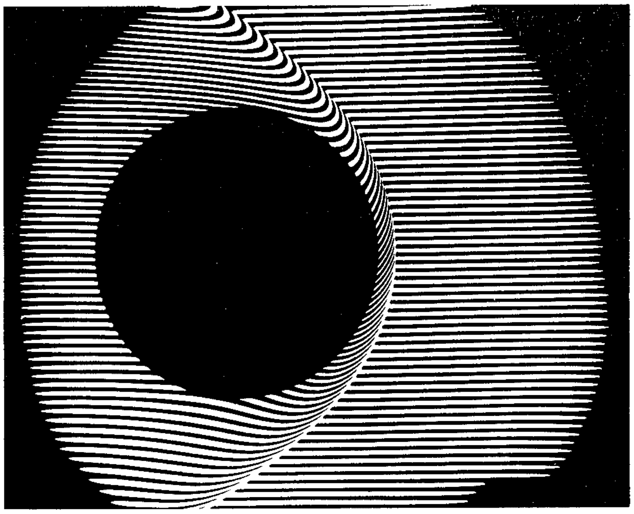
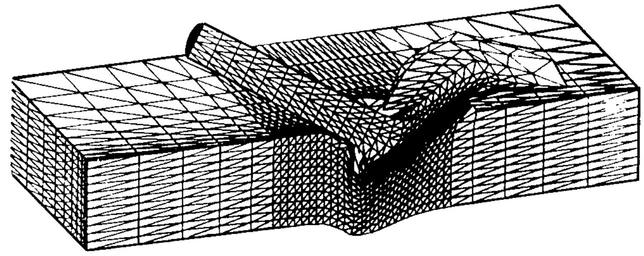
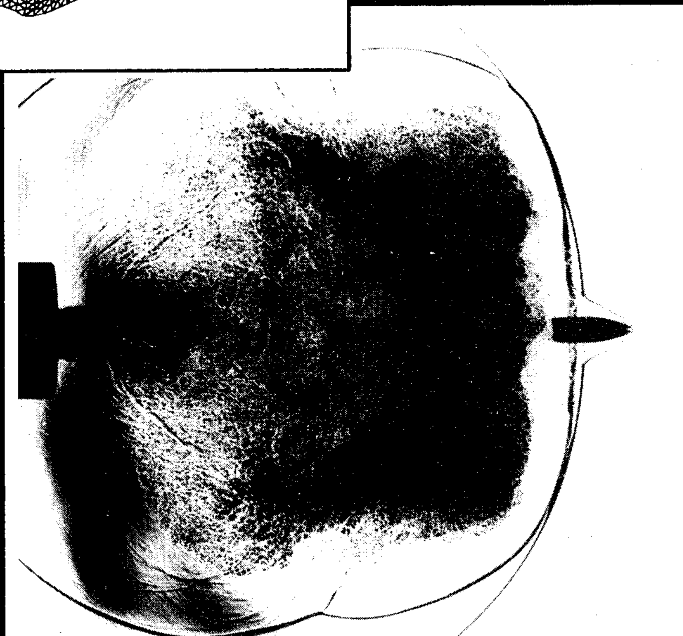
Ballisticians in War and Peace



A History of The United States Army Ballistic Research Laboratories





Volume II

1957 - 1976

Cover

Spark shadowgraph shows the muzzle blast from a 5.56 mm rifle 125 microseconds after projectile emergence. At a pressure of 600 atmospheres, the propellant gas exhausts from the gun reaching velocities up to 1800 m/s twice the projectile velocity). This energetic flow can perturb the projectile flight path and generates the strong blast wave seen in the shadowgraph. Experiments using both optical and intrusive probing techniques generate the data needed to validate computer models which are in turn applied to develop means for controlling the weapon exhaust.

Center illustration shows a three-dimensional EPIC-3 computer code prediction of the deformation of a high density kinetic energy rod 25.6 microseconds after impacting rolled homogeneous armor (RHA) at 60 degrees obliquity. A Lagrangian finite element code, EPIC-3 used 4900 nodal points, some 23,000 elements to perform this calculation. Such computer simulations are invaluable for predicting penetrator-target interactions and evaluating performance of penetrator designs, penetrator materials, high explosive anti-tank (HEAT) warheads, advanced armors and novel armor technologies.

Interferogram of 90 mm Lexan sphere in-flight at Mach 10 in the Controlled Temperature and Pressure (CTP) Range. The fringe shift in the neighborhood of the sphere is produced by the shock wave and is directly proportional to the shock pressure. Firing in the CTP range at reduced pressures enabled the gathering of data at higher Mach and Reynolds numbers than standard atmospheric pressure ranges. This photograph was obtained from test firing conducted at an ambient pressure of 1/20 atmosphere corresponding to an altitude of 21 kilometers.

Ballisticians in War and Peace

Volume II

A History of the United States Army
Ballistic Research Laboratories
1957–1976

Aberdeen Proving Ground, Maryland

Prepared for the U.S. Army Ballistic Research Laboratories

by John G. Schmidt, Inc.
Sherwood Forest, Maryland

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Maryland

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Aerial View of BRL Complex

overview

The Ballistic Research Laboratories occupy a unique position among US Army agencies; the Laboratories must address problems dealing with the entire spectrum of Army systems—those existing, those on the drawing boards, and those still in the conceptual stages. Within this spectrum, the weapon systems range from small arms and their ammunition to large missiles and their warheads. The lethality and effectiveness of these Army weapon systems against foreign targets must be known and understood; corollary to this, methods for decreasing the vulnerability of US systems to foreign materiel must be known and understood. The Laboratories must be aware of current systems and must also anticipate future systems relevant to the Army's mission responsibilities so they can make useful and significant contributions to the design and evaluations of systems. The pages which follow provide a twenty-year history of the Laboratories and their scientific and engineering contributions to the group of technologies comprising Army Weapons Technology.

INTRODUCTION

The opening year of these next two decades, 1957–1976, in the Ballistic Research Laboratories' history revealed a program that had undergone little change in content or direction since the Korean conflict. The Director's main concern was the achievement of a proper balance between a program of well-planned long range research and the set of tasks designed to provide immediate solutions or approaches to urgent military needs.

There was always pressure to digress from fundamental work, results from which could be directly applicable to weapons systems many years later, in order to solve current development problems, and to provide data for use in weapon systems evaluation or decisions for ordnance materiel development. Ironically, these digressions delayed the progress in ballistic fundamentals which could ultimately eliminate the need for some of these *ad-hoc* tasks.

However, as United States involvement in Southeast Asia increased in scope and intensity, the frequency and urgency of *ad-hoc* work at BRL increased correspondingly. Fortunately, the extensive background of the scientists and engineers in ballistics and its related subjects, the continually evolving sophistication of computer technology, and improved scientific and ballistic instrumentation all combined to enable BRL to fulfill its mission.

Throughout the period, productivity was sustained through continual review of activities; the Laboratories discontinued work for which the technology had matured sufficiently for it to be transferred to a commodity command, turned to contract or other agency support for work that had become routine, and transferred responsibility for operation of facilities or activities that had become primarily service functions to other agencies. Notable examples of the last action included the transfer of the Pulse Radiation Facility from BRL to the Army Test and Evaluation Command, the closing of the BRL wind tunnels as adequate support became available elsewhere for BRL investigations in transonic and supersonic aerodynamics, the transfer of the mission for research in aeronomy to the Atmospheric Sciences Laboratory at White Sands Missile Range, New Mexico, and the closing of the Tandem Van de Graaf Accelerator and its subsequent transfer to the University of Pennsylvania. The last instance made it possible for BRL to use more effectively the group of highly competent scientists from that facility. Reassigned to the Applied Mathematics and Sciences Laboratory, they worked on more defense-relevant, higher priority tasks in physics, particularly in radiation-related work in nuclear weapons effects research, defense against nuclear weapons, and X-rays.

An important change in program direction occurred when, beginning in 1957, the Interior Ballistics Laboratory shifted emphasis from problems associated with closed-breech guns to the propellant aspects of rockets. This interest peaked in the 1960's when excellent work was done in identifying causes and cures for combustion instabilities in rocket motors. BRL interest decreased thereafter as capabilities developed elsewhere; however, as late as 1976, there was a small effort ongoing in combustion instability.

overview

The first major change in program content came with the realization of the Army's need to develop competence in target acquisition, guidance and control technology, a competence which BRL subsequently achieved by the end of the first decade, 1957–1966. If not first indeed, BRL was certainly an early investigator of the infrared signatures of tanks in the micron region of the electromagnetic spectrum; BRL researchers were also groundbreakers in millimeter radiometry, not only in theory, but in practice as well as they developed radiometric components and solid state radiometric devices.

The first major change in research philosophy and overall direction occurred in 1968, as Director Robert J. Eichelberger restructured the laboratories into organizational elements that reflected the Laboratories' research and development program—rather than the classical divisions of ballistics or arbitrary assignments of responsibility. At the same time he stressed that the path BRL had to follow should lead toward more fundamental and general solutions to broad problems.

This goal could be achieved through long-term concentration on solutions to real problems associated with military applications of advanced technology; program integration to exploit fully the common physical, chemical, and mathematical features of research and technological problems; strict orientation of the program elements according to criticality of the work and its urgency; and the development of a more readily usable form of output than the sequence of scientific and technical papers that normally evolve from research programs. The key to the achievement was the high-speed digital computer; the root of the approach was the mathematical model, which could not only illuminate and explain phenomena, but also provide a better way to plan research and communicate its results.

ORGANIZATION

As pointed out in the closing chapter of the first volume of this history, the creation of the Weapons Systems Laboratory in January 1953, was the most significant organizational change made in the first decade following the end of World War II. Except for this replacement of the Ordnance Engineering Laboratory by the Weapons Systems Laboratory, the overall organization of the Ballistic Research Laboratories had remained unchanged since 1945.

In the spring of 1958, a Future Weapons System Agency was formed at BRL to provide to the Assistant Chief of Ordnance for Research and Development, an unbiased source of advice on the choice of new weapon development programs. Mr. Charles L. Poor, then Chief of BRL's Exterior Ballistics Laboratory was appointed chief of the Agency. The activities and accomplishments of the agency are recounted later in this book.

During 1962, the Department of the Army undertook a major reorganization. Following the recommendations of the Hoelscher Report released by the Office of the Secretary of Defense in 1961, Secretary Robert McNamara approved a plan which consolidated the former Technical Services (Ordnance Corps, Signal Corps, Quartermaster Corps, etc.) under a new Army Materiel Development and Logistics Command, subsequently designated the US Army Materiel Comman (AMC). Army agencies were rearranged completely into a group of commands designed to be in closer accord with then current trends in management and weapons development.

The reorganization placed BRL in the Research and Development Directorate of the Army Materiel Command with other groups such as the Harry Diamond Laboratory, the Human Engineering Laboratories and the Coating and Chemical Laboratory. At the same time, August 1962, the Ballistic Research Laboratories were designated a Class II Activity, that is, an activity reporting directly to the Research Directorate, AMC, and receiving funds directly from AMC. This action separated the Laboratories from the administration of the Aberdeen Proving Ground Command. That action had been long desired by the Laboratories' Director and Staff and equally long advocated by BRL's Scientific Advisory Committee. The rationale supporting the desire and the advocacy was that administrative problems of a research organization are sufficiently different from those of other Ordnance organizations that the BRL should be directly responsible to an office primarily concerned and familiar with research, its special requirements, and mode of operations. In addition, this direct responsibility should avoid the almost inevitable tendency of an intermediate command to apply inappropriate general policies to a research organization.

After about six years, BRL's independence from an intermediate command came to an end at the beginning of 1968, when the Laboratories became part of the provisional US Army Aberdeen Research and Development Center (ARDC). Concurrently, the Commanding Officer of BRL was given additional responsibility when he was designated Commanding Officer of the Human Engineering Laboratories and the Coating and Chemical Laboratory. Each of the three laboratories had its own civilian technical director, but a common commanding officer. The mission of the Center was "to perform basic and applied research in the broad fields of weapons effects, automotive coatings and chemicals, petroleum products, human factors engineering, and allied disciplines, and to plan and conduct broad programs of materiel oriented systems analysis." The operating elements of ARDC were the Ballistic Research Laboratories, the Coating and Chemical Laboratory, the Human Engineering Laboratory, the Nuclear Defense Laboratory (located at Edgewood Arsenal, Maryland) and the Army Materiel Systems Analysis Agency (AMSAA). This last agency developed from AMC's need for an organization that could furnish the professional leadership and guidance needed to ensure the application of systems analysis throughout the Army Materiel Command. An intermediate organization, the Army Materiel Systems Analysis Center, antedating the concept for AMSAA, had been established in 1966, with Dr. Frank Grubbs of BRL as Director.

The assignment of the Laboratories to ARDC coincided with a major internal re-organization. The Interior, Exterior, and Terminal Ballistics Laboratories retained their identities within BRL; the Ballistic Measurements Laboratory became the Signature and Propagation Laboratory of BRL; and the Weapons System Laboratory became the nucleus of the Army Material Systems Analysis Agency of ARDC. The Computing Laboratory was divided into two groups: a Computer Support Division placed within Headquarters, ARDC, and the Applied Mathematics Laboratory formed from a group of mathematicians and other scientists who remained within BRL.

In mid-1968, to better meet the Army's need for vulnerability analysis and vulnerability reduction techniques, the Director of BRL established a Vulnerability Working Group within the Terminal Ballistics Laboratory. At the same time he initiated formation of a Systems Analysis Group whose functions were to interpret the output of research in a form meaningful to developers of weapons systems and to translate Army functional requirements into research objectives.

Except for AMSAA, the operating elements of the Aberdeen Research and Development Center remained unchanged when ARDC was officially established in January 1969. AMSAA became a Class II Activity reporting to the Director of Plans and Analysis, Headquarters, Army Materiel Command. However, later in 1969, the Nuclear Defense Laboratory changing its name to the Nuclear Effects Laboratory became part of BRL. Around the same time, the Vulnerability Working Group, initially composed of personnel from the Target Applications Branch of the Terminal Ballistics Laboratory, had been augmented by a group of vulnerability specialists from AMSAA to become the Vulnerability Laboratory.

