterministic, yielding a single-value (mean) result. With the new stochastic point-burst model, called SQuASH, all damage processes are modeled probabilistically. As the model is exercised, various discrete damage states are predicted, together with a likelihood of occurrence and the attendant effects on battlefield functions. Testing of the model shows that, for marginal weapon overmatch, the historic approach of simply averaging the outcomes provides a poor characterization of the true loss of function, whose histogram is multimodal. One implication of these results is that the Army (as well other services) must rethink the way it interprets the results of single field shots, since a shot can only represent one of the many possible damage outcomes."[17]

The logic of the SQuASH code is:[18]

1. Intersect 9 rays with the target geometry to simulate the threat trajectory; from each possible interior spall point-burst 10,000 rays.
2. Randomly pick one of nine rays and fire the threat munition.
3. Check for suspension and other exterior damage.
4. Check for perforation.
5. If perforation, randomly deflect residual penetrator.
6. Assess components killed due to residual penetrator.
7. Check for K-Kill due to impact on fuel and ammunition.
8. Assess presented area and barrier shielding for all critical components in spall domain.
9. For each component, calculate the expected number of lethal fragments from the spall model and use the Poisson distribution to perform a random draw for the specific number (n) of fragments.
10. Play n fragments individually against the component probability of kill given a hit (PK/H), power up individual PKs using the survivor rule, take a random draw to calculate a kill/no-kill outcome.
11. Repeat the spall processing for all remaining critical components.
12. Record the vehicle's damage state.
13. Repeat the above damage assessment processes 999 times.
14. Sort and rank all vehicle damage states.
15. Map all (weighted) damage states to PK space to build M, F, and M/F histograms using deactivation diagrams and DAL.

SQuASH was declared "operational in FY87," and "it provided predictions for the shots of the Abrams survivability test program. In the future, it will be used as a part of all other ground-vehicle test programs. In addition to providing direct evaluations of vulnerability, it is intended that SQuASH will be used to generate new damage correlations for use by BRL's compartment model VAMP, a low-resolution but more production-oriented vulnerability code."[19]

Actually, since SQuASH is so computationally intensive, the goal became to use SQuASH to develop and validate a VAST model, which in turn could be used to develop the compartment-damage correlations for a VAMP model, which then could be used for production. In a sense, VAST/SQuASH will be the CARDE data source in the future; VAMP will be the production model.[20]

In FY88, Shnidman's approach for BAD was added to SQuASH, and "the SQuASH model was enhanced in order to more accurately reflect preliminary data and to account for processes involving KE projectiles and EFPs in a more realistic fashion. In addition, configuration control and specification of vehicle

The SQuASH Model Uses a Bundle of Rays as Part of Its Stochastic Approach.

components have been improved, while enhanced efficiency of calculations now offers the possibility of stochastic modeling of the total vehicle."[2]

In FY89, the "capability to produce view averages for SPARC applications was added to SQuASH."[20] Also, "SQuASH has been used to predict 48 shots in the Abrams live-fire program, making it possible to make detailed comparisons with field observations and computer predictions. Subsequent analysis has established areas of excellent predictive capability and areas where better agreement can be achieved by modifying component PK."[21]

In FY90, the Kokinakis-Sperrazza personnel incapacitation model was incorporated in SQuASH. Applications of SQuASH included the development of data for developing DS metrics and the preparation for analyses of the Paladin and M109 howitzers.[20]

In FY91, first-order predictions for Paladin and the M109 howitzers were produced for shot selection to be use in LFT, and full SQuASH predictions were made for four of the live-fire shots on each. Also, SquASH was used to produce DS metrics for the Soviet T72 tank.[20]

SQuASH was further improved in FY91. "SQuASH has been upgraded to allow most of the previously hard-wired, target-dependent features to be entered via user input. These changes, along with upgrades in the user interface, have made the use of the code for new vehicles simpler and much faster. SQuASH is the most advanced tool for estimating vehicle vulnerability."[16] Also, "The direct lethality BAD methodology has been implemented in SQuASH. This methodology describes the threat in terms of the remaining hole-producing capability of the debris after traversing any specific thickness of material."[16]

A vulnerability study that compared the M1A1 tank with the M1A2 version was made in FY92.[20] This is of particular interest since it involved a change in the stochastic approach. Rather than do a large number of Monte Carlo replications for a given shot condition, a small number of replications were done for each of a large number of grid points for each target view.[22]

Degraded States (DS). For a long time,[23] it was generally recognized that there was a fundamental variance between the *fractional functional loss* as determined in full-scale tests such as the CARDE trials and the *probability of total functional loss* as calculated in VAMP, VAST, and early versions of SQuASH. To ignore this difference is equivalent to saying things such as: "The result of a particular encounter with the threat causes a 50% loss of speed" is equivalent to "There is a 50% probability that the result of the encounter is a total loss of mobility."

This issue has surfaced for two reasons—first, because the use of vulnerability numbers in analyses can be sensitive to more of the details of the functional loss than is represented in PKs, and, second, because it is difficult to relate models such as SQuASH that treat damage in detail with models such as VAMP that do not.

For example, the latter case arose, circa 1986, when there was a need to compare the SADARM smart-munition warhead with the terminally guided sub-munition (TGSM) warhead for MLRS. Of necessity, VAMP was used to develop lethality data for the (SC) TGSM, and VAST was used for the (EFP) SADARM. There was considerable difficulty in resolving the results of the two different methodologies; the issues were resolved for this case, but the concern for future situations remained. Likewise, there were difficulties in developing DALs that relate specific component damage (e.g., the loss of a night sight) to PKs (e.g., probability of total loss of the ability to fire).[24]

Mike Starks saw the need for a new approach to vulnerability metrics and has led the development of the concept of DS. Lisa K. Roach has written an article for *Update*[25] that expounds on the idea of DS. The following excerpt has been taken from that article:

"VLD has developed a new improved methodology for (PK) calculation. This new approach, DS vulnerability methodology, yields probabilities that a combat system is in various

DS. ... To understand the significance of the new methodology, a brief discussion of the traditional methodology, and its inherent shortfall, is provided.

"To relate the damage of components to the resulting performance degradation of a target, traditional vulnerability calculations made use of a mapping procedure called standard damage assessment lists (SDALs). SDAL maps killed components and sets of components into degradation of combat utility (DCU). However, specific problems with the SDAL process have been discussed over the last decade and include the following. [First,] the DCU estimates developed in the SDAL process, and defined as expected loss of function values, are universally and wrongly used as if they reflected probabilities of no capability of the combat system. A second problem is the use of probability mathematics for combining these expected loss of function values. Third, SDALs have traditionally developed by conclaves of experts who must mentally integrate over all possible combat missions, combining the effect of damage on all these missions into a single mobility and a single firepower DCU estimate. There are several problems with this sort of process. First, mental integration is not a well-defined analytical process and should be replaced by explicit integration where possible. Moreover, the set of all possible missions countenanced by today's doctrine may not be appropriate for tomorrow's. Finally, being limited to only firepower and mobility functions, the SDAL process does not provide enough detail or flexibility to support all studies.

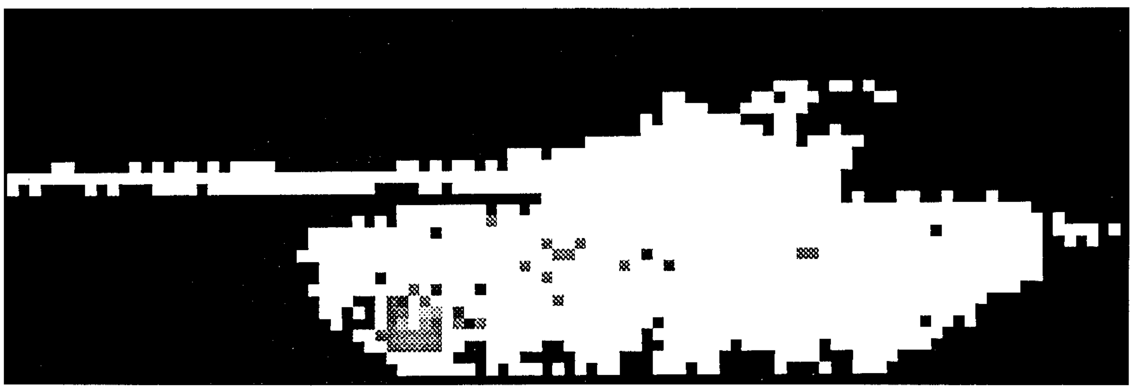
"The DS methodology overcomes the difficulties with the traditional SDAL process noted above. For this new approach, a fuller and more specific set of metrics is developed. The major functions of the combat system are divided into kill categories: for example, six kill categories were developed for the M1A1; specifically, mobility, firepower, acquisition, crew, communication, and ammunition. Each kill category is further divided by using a number of kill definitions which describe damaged states of the combat system. These damaged states encompass various functional levels (e.g., slight or significant) and include a *no damage* state and a *killed* state. Within all the kill categories, except crew, each possible combination of definitions is also defined separately. Therefore, for a given damage vector (i.e., set of killed components where each component is either 0% or 100% damaged), one and only one kill definition from each kill category will be satisfied. This, in turn, generates a combat-system DS. This combat system DS, which reflects the damage states for each of the combat system's critical functional capabilities, presents a full picture of the system's specific capability following an encounter with a damage mechanism, and is not subject to the kind of mathematical misinterpretation which is associated with DCUs.

"Once combat systems' kill definitions are described, they are expanded into mathematical fault trees to allow calculation of their probability of occurrence. These fault trees consist of combinations of the system's critical components that, if killed, would result in the satisfaction of that particular kill definition. A kill definition is satisfied if no uninterrupted path from top to bottom exists in the fault tree. The fault trees are then converted into computer-language statements and incorporated into the DS methodology; specifically, the BRL-developed point-burst model SQuASH.

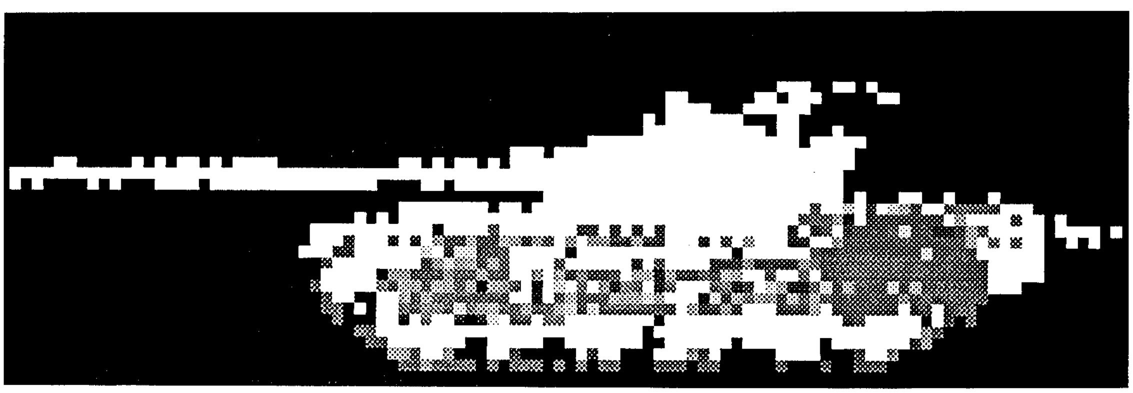
"The methodology was ... applied to the M1A1 tank and the calculations supplied to AMSAA, which successfully incorporated the new metrics into the GROUNDWARS force-level model. AMSAA used the new version, called DSWARS, to address the difference between the SDAL values and the new DS values at the force level."[25]

Army Unit Resiliency Analysis (AURA).[26] Circa 1978, there was a Congressionally inspired program called Theater Nuclear Force

Slight Reduction in Speed.



Significant Reduction in Speed.



Total Immobilization.

DS Calculations of Mobility Effects for a KE Round vs. a Foreign Tank.
Darker Areas Represent Higher Probabilities of Achieving the Effect.

Survivability to assess how well a theater nuclear force would survive after conventional strikes and possibly after a preemptive nuclear strike. A multiagency team that included the BRL, HDL, AMSAA, and TRADOC schools was created, and the BRL was assigned the task of deciding whether the theater nuclear force would survive a conventional attack. Methodologies for determining what happens on the integrated battlefield were not available; so an attempt to develop such methodology on contract was made to little avail.

The lack of a methodology became critical, and in August 1978, Dave Rigotti said "we (the BRL) will do it, but with the cooperation of all other agencies involved!" The job was given to Terry Klopcic, and the residual combat capability (RCC) model resulted.[26]

RCC is an event-sequenced simulation model. If the event is a lethality event (e.g., the arrival of an artillery volley), the effect is calculated. If the event is a reconstitution event, all the time-dependent events are updated, the status of the unit is reported, the commander reviews the status, and the commander does an optimized reallocation of remain assets (this part uses 10,000 lines of FORTRAN coding). The output is how well the unit can do its job with the remaining assets.[26]

In 1978, the optimization algorithm was crude. Since then it has become more complicated (including backtracking over previous decisions) and it now (1992) represents a much smarter commander—"A system is only as strong as its weakest link" is the basic principle of optimization (e.g., there is no point in loading 20 trucks if there are only 10 drivers). The idea is to produce a balanced solution.[26]

By 1980, a nuclear algorithm had been added, and, by about 1982, chemical algorithms were in place. The latter is very important since chemical effects are mainly related to the performance of people—this ushered in a renewed interest in personnel vulnerability and related effects. For example, issues such as the effects of cross training are of concern.[26]

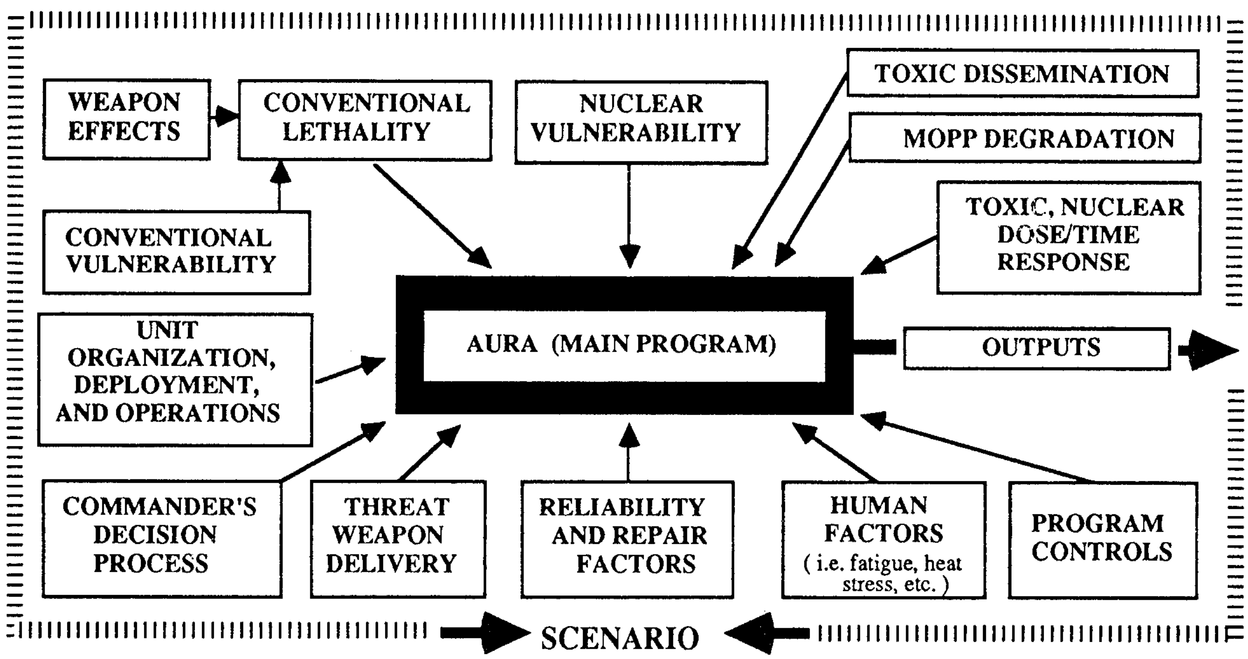
RCC became the only game in town for use on chemical effects because the major impact of chemical weapons is not in the immediate casualties. The major effect is in the degraded performance of the people after they have taken protective measures. "Of particular interest are those models that apply in nuclear and chemical scenarios. The consideration of these non-conventional weapons in a combat situation introduces a large number of factors that must be modeled in order to assess the ability of an affected unit to continue to function. For nuclear, these factors include the environments produced by a nuclear detonation, the vulnerability of equipment and personnel to these environments, and—in particular—the time-dependent dosage effects of nuclear radiation upon personnel performance. For chemical weapons, these factors include the dissemination of the chemical agent (both in liquid and subsequent vapor forms), the effects of the agent upon personnel (both lethal and sub-lethal doses), the deleterious effects of chemical protective clothing upon performance, the incidence of heat stress, the exacerbation of fatigue effects, and the burdens of decontamination activity. Models associated with these factors have been assembled from several sources and assimilated into the AURA family."[27]

Around 1982–83, the name RCC was changed to AURA to reflect the emphasis on the unit. "AURA ... is a large, interconnected collection of analysis models which provides a detailed evaluation of the ability of an Army unit to accomplish a series of missions in a combat scenario. Briefly, AURA is an event-sequenced, one-sided combat-simulation methodology. The methodology consists of an (expanding) number of highly detailed models from the various technical communities interfaced into a large, time-dependent event-playing and optimization routine. The interfaces are varied, involving such diverse kill probabilities as lethal footprints for conventional munitions, log-normal kill probabilities for nuclear effects, toxic-chemical dispersions and evaporations, mission-oriented protective posture (MOPP) degradation, reliability, and target-acquisition probabilities. The optimization is a dedicated, non-linear routine which models the commander's reallocation of surviving, degraded assets in order to minimize the choke points in the optimal functional path. The logic process required the development of a general model for the functional structure of a military unit. Such a model was developed and forms an essential part of the AURA methodology."[28]

AURA is continually (as of 1992) being updated and used for analyses that move from the individual weapon to the unit. The Navy has NAURA, which is a variant of AURA that is based on AURA. It is also worth noting that AURA is for incoming indirect fire. The JANUS model (developed by the Lawrence Livermore Laboratory) is a related direct-fire model (AURA and JANUS are complementary); in fact, AURA has been used to simplify artillery data for input to JANUS.[26]

Modular UNIX-Based Estimation Suite (MUVES). The development of MUVES was initiated in 1985. MUVES has been designed for the study of target-threat interactions in an environment capable of accommodating existing vulnerability methodologies as well as providing flexibility to support new requirements.