Major organizational changes again affected the Laboratories in September 1972, with the abolition of the short-lived Aberdeen Research and Development Center and the reconstitution of BRL as a Class II Activity reporting to the Office of Research and Laboratories Headquarters, US Army Materiel Command. The net local results of those actions were a streamlining of administrative and support operations through the elimination of overlapping and sometimes conflicting functions and the elimination of duplicative offices existing at the BRL and ARDC levels, and improved rapport between the technical and supporting divisions at the Laboratories. Continuing his efforts to restructure the Laboratories into organizational elements reflecting the research programs, rather than arbitrary divisions of responsibility or the classical divisions of ballistics, the Director formed a Concepts

Analysis Laboratory which replaced the Signature and Propagation Laboratory and established a Radiation Division (later Laboratory) which succeeded the Nuclear Effects Laboratory. Upon the abolition of ARDC, the Computer Support Division returned to BRL control.

Subsequently in 1974, the Terminal Ballistics Laboratory was divided into two units of more manageable size and technical breadth. The Terminal Ballistic Laboratory concentrated on the terminal ballistics of chemically non-reactive devices; the new Detonation and Deflagration Dynamics Laboratory, concentrated on the terminal effects of chemically reactive devices. The Applied Mathematics Laboratory and the Radiation Laboratory were consolidated to form the Applied Mathematics and Science Laboratory.

The final reorganization of the Laboratories during the period covered by this history occurred in 1976, when the Director, anticipating the integration of the US Army Ballistic Research Laboratories into the Army Armament Research and Development Command, formed six divisions from the seven existing Laboratories. The major change consisted of the combination of the Concepts Analysis Laboratory and the Applied Mathematics and Science Laboratory into a Ballistic Modeling Division. Thus, at the end of 1976, the new Ballistic Research Laboratory was composed of these divisions:

- Interior Ballistics Division
- Launch and Flight Division
- Terminal Ballistics Division
- Ballistic Modeling Division
- Vulnerability Analysis Division
- Computer Support Division

The decision to realign the BRL under a new armament development center resulted from the recommendations of an Army Materiel Acquisition Review Committee (AMARC) appointed in 1973, by the Secretary of the Army. The Committee's task was to analyze methods for improving the Army's armament research, development, acquisition and logistics operations. Following the AMARC recommendations, in December 1975 the Department announced the formation of two new organizations; the Armament Development Command, responsible for materiel development and the Armament Logistics Command, responsible for logistics support. AMARC recommended that the new Armament Development Command be created by consolidating research, development and engineering elements of Frankford, Picatinny, Rock Island, Watervliet, and Edgewood Arsenals, with the Ballistic Research Laboratories. The new development center was designated the Armament Research and Development Command (ARRADCOM); it was officially activated January 31, 1977, with its headquarters at Dover, New Jersey. When officially established, the logistics command was called the Army Armament Materiel Readiness Command (ARRCOM).

While continuing to serve as the Director of BRL under the new organization, Dr. R. J. Eichelberger also served as the Associate Technical Director for Science and Technology at ARRADCOM.

LEADERSHIP AND MANAGEMENT

Ever since the Ballistic Research Laboratory had been established in 1938, it had been the policy of the Chief of Ordnance and his functional successors in the Army Materiel Command to confer overall responsibility for BRL operations upon a commanding military Director and to place responsibility for scientific operations upon a civilian scientist known variously as an Associate Director, or Technical Director. This policy continued unchanged until 1972, when with the abolishment of the Aberdeen Research and Development Center, a civilian Director, Dr. Robert J. Eichelberger, was given responsibility for all Laboratory operations, scientific and administrative, and Col. Thomas R. Ostrom was appointed Deputy Director/Commanding Officer.

To return to a recital (see Volume I) of those commanding officers and civilian scientists who administered, organized, and coordinated the activities of the Ballistic Research Laboratories, we can start with Col. James P. Hamill who became Director in October 1957, succeeding Col. Charles L. Register. Colonel Register retired from the Army to take a position with the Ballistic Missile Division of the Burroughs Corporation Research Center. Colonel Hamill's previous as-

Col. James P. Hamill, Director of BRL 1957 to 1961

signment had been Commander, Army Missile Test Activities, White Sands Proving Ground, New Mexico. Earlier, he had served in the Research and Development Division of the Office of the Chief of Ordnance.

Dr. Robert H. Kent, the Associate Director of BRL since 1938, retired from the Laboratories in July 1956 and became a consultant to the Laboratories. Dr. Curtis W. Lampson, then Chief of the Terminal Ballistics Laboratory, replaced Dr. Kent as Associate Director.

Dr. Lampson, like his predecessor Dr. Kent, was an internationally known scientist. As a leading authority on ground shock and air blast resulting from large explosions, he had been a frequent advisor to the US Atomic Energy Commission concerning nuclear tests and had been chief of the air blast group for the Navy Bureau of Ordnance at the Bikini Test in 1946. Dr. Lampson had joined BRL in 1946 and had become chief of the shock research section. In 1948, and again in 1951, he had been asked by the Atomic Energy Commission to organize, equip and direct a group to make air blast measurements of nuclear tests at Eniwetok Atoll. Dr. Lampson was also widely known for his work in neutron-proton interactions.

A graduate of South Dakota State College, Dr. Lampson received his master's degree and doctorate in physics from Princeton University. Before joining the Ballistic Research Laboratories in 1946, Dr. Lampson had been a senior physicist and consultant with the National Research Committee at the Palmer Physical Laboratory at Princeton, from 1941 until 1946. In 1951, he was named Chief of the Terminal Ballistics Laboratory, BRL.

Dr. Lampson was designated Technical Director of BRL in 1959; at the same time, Dr. Lewis A. Delsasso was appointed Associate Director to assist in the administration of the Laboratories' scientific program. While acting as Associate Director, Dr. Delsasso also retained his position as Chief of the Ballistic Measurements Labora-

Dr. Curtis W. Lampson, Technical Director of BRL 1959 to 1967

Dr. Lewis A. Delsasso, Associate Technical Director of BRL 1959 to 1962 (Also Chief, Ballistic Measurements Laboratory c. 1946 to 1963)

tory. Dr. Delsasso had joined the staff of BRL in 1943.

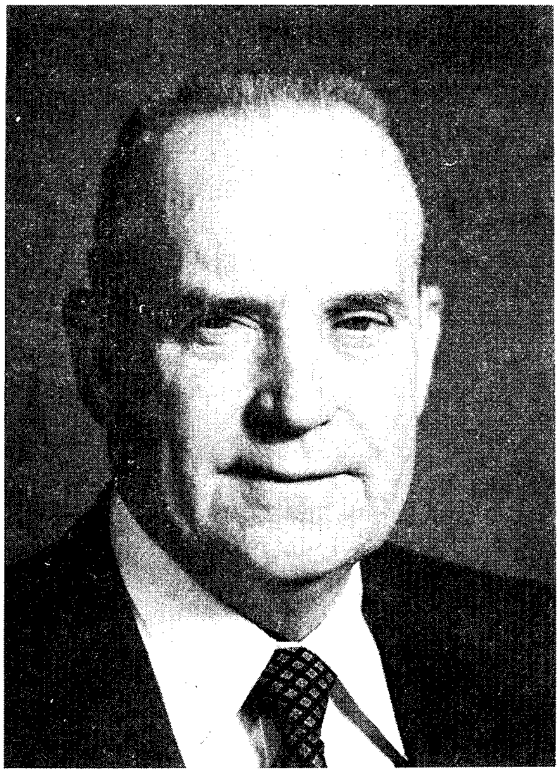
Upon the retirement of Colonel Hamill in 1961, Col. Richard R. Entwhistle assumed command of BRL. Colonel Entwhistle's immediately prior service had been as Special Assistant to the Chief of Ordnance for Nuclear Applications, a position to which he was appointed after organizing and heading the Nuclear Weapons Special Components Branch, Office, Chief of Ordnance.

Almost concurrently with the Army reorganization in 1962, that brought about the Army Materiel Command, Colonel Entwhistle instituted a modest change in management structure. Four Associate Technical Directors were appointed to assist Dr. Lampson: Dr. Frank E. Grubbs, formerly Chief of the Weapons Systems Laboratory, as Deputy, and Dr. Robert J. Eichelberger, Dr. Joseph Sperrazza, and Mr. Abraham Golub as Associates who were to help coordinate efforts in the areas of research, weapons technology, and operations analysis, respectively. The four Associate Technical Directors were considered to be a coordinating staff which could provide the Technical Director with the means for maintaining close surveillance of the research program and for managing major interlaboratory research projects, neither of which were simple tasks because of the wide range of BRL's efforts.

Dr. Grubbs, a specialist in mathematical statistics and operations research, was known internationally for his contributions to applied statistics, reliability and quality control. He earned bachelor and master of science degrees at Auburn University, Alabama, and master of arts and a doctorate at the University. He had first come to BRL in 1941.

Dr. Eichelberger first came to BRL in 1955 when he assumed duties as the Chief of the

Col. Richard R. Entwhistle, Director of BRL, 1961 to 1963



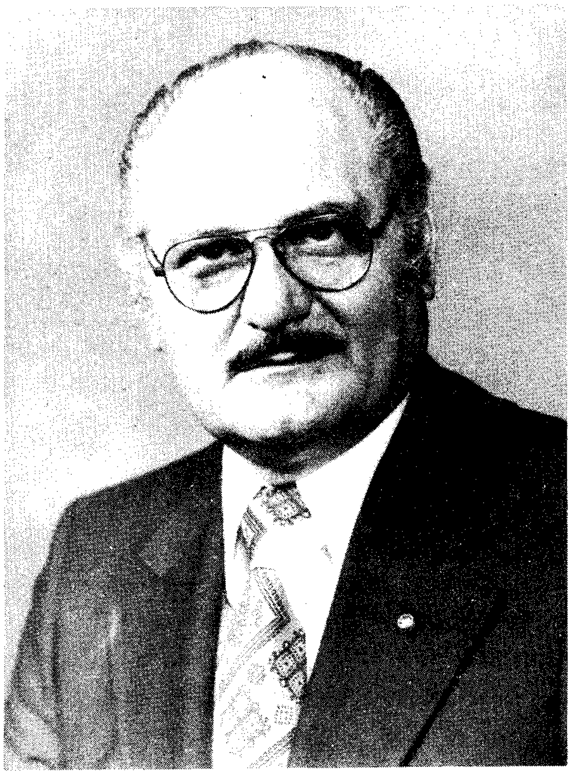
Dr. Frank E. Grubbs, Deputy Technical Director of BRL 1962 to 1968

Detonation Physics Branch. He is an internationally recognized authority in ballistic technology, specifically for achievements in physics, combustion, high-speed-high-pressure fluid dynamics, and in the development of systems engineering and computer modeling. He was recognized early for his development and proof of a generalized theory on the formation of jets by shaped charges. Dr. Eichelberger received his BS degree from Washington and Jefferson College and his MS and PhD degrees from Carnegie Institute of Technology (now the Carnegie-Mellon Institute).

Mr. Golub began his professional career as a civilian in the Office of the Chief of Ordnance, Washington, D.C. After completing active military service, he joined the staff of BRL. He served as Assistant Chief of the Surveillance Branch, then later as Chief of the Artillery Weapons Branch, both branches of the Weapon Systems Laboratory. Mr. Golub was an expert in operations research and systems analysis; he was particularly recognized for his capability in all aspects of weapon system evaluation. Mr. Golub received his bachelor of arts and a fellowship in mathematics from Brooklyn College, and his master of arts from the University of Delaware. (Mr. Golub left BRL in 1965 to become Deputy Assistant for Operations Research, Office of the Assistant Secretary of the Army, Financial Management.)

Dr. Sperrazza began his career in 1941 as an engineer in the Arms and Ammunition Section of the Proof Department, Aberdeen Proving Ground. Subsequently, he became a physicist, then a branch chief in the Terminal Ballistics Laboratory. Dr. Sperrazza had specialized in wound ballistics, penetration mechanics, small arms technology, and air blast phenomena. He received his bachelor degree in engineering from

Dr. Robert J. Eichelberger, Associate Technical Director 1962–1967. Director of BRL 1967 to date



Mr. Abraham Golub, Associate Technical Director of BRL 1962 to 1964 (Appointed Deputy Assistant for Operations Research, Office of the Assistant Secretary of the Army for Fiscal Management, 1964)

Cooper Union School of Engineering, his master's degree and doctorate from the Johns Hopkins University.

Colonel Charles D. Y. Ostrom, Jr. replaced Colonel Entwhistle in 1963. Pending his retirement and subsequent appointment as Director of the Army Research Office, Durham, Colonel Entwhistle remained as a special assistant to the commanding officer of BRL.

Colonel Ostrom came to BRL from his post as Commander, European Research Office, US Army Research and Development Group, Frankfurt, Germany. This was not Colonel Ostrom's first assignment to BRL; as a Major, he had served as executive officer of the Ballistic Measurements Laboratory from July 1948 to June 1950. Other research-oriented assignments in which Colonel Ostrom served were Executive Officer, Research and Development Division, Samuel Feltman Laboratories, Dover, New Jersey; and Chief, Research and Materials Branch, Research and Development Division, Office of the Chief of Ordnance, Washington, D.C. Colonel Ostrom remained at BRL until he was relieved by Col. John D. Raaen in 1967.

Colonel Raaen's previous assignment was Commander, US Army Research Office-Durham (ARO-D), North Carolina. During the Korean War he had served in the Ammunition Development Office in the Office of the Chief of Ordnance. He served with the Ordnance Board at Aberdeen Proving Ground and before going to ARO-D, he was the staff officer for the Military Liaision Committee, Atomic Energy Commission.

Late in 1967, two major staff adjustments were made when Dr. Lampson, formerly the Technical

Dr. Joseph Sperrazza, Associate Technical Director of BRL 1962–1968. (Became first Director, US Army Materiel Systems Analysis Agency in 1968)

Col. Charles D. Y. Ostrom, Director of BRL 1963 to 1967

Director was appointed to the newly-created position of Chief Research Scientist, and Dr. Robert J. Eichelberger, formerly an Associate Technical Director, was appointed Technical Director. In his new post Dr. Lampson was to furnish scientific advice to the Commanding Officer, provide liaison with the national and international scientific communities, and resume his research in air-blast and shock tube physics.