"MUVES is the new software environment under which all vulnerability/lethality analyses conducted by VLD of the BRL will be performed. MUVES is a very general environment that is designed to evaluate the interaction of a threat with a target where the target information is provided via ray-tracing. Target descriptions built using the BRL MGED are ray-traced via an interface to the BRL-CAD



The AURA Family of Methodologies.

package. Although currently only the compartment-level vulnerability/lethality model has been implemented under MUVES, all models in the vulnerability/lethality hierarchy of models will be converted to run under the MUVES environment. MUVES is written in the C programming language and employs state-of-the-art computer programming techniques, such as structured programming, for ease of maintenance and extension. MUVES incorporates a user-friendly menu-driven user interface to facilitate the conduct of vulnerability/lethality analyses and a set of post-processors for the textual and graphical display of results."[29] MUVES was released in 1991.[16]

Live-Fire Testing (LFT).[30] As has been previously noted, there was a dearth of full-scale testing of the vulnerability of armored vehicles from the CARDE tests in the late 1950s until the mid-1980s.[4,31]

From 1980 to 1983, there was a firing program of SC warheads against armor in which the blast effect was found to be less severe than previous predictions (based on spherical charges). From the front, the SC warheads were found to have little blast effect, but they were very effective from their sides, especially for rounds with a good bit of metal that could provide fragments. If the warhead got into the running gear, the blast effect was greater.[31]

A Firing Against a BFV to Test the Vaporific Effect.

The side spray of the warhead did produce big holes in light armor; so John Jacobson had a box built to simulate the crew compartment. The pressure and temperature rises in that compartment were observed, and they were found not usually to be life-threatening.[31]

In 1983, the popular press was playing up the *vaporific effect* that was alleged to make the BFV a *death trap*. A catastrophic increase in fire and pressure was alleged to occur due to jet penetration of the aluminum armor. There were some basic data that supported this contention, but no full-scale compartment data were available."[31]

The BRL saw the need for full-scale testing for all major combat vehicles: Abrams tank, BFV, M109 howitzer, etc. At that time, COL Burton from DOD was visiting AMSAA in search of proposals for programs to gather vulnerability data. He got a BRL proposal to do full-scale testing of vaporific effect, which involved adding aluminum to the box previously mentioned. Burton supported the idea, and the tests were carried out in 1984. The results showed some enhancement of lethality against aluminum over that for steel, but the effect was not enough to cause a significant increase in crew casualties.[31]

"The BRL's vulnerability-assessment capability has been dramatically enhanced by the quantification of behind-armor effects in lightly armored (aluminum and steel) fighting vehicles (LAFV) when attacked by antitank munitions. One of the most significant results was the verification that there is no danger to the crew from exposure to overpressure, heat, flash, and residual vapors during and after the warhead-penetration process, provided the crew is outside the spall cone. These tests provide a state-of-the-art data base for vulnerability assessment, both for current and future LAFV systems."[32]

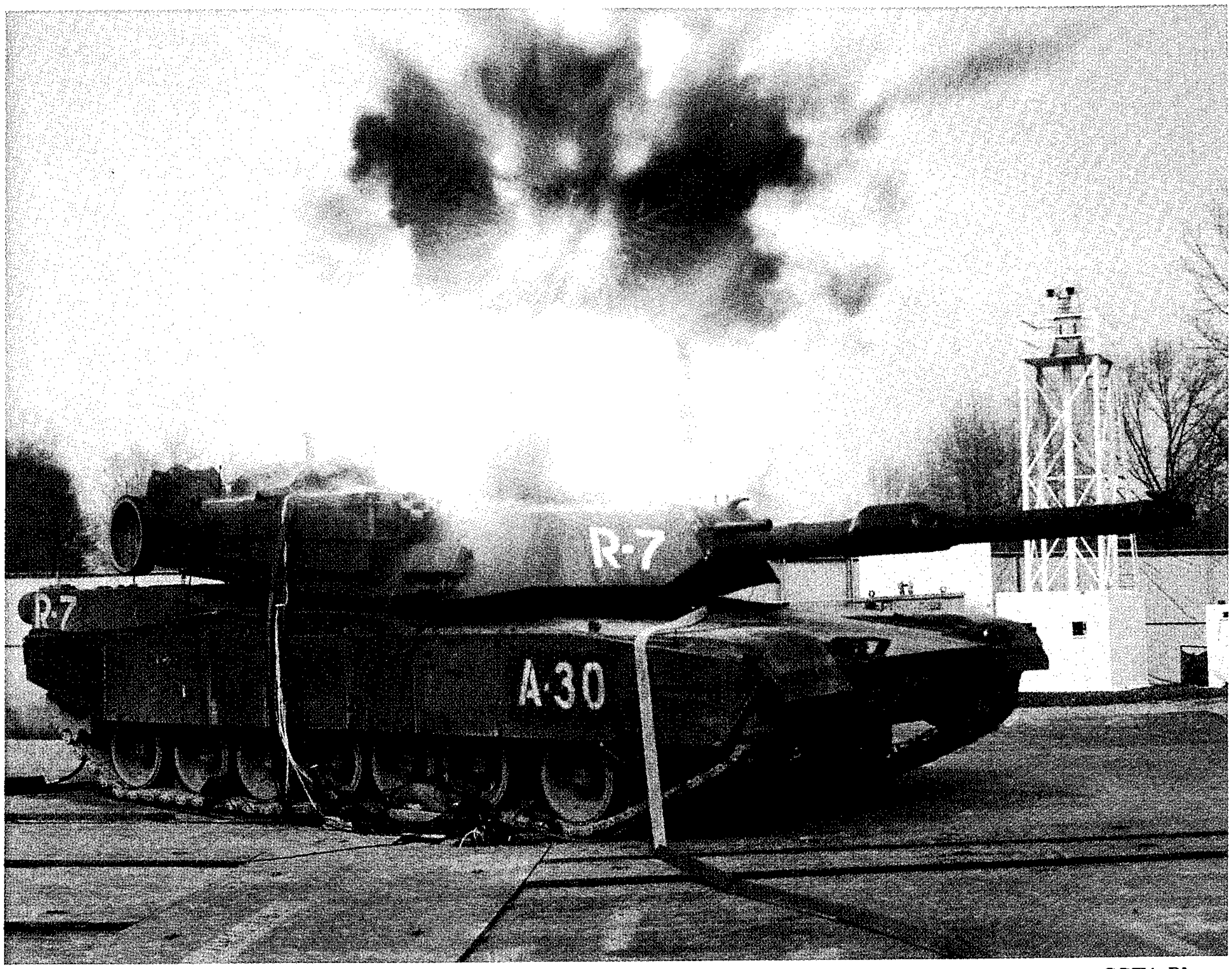
This helped lead to the LFT law. On 19 September 1984, Burton testified to Congress on the need for realistic, full-scale testing of the vulnerability or lethality of all major U.S. combat systems. The requirement for LFT was included in the FY86 DOD Authorization Act, has been elaborated on in further years, and is still in effect (as of September 1992).[31]

About the same time, the BRL had created a test plan for Abrams tanks, BFVs, etc., which Garry Holloway took over. The Army decided upon the Bradley LFT, which it defined and executed with participation by DOD (in particular by COL Burton).[31]

The Bradley LFT started in March 1985 and finished in mid-1987. "The BRL has been a major contributor to the design and testing of survivability enhancements for the BFVS and is currently leading the development of an advanced survivability concept for the next generation of Bradley vehicles. Concurrent with these efforts, a vulnerability-assessment test series involving the M113 family of vehicles was initiated and will continue into FY87. All of the test data produced are being used to upgrade the vulnerability models and provide insights for the design of future armored vehicles."[17]

As a result of LFT of the Bradley, the BRL developed spall liners, redesigned stowage of ammunition, and enhanced armor protection. The BRL also developed an RA package for protection against hand-held SC weapons. Many of these items were tested during the LFT effort.[31]

The Abrams tank was also the subject of LFT. "The BRL was responsible for the initial planning of the Abrams LFT until this responsibility was transferred to TECOM in April 1987. The BRL, with AMSAA, was responsible for establishing the test objectives, selecting the shots, initiating requests to obtain U.S. and foreign threat munitions, establishing instrumentation requirements, and evaluating the results. The BRL continued to provide technical support to TECOM during the execution of the testing and is also responsible



CSTA Photo.

Top-Attack Shot Against an Abrams Tank—Part of the LFT.

for identifying potential vulnerability reductions (VRs)/improvements for the phase II tests. LFTs are the most significant vulnerability tests since the CARDE trials."[19] CSTA of TECOM built an LFT facility (Range AA5) to allow testing at combat ranges. The tests were conducted from August 1987 to August 1988. The final report was prepared on January 1989.

We also note the following items with respect to the Abrams tank tests:

In FY88, "An LFT program (funded by PM-Tanks) was conducted to determine the vulnerability of various Abrams tank components to behind-armor spall fragments. For the first time, a data base was created which contains experimental data associated with the expected damage to components from fragments. These data will be invaluable in developing component-damage algorithms for use in vulnerability-assessment codes for the Abrams and other modern tank systems."[2]

Also from a report on FY88 technical accomplishments, "All the program objectives were achieved with the following generalized conclusions: The Abrams meets current survivability requirements regarding ballistic protection—the armor and ammunition compartmentation perform to design. The Abrams capability to survive and protect its crew makes the use of Battle Damage Assessment and Repair (BDAR) an essential element, and the vulnerability models currently appear to predict the correct Abrams internal damage and crew casualties from the primary penetrator and spall as compared to the test results. Lessons learned from this highly successful test will expedite the design and reduce costs of future tests."[2]

Off line from the M1's LFT, the BRL conducted tests and verified the DU-armor package for the Abrams and evaluated the environmental impact of using DU. The tests were full-up. The environmental effect of using DU was judged to be minimal (no significant hazard). These tests were conducted under an MOU with the DOE at their Nevada Test Range. Under that MOU, a firing range (tunnel) was created for full-scale testing that involved the use of DU. This facility has been in use since its creation for a variety of tests including the lethality of DU munitions against foreign systems under the Joint Live Fire (JLF) Program.[31]

The Abrams tank met its design protection levels. At the same time, important lessons were learned, including details of lethal processes that were valuable in defining evacuation procedures.[31]

Joint Live-Fire (JLF) Testing. The JLF test series was chartered in March of 1984 by the Director of Defense Test and Evaluation, Office of the Secretary of Defense (OSD). The series was established to develop data on the lethality of U.S. weapons against Soviet systems and the vulnerability of U.S. systems to Soviet weapons. The responsibility for the program was assigned to the JTCG/ME for tests against armored systems and the Joint Technical Coordinating Group/Aircraft Survivability (JTCG/AS) for tests against aircraft.[33]

Al Rainis (of the BRL) was PM for the armor/antiarmor phase of the tests from 1984 to 1987 at which time he joined the LFT office in the DOD. Jim Walbert (also from the BRL) has been the PM since.[33]

It took 3 years to develop a plan of action that included lists of targets and weapons to be used in the texts, issues to be addressed, etc.[33]

The tests on ground vehicles started in January 1987, and those on aircraft started later in the year. The JLF test program is closing out in September of 1992 since everything called for in the charter has been accomplished. The program will be rechartered as JLF-2.[33]

The BRL actually extended the charter in looking at Soviet systems to considering not only current systems but also developmental systems such as tank-fired ATGMs. They also considered upgrades of the Soviet systems based on intelligence and on technology.[33]

For Operation Desert Shield/Storm, the JLF office briefed every action unit that went to the Persian Gulf Region during the period from August 1990 to November 1990.[33]

There was a very close association possible between JLF and LFT because of the involvement of the BRL in both. For example, in the JLF testing of the Marines' LAV-25 at APG, MD, Rick Grote, along with VLD analysts and help from HEL, was able to use lessons learned from the LFT on the Bradley to develop improved stowage for the LAV. This resulted in greatly improved crew survivability.[33]

ComputerMan. ComputerMan was introduced in the second volume of this history. While ComputerMan was used for many analyses, little work was done on it through most of the 1980s.[34]

It was adapted to a variety of computers including the BRL's X-MP supercomputer. For comparison, a manual shotlining took a few man-months for a single projectile over a grid, the UNIVAC took a week, and the X-MP took on the order of 15 min. However, Sun workstations are quite efficient, requiring a few hours to do a grid.[34]

Rick Saucier wanted to display cross sections on CRT displays as opposed to printer-like displays. He started working with a graphical interface, using Precision Vision Incorporated (PVI) interfaces (software using the international standard-package graphics-kernel system [GKS] for displaying graphical information).[34]

He also introduced limb degradation as an intermediate stage. (In the original ComputerMan, tracks were translated directly into overall kill.) This allowed a better assessment of multiple wounds (rather than the application of the survivor rule at the end). Also, a civilian trauma-injury classification, abbreviated injury score (AIS) was added. This gave mortality data in addition to incapacitation data.[34]

In 1990–91, the effects of protective clothing were added.[34]

The present user guide on Computer Man is interactive, includes retardation in tissue, uses AIS, provides expert medical opinion on performance vs. type of injury, calculates the limb state for injuries, and provides level of incapacitation and survivability. The model uses a Monte Carlo method over a 3-in-diameter circle for a single shot and handles shots over a grid or for a burst point (spall cone). It is being used (1992) in a single-shot mode for LFT of the Paladin howitzer to evaluate manikin hits.[34]

Since ComputerMan is for stable fragments (not for tumbling bullets), work in 1992 is directed toward a version that incorporates tumbling bullets.[34]

Individual Protective Equipment (IPE) Data Base. "A data base has been developed which includes all known field measurements of individual degradation caused by the use of protective equipment. This data base is fully functional and can be used to estimate the performance corrections to be used for soldiers wearing IPE. For the first time, these correction factors can be determined for either tasks, human abilities, or by scenario (sub-tasks combined to create a task). As a result of the BRL development and authorship of the U.S. position on performance decrement for NATO countries, this data base has been accepted for use by NATO for predicting the degradation of personnel using IPE and the determination of future field data to be collected and collated. In the future, the BRL will be responsible for the approval and addition to the data base of any new data collected by NATO countries and U.S. Tri-Services tests."[17] "An international performance data base and force-ratio model was formatted and developed by the BRL. ... The force-ratio model provides a means for military planners to predict additional battalion-sized units required for large-force operations operating in IPE. The data base and force-ratio model are of such utility that they are widely used within DOD, CENEUR and form the basis for a NATO STANAG."[2]

Some Other Army Programs Supported. As noted in the introduction to this section on vulnerability and lethality, VLD responds to myriad requests for assistance on the entire panoply of Army combat materiel. The following are samples of some more of VLD's activities.