Not long after, in 1968, Dr. Floyd A. Odell joined BRL as Associate Director. Dr. Odell had received his bachelor degree from Linfield College, McMinnville, Oregon and his doctorate from Yale University. Following World War II service as an officer in the Army Air Corps, Dr. Odell became Chief, Biophysics Branch, Medical Laboratories, Edgewood Arsenal, Maryland. While in that position he served a year as a research scientist in the British Ministry of Defence. In 1958, he became Technical Director of Research at the US Army Medical Laboratories, Fort Knox, Kentucky. After four years, Dr. Odell resigned from that position to become Director of Biophysical Research for the Field Emission Corporation, McMinnville, Oregon; he remained with that corporation until he came to BRL.

Colonel Howard C. Metzler took command of ARDC in 1968, when he relieved Colonel Raaen who had been reassigned to duty in the Republic of Vietnam. Before coming to Aberdeen, Colonel Metzler had been the commanding officer of Seneca Army Depot in New York. Colonel Metzler's research-related assignments in the United States had included tours of duty as Research and Development Staff Officer and Staff Officer, Materiel Development Division, OCO; Assistant Chief and later Chief of the Blast and Shock Division, Defense Atomic Support Agency (DASA); and Chief of the Shock-Physics Division, DASA.

Upon the departure of Colonel Metzler in 1970,

Col. John D. Raaen, Director of BRL 1967 to 1968

Dr. Floyd A. Odell, Associate Director of BRL 1968 to 1976

Colonel Rudolph A. Axelson assumed command of ARDC. He came to ARDC from an assignment as commanding officer of the US Army Land Warfare Laboratory, Aberdeen Proving Ground Maryland—a position he had held for about a year. Before an assignment to Vietnam in 1968, Colonel Axelson was the Chief of the Environmental Effects Division, Office of the Project Manager for Selected Ammunition. He served as the Research and Development Staff Officer, Headquarters, US Army Materiel Command in 1962–1963, and as a staff officer in the Office of the Chief of Ordnance in 1961–1962. Colonel Axelson served as commanding officer ARDC until 1972 when he retired.

Our narrative pauses here to acknowledge the long and loyal service of "Peachy" (Mrs. Louis) Watson who retired after the departure of Colonel Metzler, but before the assumption of command by Colonel Axelson. Beginning with Colonel Zornig in 1938, Mrs. Watson had been the secretary to every BRL commanding officer since then.

Col. Thomas R. Ostrom, a brother of Col. Charles D. Y. Ostrom, Jr., was the first military officer to serve as Deputy Director/Commander of BRL. Col. Thomas Ostrom was assigned to the Ballistic Research Laboratories in 1972. Colonel Ostrom remained Deputy Director/Commanding Officer until his retirement in 1975.

Fiscal Resources. By the end of 1956, the annual appropriation had leveled off in the neighborhood of $15 million. That amount was for research and development expenses only and did not include, for example, the funds expended for permanent construction. In terms of current dollars, the average over the next seven years had increased to just under $21 million, with a low of about $19 million in 1958 and a high of about $24 million in 1963. Funding then took a jump in 1964 to about

Col. Howard C. Metzler, Director of BRL 1968 to 1970

Col. Rudolph A. Axelson, Commander, Aberdeen Research and Development Center 1970 to 1972

$35 million dollars and with minor deviations tended to increase annually to a high of about $41 million. However, when the dollar amounts are converted to constant 1967 dollars (1967 was selected because it is the approximate midpoint in the two decades) additional dollar amounts did not compensate the Laboratories for the effects of inflation.

Nevertheless in 1976 the BRL program was a broad comprehensive mix of closely-coupled basic research and exploratory development projects. The more than 400 individual work units comprising the program were funded through DARCOM mission and Army Customer projects; other DOD organizations including the Air Force, Navy, Advanced Projects Research Agency and the Defense Nuclear Agency; and other US Agencies such as the National Aeronautical and Space Administration, the Department of Transportation and the Defense Preparedness Agency.

Historically, DARCOM mission funds (that is, money supplied to BRL to accomplish its mission) have not been sufficient to finance fully BRL operations; BRL met the deficit by soliciting or accepting "Customer" support from other DARCOM subordinate commands and the other agencies listed above. The favorable aspect of this underfunding (deliberate policy of DARCOM and its predecessor AMC) was the assurance to the customer and to Headquarters, DARCOM that the Laboratories were addressing problems relevant to the customer's needs. The unfavorable aspect was that meaningful planning was inhibited by the Laboratories inability to forecast the amount of customer funding to be received.

The trend to depend on private contractors and other government agencies for performance of work essential to BRL's program, as noted in the first volume of this history was to continue. There were three reasons for letting contracts:

Col. Thomas R. Ostrom, Deputy Director/ Commander of BRL 1972–1975

TWENTY YEAR HISTORY OF BRL FUNDS IN $MILLIONS
(LOWER FIGURES HAVE BEEN ADJUSTED TO REPRESENT CONSTANT 1967 DOLLARS)

	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
MISSION (PROJECT) FUNDS	12.0	N.A.	12.6	11.4	10.0	13.5	17.0	18.8	20.9	21.1
	14.6		14.7	13.0	11.3	15.0	18.6	20.3	22.1	21.8
ARMY AND OTHER DOD CUSTOMER FUNDS	6.6	N.A.	10.4	9.3	6.8	8.0	7.4	15.8	16.2	15.5
	8.0		12.1	10.6	7.7	8.9	8.1	17.1	17.2	16.0
TOTAL	18.6	20.2	23.0	20.7	16.8	21.5	24.4	34.6	37.1	36.6
	22.6	24.0	26.8	23.6	19.0	23.9	26.7	37.4	39.3	37.8

	1967	1968	1969*	1970*	1971*	1972	1973	1974	1975	1976
MISSION (PROJECT) FUNDS	23.2	25.0	17.3	17.2	17.8	22.9	22.6	22.2	16.8	23.6
	23.2	24.0	15.7	14.8	14.6	18.3	16.9	15.1	10.4	13.9
ARMY AND OTHER DOD CUSTOMER FUNDS	12.0	11.5	8.2	3.9	6.6	13.1	16.1	17.9**	20.0	17.2
	12.0	11.0	7.5	3.4	5.4	10.5	12.1	12.2	12.4	10.2
TOTAL	35.2	36.5	25.5	21.1	24.4	36.0	38.7	40.1	36.8	40.8
	35.2	35.0	23.21	18.2	20.0	28.8	29.0	27.3	22.8	24.1

* During these years BRL was part of the Aberdeen Research and Development Center. Funds required to support Headquarters, Administrative and other services, and the Computing Division are not shown.
** Approximately $4 Million of this amount was for Project HITVAL.
Note: Multipliers used to convert annual funds to constant 1967 dollars are from DARCOM.

- Acquiring the best talent available to work in a scientific area applicable to Army problems, long-range or immediate. University contracts were considered to be very productive. (An important aspect of the BRL—academic relationship was the opportunity for cross-fertilization; i.e., stimulation of BRL scientists through contact with academicians of national and international rank and the opportunity of BRL researchers to acquaint university researchers with the problems of most interest to the Army.)
- Augmenting BRL efforts in those areas where in-house capabilities were marginal or nonexistent, or where unique facilities might be needed.
- Performing routine tasks or tests that would otherwise occupy time of BRL personnel who could be more profitably employed in tasks more commensurate with their ability.

Over the 20-year period from 1957 to 1976, the average percentage of BRL funds expended annually on university and commercial research contracts was about 14 percent; the average percentage of all funds spent out-of-house during that period was about 26 percent annually.

Human Resources. When these two decades began, the BRL staff numbered 1039 employees of whom 912 were civilians and 127 military. Nearly all of the military employees were scientists or engineers; about 45 percent of the civilian employees were professionals. Between 1957 and 1963, the number of professional civilian employees remained relatively static—within 5 percent of the average number of 450. However, during the same period, the number of military professional employeees declined to 50. The loss of these military professionals had an adverse effect on BRL efforts that was not overcome until manpower authorizations permitted BRL to hire additional civilian employees.

Such authorization came in August 1963, when an Army manpower survey team recommended an increase of 153 positions, mostly for professional employees. This recommendation was shortly amended to impose a ceiling of 1087 civilian employees by the end of fiscal year 1965. Later authorizations did permit the Laboratories to achieve a peak strength of 1141 employees, including 645 professionals, in 1968. These 645 scientists and engineers also represented a maximum at BRL.

Following the establishment of the Aberdeen Research and Development Center, in 1969 the staff of BRL was once more reduced as civilian positions were allotted to ARDC Headquarters support elements and other ARDC organizations. With this reduction the professional civilian staff dropped to an average of about 400 through 1972.

After ARDC was discontinued in mid-1972, the number of BRL employees fell to a new minimum of 675, which included 60 military employees. This number gradually rose to 867 in 1974, but it fell gradually to 795 by the end of 1976. At the end of that year there were 402 civilian professional employees, 22 military scientist or engineers, 172 sub-professional civilian employees, 20 non-professional military employees, and 179 administrative, clerical, and support employees. Compared to the number of employees in 1957, the number of civilian scientists and engineers had increased by about 10 percent, military professionals by about 80 percent, and support personnel by about 45 percent. The number of civilian sub-professionals had increased by about 23 percent, the number of non-professional military personnel by 70 percent.

However, numbers and statistics aside, the policies adopted by the Director in the mid-1960's (see next section) had improved the quality of the staff and extended and strengthened the Laboratory capabilities—a dynamic result despite the static manpower situation that had existed essentially from 1969 through 1976.

Recognition of Achievements. Through its continuing contributions to ballistics and fundamental sciences, BRL sustained the favorable reputation accorded by the national and international defense and civilian research and development communities.

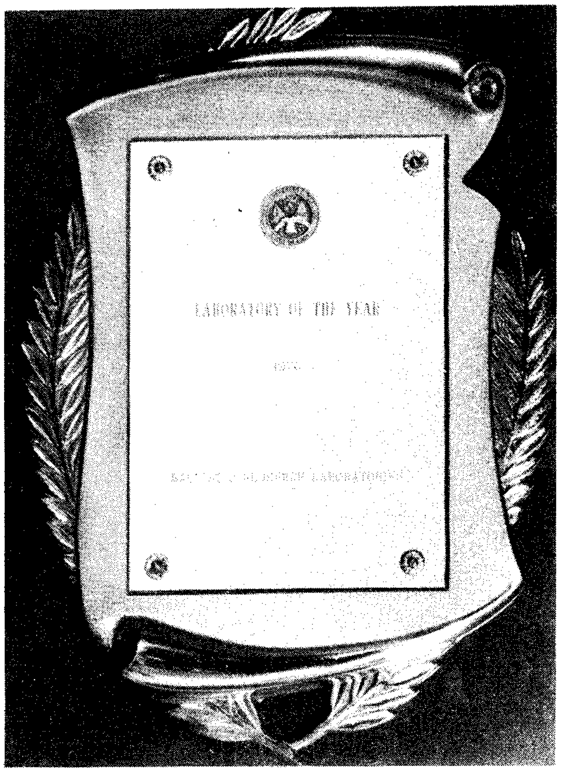
One testament to this reputation is the long list of panels, committees, and working groups of which BRL scientists and engineers were (or are) members, often chairmen. (In many instances, BRL took the initiative in establishing such groups.) Sponsors for these groups included DARCOM, the Department of the Army, the Joint Services and the Marine Corps, the Department of Defense, countries within the Tri-Partite Agreement, and various NATO groups.

A second testament is the number of Army awards presented to the Laboratories and to its people. To provide local recognition of personal accomplishments, the Laboratories established the R. H. Kent Award, the Colonel H. H. Zornig Award, and the BRL Fellow Program.

Army Awards. In 1961, Lt. Gen. Arthur G. Trudeau, then Chief of Army Research and Development, initiated an annual award program to recognize achievements in Army research and development. Criteria for the award were that the achievement establish a scientific basis for subsequent technical improvement of military importance, materially improve the Army's technical capability, or contribute materially to national welfare.

Mr. Warren W. Berning and Dr. R. J. Eichelberger, BRL scientists, were each given the Army R&D Achievement Award in 1961. Each year since then, BRL scientists or engineers have received the R&D Award in recognition of their individual or group efforts. Through 1976, the total number of such recipients was about thirty-five.

In the fall of 1974, Mr. Norman R. Augustine, Assistant Secretary of the Army (R&D) instituted a program for annual evaluation of all Army in-house laboratories. The evaluation would be marked by presentation of two awards—Army Laboratory of the Year and Army Special Award for Accomplishment. The criterion for the Laboratory of the Year is the degree to which each laboratory reaches its full potential impact in enhancing the capability of Army operational



Laboratory of the Year Award—1976

forces—based on work done by the laboratory in the previous year. The Special Award for Accomplishment would go to the laboratory showing the greatest improvement during the previous year.

In addition to these two awards, special awards for excellence would be given to those laboratories whose evaluation placed them in the top twenty percent of the laboratories in each specific Command.

BRL received the Army Award for Excellence in 1974, 1975, and 1976; the Laboratories received the Army Laboratory of the Year Award in 1976.

BRL Awards. To recognize outstanding achievements of BRL personnel, the Ballistic Research Laboratories presents two awards annually. These are the R. H. Kent Award and Colonel H. H. Zornig Award. The two awards complement each other and cover all BRL activities.

The Kent Award established in 1956 in honor of BRL's famous scientist and ballistician, Dr. Robert H. Kent, recognizes scientific or engineering accomplishments that reflect the highest personal achievement. The 1957, and first, recipient was Mr. Harold Zancanata of the Ballistic Measurements Laboratory.

The Zornig Award established in 1959 recognizes technical, administrative, mechanical, or other accomplishments supporting the BRL mission. The Award honors Colonel H. H. Zornig who took charge of ballistic research at the Aberdeen Proving Ground in 1935 and was largely responsible for the organization of BRL in 1938. The 1959, and first, recipient was Mr. Frank Sirangelo, Drafting Section, Weapon Systems Laboratory.

The BRL Fellow Program was instituted at the Laboratories in 1972. Its purpose is to formally recognize the competence of an individual scientist whose work at the Laboratories is considered to be at the forefront of research. The sixteen members in the initial group of Fellows were chosen by votes by the Director and Associate Director of BRL and the chiefs of the various laboratories and divisions. The sixteen members included five Kent Award recipients: Harold Zancanata, Dr. Lester P. Kuhn, Arthur E. Thraillkill, Herman P. Gay, and Dr. Ceslovas Masaitis. The other members of this first group of Fellows were Richard H. Comer, Alexander S. Elder, Dr. Coy Glass, Luther M. Hardin, Dr. Norris J. Huffington, Orlando T. Johnson, George D. Kahl, Nathan Klein, Leonard C. MacAllister, Dr. Franklin E. Niles, and Richard Vitali. In subsequent years, election to the BRL Fellows would be made annually by the Fellows.

Staff Development. As noted before, about midway through the 1957–1976 period, the Director increased emphasis on theoretical research and mathematical modeling. This emphasis demanded an increase in the number of laboratory employees capable of generating high quality research. The Laboratories took two approaches to satisfy this demand.

The first approach, designed to have an immediate effect, was an intensified recruiting effort to hire scientists with advanced degrees, preferably doctor's degrees. The second approach, which was longer in range, was an expanded educational program through which the Ballistic Institute would support laboratory employees in graduate schools.

The Recruiting Program. Beginning in October 1967, the Laboratories vigorously recruited PhD's, particularly theoreticians. These efforts were marked by the personal involvement of the Director and his Special Assistant. The sources for prospective employees were referrals from AMC Technical Placement Officers, the local Civilian Personnel Division, BRL personnel, and the placement registers of national technical and scientific societies such as the American Institute of Physics and the American Chemical Society. Scientists and engineers assigned to the Laboratories in fulfillment of their military obligations comprised another source of employees.

The recruiting campaign was a notable success. During the first fourteen months of the effort sixteen new employees with doctor's degrees joined the BRL staff. The society placement registers were the source through which the majority of these new employees were found. (Interestingly, as of 1984, twelve of these scientists were still with BRL.)

The Educational Programs. In-service training and graduate support were provided through the Ballistic Institute which had been established in 1948 at BRL. The first Chief of Scientific Training was Mr. D. C. Jackson who served in that position until his retirement in 1963. From December 1963 until November 1965, Dr. Joseph Frazer, Chief of the Interior Ballistics Laboratory, acted also as the Chief of Scientific Training for the Institute. Dr. Frazer was succeeded by Mr. T. Robert Bechtol, who supervised the Institute as its course offerings and services were expanded during the next decade.

In the first year of the expanded graduate support program, among the BRL employees enrolled in graduate schools were nine PhD and two MS candidates attending school full time, and two PhD and seven MS candidates attending school part time.

The courses taught at the Ballistic Institute satisfied the job-related training needs of the BRL employees. By agreement with the University of Delaware, who provided many of the instructors for the Institute courses, the University gave academic credit for some but not all courses taken by BRL students registered in a degree program. One should note that the University of Delaware provided exemplary cooperation and outstanding administrative and academic assistance to the Ballistic Institute.

In-house courses taught at the Ballistic Institute at the end of 1976, typical of such courses taught throughout the years, included FORTRAN IV, Advanced FORTRAN IV, Statistical Analysis, Physics and Mechanics of Impact, Computer Graphics, Mathematical Foundations for Computations, and Design and Analysis of Experiments. A Weapons Systems Engineering Course, designed and introduced by Mr. Bechtol provided an introduction to a highly specialized field not ordinarily encountered in undergraduate or graduate academic work.

In closing this discussion of BRL's two approaches to staff development, the success can be manifested by noting that in 1966, the BRL professional staff numbered 43 people with PhD's, 97 with MS's, 393 with bachelor degrees and 36 with no degree; by 1976, the staff included 106 people with PhD's, 90 with MS's, 195 with bachelor degrees, and 10 with no degree.

Managerial Development. External factors neglected, the development and growth of the Ballistic Research Laboratories would be managed and controlled by BRL's most valuable asset—its people. Thus, it was incumbent upon the Director to develop managerial talent so that management progression and succession could occur in an orderly and logical fashion. Consequently, in 1965 the Director initiated a program whereby two junior scientists or engineers from within the Laboratories work temporarily in his office. These two people serve as his assistants for one year; their assignment dates are staggered so there is a six-month overlap in tenure. Candidates for this managerial "internship" are selected by a laboratory chief from people in his organization.

The objectives of the intern program are to give the assistants management experience in projects that require coordination of activities within several laboratories, to give them a more comprehensive view of the overall efforts of BRL and intermediate and higher Army headquarters, and to allow them an opportunity to interact and become familiar with the structure and personnel of other AMC (now DARCOM) organizations and offices.

The first two "graduates" of the program, Mr. Richard Vitali and Mr. Leland A. Watermeier, eventually became, respectively, Chief of the Terminal Ballistics Division and Chief of the Interior Ballistics Division.

THE PHYSICAL PLANT

The central buildings of the BRL complex occupy about 70 acres in a technical compound near the headquarters of the Aberdeen Proving Ground Command, a host organization that provides several support services to BRL.

Spesutie Island, now connected by a causeway to the mainland of the Proving Ground, provides space for many of the field facilities needed by the Laboratory. BRL controls most of the island, which encompasses about 1800 acres when large areas of marshland are included, but shares it with the Army Materiel Systems Analysis Agency, the Army Human Engineering Laboratories, and elements of the Army Test and Evaluation Command.

In 1976, the Army's fiscal investment in the physical facilities of the Ballistic Research Laboratories was more than 50 million dollars, a total that does not consider the effects of inflation or replacement costs. That investment was supplemented by more than 20,000 items of scientific equipment with an acquisition cost of 20 million dollars. Many of the facilities were either designed or adapted for highly specialized use; in view of the unique mission of BRL, that should not be surprising.

Field facilities on Spesutie Island include barricaded positions for conducting live investigations into blast, penetration, or fragmentation effects, and for carrying out other hazardous experiments. Buildings nearby house the laboratories, shops and ammunition loading and storage facilities needed for the activities on the island.

THE TECHNICAL LIBRARY

By 1976, the holdings of the library had expanded dramatically to about 38,000 books, 25,000 bound volumes of scientific and engineering journals, 230,000 technical reports, and over half a million firing records of guns and ammunition (this last probably an unparalleled source of information on weapon and ammunition performance covering 60 years of proof, test and evaluation firings), more than 1000 reels of microfilm, and 140,000 microfiche. The collection is housed in the main BRL Technical Library Building located near the BRL complex and in a Branch Library Building within the complex. Seventeen employees provide a broad range of scientific and technical information services to the staff of the Ballistic Research Laboratories, the Army Materiel Systems Analysis Agency, the Test and Evaluation Command, and the Human Engineering Laboratories.

THE SCIENTIFIC ADVISORY COMMITTEE

First established in 1940 through the efforts of Col. H. H. Zornig, the Scientific Advisory Committee of the Ballistic Laboratory convened several times a year, except for 1971 and 1972. The committee was composed of a group of eminent scientists and engineers who advised the Director of BRL on the scientific and technical aspects of the research and development of ballistic weapons.

Through the years, to 1976 when the final meeting was held in August, the advice and recommendations of members contributed to the design (based on technological principles rather than cut-and-try experiments) of better weapon systems, to economy in research and development through advice leading to profitable avenues for research, to the avoidance of false trials, and to the exploitation of a wide body of scientific and technological information.

Specific advice provided by the Committee in the last years of its existence, and used by the Director in his decisions, included an expansion of work in gun propellant technology, broadening the scope of work on kinetic energy armor penetrators, embarkation on a three-year program in particle beam technology, and confirmation of the proper balance between experimental approaches and mathematical modeling.

The Committee was abolished on the 1st of April 1977, as a result of the decision by the Carter Administration to decrease the number of committees being used by Federal Agencies. In 1976, as in past years, the cost of the Committee compared to the value of the recommendations, criticism, or advice was extremely low; members frequently served at no cost to the government, or at costs considerably below their customary consultation fees.

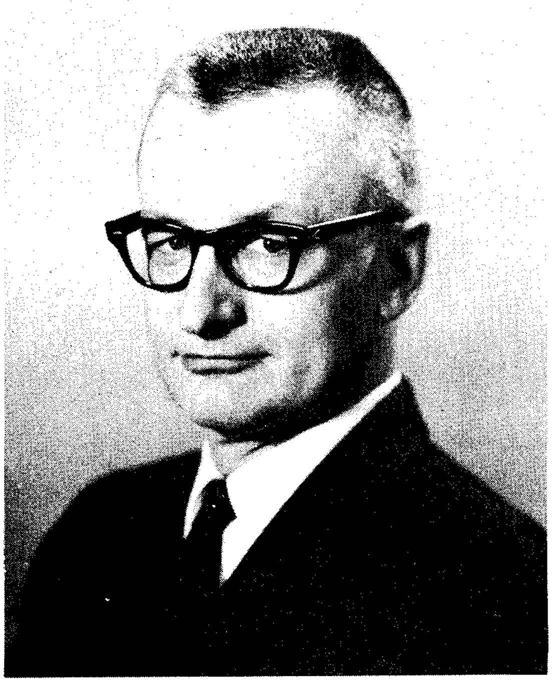
At the time the Committee was abolished, the Director of BRL expressed his appreciation to the members of the Committee, in particular to three long time members whose years of service appear in the text below. Members of the last committee were:

- Prof. Joseph E. Mayer, an expert in statistical and quantum mechanics, Revelle College, University of California, San Diego, La Jolla, a member at various times from 1942 to 1977.
- Dr. Homer J. Stewart, a professor in the Department of Aeronautics, California Institute of Technology, Pasadena, whose specialties are dynamic meteorology, theoretical aerodynamics, fluid and supersonic flows, guided missiles, and space and planetary exploration systems. He served from 1959 to 1977.
- Retired Army Maj. Gen. Leslie E. Simon, Winter Park, FL, a specialist in quality control, statistics, proof testing and surveillance of munitions, and exterior ballistics. He was a member from 1956 to 1977.
- Retired Army Lt. Gen. Austin W. Betts, Southwest Research Institute, Houston, TX, Army Chief of R&D until December 1970.
- Dr. J. V. Richard Kaufman, Great Falls, VA, recognized as an expert in explosives, radioisotopes, ultrahigh speed photography, solid state chemistry and radiation damage.
- Charles L. Poor, Washington, DC, longtime Deputy Assistant Secretary of the Army (R&D) until he retired in 1975, and an established expert in exterior ballistics, weapons technology and systems engineering.
- Prof. Morris Rubinoff, Moore School of Electrical Engineering, University of Pennsylvania, renowned for research in systems engineering, computer logic design, electronic circuit design, and mathematical analysis.
- Prof. Martin Summerfield, Princeton University, honored for his work in infrared spectroscopy, soil erosion, rocket propellants, combustion and jet engines.
- Herbert K. Weiss, Palos Verde Peninsula, CA, acclaimed for achievements in aeronautical engineering, fire control and systems analysis.

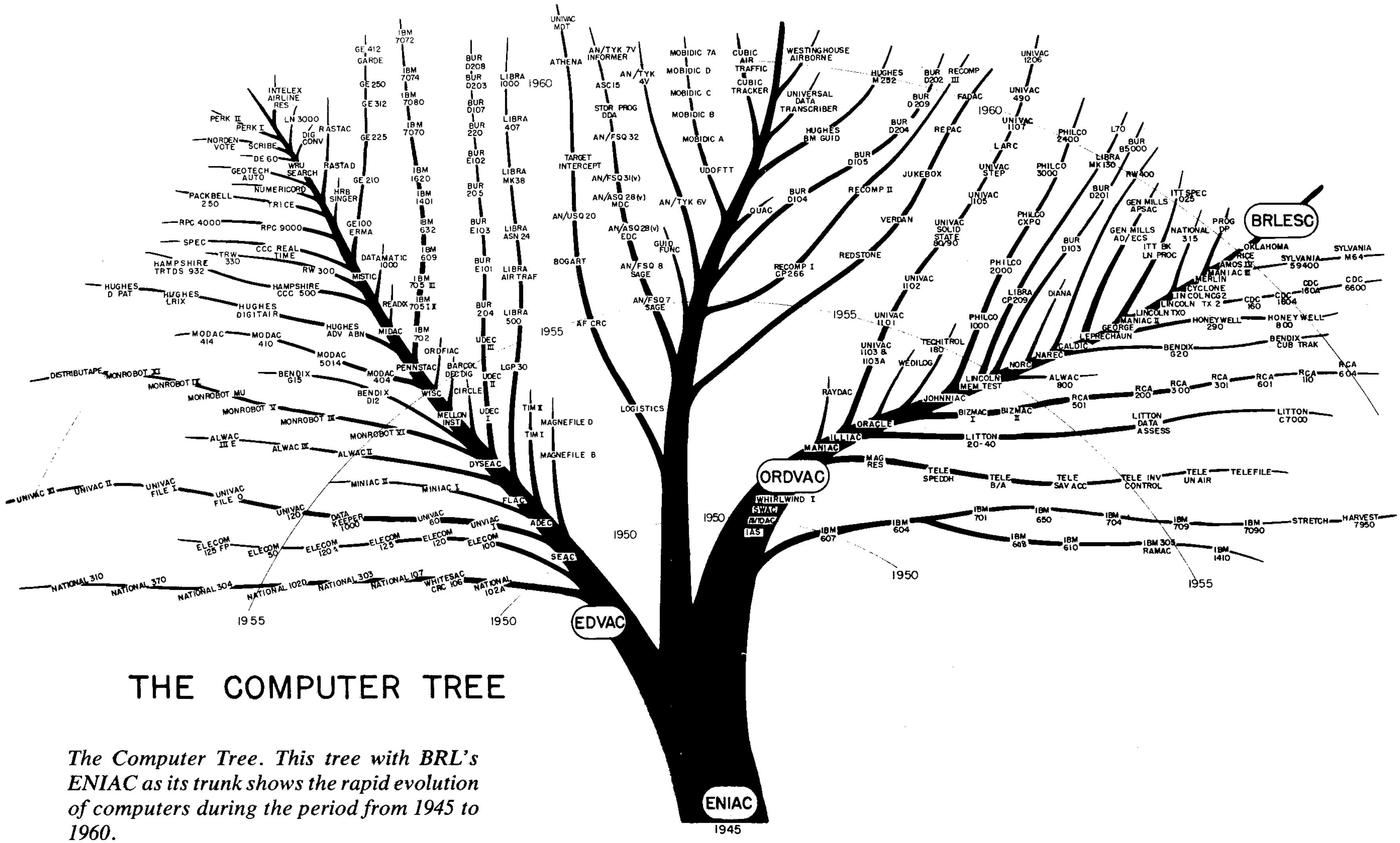
It is interesting to note that for a brief period in 1952, BRL, with three large-scale, high-speed, electronic digital computers, was the world's largest computer center. These three, the ENIAC, ORDVAC, and EDVAC were all dedicated to solving defense problems.