Howitzer Improvement Program (HIP) and Field Artillery Ammunition Supply Vehicle (FAASV). "The BRL has been conducting analyses for the Program Manager-Cannon Artillery Weapon Systems (PM-CAWS) in VR for HIP and with TACOM for FAASV. The two efforts, though independent, have benefitted from and reinforced one another by allowing efficient resource utilization and cross-application of

Artillery Shot Against a Soviet BMP-1—Part of the Study of Artillery Effects.

results. Survivability enhancements range from the protection of critical sub-systems by rearranging components to the creation of new, lightweight armor technology."[17]

Advanced Survivability Test Bed (ASTB). "On 20 May 1986, AMC directed TACOM to establish a task force to develop ASTB in response to public and Congressional criticism of BFV battlefield survivability. The task force was formed, staffed, and provided required facilities by July 1986."[35] "During the following 13 months, the task force managed extensive design, component testing, and analysis; fabrication of four fully OT beds; and supported both operational and Congressionally mandated LFT."[35]

Gil Bowers was a member of the task force and the BRL Principal Investigator for the ASTB program. Other BRL team members included Jerry Watson, Gould Gibbons, Fred Gregory, and MAJ Steve Harnois.[36]

"The BRL was tasked with, and successfully accomplished, the design, development, testing, and demonstration of methodology for external stowage of TOW missiles, compartmented 25mm ammunition storage, and, with the Southwest Research Institute, externally stowed fuel. In addition, the BRL was tasked to provide vulnerability-reduction trade-offs and vulnerability analyses."[19]

"The objective of the ASTB Task Force was to minimize crew casualties. ... The ASTB M2 and M3 concepts which resulted had the following major survivability enhancement features: compartmentalized 25mm ammunition and TOW missiles, external fuel tanks, spall protection, and applique armor (30mm protection)."[35]

"Although designs had to be developed, tested, and provided to the contractor in less than 3 months, the BRL ASTB program was brought to completion with exceptional results. The compartmented ammunition storage features easy access by troops and antifratricide barriers between rounds to prevent mass detonation while holding weight increase to minimal levels. The VCSA accepted the designs and directed the PM for ASTB to have FMC build the ASTB using the designs for LFT. The vehicles were constructed by FMC, tested by TECOM, and performed flawlessly—the crew remained safe."[19]

Soviet Artillery Effects. "The effects of Soviet artillery against modern armor was investigated by the BRL in cooperation with HQDA and TRADOC. More than 500 rounds of

The Battle Damage Assessment Team Examining a Soviet Tank That Was Destroyed During Operation Desert/Shield Storm.

point-detonating and variable-time-fuzed artillery projectiles were fired at a range of 7 km against a target array of fully operational M1 Abrams tanks and M3 BFVs. This represents the first time a significant number of artillery projectiles have been fired against modern armor. The resulting data base is being used to validate and update vulnerability model inputs for fragmenting munitions with Army-wide impact, particularly by AMSAA and force-on-force analysis within TRADOC."[58] "A comprehensive vulnerability data base has been established for the M109 howitzer, FAASV, and the MLRSs subjected to Soviet 152mm artillery fire and the Abrams tank and the BFV subjected to Soviet 120mm-mortar rounds."[16]

Operation Desert Shield/Storm. Certainly, the BRL's long-term contributions to the development of survivable armored combat vehicles were significant factors in the performance of those systems in Operation Desert Shield/Storm.[37] The following two additional items are also well worth noting:

MAJ Richard Koffinke from the BRL led a team of 12 people from the BRL, USAOC&S, and CSTA to collect data on actual battle damage to U.S. systems. The team was deployed 18 January 1991 and travelled with the 7th Corps. They examined every Abrams tank and BFV that was combat damaged and assessed that damage. Among other things, their data were valuable in helping to clarify fratricide issues.[31]

Also in FY90, "VLD was responsible for the design and conduct of an important series of armor/antiarmor experiments, the nature of which is classified, but which has provided the DOD with information extremely vital to the national defense. Researchers designed the experiments and evaluated results, recommending test design changes to OSD as necessary to take advantage of emerging results. As a result of these efforts, the United States has advanced considerably in its knowledge of performance of both armor and munitions under realistic combat conditions. The information obtained from these experiments [was] extremely valuable to Operation Desert Shield/Storm."[38]

AIRCRAFT SYSTEMS[39]

ASB of VLD was responsible for the analyses of all types of aircraft and missiles.

In a very real sense, the period covered roughly by this volume of the BRL's history was a time of realization for the efforts of ASB on behalf of Army helicopters. Unlike tanks, which have a history going back to World War I, combat helicopters have a history that is limited to the last few decades. The helicopters used in the Korean Campaign were far too fragile and unreliable to be considered combat worthy. In the period after that conflict, the Army was enjoined from arming helicopters except for self-protection, and that arming was truly a bailing-wire operation. Even during the Vietnamese Conflict (before AH-1 Cobra attack helicopters were introduced), the famous Hueys were utility helicopters to which guns and rockets were affixed. During that campaign, members of VLD worked in Vietnam on adding protection for the helicopters and their pilots.[40]

Based on the experience gained in Vietnam and much work thereafter, the people of ASB campaigned hard for the inclusion of ballistic survivability in the basic design of Army helicopters through added protection, redundancy of components, the design of fuel systems, the location of critical components, etc. These efforts have borne fruit in the design of the Black Hawk utility helicopter, the Apache attack helicopter, and the family of light helicopters (LH-X). The Black Hawk and the Apache are now battle-proven systems—most recently and significantly in Operation Desert Shield/Storm in the Persian Gulf.

In addition, this involvement with the birth of the combat-worthy helicopter has given ASB a very special hands-on association with Army helicopters going back to the bailing-wire days. This is not said in any way to diminish the accomplishments of the other branches of VLD for their many important contributions to survivability of the panoply of the Army's combat materiel.

This hands-on approach has been reflected in ASB's vigilance in obtaining aircraft and aircraft parts for test. They have maintained contacts with various sources of supply including the Air National Guard for aircraft coming out of service. They have maintained a stockpile of equipment (engines, classic aircraft, etc.) for barter with the other services, museums, etc. For example, they swapped two B57 Canberra Bombers for an A-7 aircraft with the Martin Air Museum with help from the Pennsylvania Army National Guard in the form of a heavy-lift helicopter to transfer the aircraft.[39]

In the same vein, circa 1983, the BRL furnished a supply of excess parts to the Washington, DC, Police Department to support their newly acquired UH-1B helicopters, which were reportedly being placed into service on the recommendation of the White House in the aftermath of the Air Florida crash at the 14th Street Bridge. (The acquisition did not include spare parts support.) A main-rotor system, tail-rotor drive components, and three near-zero-time engines were furnished from the BRL excess assets.[41]

Tests and Analyses Performed. Over the years, ASB has supported every Army (and many USAF and Navy) aircraft program with tests and analyses on vulnerability and survivability. This also included extensive tests and analyses on foreign threat systems. We make no attempt to gave a complete recitation of the myriad efforts that were made on behalf of Army aircraft—but rather give a sampling to give a flavor.

"During the 1970s, much of the work at ASB focused on supporting the Aviation Systems Command (AVSCOM) under new Army procurement initiatives, which emphasized competitive design evaluations based on compliance with specific functional requirements and performance goals for new Army aircraft in the combat environment. ASB personnel joined this process in the specification-writing stage, bringing to bear extensive lessons-learned data from their Southeast-Asian combat-damage studies and a repertoire of design do's and don'ts developed in dynamic aircraft and component experiments at their range facilities. As a consequence, aircraft VR emerged as a recognized discipline and a weighted proposal-evaluation factor.

"Branch personnel remained involved as programs progressed. They participated in SSEBs and design reviews, and they contributed vulnerability analyses, trade-off studies, design-support tests, and post-award ballistic-qualification testing. This process enabled branch SSEB members James Foulk, Dennis, Bely, and Walter Thompson to incorporate and defend VR from design inception to production approval in the Army's UTTAS program (leading to the UH-60 Black Hawk utility helicopter) and its Army attack helicopter (AAH) program (leading to the AH-64 Apache attack helicopter). Their successful VR concepts and techniques had been skillfully and convincingly tested and refined by branch range personnel Raymond Wheeler, Jim Lewis, Tom Poole, and Emmett Donelly.

"Later, following extensive vulnerability studies on the Army's family of light helicopters, another SSEB was convened for the LH-X, which accomplished the same VR objectives for the successful new candidate, now known as the RH-66 Comanche helicopter. Robert Walther, John Anderson, Mike Vogel, Stephen Polyak, Dirck Ten Broeck, and Thompson provided the effort."[42]

In this period, extensive analyses on the Black Hawk and AAH were involved: "For the AAH the cost/operational effectiveness analysis

U.S. F-104 Being Used as a Surrogate for a Soviet MIG-21.

(COEA) developed vulnerability information on 7 aircraft to 39 threats. [To support] the AAH OT (OT II), [the branch] developed vulnerability data on the AAH as tested and on three other aircraft to 22 threats. Members of ASB participated on the following SSEBs: [UTTAS], AAH, Near-Term Scout Helicopter, Advanced Helicopter Improvement Program, and the Advanced Composite Airframe Program. Extensive support [was provided to the] AAH PM regarding vulnerability analyses, design reviews, vulnerability verifications, and design-DTs. Similar support was given to the Black Hawk PM. A truss-type tail-boom concept and prototype has been developed and tested that demonstrated invulnerability to multiple hits by Soviet 30mm high-explosive incendiary (HEI) projectiles. Detailed VR features have been developed for the 800-shaft-horsepower engine."[43]

Members of the branch also participated in SSEBs for the T700 engine, the T800 engine, and the modern technology demonstrator engine (MTDE). The MTDE evolved into the engine for the U.S. Marine Corps (USMC) V-22 Osprey aircraft.[42]

"Combat damage assessments of the Cobra and Black Hawk were made that identify components, repair personnel, and repair and replacement times for the logistics support of these aircraft systems in combat."[43] For example, "In 1980, a vigorous, 6-month effort to develop combat-damage repair-time data for the Black Hawk helicopter was completed. This information is essential to keep the critical Black Hawk fleet flying in combat. It was developed by the use of the computerized vulnerability-area and repair-time (COVART) computer code developed by the BRL.

Sustainability predictions for Army spare-component requirements for combat have received the highest priority Deputy Chief of Staff for Logistics (DCSLOG) study status by direction of the DA Management of Requirements Steering Group. The objective of this sustainability study is to enhance sustainability of critical systems in combat by:

1. Predicting parts that will be damaged in combat.
2. Product improving those parts where feasible.
3. Developing expeditious field-expedient and combat-damage repair procedures where feasible."[44]

"Occasionally the aircraft safety community tapped the collective branch expertise in aircraft systems for failure modes and damage effects to help resolve issues encountered in crash and incident investigations. For example, at the request of the Army Safety Center at Fort Rucker, AL, in 1985, a team led by Thompson along with Bob Meyerhofer, Bill Kiethley, Harry Reeves, and Pamela Duff aided in an investigation of a spurious helicopter crash in Central America. The team, with some Federal Bureau of Investigation (FBI) laboratory assistance, pinpointed the cause."[42]

As an example of the fruits of the efforts of this period, we note that "the most thorough and detailed vulnerability analysis ever performed in the United States has been accomplished for the AAH. This analysis uncovered certain deficiencies in AAH that were brought to the attention of the AAH PM and the contractor. The ASB staff was successful in getting action started by the PM to correct the problems."[45]

The following series of items highlights the accomplishments of ASB for FY84 and show the shift in emphasis from the attack helicopter to the family of light helicopters:

Concepts and specifications were provided that materially reduced "the vulnerability of the Army MTDE and LH-X engines as well as the USAF joint fighter engine [that led to the F119 power plant in the YF-23 advanced fighter]. These vulnerability-reduction designs were accepted by the respective PMs. In addition, ATB staff participated on the MTDE SSEB and provided VR designs for the future Army MBT turbine engine."[46]

"These efforts were inaugurated in the T700 engine and refined subsequently in MTDE and the T800 engines."[42]

"Extensive vulnerability analysis support was provided, as requested, on the LH-X to the Army Aviation Center and School, Fort Rucker, [AL]; the Applied Technology Laboratory; and AVSCOM headquarters. This support involved threat definition as well as vulnerability assessments for the trade-off determination and the trade-off analyses.

"In response to an urgent request by JTCG/ME, a method to assess the controllability of a fixed-wing aircraft while in a maneuver and damaged by weapons fire in the wings, tail, or in its control/lifting surfaces was developed and applied to a Soviet ground-attack aircraft.

"At the urgent request of the special assistant to the CG, DCSLOG, on-site inspections at continental U.S. airfields were made on aircraft damaged in Grenada as they were returned to the United States. Combat damage and vulnerability assessments were made, and implications were noted. The results were immediately provided to DCSLOG for briefing to the Secretary of Defense.

"A concept for an LH-X gun was developed that appears to have high potential and is growing in acceptance throughout the Army-aviation and industrial communities.

"A high-power microwave test was performed on a missile, a method was developed

Soviet MI-24 (HIND-D) Prior to Test.

for the assessment of helicopter high-power-microwave vulnerability, and this method was applied to two Army helicopters."[46]

Work continued in FY85 on the LH-X: "Vulnerability data for six conceptual LH-X configurations and five Soviet helicopters were provided to the LH-X Study Group at Fort Rucker, [AL], for use in the analysis of the Army's 1990-time-frame advanced light family of helicopters, the LH-X. The majority of this analysis was conducted through the use of computer models such as COVART and High-Explosive Vulnerability Area and Repair Time (HEVART). The efforts of ASB personnel in the early stages of design and the development of the required operational capability (ROC) insured that the LH-X developers had VR and survivability near the top of their requirements."[47]

The analysis of the LH-X continued into FY86. "During conceptual development of the LH-X, the BRL assisted TRADOC and AVSCOM in the development of minimum-vulnerability LH-X designs; prepared minimum-vulnerability specifications for inclusion in the LH-X ROC, mission element needs statement (MENS), and

RFP; and proactively worked with TRADOC and AVSCOM to assure that these specifications were indeed included in these materiel-development documents so as to achieve an LH-X design of cost-effective minimum vulnerability to battlefield ballistic and directed-energy threats. In addition, to meet requests from TRADOC and AVSCOM for input data needed for the LH-X COEA, the BRL, acting on a very tightly time-constrained schedule, developed and provided, on time, extensive vulnerability and combat-damage-repair data on the many LH-X designs, current Army helicopter fleet, and threat helicopters subjected to fire from a wide array of ballistic threats. Over 1,000 combinations of these vulnerability and combat-damage repair-data matrices for an array of over 40 U.S. and Soviet threats ranging over small-arms bullets, tank-fired projectiles, and antiaircraft guns and missiles were developed and provided to TRADOC and AVSCOM as requested and on time for the COEA."[17]

The analyses paid off, and the BRL made a number of significant contributions to the design of the LH-X. For example, they "achieved inclusion of significant VR features in the LH-X ROC. ... They developed and integrated armor and avionics design to provide lightweight 12.7mm armor-piercing-incendiary (API) protection to the LH-X pilot."[48]

Also, given the BRL's involvement with computer technology, it is no surprise that they "achieved inclusion in the LH-X RFP, specifications that will save millions of dollars through the mandatory use of initial graphics exchange specification (IGES) by CAD/CAM systems in engineering, design, and manufacturing of the LH-X."[49]

As proof of the work done by ASB, we have the following report for FY91: "JLF tests of the Army's Black Hawk and Apache helicopters and two Soviet combat aircraft have substantiated the effectiveness of the vulnerability-reduction features built into the Black Hawk and Apache and have demonstrated the accuracy of predictive methodologies."[16]

"In 1987, the branch was tasked by the U.S. Navy to apply its ballistic-vulnerability knowledge to optimize the protection assets on the USMC landing-craft air-cushion (LCAC) assault vehicle, which featured aircraft-style power plants and propulsion systems. This effort reduced the vulnerability of the craft to nearly zero against the primary threat."[42]

As noted in the next section on the Test Range for Advanced Aerospace Vulnerability (TRAAV), the BRL has been participating extensively in JLF testing under the auspices of JTCG/AS and JTCG/ME. JTCG/AS is concerned with the survivability of U.S. aircraft, and JTCG/ME with the effectiveness of U.S. weapons against foreign systems. An example of the things that must be done to support that effort is the following item for FY91: "The BRL and the USAF have collaborated in the design and testing of a low-cost anthropomorphic manikin (AIRMAN). The manikin will be used in LFT to measure fragment-penetration data for vulnerability/lethality analysis. The manikin is constructed of low-cost polyurethane segments, which are easily exchangeable, easy to set up in realistic crew positions, impervious to contamination, and easy to calibrate and extract penetration data."[16]

For some time, the BRL was involved in analysis, consultation, and testing for Patriot missile development of a warhead to destroy enemy missiles. The Patriot advanced combat-2 concept (PAC-2) warhead flew in Operation Desert Shield/Storm against SCUD missiles, and Richard Grayson from ASB went to the Persian Gulf region immediately after Operation Desert Shield/Storm to evaluate the warhead performance of Patriot against SCUDs.[39] From FY84, we have the following note: "At the urgent request of MICOM, a vulnerability analysis of a tactical ballistic missile was performed in support of a Patriot upgrade."[46]

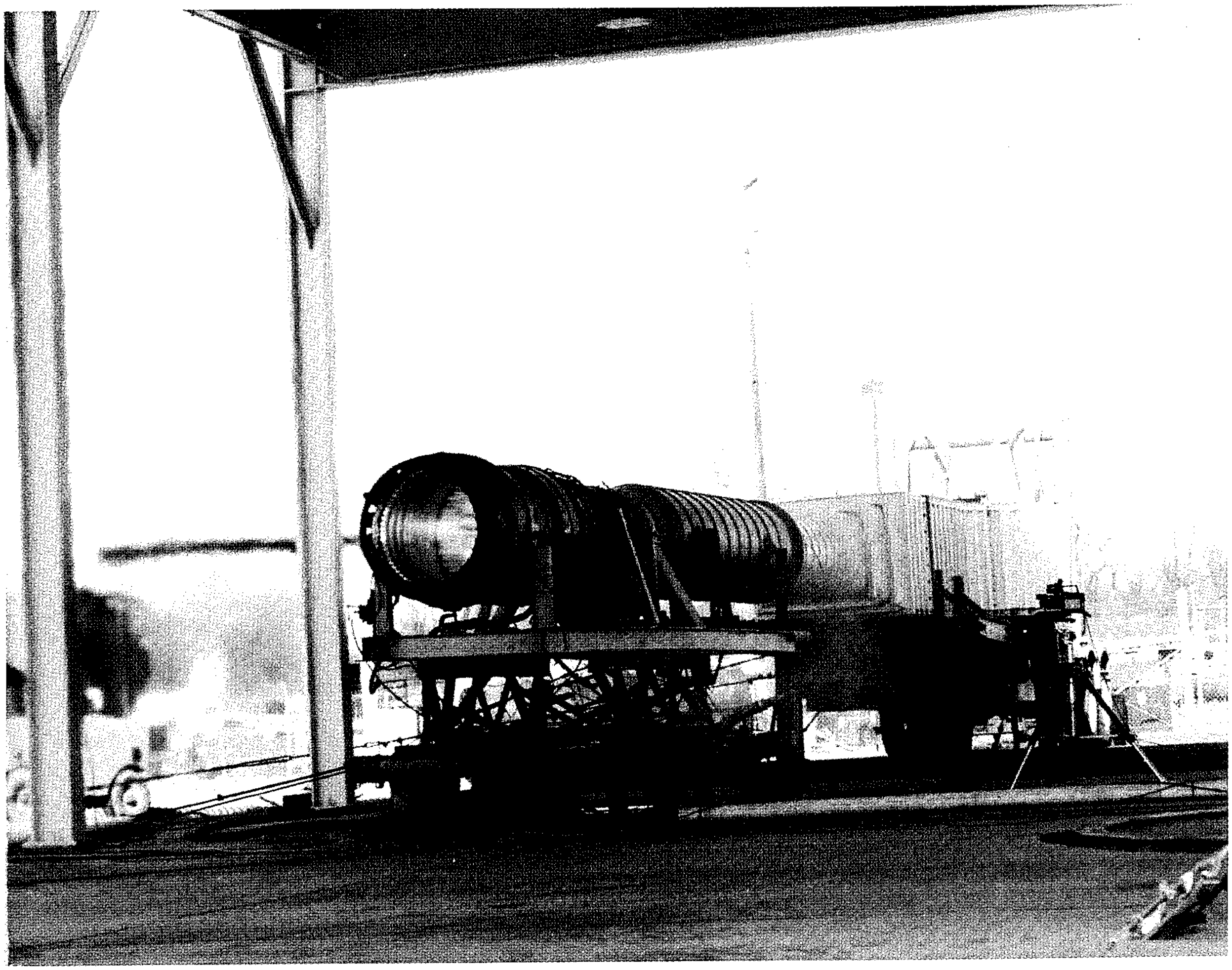
Test Range for Advanced Aerospace Vulnerability.

And more recently in 1991, "At the request of ASARDA, an evaluation of the effectiveness of the Patriot in its antitactical-ballistic-missile role was performed. This involved on-site effectiveness evaluations at the Patriot missile batteries in and around Riyadh and Dhahran."[16]

Aircraft-Vulnerability Test Facility. In 1985, Congress approved construction of an aircraft-vulnerability test facility at the BRL for inclusion in the FY87 construction request.[50]

Michael Vogel and Joseph Gatto have written an article for the BRL's *Update* publication on this facility.[51] "As the Army's lead laboratory for conventional ballistic vulnerability/lethality assessments and for VR technology for Army materiel, the BRL waged a campaign for a much-needed, new, state-of-the-art aircraft-vulnerability test facility."

"The completion of the $5.7-million TRAAV gives VLD a modern, centralized complex to evaluate the effects of explosive blast and



Jet Engine on a Test Stand at TRAAV.

fragmentation warheads, API and HEI projectile impacts, experimental penetrators and weapons, as well as unconventional threats on aircraft components, sub-systems and full-up operating fixed-wing and rotary-wing aircraft. This advanced vulnerability testing facility will directly benefit current BRL participation in the DOD JLF program as well as future developmental, specification, and live-fire test and evaluation (LFT&E) testing associated with several major Army aviation and antiaircraft development programs.[51]

"During FY91, over 10 JLF test programs have been scheduled at TRAAV which involve ballistic testing of UH-60A Black Hawk and AH-64A Apache components and sub-systems as well as several foreign-aircraft sub-systems. Additional JLF-sponsored vulnerability testing will continue into FY92 with completion in FY94. Future large-scale Army aircraft-vulnerability test activities will involve development, specification, and LFT&E testing of Longbow-Apache, Comanche (LH attack helicopter), and FAADS lethality. In addition to Army test requirements, TRAAV is scheduled to support USAF- and Navy-sponsored antiaircraft-warhead lethality evaluations and aircraft battle-damage repair (ABDR) technique development."[51]

Methodology. We should also note that the distinction between the inside and the outside of an aircraft is not so clearly drawn as it is for armored vehicles as manifested in the compartment model for armored vehicles; so while the compartment correlations were developed for the tank models, the aircraft models proceeded with more concern for the paths of bullets and fragments and the specific destruction of components.

As Don Haskell puts it, "The aircraft community was not hampered by a compartment model,"[52] they needed data on components, and they were able to get enough money (or a reasonable amount of money from projects) to develop the needed data. JTCG/ME was an especially good source for tests of fuel cells; the USAF, for blast effects and blast-kill methodology; and the Navy, for testing engines. In this way, ASB was able to maintain a continuous test program and a moderately complete data base. Testing has been continuous over the years (as opposed to ground systems). All three services are involved with aircraft and have an interest and a huge investment in keeping aircraft flying.[39]

The main theme has been the development of a methodology that goes from first principles to the bottom line of performance degradation and kill of the aircraft. As in ground systems, there is a hierarchy of vulnerability space relationships:[39]

1. Initial hits by fragmentation.

2. Effects of fragmentation and blast (e.g., broken-tail surface).

3. Result of maneuver-target code.

4. Categories of kills (e.g., crash, forced landing).

It is also worth noting that, in the case for aircraft, the kills are events (e.g., crashes), and the PKs are really probabilities of the occurrences of those events. This avoids some of the difficulty discussed under DS in the section on ground systems.

The basic models to develop data on the effects of fragmentation and blast were created under the auspices of JTCG/AS and JTCG/ME. Circa 1973, the BRL was the agent for the development of the single-fragment code (COVART); circa 1980, the HE-round burst code (HEVART); and circa 1990, the code for Hypervelocity Impact Vulnerability Area and Repair Time (HISVART). Kentron Inc. (known earlier as Falcon Research) developed the codes under contract. The codes were then *socialized* with the three services. Issues such as how to handle fires, engine kills, crew kills, etc., were agreed upon and updated through a series of modifications. When finally jointly agreed upon, these codes became standard among the three services.[39]

Much of the effort in methodology has been the creation of codes that will predict the effect of damage on the aircraft to its performance—in particular, flight response. A maneuvering-target code that computes flight response to damage for fixed-wing aircraft has been developed. This model includes a 6-degree-of-freedom model of the aircraft and pilot-control laws based on the expert opinion of pilots. It has been validated in 1984 against data for the B57 aircraft (discussed later).[39]

Some vignettes of accomplishments in the development of methodology follow:

In 1981, we have, "A new lethality method of analysis applicable to the ROLAND warhead was developed. The use of radiographs of aircraft electronic components in conjunction with a microdensitometer to obtain equivalent ballistic shielding was developed. An engine fuel back-up kit concept for helicopters was developed and evaluated to maintain engine power after loss of the main fuel supply to the engine. The generation and use of air-speed/altitude curves to delineate engine and tail-rotor failure effects on helicopter flight capability for application to vulnerability analysis was initiated. An outstanding contribution to new methods was the project of W. Thompson that identified how to achieve a K-Kill of a turbo-jet engine. Also, an existing turbine-engine-simulation computer model has been adapted for aircraft-engine vulnerability analysis."[45]

For 1984 we have, "The following steps in the large-warhead multiple-fragment-analysis methodology development have been accomplished: (1) a method to treat regions in which both singly and multiply vulnerable components are contained and (2) a computerized scheme to combine region hit probabilities with region conditional kill probability sets and sum these products by aircraft system have been developed."[53]

"Computer techniques involving interactive data preparation, validation, data-base insertion/retrieval, and input-stream generation have been developed which dramatically reduce the effort previously required to perform vulnerability and logistics analyses using the COVART/HEVART codes. A key feature of these techniques is their ability to capture critical data from target descriptions and a vulnerability/logistics data base. This task represents a significant step for the Army by reducing labor-intensive and error-prone portions of vulnerability analyses in support of combat-materiel development.[53]

"A technique to produce disablement diagrams from standard engineering drawings of advanced flight-control systems was developed, and the probability of loss-of-critical-function given ballistic damage to critical sub-system elements was evaluated."[53]

"Based on vulnerability tests of B57 aircraft, changes in aft-fuselage-body bending, torsional rigidity, and orientations of the principal axis were estimated for the MIG 21 aircraft. The changes in controllability of this aircraft due to combined aerodynamic and structural damage during maneuvers were then calculated, and the results were compared with the previously completed purely aerodynamic damage analysis of the MIG 21."[53,54]

Significant accomplishments in 1985 include: "A very useful tool, computer-aided analytical techniques for vulnerability assessments in varying levels of detail (COVIN), was written by Mr. J. Anderson and was successfully used in the LH-X COEA study. The utilization of COVIN proved to save many hours during the input of data to COVART. Further development in this program is the ongoing effort towards compiling a PK/H data base utilizing the INGRESS data-base-management system."[47]

Work by R. Oehrli on "loss of aircraft controllability from wing/tail damage ... [was scheduled to] result in the completion of Volume III of the Maneuvering Target Analysis which [included] aeroelastic effects of wing damage on recovery characteristics of damaged aircraft based on static-deflection testing of a typical fixed-wing aircraft. The test plan utilizing an F101 as the test aircraft [was] completed, and the analysis [was] projected for completion in December 1985. This program [carried over] into FY86 when Volume III [was] scheduled for completion."[47]

A program on the vulnerability of advanced flight control with Mike Vogel and J. Williams "was initiated in anticipation of LH-X, which was expected to utilize advanced digital flight controls. At the outset of this project with the Army community, very little information was available with reference to advanced digital flight controls and their vulnerability. Therefore, Mr. Williams was required to assimilate a vast amount of information regarding digital flight controls on both current-day fighter aircraft and future Army helicopters. This information became the basis from which the analysis was conducted and has greatly enhanced our capabilities. The efforts of this program have reduced the vulnerability of digital flight controls used in U.S. Army aircraft and has provided a foundation for assessing threat aircraft employing similar technology. A spinoff of this program was Mr. Williams' efforts in determining the protective capability of light armor and avionics equipment against the 12.7mm armor-piercing (AP) projectile. The results of this spinoff clearly concluded the judicial use of light armor and avionics will greatly enhance the protection of the LH-X pilot."[47] Later work considered the ballistic and high-power microwave vulnerability of advanced digital flight control avionics, which was used in LH-X analyses.[48]

Steve Polyak and W. Thompson considered the application of fuzzy-vulnerability and ESs technology "to develop an interactive ES for analyzing the ballistic vulnerability of aircraft air-breathing turbine-engine systems. The area of concentration for FY85 was the engine's compressor section. The results of FY85's efforts support the development of improved vulnerability analysis capability for aircraft turbine-engine systems via application of AI. The program has the potential for follow-on studies directed to the other major components of the turbine engine."[47] "During FY86, emphasis has been directed at turboshaft-engine compressors vs. small AP bullets (.30 and .50 cal) and fragments up to 1,000 grains. To date, a matching routine has been developed which quantifies the similarity of ES program data base engines (engines *A*), having defined vulnerability values, relative to an analysis engine *X* compressor operating and physical characteristics, and the evaluation of similarities and differences in relation to their contribution to vulnerability."[49]

The year 1986 saw yet more work on performance models: "[The BRL] developed a method for the quantitative evaluation of loss of control of maneuvering fixed-wing aircraft caused by combat damage to lifting and control surfaces and primary structure. This establishes a rigorous scientific basis for substantial improvements in antiair-weapon systems' effectiveness."[48]

"A helicopter performance evaluation code has been developed [by A. Kiwan and MAJ A. Thompson]. The code predicts the horizontal speed, maneuverability capability, and power requirements in terms of the weight. The code also evaluates the maximum attainable speeds at a given weight. The code also predicts the hover and vertical-flight capabilities of a helicopter at a given weight in both the out-of-ground effect and the in-ground-effect [regions]. The computational results with this code are within 10% of other performance codes.

"A structural analysis of a swept wing [or tail] has been developed [by Oehrli] as the basis for an aeroballistic analysis of the effects of combat damage on the wing [tail]. This structural analysis covers a swept wing consisting of up to and including nine spars and seven ribs. Next, new aerodynamic coefficients will be developed for the analytical deflection coefficients. These coefficients will represent the difference between the damaged and undamaged states."[49]

Joseph Fries wrote an *Update*[55] article that summarizes the work on the performance model for helicopters. Most of that article is repeated here: "ASB of VLD has developed a helicopter-engine power-loss [and] descent analysis and computer code for establishing helicopter-kill boundaries. When a helicopter is flying at a given height above the ground, at a prescribed forward speed, and engine power is lost, the helicopter is forced to change its flight regime. Depending on how much engine power is lost, the helicopter will either crash resulting in the attrition of the aircraft, perform a soft landing, aborting the mission, or continue to fly but with reduced capability, and limp back to base. This analysis and computer code predict the kill category calculating the PK given a prescribed engine power loss.

"The analysis consists of main-rotor-blade flap degrees of freedom, a main-rotor rotational degree of freedom, and aircraft longitudinal and vertical degrees of freedom. Rotor-blade-element aerodynamic theory is used. The main-rotor airloads are calculated by a double integration, first radially along the length of each rotor blade, and then azimuthally, adding the contribution from each rotor blade to give total main-rotor forcing function. There is large coupling between the helicopter motions and the aerodynamic forcing function resulting in a highly non-linear analysis with inter-harmonic coupling. A Taylor series time-domain numerical step-integration solution is used.

"The program now is in ASB's inventory of analytical tools for evaluating kill boundaries, and is presently being used to evaluate kill boundaries for the Soviet HIND, Apache, Longbow-Apache, and the OH-58D (Improved AHIP) helicopters."[55]

There is always a desire to create simple models that will allow quick estimates to be made for conceptual systems or systems for which little data exist. Ronald Bowers has written an *Update* article on recent work on such a model: "Closed-form equations for vulnerability give the PK/H as a function of target and threat characteristics. The equations are developed on the premise that similar aircraft share similar vulnerability characteristics. That is, aircraft which have several physical features in common tend to have similar PK values. By grouping together systems with similar physical characteristics, trends in the vulnerability of systems with that set of features can be determined. The analyst can then use these trends to estimate the vulnerability or lethality of a system for which only a few characteristics are known.