The rapid competitive evolution of computers during the early 1950's prompted the Department of Defense to ask BRL's Computing Laboratory to conduct a national survey of electronic digital computing machines—for the benefit of prospective users and designers in government and industry. The results of a nationwide survey in 1955, appearing in a report by Martin Weik of BRL, showed that there were then 87 different kinds of commercial and scientific digital computers operational in the United States. A second survey in 1957, showed that the number had risen to 103; a third and final survey by BRL in 1961 showed more than 220 different types of digital computers existing in the United States. These computers were committed to the solution of

Dr. Donald Eccleshall, Chief, Applied Mathematics and Science Laboratory, received his PhD (Physics) from the University of Liverpool, England. After his graduation, he worked at the Atomic Weapons Research Establishment, Aldermaston, United Kingdom. After a two-year research appointment at the University of Pennsylvania, Dr. Eccleshall came to Edgewood Arsenal to take charge of the Tandem Accelerometer Facility. When that facility and its work were transferred to BRL in 1970, Dr. Eccleshall became Chief of the Radiation Laboratory, and in 1974, Chief of the Applied Mathematics Laboratory.



Dr. John H. Giese, Chief, Computing Laboratory 1959 to 1968, Chief, Applied Mathematics Division 1968 to 1974. Dr. Giese received his BS from the University of Chicago and his PhD (Mathematics) from Princeton University. Before joining the BRL staff in 1946, Dr. Giese had been an aerodynamicist at Bell Aircraft Corporation. He retired from BRL in 1974.



THE COMPUTER TREE

The Computer Tree. This tree with BRL's ENIAC as its trunk shows the rapid evolution of computers during the period from 1945 to 1960.

almost every conceivable type of computing and data processing tasks for defense, science, commerce, industry, service and manufacturing. ENIAC provided the initial impetus to this benign, continuing technological revolution that in its depth and breadth rivals the industrial revolution of the 18th century.

It was apparent by 1955 that the scientific computing facilities at the BRL would soon become unable to support the increasing and expanding demands for computations. Improved versions of the EDVAC and ORDVAC were in use 24 hours a day, seven days a week, except for brief shut-downs for maintenance and improvements. The computer improvement programs which had expanded the capabilities of these computers were only stopgap measures delaying the inevitable: the inability to adequately support the active problems being solved in ballistic research and the computations of firing tables and other ballistic data for artillery, rockets and guided missiles. The ENIAC having outlived its usefulness because of its inability to solve the increasingly complex problems was taken out of service at exactly 11:45 p.m. on October 2, 1955. Static and dynamic displays of ENIAC components were prepared in 1963 for installation in the Computer History Section of the Science and Technology Museum of the Smithsonian Institution.

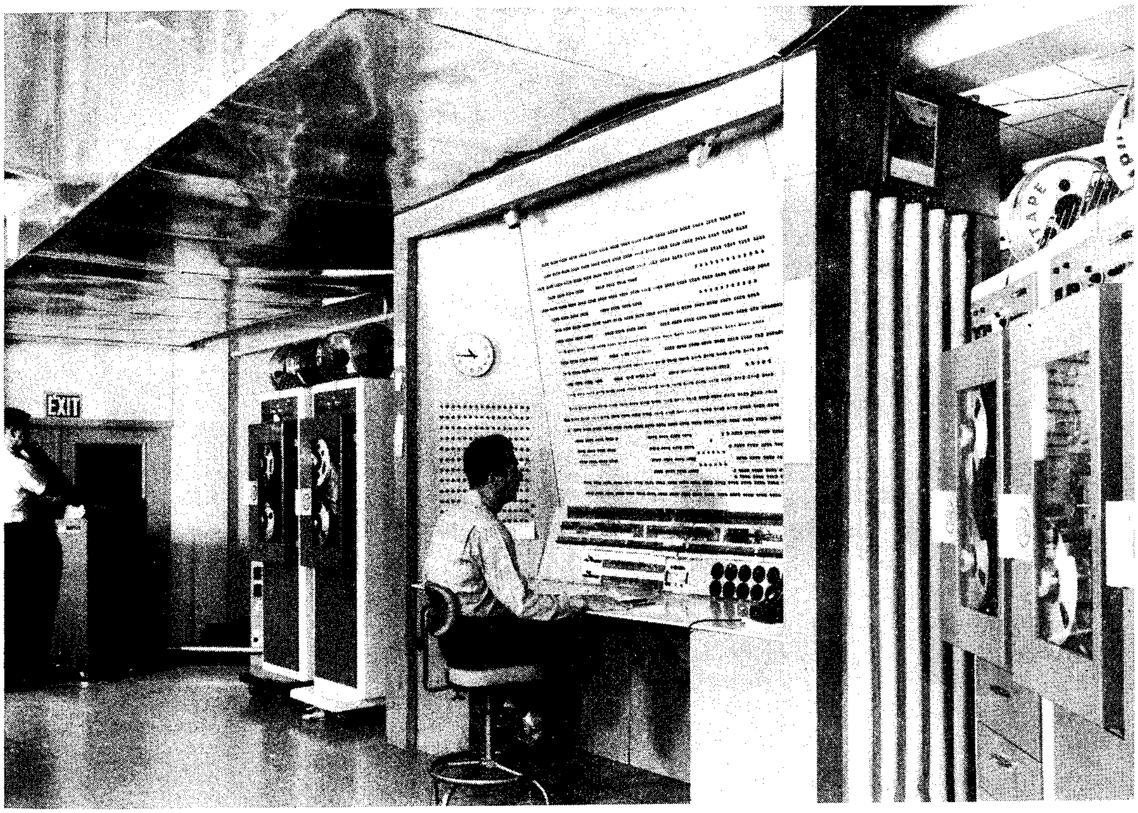
COMPUTER DEVELOPMENT

In 1956, engineers and scientists in the BRL Computing Laboratory began to develop a new computer to be called the Ballistic Research Laboratories Electronic Scientific Computer (BRLESC). Also that year, the Ordnance Department transferred money to the National Bureau of Standards for use in developing universal logical packages which could be used in the construction of a new, fast, reliable, scientific computing machine. The money helped the Bureau to arrive at a tentative design of arthmetic, logical, and control units. The design and samples of the logical packages were sent to BRL where computer specialists evaluated the design and conducted tests. BRL concluded that improvements in the design were necessary. The Bureau agreed with the BRL findings, approved modifications to the design, and in February 1958, received funding from the Ordnance Department to cover the costs of some 6000 packages to be procured in addition to those needed for the NBS computer, PILOT.

Also at that time, BRL programmers had prepared a description of the instructions that would be executed automatically by the new BRLESC. (The programmers had also prepared a program for ORDVAC which would interpret all of the BRLESC instructions; thus most of the BRLESC software was tested on ORDVAC before BRLESC was completed.) Emphasizing speed of operation, ease of programming, and overall economy, BRL designers continued to develop BRLESC independently of NBS's further computer development. The differences in end applications of the computers also played a role in that decision.

About 95 percent of the computer had been designed, assembled on the former site of ENIAC, and tested by 1960. Complete testing was not possible without the high speed memory (storage unit) which had been delayed by the contractor for about six months. Not so surprisingly, given the rapid growth in complexity and breadth of problems and an equally rapid growth in computer technology, when the memory unit did arrive in May 1961, BRL personnel decided that the word capacity of the memory was quite out of proportion to the already demonstrated performance and capability of the rest of the computer. The length of words was quite satisfactory; the speed, 1.5 microseconds read-write cycle time, was then the fastest in the world. The solution, of course, was the procurement of additional memory capacity. The initial memory of 4096 words was later increased in several steps to 147,456 words.

A valuable feature in BRLESC was the introduction of the indexing process whereby a programmer could use the same set of instructions in storage to process as much data as he desired simply by changing the index value instead of modifying the basic instructions. The details of modifying index registers and thus changing the course of the program, known as housekeeping, could be done concurrently with arithmetic operations on the BRLESC. Since as many as four



BRLESC I, 1962 to 1978

housekeeping instructions could be processed independently of the arthmetic unit, the result was a great savings in time in an overall computation.

The BRLESC went on-line in 1962 and its performance exceeded expectations; about 2400 hours of computations were performed during that year. The time to run a problem indicated that the machine was two- to eight-times faster than the most advanced, widely-used commercial systems—a tribute to the skills and talents of the BRL personnel who designed and assembled the machine. Only the components had been procured under commercial contracts.

During the first year of its operation, BRLESC was also used to test and "debug" programs for the Aberdeen Proving Ground Comptroller's accounting, record keeping, and reporting operations. The programs would be used eventually on the Proving Ground's own automatic data processing system.

Efforts were continued to improve the reliability of BRLESC and to increase its storage capacity. BRLESC originally used circuit boards with vacuum tubes. These were replaced by transistor boards which were not only more reliable, but more economical than the vacuum tubes that had an annual replacement cost of about $25,000 per year (about $85,000 per year in 1982 dollars). Eventually the entire arthmetic and control units were duplicated and replaced by integrated circuit boards, a procedure that reduced the space occupied by BRLESC to only 20 percent of that which had originally been needed.

During the time that the BRLESC was being developed, continual improvements were being made to the EDVAC and ORDVAC facilities.

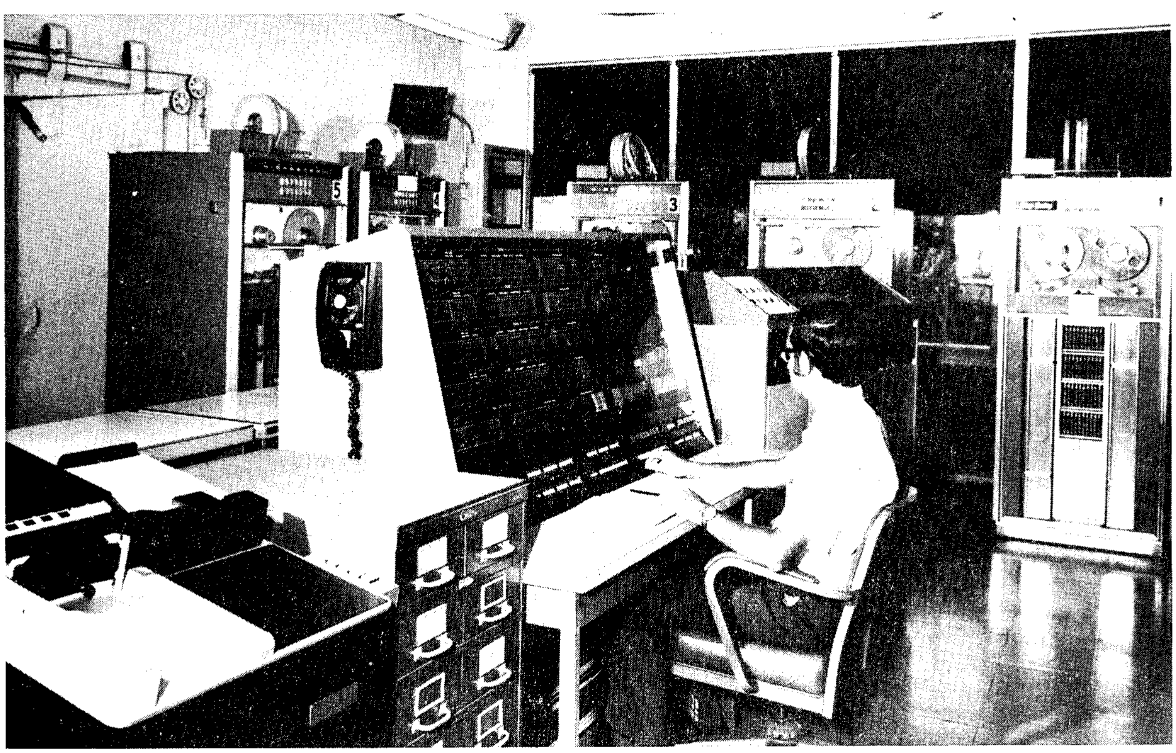
After ten productive years of service, the EDVAC was taken out of operation on December 19, 1962. This was a planned consequence following the installation of the BRLESC. The EDVAC had been installed in 1949; for several reasons its initial performance was unsatisfactory and extensive redesign and reconstruction were required for several years so BRL could redeem its investment in the system. However, it had begun to produce on a regular basis by 1952, and during the ensuing years, it operated on a round-the-clock basis seven days a week. Considering components and speed the EDVAC had become a quaint antique, but most of the fundamentals of operation embodied in EDVAC were still applicable to more modern computers. The EDVAC was dismantled during 1963.

Again, not surprisingly, demand upon computer facilities increased so rapidly that by 1965 studies were underway to quadruple the capacity of the BRL computer facility. These studies were to lead to BRLESC II, which began life in 1967 as ORDVAC II. (The original BRLESC became known as BRLESC I.) Although the design approaches differed for the two computers, BRLESC I and BRLESC II, the computer software was compatible.

BRLESC II was a solid-state digital computer designed to be 200 times faster than the ORDVAC it replaced in November 1967. The integrated circuits for BRLESC II were produced under an industrial contract. Logic design, back-panel wiring, and assembly of the computer again were all done by BRL employees.

BRLESC II provided more memory and decision-making cells and other components while occupying much less volume than that required by the old ORDVAC. As it came on line, BRLESC II initially shared a 96,000 word memory with BRLESC I.

The reorganization of BRL in 1968 brought about an even more intense focus upon mathe-



BRLESC II, 1968 to 1978

matical modeling and the construction of complex modular computer programs that describe in detail the course of physical and chemical events in weapons phenomena. Such computer programs and their applications to BRL problems necessitated the use of a very large, very flexible, expandable computational facility with an extremely large "conventional" computer as its major distinguishing feature.

Since BRL had been directed not to design and build any more computers in-house, primarily because of the extensive capabilities achieved by the commercial computer industry, commercial specifications and requests for proposals had to be prepared. In 1971, BRL interrupted an ongoing procurement action so that specifications could be upgraded in view of the projected long-term work load and the need for an extremely versatile and flexible computer system. It had become obvious that the initially projected requirements had been too conservative.