"In order to generate the closed form equations, a set of characteristics which appear to influence vulnerability was selected. The systems in the vulnerability data base were then segregated into groups according to those characteristics. The vulnerability data for each of the systems within a group were then combined by averaging the PK/H values at each threat mass-velocity point. The combined data were then curve-fit to produce the closed form equations.

"Closed form equations for vulnerability are potentially very useful. They allow the analyst to estimate quickly the vulnerability of a system to a specific threat. These calculations can be done quickly in a *back-of-the-envelope* fashion. The equations could also be incorporated into end-game programs to replace table look-up routines. However, the more likely use of the closed form equations is in the initial phases of weapons design. The equations allow the analysts to estimate quickly whether the weapon system will be capable of defeating the intended target. They can also be used to assist in warhead design through selection of optimum fragment size and speed to achieve desired kill levels."[56]

Fuel fires are always a cause for concern, A. R. Kiwan has recently (1991) completed an analysis of the initiation of fuel fires. The following has been extracted from his paper on the subject:

"ASB ... conducted a series of test firings of single fragments against simulated fuel cells of a fixed-wing aircraft. This series of tests took place in 1983 and consisted of 108 shots fired against two configurations of fuel cells for parked fixed-wing aircraft. The first configuration simulated an integral fuel cell of a parked aircraft representing a wing fuel cell. The second configuration was the same [except that a plate was added], representing the skin of the aircraft. This report analyzes the data representing fuel fire and hydraulic ram in an integral fuel cell.

"The objectives of this series of experimental field tests were to obtain fuel-fire data for this fuel system due to fragment attacks and to support the development of PK/H by a fragment on the fuel cell for such aircraft due to fire and prevent take off (PTO) of the aircraft, or prevent mission (PM). Available fuel-fire data up to the time these tests were performed were for aircraft in flight-mode configuration.

"Empirical mathematical models for the occurrence of sustained fire and for hydraulic ram were derived for the conditions studied. The mathematical equations derived for the models can be used for predicting probabilities of occurrence of these phenomena under PTO conditions for the fuel cell and test conditions studied.[57]

COMPUTER APPLICATIONS

The BRL's computer revolution of the late 1970s had a profound effect on VLD, and, conversely, VLD had a profound effect on BRL's computer revolution. In the software arena, it led to the development of an excellent suite of graphical tools that both allowed the rapid representation of complex targets and the ability to interrogate those descriptions to determine various characteristics such as vulnerability and signature. In the hardware arena, VLD took a somewhat different tack from some of the other divisions in emphasizing large networks of very powerful minicomputers and graphical workstations since the vector supercomputers were not so appropriate to vulnerability analyses as they were to the solution of problems in continuum mechanics.

The close relation between VLD and SECAD in the development of interactive and networked computing laid the foundation for BRLNET [see discussion under Computers in the BRL], and the computer-graphics developments not only benefitted VLD but also contributed to the use of computer graphics for the visualization of physical phenomena in general. "Computer graphics generated by the BRL's supercomputers has resulted in a better representation and more rapid understanding of results produced by large-scale computer codes used to assess vulnerability, ballistics, and mechanics modeling. These visualization techniques are used in many applications, but they were instrumental in solving the basic research associated with the multibounce effects in radar signatures and in the turbulent flow in a channel. Rotation of these three-dimensional images allows for minimized analysis time and for the first time an extensive understanding of these physical phenomena."[58]

Much of the computer-related efforts in VLD have been carried out by the Vulnerability Modeling Branch (VMB), which was the follow-on to VMT, and much of that accomplishment was due to a combination of the aggressive leadership of Paul Deitz, the creativity of Mike Muuss, and a skilled and dedicated team.

There are two starting points for a vulnerability analysis: the description of the target and the description of the physical processes involved in the damage mechanisms. The former is the subject of this section. In the early days of the BRL, the description of targets was often accomplished by using photographs and measuring sub-areas with a planimeter (or even cutting out pieces of a picture and weighing them) to get presented areas. Later, one meticulously took measurements from drawings and entered them into a computerized geometric model. Of course, this was all highly labor intensive. The technology of CAD and the related computer-aided manufacturing brought two powerful new capabilities—the ability to create systems interactively and rapidly on the computer, and the ability to use computer files (the modern blueprint) from the manufacturing-design process as input to the target-description process. Not only has the CAD process made the detailed description of targets much more economical, but it has reduced human error, and it has allowed highly sophisticated models for other applications (e.g., signatures).

The BRL-CAD Package. For this section, we rely heavily on an *Update* article by Bill Mermagen, Jr., and on information provided by Mike Muuss and Chuck Kennedy. "BRL-CAD is a powerful, solid-modeling system that includes a robust network-distributed image-processing capability. Over 600 copies of the software have been distributed world-wide, including 175 different businesses (23 Fortune-500 companies), 50 Government organizations representing all three services, and over 100 academic institutions.

"BRL-CAD was originally designed for interactive creation and analysis of highly detailed three-dimensional solid models in support of item-level weapons modeling. Item-level weapons modeling is a process in which a weapon system is studied, and estimates are provided on the performance of that system. Some examples of estimates are weight, size, ability to withstand enemy fire (vulnerability), mobility, detectability (across many wave-length bands), and ability to inflict damage on a particular target class (lethality). BRL-CAD is a major component of this process.

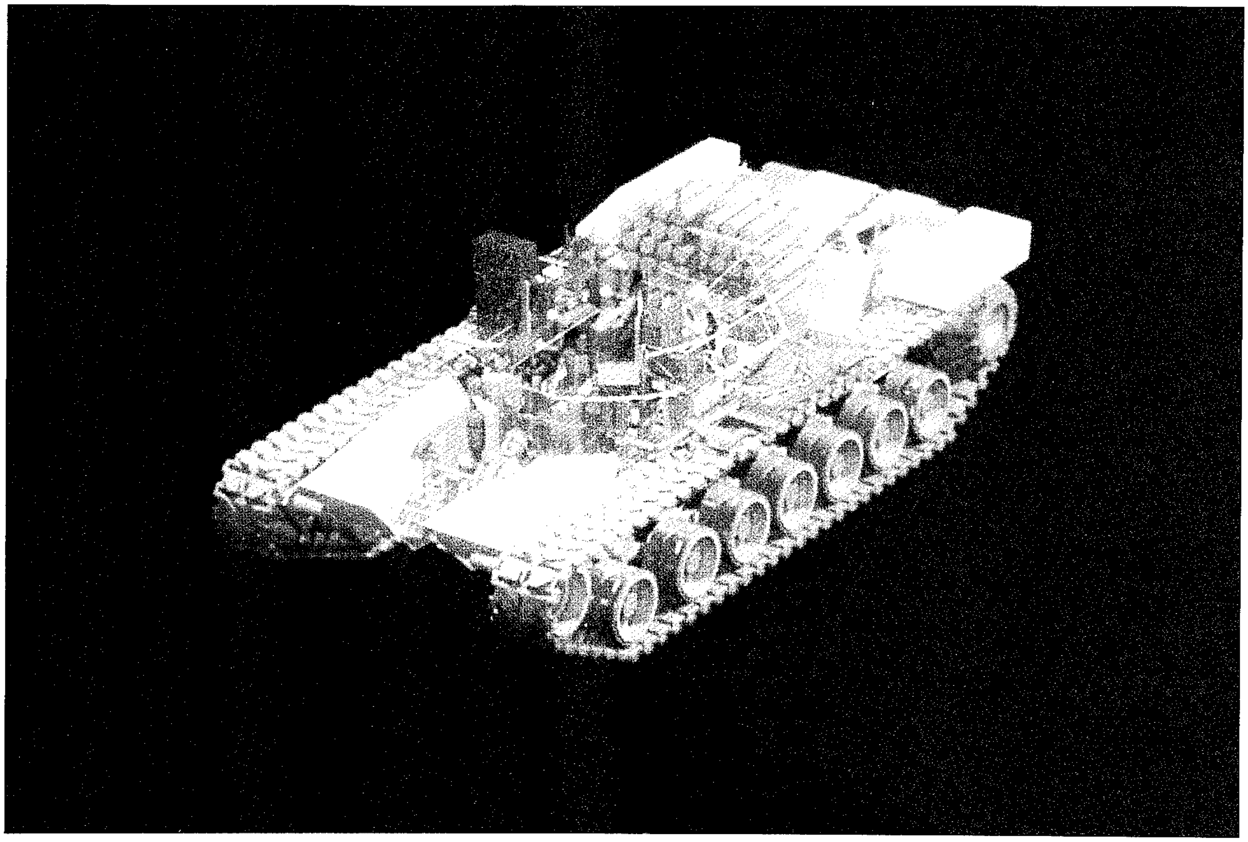
"... Item-level modeling can be divided into a two-step process. The first CAD phase describes the item including materials and shapes. Phase two involves linking the description to an application code to gain understanding of the item's nature or potential behavior.

"... Following World War II, when the discipline of vulnerability analysis first developed, analysts utilized blueprints to project shotlines through targets. These shotlines were traced manually to catalog lists of engaged components. Points of intersection, surface normals, thicknesses, and materials were also extracted by hand, making it a time-consuming process.

"The shotline interrogation process was first automated in the late 1960s. Shapes and defining materials were combined to describe the target. A computer program then projected rays (or shotlines) through the target, making it possible to compute thousands of shotlines. However, a substantial bottleneck remained during the 1970s; building, modifying, and validating target descriptions entirely by hand took too long. In fact, the initial design process of the X-M1 tank became so cumbersome that none of the automated ray-casting analysis could be invoked. It was not possible to model the competitive designs in time."[59]

"In mid-1979, Muuss improved the implementation of his terminal-independent graphics (plotting) package, bringing it to full production status. In late 1979, with the advice and encouragement of Earl Weaver, [he] began an independent, unfunded research effort to investigate the use of three-dimensional graphics display hardware to assist in the development of combinatorial-solid-geometry (COM-GEOM) descriptions of military vehicles. The early and widely noticed success of this effort prompted [him] in early 1980 to begin the development of a natural hierarchical description of the relationships between the various sub-systems of the vehicles being modeled, stored in a specially designed data base. Geometry so described could be viewed and modified using a special graphics editor (GED) designed and implemented by [him]. In the spring of 1980, Muuss and Weaver created a monochrome movie (with soundtrack) which demonstrated the capabilities of the GED software, and made a variety of presentations."[60]

"In the early 1980s, the BRL conducted a thorough requirements study and market search for necessary CAD tools to alleviate the bottleneck."[59] "... In an industry-wide search for CAD systems capable of meeting the BRL's expanding requirements, many systems were evaluated, but none met the BRL's complex needs."[60] An in-house development program was begun which has resulted in BRL-CAD."

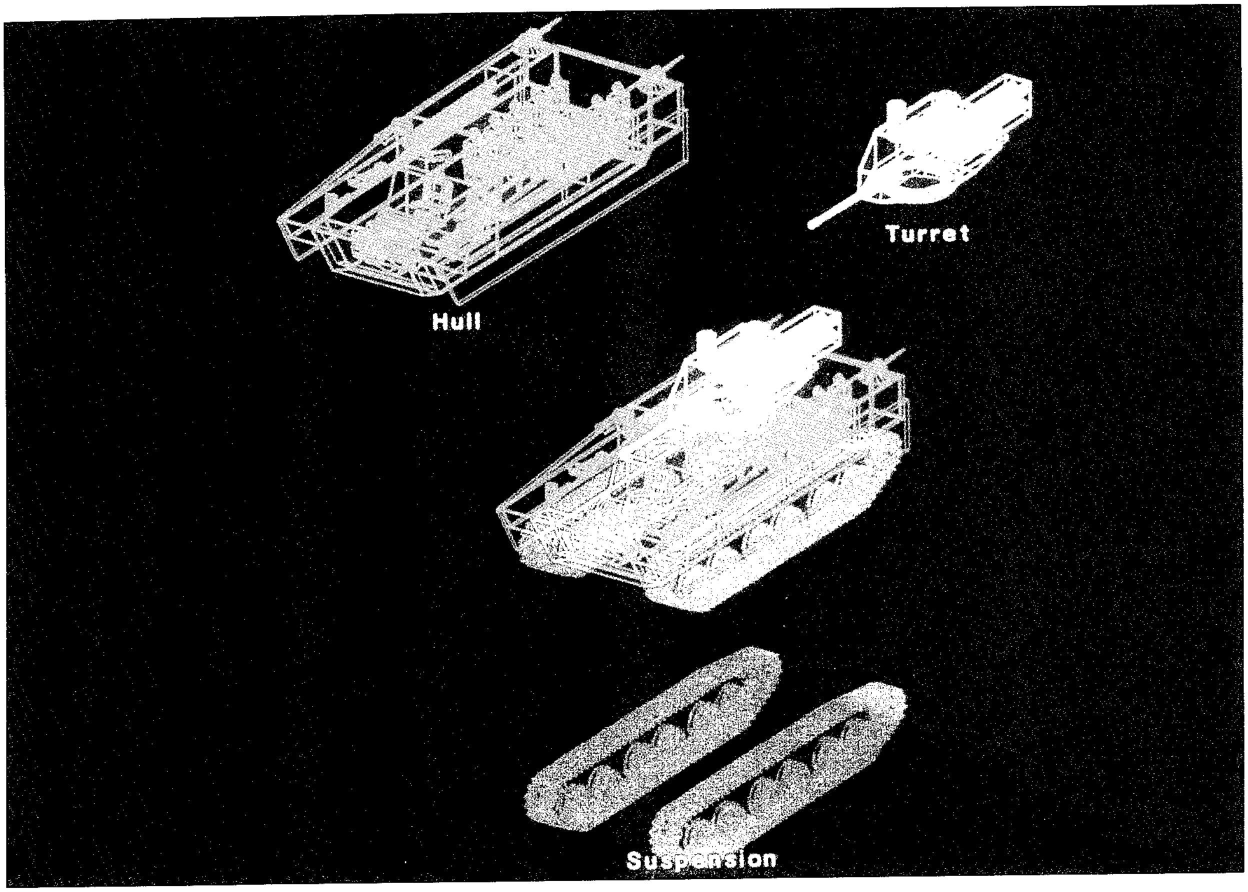


A Computer Model of an Abrams Tank With Armor and Main Gun Removed. Individual Hydraulic Lines, Wire, and Rounds Can Be Seen.

"Then, through 1981, with the assistance of Keith Applin, the power of the GED software was greatly increased, making it far easier to modify complex geometry. Necessary interface packages were created to allow GED-processed models to be converted back into GIFT-format COM-GEOM files for ray-tracing. The overall result was a state-of-the-art software package capable of meeting the BRL's CAD needs for the preparation of the geometry descriptions (models) needed for vulnerability and lethality assessment."[60]

In early 1982, VLD acquired the second BRL UNIX machine, the first being SECAD's BMD-70. This was VMB's first minicomputer. "Muuss [and Chuck Kennedy] led a team effort to install the newly acquired PDP-11/70 and associated graphics-display hardware, creating the BRL's first production CAD facility."[60,61]

With a new methodology for generating geometric descriptions, it now was appropriate to develop a ray-tracing routine that would operate directly on GED data bases and replace the GIFT shotline model. This was implemented by the VMB staff[60] and came to be known as *rt* (for ray tracer). As a representative of the computationally intensive scientific applications run at the BRL, *rt* has become an important benchmark program for evaluating computer hardware systems.