Procurement of the new facility was a five-year process involving definition of requirements, detailed specifications, requests for proposals, site preparation, cost analyses, proposal evaluation, negotiations, Department of the Army approval, and finally contract award. The competitive procurement resulted in a contract award late in 1976, to Control Data Corporation of Minneapolis, Minnesota and Vector General, Inc. of Woodland Hills, California. Control Data Corporation was to provide the central facility consisting of two major processors: a CDC CYBER 170/173 with host communications, processors, data channels, card readers, card punches, high-speed printers, magnetic tape handlers, control consoles, and intermediate access storage devices; and a CDC CYBER 70/76 with control console, small semi-conductor memory with 131,000 words, large core memory capacity of 512,000 words, and 800 million characters of intermediate access storage. The CYBER 70/76, the heart and brain of the system would be capable of handling 15 million instructions per second. CDC would also provide the remote facilities consisting of various interactive, batch, data acquisition, and graphics terminals. Vector General would provide four additional remote graphics terminals and all interfaces with the central site. (Acceptance testing of the computer facility began in October 1977; all 72 remote terminals were operational by February 1978.)

However, throughout 1976, BRLESC I and BRLESC II were the mainstay of computational services provided by the Computer Support Divison of the Applied Mathematics and Sciences Laboratory—services which were provided to the Laboratories, the Army Materiel System Analysis Agency, and the Human Engineering Laboratories.

The computational facilities are operated on an open-shop basis; members of the Laboratories' professional staff do their own problem formulation, programming systems analysis, and documentation. As needed, members of the Computer Support Division provide assistance and consulting service.

The computer hardware support is balanced by equally important software support that simplifies the use of BRLESC I and II. The software consists of compilers for the FORTRAN and FORAST languages, the operating system, predefined functions, a library of FORTRAN subprograms, some plotting routines, and several complete programs of general scientific usefulness.

BRLESC I and BRLESC II, early second generation batch computers, represented the last in the line of BRL designed and developed computers that had their genesis in ENIAC. (BRLESC I was shut down April 3, 1978 after 16 years of essentially round-the clock operation; BRLESC II was shut down July 1, 1978).

SOFTWARE DEVELOPMENT

The rapid growth of computing facilities in the United States during the latter half of the 1950's made it difficult for BRL to retain experienced programmers at BRL and to attract well-trained recruits. To minimize the impact of the personnel problem upon computer operations, training procedures for programmers and computer operators were streamlined so new employees and current employees with a minimum of formal mathematical training could be utilized as soon as possible. A second approach was the concept of "open-shop" computing, described previously. The success of this second approach depended largely upon the simplification of programming methods [and the provision of adequate instruction texts] so as to allow the originators of problems to program their short calculations after a minimum of instruction.

Before 1960, essentially all programming at BRL was done by having the programmers translate their assembly language into the actual numeric code required by the computer. In July 1959, Glenn A. Beck and Lloyd W. Campbell, BRL, proposed to simplify programming by combining an assembly program and formula translation into one routine which allowed symbolic addresses and a mnemonic language to be used rather than the final machine code. The routine should reduce both programming time and code-checking time without requiring an excessive increase in machine time to read-in a program.

In less than a year, the simplified language and translator program FORAST (FORmula and ASsembly Translator) had been devised and used on the ORDVAC. This language, much easier to program, allowed the programmer to write actual machine orders in symbolic assembly language, some arithmetic formulas written in a manner similar to conventional mathematical notation, and English words for high level statements instructing the machine.

During 1960–1961, FORAST was also implemented for the new BRLESC. Using FORAST, programmers found it relatively easy to communicate with BRLESC and to translate from a formula-type language into BRLESC instructions. Included in the FORAST compiler was a simple operating system that allowed automatic sequencing from one job to the next job.

In the course of development of the BRLESC FORAST compiler and other BRL software, BRL computer specialists wrote an interpretation program for ORDVAC that could interpret all of the BRLESC instructions; this allowed most of the BRLESC software to be tested on ORDVAC before the new BRLESC was completed.

FORTRAN (FORmula TRANslation) is a programming language, devised by IBM, used widely on a variety of computers. It was designed primarily for programming scientific problems and evaluating arithmetic formulas. During 1962–1963, a FORTRAN compiler was written for BRLESC; this was one of the first uses of the FORTRAN language on other than IBM computers. This was not an inconsequential achievement; FORTRAN is not the same for all computers. BRL experience with about two dozen FORTRAN programs acquired by various BRL laboratories disclosed many incompatibilities in these numerous FORTRAN "dialects". Elimination by BRL specialists of these incompatibilities required tedious, detailed, and subtle analyses. By 1966, the compiler had been upgraded to accommodate FORTRAN IV.

When BRLESC II came on line, the FORAST and FORTRAN IV languages were implemented for that computer during 1965–1966 and 1967–1968, respectively.

In 1974, most of the then proposed FORTRAN 77 language was being implemented on BRLESC II; this was one of the earliest implementations of the language.

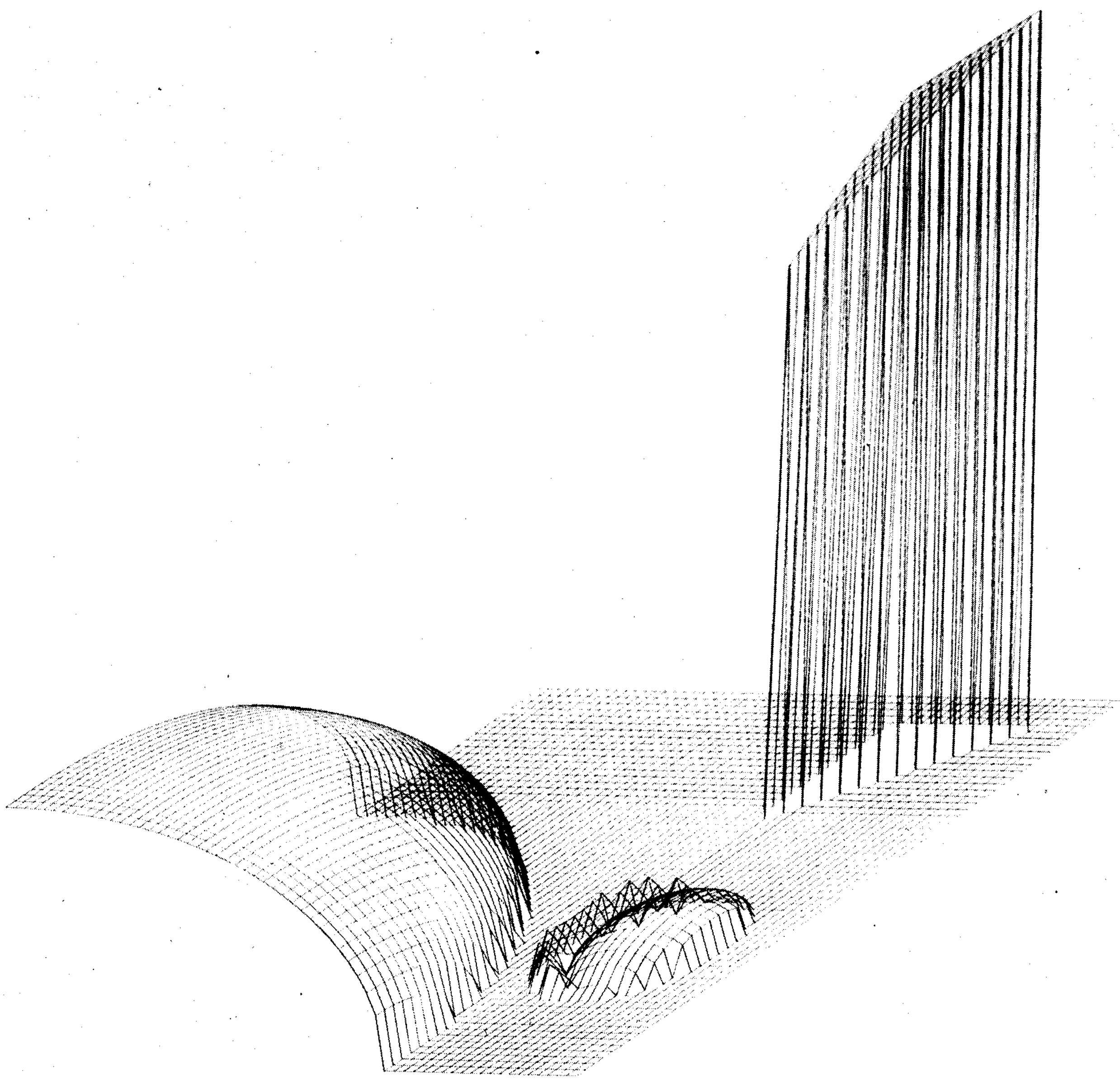
Applications of mathematical programming led to the formulation of several optimization problems and the development of appropriate algorithms for their solutions. These algorithms involved generally known techniques such as linear programming, dynamic programming, non-linear programming, and specific methods devised for the problem at hand. Illustrative of such applications are: the optimum choice of long-range study tasks for the Army Materiel Command ammunition contract bid, policy for the Ammunition Procurement and Supply Agency, cost analyses for BRL, and minimization of a guided missile fuzing error for the Army Missile Command.

When the software specifications were being prepared for the new facility in 1971, BRL computer experts had about 25 years of corporate experience in the design, development, or adaptation of software programs and operating systems. This experience was to be valuable because, for the first time at BRL, the necessary software would be provided by the successful bidder. Each software system or capability would be developed in response to a stringent BRL specification.

Thus in 1976, Control Data Corporation provided two integrated operating systems to organize and regulate the flow of information through the computational facility. These were the SCOPE operating system for the Model 76 System and the Network Operating System/Batch Entry (NOS/BE) for the Model 173 System.

SCOPE performs the executive functions to control the flow of jobs efficiently in the Model 76. It regulates the job input-queue from the batch jobs forwarded by the Model 173; monitors the queue; and, based on priority or other resource allocation, schedules jobs for execution. In addition to other functions, SCOPE operates the system library which allows BRL programmers to use the library and to create, modify, maintain and use their own libraries.

The NOS/BE operating system supports SCOPE



Computer graph of probability distribution and is the main element for interactive time-sharing and business-type data processing. However, very little business-type data processing is done.

Specified software packages and compilers include FORTRAN-Extended, SIMSCRIPT, SORT/MERGE, COBOL, DDL (Data Description Language), PERT/TIME (Project Evaluation and Review Technique with capability to determine critical path), INTERCOM, IMSL (International Mathematics and Statistical Library), and software test packages.

BRL computer specialists had early recognized that growth in the computer world was not only to be expected but inevitable. The design of the software as well as that of the hardware would permit necessary expansion in computational facilities which the future might require.

Although ballistic measurements of many kinds were being made throughout BRL, the history of ballistic measurements is treated here in a restricted sense as it parallels the activities of the Ballistic Measurements Laboratory up to the time, when with a change in name to the Signature and Propagation Laboratory, the emphasis in its program changed to research primarily concerned with target acquisition, guidance and control.

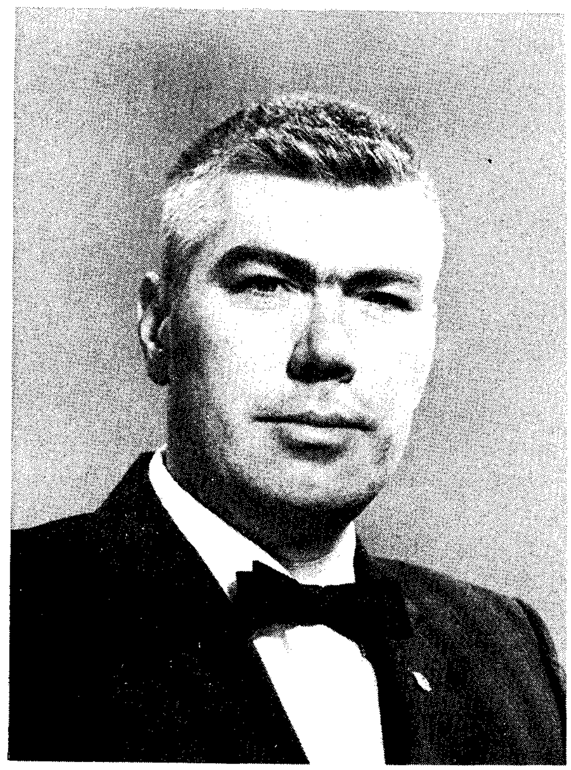
As this chapter in BRL history unfolds, the Ballistic Measurements Laboratory was heavily involved in optical instrumentation and measurements and in atmospheric physics. In the former subjects, the emphasis was on the development of missile tracking telescopes and ballistic plate cameras for use respectively in missile or satellite tracking and stereophotogrammetry. In the latter subject instrumentation development and data acquisition from *in situ* experiments were stressed. In both cases, much effort was expended in work that ultimately supported activities at White Sands Missile Range and other government agencies.

However, by 1959, the laboratory with members of the Special Projects Group (sucessor to the Future Weapon Systems Agency at BRL) had undertaken a program—which might be considered the beginning of target acquisition, guidance and contol activities at BRL—when inhouse support for guidance system analysis was provided to the Heavy Assault Weapon (HAW) Program. The results of this work found application in the concept for the Tube-Launched, Optically-tracked, Wire-command link (TOW) anti-tank weapon. The discussion of these early efforts is deferred until the section titled Target Acquisition, Guidance and Control.

The discussion here is concerned with BRL accomplishments in photogrammetry, instrumentation development and atmospheric research.

One of the most important and far reaching accomplishments of the late 1950's was the solution of the so-called general photogrammetric problem by Dr. Helmut Schmid. This solution developed at BRL was accepted by world photogrammetrists as the most rigorous approach available; it made possible the establishment of a world-wide geodetic triangulation system based on photogrammetric observations of a geodetic satellite carrying a flashing light, and the precise measurements of missile and satellite trajectories.

Concurrent achievement of techniques to synchronize shutters on ballistic cameras (BC-4) made possible the design and construction of a camera system capable of recording flashing-light satellites as well as "chopping" the trails of continuously illuminated targets like the Echo Satellites. The system was procured by the US Coast and Geodetic Survey for use in geodetic triangulation.