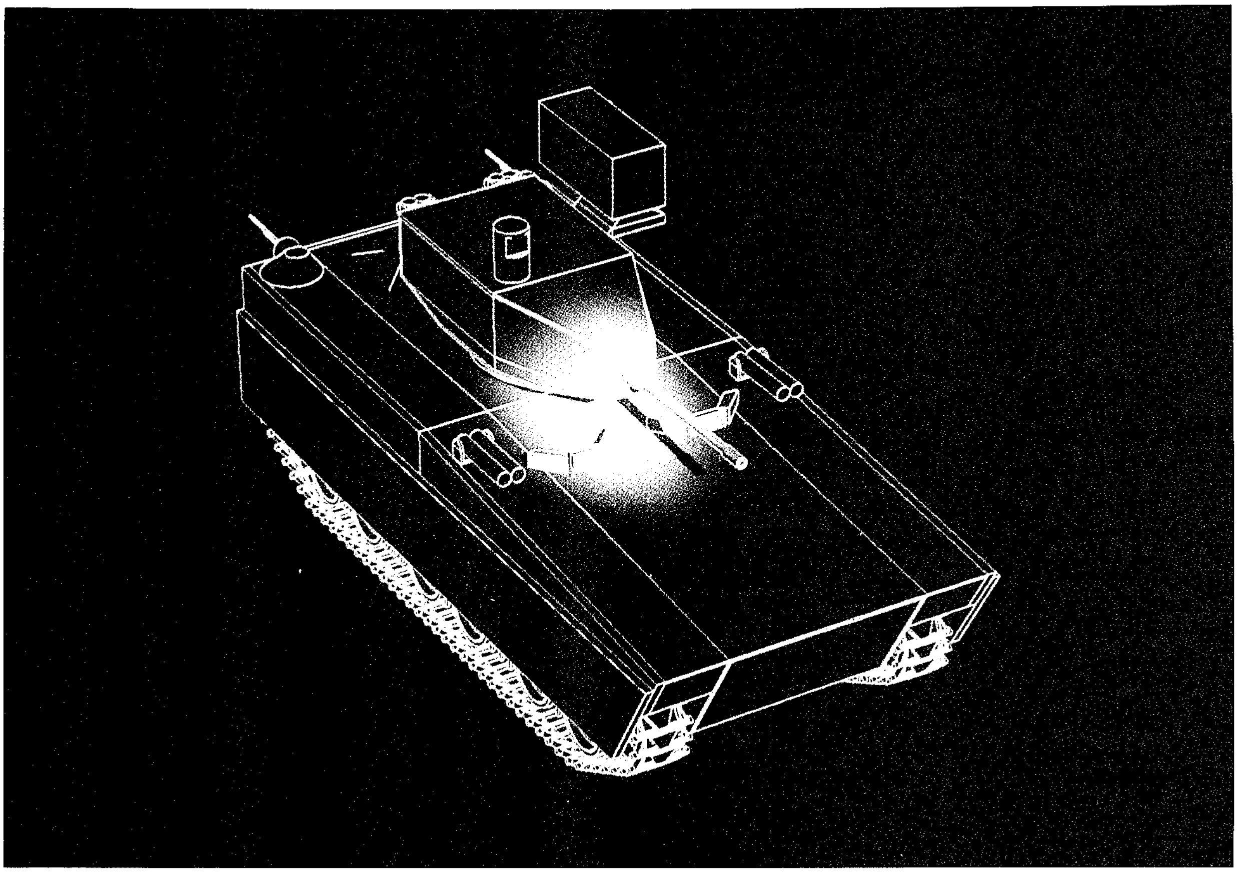


Wire-Frame View of the Future Infantry-Fighting Vehicle as Presented by the BRL-CAD Solid-Geometry Editor (MGED).[62]

In late 1983, UNIX operating-system driver routines, plus user-level library routines, were created to allow the development of a second version of GED, which produced color images on the Megatek 7250 color-display hardware.[60,61]

Always paramount was the idea that the vulnerability tools should be easily (transparently if possible) used on the totality of computers that might be used in vulnerability analyses by serious clients. "In 1984, Kennedy also developed a program written in C to convert GED data base files to a portable ASCII format for exportation of these data base files to other computer systems. The complement to this program was also written to allow the importation of ASCII format GED data bases from other computer systems."[61]

"In mid-1984," GED was generalized "to serially support multiple displays within the same program by way of an abstract *display manager* interface, resulting in the MGED program. High performance of the display manager was an important design goal. Existing graphics libraries were considered, but no well-established standard existed with the necessary three-dimensional constructs, so a lean, specially optimized MGED Display Manager interface was designed and implemented ... and additional MGED Display Managers for the Tektronix 4012/4/6 series of

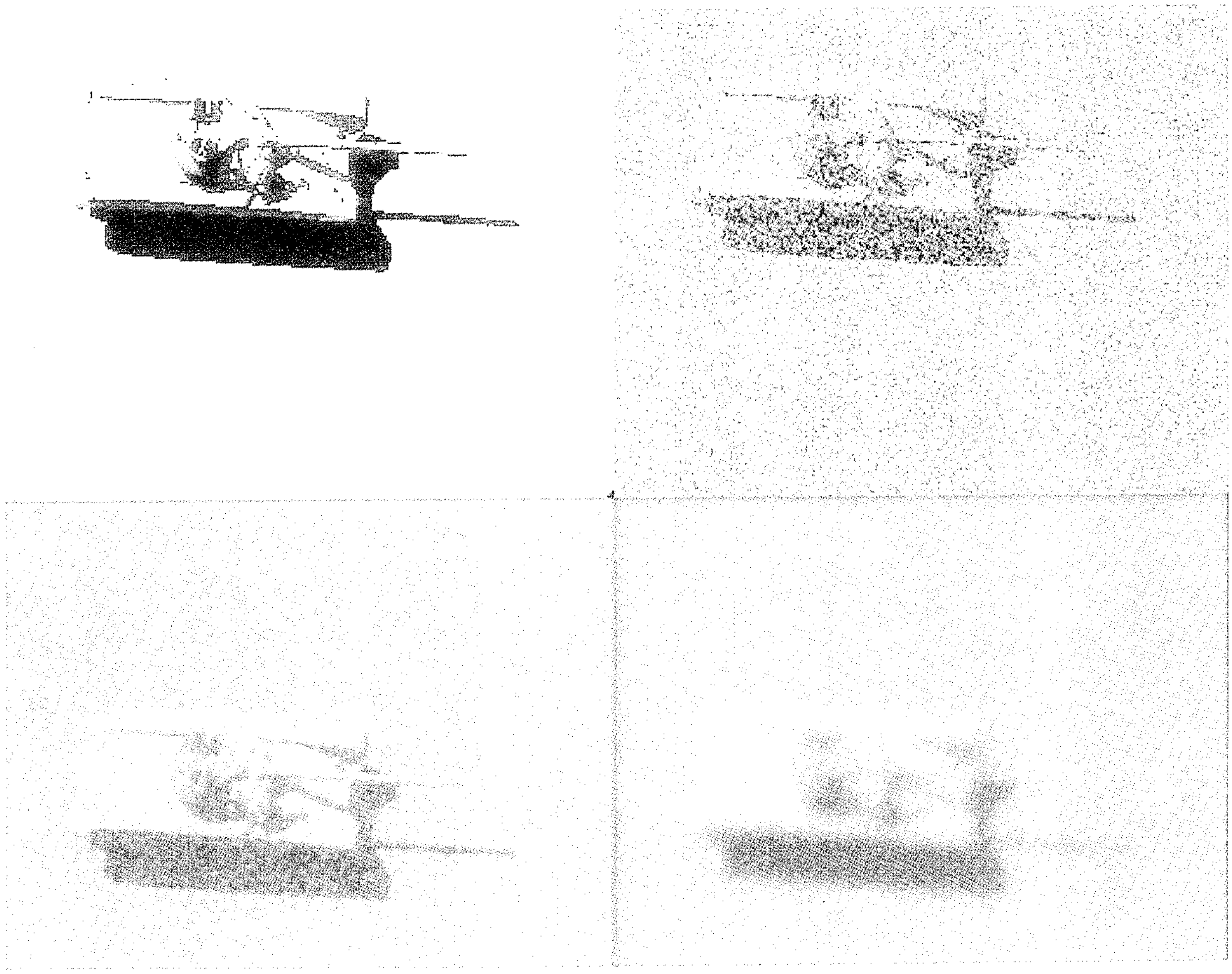


Simulation of a Laser Designator Illuminating the FIFV.[62]

displays, and the Teletype 5620 bit-mapped display" were implemented.[60,61]

"In summer 1985, the new ray-tracing package reached production status. Due to the unique power of the implementation, *rt* has permitted other Laboratory researchers to implement capabilities that were not possible using earlier software, including bi-static lighting models, and models of laser illumination. A planned major program within VLD/VMB to redesign all of the BRL's vulnerability codes around the new capabilities of *rt* was begun. Initial releases of *rt* were made to numerous other agencies, and to military research establishments of several allied governments."[60]

There was always an interest on the part of the researchers to produce time-varying representations. "Coupling the animation capability with the fully parallel version of the *rt* code developed while working with the BRL HEP supercomputer, culminated in Muuss' production of a 3-min computer-generated animation on 16mm movie film, titled: *A Quick Run Through the M-2 Bradley*.[60] This effort not only served to help sell the work, but it also was a precursor to the development of time-dependent presentation of physical



Noise Added to Simulate Image Degradation.[62]

phenomena that has shown considerable application in many areas of ballistics.

"In early 1986, Muuss separated the *rt* package into distinct portions, the *rt* program, and the *librt* ray-tracing library. This decoupling of the application programs from the details of model interrogation has become one of the key features of this software, as it allows new applications to utilize the ray-tracing capability of *librt* without any concern for the details of the ray/model intersection algorithm. As a result, new analysis applications have proliferated."[60]

One fallout of this work was the development of automatic scanning techniques for reading BAD data from witness plates. "In late 1986, Kennedy converted a driver for an Optronics film scanner which ran on a PDP-11/34 so that it would run on a VAX-11/780. This involved extensive modifications due to variations between the two computers in both the computer I/O hardware and the operating system software."[61] "In early

1987, Kennedy modified the film-scanner driver extensively to dramatically improve scanner performance, doubling the amount of scanning that had previously been possible. This was to support the scanning of film negatives of witness plates used to measure BAD and residual-penetrator effects."[61]

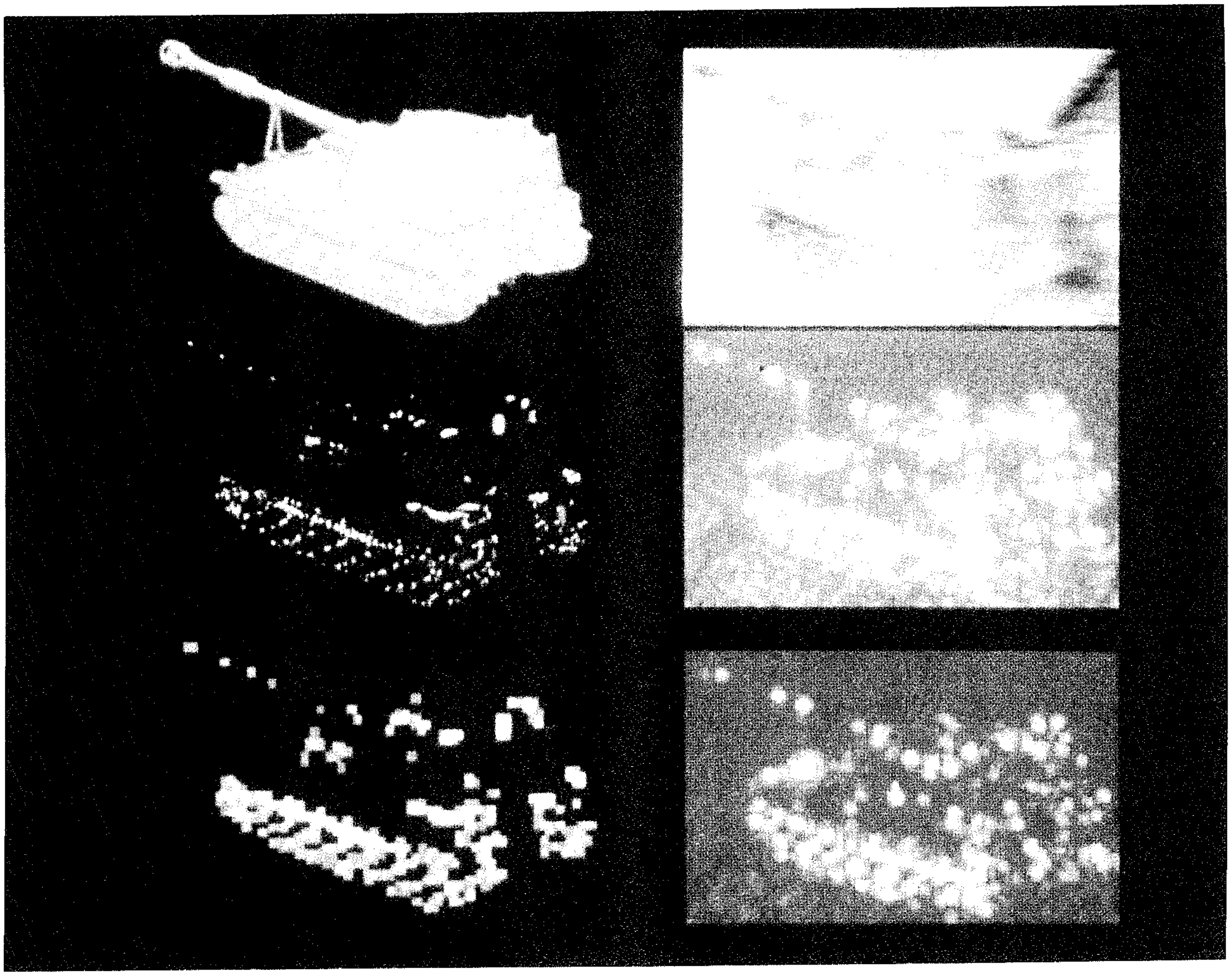
"In August 1986, in anticipation of the installation of the BRL's Cray X-MP/48, *rt* and *librt* were ported to NRL's Cray X-MP/12 running the COS operating system. This proved to be a severe test of the portability of this code, being the first non-UNIX operating system attempted, and was accomplished in 2 weeks. This was followed by various benchmark tests on the NRL Cray."[60] However, vulnerability computations are not nearly so well adapted to the vector architecture of this class of supercomputer as are the continuum-mechanics problems of ballistics. On the contrary, as noted in the next section, minicomputers and workstations have proven to be the more efficient tools for vulnerability calculations.

"In September 1986, ACST turned its attention to the expansion of existing Ikonas framebuffer support libraries into a fully general and portable interface to arbitrary full-color framebuffers. This included studying the issue of 1st-vs.-4th quadrant screen addressing, and the proper level of abstraction for the interface. A standard representation of red-green-blue (RGB) pixel images was developed for both memory and disk-file storage. The resulting library LIBFB is host independent, display-vendor independent, and network transparent, allowing an unprecedented flexibility for programmer and user alike. LIBFB and the pix-file format halves formed the basis upon which all of the BRL-CAD package image-handling and image-processing tools have been built. In October 1986, full support for parallel execution of *rt* on the Alliant FX/8 multiprocessor was added as a production feature. ACST began working on converting the existing assortment of image-handling programs into a full-fledged, powerful, compatible, and integrated set of image handling tools, as the first major step towards the production of the BRL-CAD package. Significant effort was expended by all team members to produce the BRL-CAD package, and to ensure that it was portable to all versions of UNIX in use at the BRL. In December, release 1.10 of the BRL-CAD package was distributed for BRL internal use. A great deal of time was invested in the production of reference documentation for the many tools and libraries which comprise the BRL-CAD package. The source code for the BRL-CAD package amounts to over 100,000 lines of heavily commented C source code."[60]

"In FY87, the BRL-CAD software package reached completion, and two major releases of the BRL-CAD-package software were made, as well as the associated 400-page manual. The package includes a powerful solid-modeling capability, a ray-tracing capability, and a network-distributed image-processing capability. Its portability and freedom from vendor dependence make it a most attractive CAD package. This software is now running at over 150 sites."[19]

"In November 1987, the BRL-CAD package and the BRL/VLD vulnerability analysis and signature codes were proposed as the standard modeling and analysis software platform for the entire intelligence community. As of this writing, the BRL software has been ranked as much as 5 years ahead of commercial CAD offerings, and appears to be technically the strongest system being considered."[60]

"In October 1988, release 3.0 was made available for use at over 400 sites world-wide. It is the major CAD package supporting weapons analyses (predominately vulnerability and signature calculations) used by many entities of the DOD including the Army, USAF, various intelligence agencies, and various DOD (including DARPA) contractors."[2]



Geometric-Optical Model Used to Simulate Radar Signatures and Locate Scattering Sites. Data From a Scanning Radar Are on the Right.

"The primary project for the summer and fall of 1991 was the preparation of BRL-CAD release 4.0, a significantly larger package than previous releases, and including extensive new capabilities. In total, BRL-CAD release 4.0 is comprised of over 280,000 lines of source code. If printed, this would amount to a document more than 17 in thick. Major effort was expended in *porting* this software to a variety of new hardware platforms, providing the Government with significant flexibility in the procurement of computer hardware to run this code. Benchmark testing was performed on several different configurations of over a dozen different processors. BRL-CAD release 4.0 began shipping to users on 10 October 1991."[60]

"Today this Army-developed and owned software remains unequaled in its ability to support high-resolution, item-level weapons modeling. BRL-CAD has the control necessary to build, modify, and validate highly complex models [of] tanks, aircraft, communications vans, etc. It can even support standard vulnerability modeling during the development cycle, as in the case for the ASM program. For example, BRL-CAD was used to create baseline target descriptions for the ASM program. The following descriptions were created and are currently being evaluated (concept phase): the block-3 tank (TANK), the FIFV, the combat mobility vehicle (CMV), the LOSAT, and the FAASV. Based on lessons learned in the concept phase, other configurations of these vehicles are being considered. Alternates of TANK and FIFV are being modeled, and results from these are used in trade-off analyses. BRL-CAD has also been used in component-level generation and analyses of LAV by General Motors."[59]

An important application for this technology has been signature modeling for smart munitions. "Investigations of the BRL computer lighting model have shown that it is possible to locate the positions and relative intensities of high-frequency scattering from vehicles. By assigning a mirror-reflection model to the surface of the target description and setting the lighting model for multiple-bounce interrogation, the analysts produced images of the scattering sites constructed in a plane perpendicular to line-of-sight. Comparisons of this method with [radar] data measured using a raster-scan method at 94 GHz have shown significant agreement. The method has been successfully employed in determining what scatterers to include in a vehicle mock-up. This approach has a high potential for use in smart-munition simulations."[19]

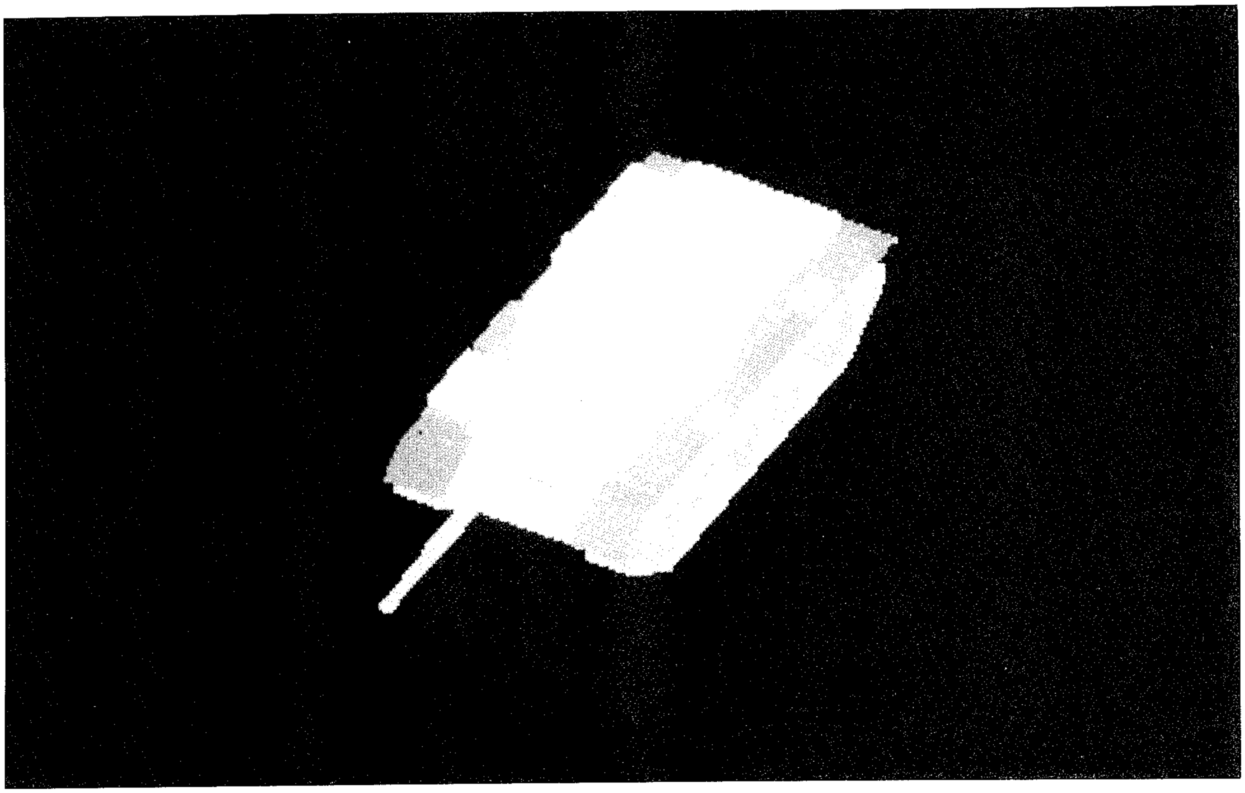
IR modeling is another application. Although there were attempts to do IR modeling in the 1970s, it was not until much later that there was enough computer power available to make it practical. "New BRL-CAD routines were developed to generate PRISM input to predict the IR signature of a T-62 tank. Surface areas, conduction path lengths, and individual target-region masses were input. Additional sub-routines to predict engine-compartment and exhaust heating as well as heat exchange in critical areas of liquid storage were developed and integrated into the TACOM PRISM code. A local expert's estimates for radiative heat exchange between hot engine components and other components were used to predict the signature of one operating state of the T-62. Computational results compared well with this prediction."[38]

"There are many possible mathematical approaches to describing three-dimensional geometry. With BRL-CAD's[63] extendible data base, the early geometric primitives (sphere, boxes, cones, and ellipsoids) for target descriptions are supported as well as the latest modeling representations such as spline, surfaces of revolution, and higher-order surfaces. The powerful, so-called *spline entity*, for example, is capable of following complex surface shapes and is a key provider of geometry for the USAF and Navy."

"There are many ramifications to the development and exploitation of this technology:

"Application Code: There is a large body of application codes which are linked to the BRL-CAD environment including the following:

1. Weights and moments-of-inertia.
2. Optical image generation (including specular/diffuse reflection, refraction, and multiple-light sources, animation, interference).
3. Bi-static laser analysis.
4. Synthetic aperture radar codes.
5. Acoustic model predictions.
6. High-energy laser damage.
7. High-power microwave damage.
8. Vulnerability/lethality codes.
9. Neutron transport code.



A MGED Description of a T-62 Tank Is Converted by the BRL IRPREP Program for the PRISM Model. Predictions for Solar Loading Are Shown.

10. Link PATRAN [TM] and hence to ADINA, EPIC-2, NASTRAN, etc., for structural/stress analysis.

11. X-ray calculation.

"Extensibility: Since the software is [the] property of the Government, the source code is available to all users. Required extensions and modifications can be made by users of the code.

"Networking: The CAD package uses the networking protocol compatible with the DARPA MILNET/ARPANET standards. Multiple machines (either local or across the country) can exchange files, share data bases, and aggregate computing power for high-demand tasks making them transparent to the user."[59]

Hardware. As mentioned above, VLD's first production CAD facility was the PDP-11/70 acquired in 1982. That computer was soon augmented by a succession of state-of-the-art minicomputers and workstations. From 1982 to 1992, VLD has continually monitored the computer market, identified the promising trends, and acquired a succession of state-of-the-art machines.

The first step up was from 16-bit to 32-bit architecture. "In 1983, Kennedy ordered the first VAX-11/780 computer system in the BRL [and] ordered additional spare parts in order to add an additional processor to double the speed of the computer system. Although the manufacturer offered a version of the VAX-11/780 with dual processors, it was substantially more costly."[61]

It was not long before that machine was upgraded. "In 1984, Mr. Kennedy constructed a dual-CPU VAX-11/780 system, as designed and prototyped by George Goble of Purdue University. The machine ... is believed to be the first constructed outside Purdue University and the first in the Government. At the time, it provided the fastest minicomputer computational capability in the BRL."[61]

Not only were the number and the individual power of the computers increasing, but it was also important to make all that power easily available to all the users. "In 1986, Kennedy installed and configured an Ethernet LAN to support the VLD in Building 328. This network allowed the connection of newly acquired graphics workstations with the BRLNET and access to other minicomputer, superminicomputer, and supercomputer resources on the BRLNET."[61]

"In 1986, ... more than $1,200,000 was obligated to acquire multiple Silicon Graphics IRIS display systems. A total of 15 display systems were acquired and installed throughout VLD. These systems support a diversity of programs including work on the M1 Abrams main-battle tank and M2/M3 Bradley infantry fighting vehicle."[61]

In 1987, development of a network driver for an 80-Mb token-passing ring network began. "This driver will allow the connection of an Alliant FX/8 superminicomputer to this high-speed network. One benefit will be faster transfers of data, especially improving the speed with which graphics output calculated on the Alliant is transmitted to the screen of the user."[61]

Over the 1980s and the early 1990s, VLD embarked on an aggressive program of acquisition of computer hardware. This involved a number of steps that kept pace with emerging computer systems and resulted in the acquisition of VAX computers, Gould Power Nodes, Alliant minicomputers, Sun workstations, and Silicon Graphics workstations. As previously mentioned, the program *rt* has become a major benchmark for rating computational power by VLD. If we take the performance of the single VAX-11/780 in running the *rt* program as the basic unit, we find that the computational power in VLD went from **1** in 1983 to over **3,000** in 1989, in which year VLD made a major jump in computer acquisitions. The capability has continued to increase through 1992, but not so dramatically.

NOTES

1. This name was given to the Vulnerability Laboratory of the BRL when ARRADCOM was formed.

2. Major Technical Accomplishment by Thrust, FY88, Laboratory of the Year Submission.

3. "Vulnerability Analysis Methodology Program (VAMP), A Combined Compartment-Kill Vulnerability Model," CSC TR-79-5585.

4. Much of this section is based on a discussion with Robert Kirby on 5 June 1992.

5. L. W. Bain, and M. J. Reisinger, "The GIFT Code User Manual; Volume I," BRL Report 1802, July 1975.

6. E-mail message from James Rapp, 2 June 1992.

7. D. F. Haskell, "Lethality of a Spectrum of Shaped Charge Projectile Anti-Tank Firepower-Kill Effects Evaluated by the AVVAM-1 Computer Model," June 1976.

8. Menne, et al., "Vulnerability/Lethality Methodology and Data Base Update for Armored Vehicles," Working Papers for the BRL Director, August 1977.

9. Discussion with Gil Bowers on 28 May 1992.

10. E-mail from John H. Suckling to Harry Reed, "Your Draft," 28 August 1992.

11. J. R. Rapp, "An Investigation of Alternative Methods for Estimating Armored Vehicle Vulnerability," BRL-MR-03290 (AD B076394LO), July 1983.

12. Discussion with Dan Kirk and Larry Losie on 1 June 1992.

13. C. L. Nail, "Vulnerability Analysis for Surface Targets (VAST), An Internal Point-Burst Vulnerability Assessment Model," CSC TR-82-5740, August 1982.

14. R. Shnidman, "Direct Fragment Lethality Interface From Witness Plate Array Data," 1988 ADPA Presentation.

15. D. Bely, "Video Scanner System Improves Vulnerability Test Data," *BRL Update*, vol. 1, no. 2, March 1989.

16. BRL Program Report - Annual FY91.

17. Technical Accomplishments, FY86, Laboratory of the Year Submission.

18. P. H. Deitz and A. Ozolins, "Computer Simulations of the Abrams Live-Fire Field Testing," BRL-MR-3876, May 1989.

19. Principal Technical Accomplishments for FY87, Laboratory of the Year Submission.

20. *SQuASH* Development Production, Viewgraphs from Jill Smith.

21. Technical Accomplishments, FY89, Laboratory of the Year Submission.

22. From a passing conversation with Jill Smith in June 1992.

23. For example, see Rapp's report from note 11.

24. Discussion with Mike Starks on 12 June 1992.

25. L. K. Roach, "BRL Implements Methodology Breakthrough," *BRL Update*, vol. 2, no. 5, September 1990.

26. Discussion with Terry Klopcic on 16 June 1992.

27. J. T. Klopcic, "Nuclear and Chemical Modeling in the Army Unit Resiliency Analysis (AURA)."

28. J. T. Klopcic, "The Army Unit Resiliency Analysis (AURA) Methodology."

29. J. H. Smith, W. A. Winner, and P. J. Hanes, "An Overview of the Modular UNIX-Based Vulnerability Suite."

30. See also J. N. Walbert and S. F. Polyak, "BRL Plays Key Position on Live-Fire Testing Team," *BRL Update*, vol. 1, no. 6, November 1989.

31. Discussion with John Jacobson, 4 June 1992.

32. BRL Program Accomplishment, FY82, Laboratory of the Year Submission.

33. Discussion with Jim Walbert on 14 September 1992.

34. Discussion with Rick Saucier on 12 June 1992.

35. Task Force Report on the Advanced Survivability Test Bed Program, ASTB-87-1.

36. E-mail from Gilbert Bowers to Harry Reed," V/L Writeup," 8 September 1992.

37. See the discussion under Armor in the section on Terminal Ballistics.

38. BRL Program Report - Annual FY90.

39. Much of this section is based on a discussion with Don Haskell on 16 June 1992.

40. See Volume II, *Ballisticians in War and Peace*.

41. E-mail message from Louise Leonard to Gil Bowers, "ADOTL ATB Tech. Transfers," 27 September 1983.

42. Comments by Walter Thompson on a draft version.

43. "FY81, What Has Been Done on Helicopters During the Past Four Years," from Don Haskell.

44. "Most Significant ATB FY80 Accomplishment," 11 August 1980, from Don Haskell.

45. "ATB FY81 Accomplishments," from Don Haskell.

46. E-mail messages from Don Haskell to Gil Bowers, "Success/failure" and "Success/no failure," 24 April 1984.

47. 1985 Program Summaries, from Don Haskell.

48. "January 1986 - Significant Accomplishments," from Don Haskell.

49. "March 1987 - Highlights of Mission Programs," from Don Haskell.

50. House of Representatives, Military Construction Authorization Act, 1986, Report 99-128.

51. E. M. Vogel, and J. A. Gatto, "State-of-the-Art Aircraft Vulnerability Test Facility Opens," *BRL Update*, vol. 2, no. 4, September 1990.

52. They were forced into a point-burst methodology from the beginning.

53. "FY84," from Don Haskell.

54. These were the B57 tests used to validate the maneuver model.

55. J. Fries, "Helicopter Engine Power Loss, Descent Analysis, and Computer Code Developed," *BRL Update*, vol. 3, no. 4, August 1991.

56. R. Bowers, "New Methodology Enables Quick Vulnerability/Lethality Estimates," *BRL Update*, vol. 3, no. 4, August 1991.

57. A. R. Kiwan, "Single Fragment Induced Fuel Fires and Hydraulic Ram in an Aircraft Integral Fuel Cell," a manuscript.

58. BRL Program Report - Annual FY89.

59. W. Mermagen, Jr., "BRL-CAD Helps Create Improved, Safer Weapon Systems," *BRL Update*, vol. 2, no. 3, July 1990.

60. "Experimental Development and Research: Factor IV," submission for Michael John Muuss, 16 October 1991.

61. Charles Kennedy, Factor IV submission.

62. Deitz, Paul H., Theodore M. Muehl, Scott L. Henry, Gary S. Moss, Edwin O. Davisson, and Susan A. Coates, "Synthesized CAD Methods for Combat Vehicle Survivability Analysis," BRL-MR-3883, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, December 1990.

63. Deitz, Paul H, "High-Resolution, Item-Level Weapons Modeling," BRL-MR-3815, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, March 1990.