Mr. Warren W. Berning, Chief, Ballistic Measurements Laboratory, 1965 to 1967, received his BA (Physics) from the University of Cincinnati and his MS (Meteorology) from the California Institute of Technology. Mr. Berning joined the BRL staff as a meteorologist in 1947. He left the Laboratories in 1967 to join the Nuclear Defense Agency from which he retired in 1976 as Assistant (for Theoretical Research) to the Deputy Director for Science and Technology

As part of United States participation in the International Geophysical Year (IGY), BRL was given complete responsibility for the overall planning, installation and operation of a rocket launching facility located at Fort Churchill, Manitoba, Canada. BRL was also assigned responsibility for designing and operating optical and electronic ballistic tracking instrumentation at the rocket facility. Participating as a scientific agency, BRL's high altitude research included measurements of electric currents in the ionosphere, water vapor distribution, photometric studies of the earth's horizon, electron densities at satellite altitudes, electron density profiles, and aeronomic recombination phenomena. Lt. Col. Lloyd G. Smith, then assigned to BRL, directed the Laboratories efforts for the IGY.

The sudden appearance of the USSR Satellite SPUTNIK and shortly thereafter of SPUTNIK II furnished an unexpected opportunity to test a method for precision measurement that had first been proposed by BRL in October 1955. A hastily assembled task force of BRL scientists and engineers set about to improvise a station at Chapel Hill, Aberdeen, Maryland, with tracking telescopes in a very short time and to prove the soundness of the method. They were successful in doing both. Shortly thereafter BRL established DOPLOC, an electromagnetic method for tracking non-radiating satellites (Dark Satellites) which was used up to 1961 when it was no longer needed.

BRL *in situ* measurements of upper atmospheric and ionospheric phenomena continued until 1972; however, before then more emphasis was being directed toward laboratory experiments.

Dewpoint hygrometers carried by balloons and infrared absorption hygrometers borne by rockets were used to gather information on water vapor distribution at upper altitudes, the rocket-borne instruments particularly being developed to measure water vapor content at altitudes above 125,000 feet.

High altitude winds were measured by using chaff or chemicals released from high altitude probes fired from extended 5-inch, 7-inch, and 16-inch guns developed for the High Altitude Research Program (HARP).

As part of its ionospheric research program, BRL conducted a series of instrumented rocket firings at Fort Churchill during the International Year of the Quiet Sun (IQSY), 1964. The objective was to determine electron density profiles and earth magnetic field profiles in the auroral zone at a time of low sunspot activity.

Electronic instrumentation design and development during the 1960's continued to concentrate on methods for collecting data from projectile and missile borne experiments and missile and satellite trajectories. For the case of projectile-borne experiments these activities required the development of miniaturized rugged circuits that could withstand high acceleration forces and, for experiments designed to acquire information during nuclear events, development of radiation-hardened circuits and components.

A program in research and development for antennas accompanied the instrumentation development as did the development of ground based equipment for data receiving, recording, and analyzing. And here as elsewhere the digital computer was exploited to automate operations and to facilitate data reduction and handling. Measurements of electron content and electron densities in the ionosphere by rockets probing the upper altitudes owed their success to the design, development, and fabrication of phase-coherent, multi-frequency beacons by BRL personnel; commercial products were either not available, or if available could not meet the rigid performance and environmental specifications.

The preceding two paragraphs require amplification. The importance of BRL photogrammetric research to progress in geodesy has been noted above. One should note, too, contributions to later improvements in geodetic techniques made possible by the Laboratories work in electronic instrumentation and antenna research during the 1960's. Now in 1983, long-base-line-RF interferometry and related techniques are being used to refine geodetic methods. BRL scientists and engineers pioneered in radiowave interferometry (for example, DOVAP and DOPLOC, which are discussed respectively in Volume I, and below) and methods for analyzing radiometric data. The two-frequency, phase-coherent transmitters, which correct for ionospheric effects, used in the TRANSIT navigation system can be traced to early work by the Naval Research Laboratory and the Ballistic Research Laboratories in phase-coherent systems. The multifrequency RF propagation beacons, essential for radiowave interferometry, were developed by BRL under the US Nuclear Test Readiness Program funded by the Defense Atomic Support Agency.

In 1960, BRL researchers developed a unique phase-lock filter for use with an RF interferometer receiver. As a consequence, the range and sensitivity of the radiometric system were improved by as much as an order of magnitude over those of systems then in use in the United States. By 1963, BRL had developed solid state phase-lock filters which made possible for the first time, a DOPPLER receiver capable of tracking missiles and yielding real-time digitized data. Subsequently, the phase-locked radiofrequency receiver became an essential component of data systems for all deep-space programs.

ANNA satellite (circled) photographed against star background

PHOTOGRAMMETRY

The large effort expended on research and development of tracking instruments was paralleled throughout the 1950's and 1960's by analytical and applied research in photogrammetry. Many problems—methods of measurement, data reduction, and to some extent atmospheric effects upon the transmission of light—were common to both fields. Consequently there was a constant exchange of ideas among the BRL scientists engaged in the fields: the "tracking" of satellites by fixed, plate cameras (Ballistic Cameras) derives from the use of similar cameras used to photograph star trails for geodetic station nets.

As the era opened at BRL, applied photogrammetric research included the investigation of errors in precision camera systems. Cameras were calibrated under laboratory conditions and scale distortion was determined by measuring star fields and aerial photographs of the Coast and Geodetic Survey photogrammetric range. Other research considered the shrinkage of the emulsion of photographic plates and the influence of environmental conditions on stereocomparator errors.

Fundamental research concentrated on a rigorous analytical approach to the general solution of photogrammetry with the view of converting the photogrammetric method from a tool of engineering to a method for precise scientific measurement. The efforts were accompanied by the development of computer programs to provide means for practical applications of the research results.

Solution to the General Problem of Photogrammetry. The classic general problem of analytical photogrammetry is the simultaneous restitution of the orientation of any number of photogrammetric records and the reconstruction of the object space through triangulation of corresponding rays. The solution, in brief, was not to be limited by restrictions on the type and orientation of any one camera or with respect to the number, type, and location of control data.

In a general solution, it must be possible to enforce any number of geometric conditions concerned with any one or all of nine orientation parameters as well as with any one or all of the coordinates of the object space. Furthermore, it must be possible to consider both the measurements made on the camera plate and the given control as erroneous, so as to introduce weighting factors into the computations.

BRL started a project for developing and testing analytical solutions to the general problem in the middle fifties, with the study of the orientation of a single camera by Hellmut Schmid. Schmid followed that case with a solution for triangulation using two photogrammetric cameras; in 1959 he solved the case for n-cameras. In so doing he provided the solution for the general problem by using matrix calculus to set up a system of equations well-suited for treatment by electronic digital computers. The solution uses space coordinates (x,y,z) rather than directions, which had been used heretofore. Consequently, there is the possibility of using "partial points" i.e., values of x, y or z, or combinations of two of these. Such treatment was not possible in earlier approaches. This BRL work is the first in which the entire photogrammetric problem was considered analytically and is the first to present least squares adjustments to original observations.

Other Analytical and Theoretical Work. The next step in analytical photogrammetry at BRL was the development of a family of computer programs written in FORTRAN. These efforts provided practical photogrammetric codes to government and industry users, without the necessity for each user to compile complex and costly programs separately.

Theoretical work then considered error propagations in complex spatial triangulation systems; results were applied to the analysis of a world-wide triangulation net. Since the precise location of a satellite against its star background was the key to establishment of the net, BRL developed programs to identify star images automatically (and to compute standard coordinates of the reference net stations).

The Laboratories' lead in this space-age field was recognized when BRL was asked to formulate and undertake the basic system analysis for the world-wide geodetic satellite project. The National Aviation and Space Agency was the director for the project which also involved the US Coast and Geodetic Survey. BRL had already been cooperating with the US Corps of Engineers in their photogrammetric mapping satellite project.

SATELLITE DETECTION: SPUTNIK AND "DARK" SATELLITES

The sudden appearance of the USSR satellite SPUTNIK I, and shortly thereafter that of SPUTNIK II, gave BRL an unexpected opportunity to confirm a method for precision measurements that had first been proposed by BRL scientists in October 1955. In the process, BRL obtained the free-world's first known precise orbit information on SPUTNIK II, November 7, 1957. This achievement marks a significant advance in the technology for long-range missile detection and defense, and in the science of astronomy.

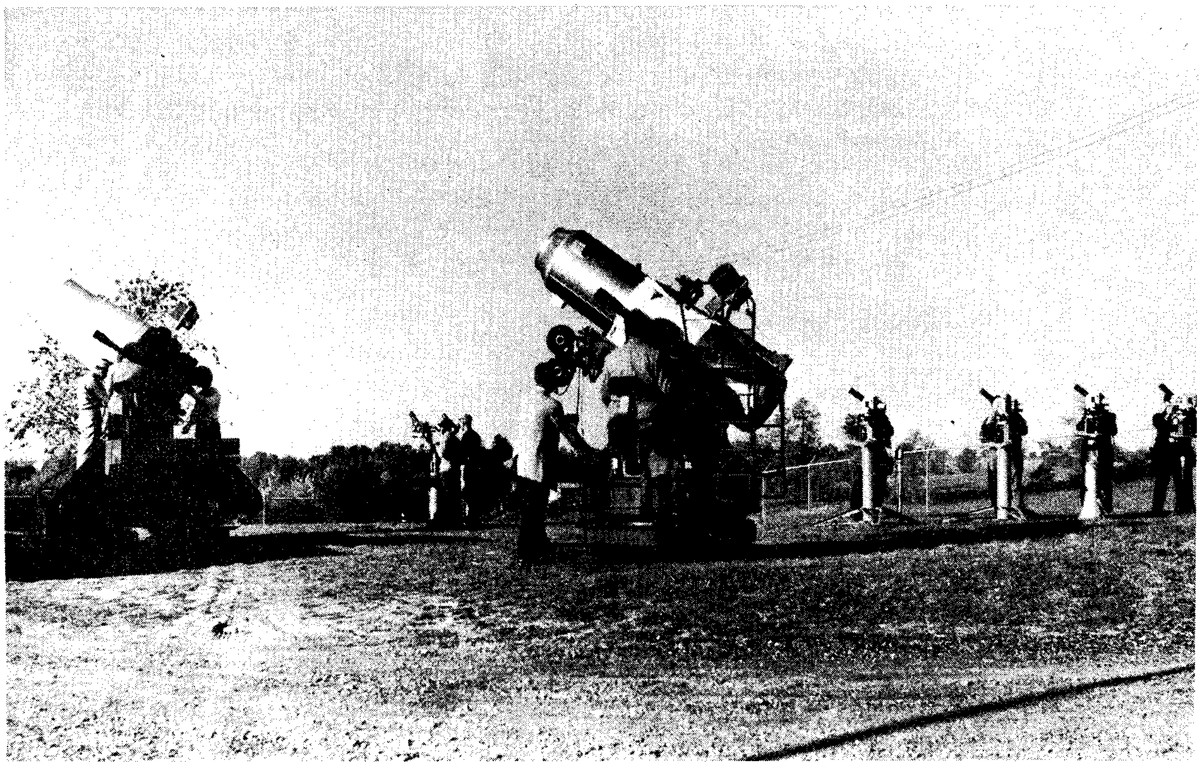
The method proposed by BRL was based on observing the satellite against a background of reference stars, by means of a tracking telescope of high light-gathering power to photograph the satellite, and a wide angle precision camera to record satellite and star images, as the satellite travels along its course in the sky.

The rapid and effective deployment of these telescopes for this unintended use was due largely to the efforts of Walter J. Carrion of BRL, their designer.

The decision to attempt to photograph SPUTNIK I (and later SPUTNIK II) meant that two systems being developed by BRL for use at White Sands Missile Range had to be hastily improvised into ballistic camera systems. These were the IGOR (Intercept Ground Optical Recorder) designed to determine the miss distance for missiles intercepting airborne targets, and SMT (Small Missile Telecamera) designed to determine accurately, points on the trajectory of small high-speed missiles.

The crash program was successful; the cameras were in place on Spesutie Island at the Proving Ground, but prevailing fog and clouds permitted only one photographic sequence of a passage of SPUTNIK I. Good filmed shots of the satellite's third-stage rocket were obtained, but it was impossible to fix the much dimmer satellite itself.

The SMT and IGOR cameras were then moved



Battery of tracking telescopes and cinetheodolites set up to track SPUTNIK

to Chapel Hill, Maryland, the highest point (400 feet) near the Proving Ground. Usable records were obtained on the dawn passage of SPUTNIK II on November 7, 1957. Seven exposures of the satellite, covering a total time of 2.4 seconds, were captured on the SMT film; the corresponding plate on the IGOR system contained a total of six stars in the constellations Bootes and Draco which served as reference points. Subsequent calculations fixed the orbit of the satellite which had been traveling at a speed of 18,000 miles per hour at an altitude of 150 miles.

In preparation for the International Geophysical Year, the Laboratories had been developing electronic equipment for tracking satellites. The equipment was being designed specifically for obtaining doppler shift data to measure electron densities at the satellite altitude. Unprepared to use this special equipment at the time of the SPUTNIK launchings, BRL personnel pressed into service a variety of standard and special laboratory instruments to receive the signal transmitted at frequences of 20 MHz and 40 MHz by the satellites.

Detecting "Dark" Satellites. Early in 1958, The Advanced Research Project Agency (ARPA) of the Department of Defense assumed responsibility for the direction of a committee established to investigate technical problems involved in a national satellite tracking project. The committee established working groups for detection and tracking, communications, data processing, United States programs, and foreign programs. The chairman from these five working groups formed an *ad hoc* committee when ARPA requested that immediate emphasis be given towards the detection of non-radiating or "dark" satellites; that is, satellites not emitting radio-frequency signals. The approach proposed was to exploit the Minitrack system developed by the Naval Research Laboratory and the DOPLOC tracking system developed by BRL, each modified to detect dark satellites.

ARPA's initial specifications were: the national network should be able to detect objects having effective radar reflection cross section of 0.1 square meter or greater at distances between 100 and 1000 miles; determine orbit parameters in a relatively short time, preferably within one orbit; and to determine immediately whether the detected object was in fact a new object, or one that had been detected previously and was known.