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acronyms

AAH	Army Attack Helicopter
AAWS-M	Antiarmor Weapon System - Medium
ABDR	Aircraft Battle-Damage Repair
ACE	Artillery Control Environment
ACST	Advanced Computational Systems Team
ADATS	Air-Defense Antitank System
ADDCOMPE	Army/DARPA Distributed Communications and Processing Experiment
ADF	Allocation and Distribution of Fire
ADNBF	Amino-Dinitro-Benzo-Furoxan
ADS	Advanced Decision Systems
AEDC	Arnold Engineering and Development Center
AEI	Armament Enhancement Initiative
AF	Adjust Fire
AFACE	Austere Field Artillery Concepts Effectiveness
AFAS	Advanced Field Artillery System
AFATDS	Advanced Field Artillery Tactical Data System
AFSM	Artillery Fire-Support Model
AGS	Armored Gun System
AHA	Ammunition Holding Area
AHCS	Advanced Hybrid Computer System
AHPCRC	Army High-Performance Computational Research Center
AI	Artificial Intelligence
AIS	Abbreviated Injury Score
ALBM	Air-Land Battle Management
ALE	Arbitrary Lagrangian/Eulerian
AMC	Army Materiel Command
AMCCOM	Armament, Munition, and Chemical Command
AMMRC	Army Material and Mechanics Research Center
AMSAA	Army Materiel Systems Analysis Activity
ANTS	ARPANET Terminal Server
AP	Armor Piercing
APC	Armored Personnel Carrier
APFSDS	Armor-Piercing Fin-Stabilized Discarding Sabot
APG	Aberdeen Proving Ground
API	Armor-Piercing Incendiary
APS	Active Protection System
ARA	Applied Research Associates
ARDEC	Armament Research, Development, and Engineering Center
ARL	Army Research Laboratory

acronyms

ARO	Army Research Office
ARPANET	Advanced Research Projects Agency Computer Network
ARRADCOM	Armament Research and Development Command
ASARDA	Assistant Secretary of the Army for Research, Development, and Acquisition
ASARDA/IMP	Army Secure Automated Research, Development, and Acquisition/Information Management Plan
ASB	Air Systems Branch
ASCII	American Standard for Code Information Interchange
ASL	Atmospheric Sciences Laboratory
ASM	Armored Systems Modernization
ASNET	Army Supercomputer Network
ASTB	Advanced Survivability Test Bed
ATAC	Advanced Tank Cannon
ATGM	Antitank Guided Missile
ATLAST	Abrams Tank Live-Fire Automated Scoring Tool
ATTD	Advanced Technology Transition Demonstrator
AURA	Army Unit Resiliency Analysis
AVSCOM	Aviation Systems Command
AVVAM	Armored Vehicle Vulnerability Analysis Model
BAD	Behind-Armor Debris
BCE	Bradley Crew Evaluators
BCH	Bose-Chaudhuri-Hocquenghem
BCS	Battery Computer System
BDAR	Battle Damage Assessment and Repair
BFV	Bradley Fighting Vehicle
BFVS	Bradley Fighting Vehicle System
BIGGRS	Bradley Improved Gun-Gas Reduction System
BLAST	Bradley Live-Fire Automated Scoring Tool; Battery-Level Automated-System Technology
BMD	Ballistic Modeling Division
BRDEC	Belvoir Research, Development, and Engineering Center
BRL	Ballistic Research Laboratory [now Army Research Laboratory]
BRLMPM	Ballistic Research Laboratory Message Processing Model
BRLNET	Ballistic Research Laboratory Computer Network
BUCS	Backup Computer System
C2	Command and Control
C4I	Command, Control, Communications, Computers, and Intelligence
CAD	Computer-Aided Design
CADAM	Cannon-Artillery-Delivery-Accuracy Model

CAM	Computer-Aided Manufacture
CAN	Campus-Area Computer Network
CAPS	Capability Profiles
CARDE	Canadian Army Research and Development Establishment
CAS	Complete Active Space
CASTFOREM	Combined-Arms and Support-Task-Force Evaluation Model
CAT	Computer-Aided Trajectory; Computerized Axial Tomography
CCF	Computer Correction Factor
CECOM	Communications-Electronics Command
CFD	Computational Fluid Dynamics
CG	Commanding General
CID	Commander's Intelligent Display
CIFV	Composite Infantry Fighting Vehicle
CMV	Combat Mobility Vehicle
CNC	Computer Numerical Control
CNR	Combat Net Radios
COE	Corps of Engineers
COEA	Cost/Operational Effectiveness Analysis
COM-GEOM	Combinatorial-Solid Geometry
COS	Cray Operating System
COVART	Computerized Vulnerability-Area and Repair-Time (Computer Code)
CPB	Charged Particle Beam
CPU	Central Processing Unit
CRDEC	Chemical Research, Development, and Engineering Center
CRREL	Cold Regions Research and Engineering Center
CSD	Computer Support Division
CSTA	Combat Systems Test Activity
DA	Department of the Army
DAL	Damage Assessment List
DARPA	Defense Advanced Research Projects Agency
DC	Dynamic Compaction
DCA	Defense Communications Agency
DCSLOG	Deputy Chief of Staff for Logistics
DCU	Degradation of Combat Utility
DDESB	Department of Defense Explosive Safety Board
DDN	Defense Data Network
DFB	Distributed Fact Base
DIC	Diploma of the Imperial College
DIVAD	Division Air Defense

DMD	Digital-Message Device
DNA	Defense Nuclear Agency
DOD	Department of Defense
DOE	Department of Energy
DPICM	Dual-Purpose Improved Conventional Munition
DRI	Denver Research Institute
DS	Degraded States
DSWARS	Tank Combat Model Using Degraded States
DT	Development Test
DU	Depleted Uranium
DUSA	Deputy Under Secretary of the Army
EFP	Explosively Formed Penetrator
EM	Electromagnetic
EM-A	Electromagnetic-Armor
EMD	Engineering and Manufacturing Development
EMP	Electromagnetic Pulse
ENIAC	Electronic Numerical Integrator and Calculator
ERAM	Extended-Range Antiarmor Munition
ES	Expert Systems
ESPAWS	Enhanced Self-Propelled Artillery Weapon System
ET	Electrothermal
ETC	Electrothermal-Chemical
ETDL	Electronic Technology and Devices Laboratory
EW	Electronic Warfare
F	Firepower Kill
FA	Fire Advisor
FAADS	Forward Area Air Defense System
FAASV	Field Artillery Ammunition Supply Vehicle
FAE	Fuel-Air Explosives
FASCAM	Family of Scatterable Mines
FAST	Field Assistance in Science and Technology
FATDS	Field Artillery Tactical Data System
FBI	Federal Bureau of Investigation
FCI	Fire-Control Input
FCS	Fire-Control Simulation
FCT	Fire-Control Trajectory
FDC	Fire-Direction Center
FDO	Fire-Direction Officer
FFAB	Free-Flight Aerodynamics Branch

FFE	Fire For Effect
FIFV	Future Infantry Fighting Vehicle
FIR	Finite Impulse Response
FIST	Fire-Support Team
FORTRAN	Formula Translation Code
FSC	Fire-Support Control
FSD	Full-Scale Development
FSED	Full-Scale Engineering Development
FSTC	Foreign Science and Technology Center
FTB	Firing Tables Branch
FY	Fiscal Year
GACS	Gun Alignment and Control System
GDLS	General Dynamics Land Systems
GE	General Electric
GED	Graphics Editor
GFT	Graphical Firing Tables
GKS	Graphics-Kernel System
GPS	Gunner's Primary Sight
GROUNDWARS	Army Materiel Systems Analysis Activity Spin-off of TANKWARS Model
HAN	Hydroxyl-Ammonium Nitrate
HARP	High-Altitude Research Project
HDL	Harry Diamond Laboratories
HE	High Explosive
HEAT	High-Explosive Antitank
HEI	High-Explosive Incendiary
HEL	Human Engineering Laboratory
HELBAT	Human Engineering Laboratory Battery Artillery Tests
HELCAP	Human Engineering Laboratory Counter Air Program
HELOVA	High-Energy Low-Vulnerability Ammunition
HELP	Howitzer Extended Life Program
HELP-1	High-Energy Low-Vulnerability Ammunition Propellant-1
HEP	Heterogeneous Element Processor (Computer)
HEVART	High-Explosive Vulnerability Area and Repair Time (Computer Code)
HFHTB	Human-Factors Howitzer Test Bed
HICAP	High-Capacity Artillery Projectile
HIMAG	High Mobility and Agility
HIP	Howitzer Improvement Program
HIRAM	Hybrid In-bore RAMjet Accelerator
HISVART	Hypervelocity Impact Vulnerability Area and Repair Time (Computer Code)

acronyms

HMMWV	High-Mobility Multipurpose Wheeled Vehicle
HQDA	Department of the Army Headquarters
HSTVL	High-Survivability Test Vehicle - Light
HTB	Howitzer Test Bed
IB	Interior Ballistics
IBD	Interior Ballistics Division
IBM	International Business Machines
ICM	Improved Conventional Munition
IDS	Information Distribution System
IDT	Information Distribution Technology
IGES	Initial Graphics Exchange Specification
IHE	Insensitive High Explosive
IHEP	Insensitive High Explosives and Propellants
ILIR	In-House Laboratory Independent Research
InterNet	World-Wide Computer Network
I/O	Input/Output
IP	Information Processor
IPE	Individual Protective Equipment
IPM1	Improved M1 Tank
IR	Infrared
ISAR	Inverse Synthetic Aperture Radar
ISL	Institute at Saint Louis
IVA	Intermediate Viscosity Agent
JHU	Johns Hopkins University
JLF	Joint Live Fire
JTCG/AS	Joint Technical Coordinating Group/Aircraft Systems
JTCG/ME	Joint Technical Coordinating Group/Munitions Effectiveness
K	Catastrophic Kill
KE	Kinetic Energy
KTO	Kuwait Theater of Operations
L/D	Length-to-Diameter
LABCOM	Laboratory Command
LABNET	Laboratory Command Computer Network
LAFV	Lightly Armored Fighting Vehicles
LAN	Local-Area Network
LAT	Lot Acceptance Testing
LAV	Light Assault Vehicle
LAW	Light Antitank Weapon
LB/TS	Large-Blast/Thermal Simulator

LBS	Large-Blast Simulator
LCAC	Landing-Craft Air Cushion
LCWSL	Large-Caliber Weapons Systems Laboratory
LFD	Launch and Flight Division
LFT	Live-Fire Test/Testing
LFT&E	Live-Fire Test and Evaluation
LH-X	Light Helicopter-Experimental
LIF	Laser-Induced Fluorescence
LIGHT	Laser Ignition in Guns, Howitzers, and Tanks
LOSAT	Line-of-Sight Antitank
LOTA	Low-Observable Technology and Applications (formerly Activity)
LOVA	Low-Vulnerability Ammunition
LP	Liquid Propellant; Liquid Propulsion
LPG	Liquid-Propellant Gun
M	M-Kill
M1	Abrams Tank With 105mm Gun
M109	155mm Self-Propelled Howitzer
M198	155mm Towed Howitzer
M1A1	Abrams Tank With 120mm Gun
M1A2	The Block II M1 Tank
M2/M3	Bradley Infantry/Scout Vehicles
MABS	Military Applications of Blast Simulation
MBC	Mortar Ballistic Computer
MBT	Main Battle Tank
MC-AAAC	Medium-Caliber Antiarmor Automatic Cannon
MENS	Mission Element Needs Statement
MERADCOM	Mobility Equipment Research and Development Center
MGED	Multidevice Graphics Editor
MICOM	Missile Command
MILNET	Military Computer Network
MIMD	Multiple Instruction/Multiple Data Stream
MIRDEC	Missile Research, Development, and Engineering Center
MIT	Massachusetts Institute of Technology
MLRS	Multiple Launch Rocket System
MMW	Millimeter Wave
MOA	Memorandum of Agreement
MOPP	Mission-Oriented Protective Posture
MOU	Memorandum of Understanding
MPAT	Multipurpose Antitank

acronyms

MPM	Modified Point Mass
MPP	Massively Parallel Processor
MTDE	Modern Technology Demonstrator Engine
MTI	Moving Target Indicator
MTL	Materials Technology Laboratory [formerly Army Material and Mechanics Research Center]
MUVES	Modular UNIX-based Estimation Suite
MVV	Muzzle-Velocity Variation
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NAVAIR	Naval Air Command
NAVSEA	Naval Sea Command
NBC	Nuclear, Biological, Chemical
NED	Nuclear Effects Directorate
NMERI	New Mexico Engineering Research Institute
NMR	Nuclear Magnetic Resonance
NONPARE	Non-Parametric Data Analysis (Expert) Consultation System
NOS	Naval Ordnance Station
NRL	Naval Research Laboratory
NSI	NASA Science INTERNET
NSOM	Nested System of Battlefield Simulation Models
NSWC	Naval Surface Weapons [now Warfare] Center
NSWC-WOL	Naval Surface Weapons [now Warfare] Center-White Oak Laboratory
NTC	National Training Center
NWS	Naval Weapons Station
OPM	Office of the Project Manager
OSD	Office of the Secretary of Defense
OT	Operational Test
PAC-2	Patriot Advanced Combat-2
PAT	Precision Aim Technique
PBT	Particle-Beam Technology
PC	Personal Computer
PCIP	Productivity Capital-Investment Program
PEG	Polyethylene Glycol
PEO	Program Evaluation Office
PFN	Pulse Forming Network
PGA	Paul Gough Associates
PIMS	Precision Imaging System
PIP	Product Improvement Program

PK	Probability of Kill
PK/H	Probability of Kill Given a Hit
PM-AMMOLOG	Project Manager - Ammunition Logistics
PM-CAWS	Program Manager - Cannon Artillery Weapon Systems
PM-MEP	Project Manager - Mobile Electric Power
PM-TMAS	Project Manager - Tank Main Armament System
PM	Project Manager; Program Manager; Prevent Mission
PMO	Project Manager's Office
PNS	Parabolized Navier-Stokes
POMCUS	Prepositioned Overseas Materiel Configured to Unit Sets
PRISM	Physically Reasonable Infrared Signature Model
PTO	Prevent Take Off
PVI	Precision Vision Incorporated
R&D	Research and Development
RA	Reactive Armor
RCC	Residual Combat Capability
RCS	Radar Cross Section
RDEC	Research, Development, and Engineering Center
RFP	Request for Proposal
RGB	Red-Green-Blue
RHA	Rolled Homogeneous Armor
RLPG	Regenerative Liquid-Propellant Gun
ROC	Required Operational Capability
RST	Remote Sensing Team
RWE	Refraction-Wave Eliminator
SADARM	Sense and Destroy Armor
SAIC	Science Applications International Corporation
SAP	Special-Access Program
SAW	Squad Automatic Weapon
SBIR	Small Business Innovative Research
SC	Shaped Charge
SCJ	Shaped Charge Jet
SDAL	Standard Damage Assessment List
SECAD	System Engineering and Concepts Analysis Division
SFRJ	Solid-Fuel RAMjet
SHAFTS	Shift Hand-Activated Fuel Transmission System
SHAMS	Smart-Howitzer Management System
SHS	Self-Propagating High-Temperature Synthesis
SHUTE	Spall-Handling Universal Threat Evaluator

acronyms

SIMD	Single Instruction/Multiple Data Stream
SNR	Senior National Representatives
SPARC	Spare Components Required for Combat
SPETC	Solid-Propulsion Electrothermal Chemical
SPRAE	Stochastic Processor for Artillery Effectiveness
SQuASH	Stochastic Quantitative Analysis of System Hierarchies
SSEB	Source Selection Evaluation Board
STAFF	Smart Target Activated Fire and Forget
STANAG	Standardization Agreement
STILAS	Scientific and Technical Information Library Automation System
STROM	Safe Transport of Munitions
SUNY	State University of New York at Buffalo
SWS	Smart Weapon Systems
TAACOM	Theater Army Area Command
TACFIRE	Tactical Fire
TACOM	Tank-Automotive Command
TBD	Terminal Ballistics Division
TC	Traveling Charge
TCP/IP	Transmission Control Protocol and Internetwork Protocol
TDNOVA	A Two-Dimensional Axisymmetric Interior Ballistics Code
TDP	Technical Data Package
TECOM	Test and Evaluation Command
TFT	Tabular Firing Table
TGSM	Terminally Guided Sub-Munition
TGW	Terminally Guided Weapon
TI	Texas Instruments
TOC	Tactical Operations Center
TOW	Tube-Launched, Optically Tracked, Wire-Guided
TP	Target Practice
TRAAV	Test Range for Advanced Aerospace Vulnerability
TRADOC	Training and Doctrine Command
TRS	Thermal Radiation Source
TTCP	The Technical Cooperation Program
TWT	Traveling-Wave Tube
UAV	Unmanned Aerial Vehicles
UCSD	University of California - San Diego
UGV	Unmanned Ground Vehicle
UK	United Kingdom
UMBC	University of Maryland - Baltimore County

UNICHARGE	An artillery propulsion system that uses a single increment
UNIX	Trademark for a computer operating system developed by AT&T
UNICOS	UNIX Cray Operating System
USAF	U.S. Air Force
USAFAS	U.S. Army Field Artillery School
USAOC&S	U.S. Army Ordnance Center and School
USAREUR	U.S. Army Europe
USMC	U.S. Marine Corps
UW	University of Washington
VAMP	Vulnerability Analysis Methodology Program
VAST	Vulnerability Analysis for Surface Targets
VCSA	Vice Chief of Staff of the Army
VEMASID	Vehicle Magnetic Signature Duplicator
VHBR	Very High Burning Rate
VLD	Vulnerability/Lethality Division
VMB	Vulnerability Modeling Branch
VMT	Vulnerability Methodology Team
VR	Vulnerability Reduction
WAM	Wide-Area Mine
WASPM	Wide-Area, Side-Penetrating Mine
WES	Waterways Experiment Station
WIPS	Wide Internal Pulse Spacing
WP	White Phosphorous
WSTB	Weapon Systems Technology Branch