However, the committee pointed out to ARPA that the state-of-the-art restricted system capability to targets having a radar cross section of one square meter at an altitude of one thousand miles or less; the effects of meteors, aircraft and so forth on the tracking systems could not be predicted completely; and computational programs for orbit determinations had not been developed. The group estimated that a satellite "fence" spanning the United States in an East-West direction, at about North Latitude 32°, composed of two Minitracks and one DOPLOC complex could be installed and in operation within six months.

In June 1958, ARPA directed BRL to develop a long-range tracking system; to construct, instrument, and supervise the operation of tracking stations; to analyze reflected signals; and to reduce orbital parameters of passive satellites passing over a specified area of the US.

Using state-of-the art techniques and essentially available equipment, under the leadership of Dr. L. G. DeBey, BRL with some help from the Army Signal Corps within six-months, 20 December 1958, had installed a three-station complex consisting of a fifty kilowatt illuminator/transmitter at Ft. Sill, Oklahoma, and receiving stations at Forrest City, Arkansas, and White Sands Missile Range, New Mexico. Three Minitrack antennas were used at each station. The satellite was detected when the receiving stations acquired the transmitter signal reflected from the satellite. The receiving antennas were designed to detect the approach of a satellite as it came over the horizon, to intercept it again as it passed overhead, and again as it receded towards the horizon.

Realizing from the beginning that the interim system would have limited range and coverage, BRL personnel urged ARPA to supply funds for research to develop a tracking system capable of meeting the original specifications. ARPA provided the necessary funds and also relieved BRL from routine tracking which was supplying data to an information filtering center.

As a result of the technical evaluation of the competing "Shepherd" system, ARPA decided that the extended DOPLOC system, proposed by BRL in 1959, would not meet the immediate objectives of the detection program. Consequently further research in the DOPLOC system was not needed; ARPA directed BRL to plan for an orderly close-down of the DOPLOC complex. The complex ceased operations in June 1961.

The DOPLOC system had shown its ability to detect, track, and compute reliable orbits within minutes after a single passage of a non-radiating satellite over a single station. In its time, it had the highest discrimination or resolution capability against meteors and other extraneous signal sources of any known system for satellite detection.

HIGH ALTITUDE RESEARCH

Compared with other civilian and military organizations, the Ballistic Research Laboratories were latecomers in the field of upper altitude research using rocket and balloon sounding systems. On the other hand, the Laboratories had been associated with and had provided services for the Army's upper atmosphere program since its inception.

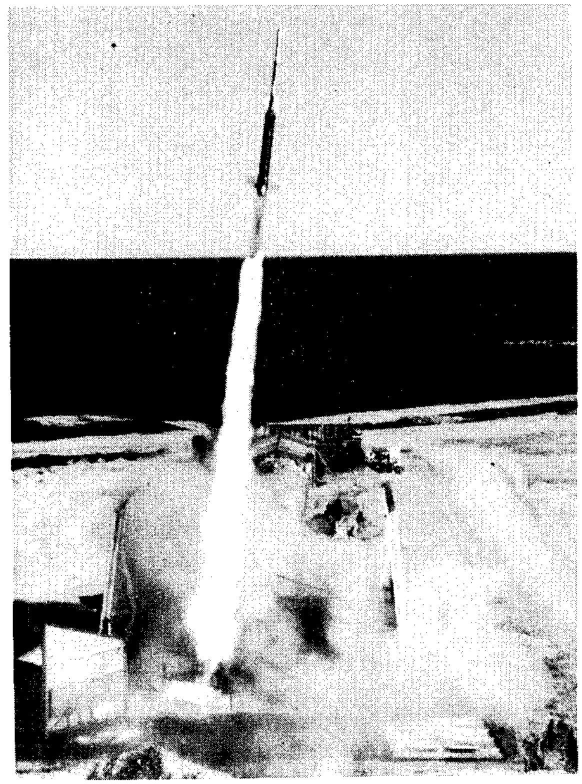
The development of a radio Doppler tracking system (DOVAP, standing for Doppler Velocity and Position) led to its use, in 1950, for measuring electron densities in the atmosphere. Computer methods were developed for extracting ionospheric information from DOVAP records of V-2 and Viking rocket trajectories at White Sands Missile Range. A two-stage V-2/WAC Corporal rocket launched in 1949 had carried DOVAP equipment. Later reduction of the data gave, for the first time, quantitative measurements of electron densities above the F-2 maximum of the ionosphere, at approximately 300 kilometers.

The pace and complexity of the Army's materiel development program require a substantial portion of research to be long range so that solutions, if they exist, will be available at the proper time. BRL's programs exploring the high altitude environment in which some army systems are expected to function illustrates such research.

The plasma structure and the electron and ion content along a ray path and the ion densities at certain altitudes affect the performance of long range command, control, and communications systems and Ballistic Missile Defense (BMD) radar. Thus one needs to know the constitution of the normal atmospheric environment, the naturally disturbed environment, and the nuclearly disturbed environment. Changes induced through nuclear explosions are extremely deleterious to the performance of those systems. To predict the performance of the systems following such an event, one must be able to predict the manner and time for the atmosphere to deionize or return to an operational condition. In addition to the densities, one must know the spatial variability of the densities and the effect of the variability on electromagnetic propagation.

For several years (1968–1976) the BRL program centered about the development of computer codes used to describe conditions of the atmosphere encountered by the system and to predict the effects of the conditions on the system. Development and evaluation of codes required direct and indirect probing of the atmosphere under difficult conditions, laboratory measurements of the controlling rate constants, theoretical calculations, and model construction.

The partial summary here is a measure of BRL's efforts in equipping probes with instrumentation to make *in situ* measurements at high altitude



Nike-Cajun rocket firing at Wallops Island, Virginia

In 1976, the responsibility and mission for research in atmospheric sciences was transferred to the Atmospheric Sciences Laboratory at the White Sands Missile Range.

PARTIAL SUMMARY OF HIGH ALTITUDE PROBES		
Probe Type	Dates	Number of Launches/ Flights
Sounding Rockets	Aug 56–Nov 71	99
Balloon Borne Hygrometer	Apr 58–Mar 66	91
Project HARP 5-Inch Gun	Jun 61–Jul 72	607
Project HARP 7-Inch Gun	Dec 64–May 72	147
Project HARP 16-Inch Gun	Jun 63–Jan 67	279

Some BRL efforts and contributions in *in situ* measurements and laboratory experiments appear below, chronologically.

The International Geophysical Year (IGY). In 1951, the Special Committee for the International Geophysical Year of the International Council of Scientific Unions set the date for an International Geophysical Year—July 1957 through December 1958. Basic and applied research to be carried out in the interval included meteorology, geomagnetism, aurora and airglow, ionospheric physics, solar activity, cosmic ray, latitude and longitude mensuration, glaciology, oceanography, and so forth. A United States rocket program for upper air research during the IGY was developed by the Special Committee for the International Geophysical Year (Working Group on Rocket Operations) of the Technical Panel on Rocketry for the United States National Committee for the IGY. The primary mission for SCIGY was to implement the scientific objectives of the sounding rocket program. The mission also included planning and supervising site construction, coordinating rocket firing schedules, and operating a rocket range at Ft. Churchill, Manitoba, Canada. The SCIGY received assistance from many quarters, among whom was the Inter-service Coordinating Group, created by the Department of Defense to implement the SCIGY requirements and to coordinate DOD logistical support. Subsequently, in 1955, the Chief of Ordnance directed the Ballistic Research Laboratories to support the IGY rocket project at Ft. Churchill.

Given to BRL were responsibilities for conducting a first-order geodetic survey of the range and support facilities, installation and operation of Doppler Velocity and Position (DOVAP) receiving and recording systems, and DOVAP telemetering and ballistic camera equipment at Ft. Churchill. BRL was also responsible for reducing DOVAP and ballistic camera data and supplying the results in a usable form to the agencies sponsoring rockets.

So that any problems requiring corrective action could be determined before the start of the IGY program, a pre-IGY rocket launching program was scheduled at Ft. Churchill for October and November 1956. During that period, one Nike-Cajun and six Aerobee research rockets were launched. The pre-IGY program was a notable success. Six of the scheduled seven rockets were launched (one Aerobee rocket exploded in the launch tower); the upper air research experiments carried by each were successful as well.

Two problems of major importance did become immediately apparent: more serious was that of radio-frequency interference among the DOVAP and other carrier systems; less serious was the installation of DOVAP antennas on the rockets. Both problems were corrected before the onset of the program.

The IGY program at Ft. Churchill began on International Geophysics Day, 4 July 1957, and ended 5 December 1958. During that time, BRL launched 35 Aerobee rockets, 44 Nike-Cajun rockets, and 5 Aerobee-300 rockets (Spaerobees). Approximately 45 percent of all rockets used during IGY were launched at Ft. Churchill. Of the total launched there, 60 carried DOVAP transponders to provide information for trajectory determination. Three Wild BC-4 cameras were used during five rocket flights. These ground-based stations measured the coordinates of rocket borne grenades exploding at altitudes ranging from 18 to 55 miles.

Several "firsts" were achieved by the successful performance of BRL high altitude experiments, but even when they did not represent such a "first" the results from BRL's participation were gratifying:

- Electron Density Profile. Ionospheric charge densities were obtained from the DOVAP tracking records for those firings at Ft. Churchill where the rockets penetrated sufficiently into the ionosphere. Of special interest are the magnetometer experiments where for the first time simultaneous measurements of the Earth's magnetic field and the electron charge in the ionosphere were made.
- Photometric Studies of the Earth's Horizon. To study the absorption bands in and about the tropopause, rocket-borne cameras photographed the horizon. Varying degrees of stratification, believed due to local concentrations

of water vapor, were discernible in photographs of the horizon haze layer. The computed average height of the photometric horizon was approximately seven miles. The estimate agrees with the hypothesis that the Ft. Churchill photometric horizon represents the polar tropopause. Pictures from two of the flights were combined by the U.S. Weather Bureau into a composite which represents for the first time a view of the Arctic cloud structure as seen from high altitudes.

- Electric Currents in the Ionosphere. Short term variations in the earth's magnetic field have been attributed for many years to the existence of tidally induced motions of charged particles in the lower ionosphere. The nature of the resulting currents, particularly in auroral regions, is of great geophysical interest. BRL fired three Nike-Cajun rockets instrumented with proton precession magnetometers. The magnetometers performed successfully; in one case, the experiment took place on a day with exceptionally few variations; results from those measurements can serve as an excellent calibration standard for the earth's magnetic field above Ft. Churchill.

Project Frost Point. Water vapor concentrations to the altitude of the mesosphere are quite important to the meteorology of higher atmospheric levels and to atmospheric chemical processes. The horizontal as well as the vertical distribution of water vapor are useful in the study of transport and mixing processes in the atmosphere. Furthermore, the chemical properties of water vapor play an important role in determining temperature and composition in the stratosphere. To determine quantitatively the water vapor content, BRL developed an infrared hygrometer sun-follower to be flown in a Nike-Cajun rocket.

Balloon-borne dewpoint hygrometers were flown in support of the rocket flights to give independent measurements up to 30 km and to check the correct operation of the rocket instrumentation.

The principle behind the balloon-borne hygrometer is dewpoint determination by measurement of the temperature at the time of dew spot deposition; and in the case where the dewpoint is below 0°C, the temperature of frost spot deposition. The information obtained by the hygrometer is transmitted via a weather sonde. Data from a successful flight to 110,000 feet in support of the photometric horizon investigations at Ft. Churchill showed considerable moisture in the lower stratosphere and numerous stratified layers, especially in the tropopause. Several layers of moisture in the tropopause were delineated in sharp detail.

Subsequently, in 1960 and 1961, the balloon-borne experiment, then called Project Frost Point, expanded its scope to investigate variations of stratospheric water vapor with respect to season and latitude.

The first of the seasonal tests was carried out in April 1960 in the northern hemisphere. Five stations were used in this synoptic test: Thule AFB, Greenland; Ft. Churchill, Canada; Annapolis, Maryland; Patrick AFB, Florida, and Albrook AFB, Panama Canal Zone.

A comparison of moisture profiles at Thule and Ft. Churchill during 1960 with profiles of flights made at Ft. Churchill in the fall of 1958 showed a decidedly dryer atmosphere, thus indicating the seasonal variation of water vapor content in the atmosphere. A cross-sectional graph of dewpoint data using both standard radiosonde flights and data from the April 1960 Frost Point operations show a decrease in stratospheric content with increase in latitude.

The second seasonal test began during December 1960 at McMurdo Sound in the Antarctic. The series was sponsored by the National Science Foundation. No seasonal trend was apparent possibly because the time interval, late December to early February, was too short. Concentrations varied extremely from flight to flight and seemed to depend more on prevailing weather rather than on the season.

The next series of launchings in the northern hemisphere took place in September 1961. The major finding was that the top of the water vapor inversion layer (water vapor increasing with altitude) was observed in the stratosphere.

The existence of a significant amount of water vapor in the upper atmosphere came to be generally recognized by 1962. The influence of this water vapor on such phenomena as radiation from shock waves emanating from re-entry vehicles and absorption of infrared radiation at high altitudes remained to be determined. Results of BRL work indicated that water vapor concentration may be even more variable at high altitudes than close to the earth. Continuing its program in this field, BRL launched additional balloons at the National Center for Atmospheric Research (NCAR) in Palestine, Texas. These flights carried complementary, but independent measuring devices, the dewpoint hygrometer and an infrared absorption hygrometer. During those flights both instruments were carried on a single balloon to collect water vapor data and to compare instrument performance.

High Altitude Research Program, HARP. Except for the results of scientific experiments at altitude, the details of HARP appear in the chapter on exterior ballistics. The initial payloads for the 5-inch HARP probe were chaff and grenade packages; later in 1962 and 1963, they included flare and parachute packages as well as experimental high-acceleration telemetry packages. When a 7-inch system was developed during 1963–1964, the larger diameter permitted packaging significant on-board electronic instrumentation (sun sensors, Langmuir probes for measuring electron density, and on-board temperature measurements), as well as meteorological-sonde parachute packages capable of measuring pressure and temperature from 250,000 feet to sea level. The 16-inch guns at Barbados and Yuma were used to measure wind shear at altitudes from 80 to 150 kilometers. The 16-inch gun at Barbados was also used to measure lower level winds, temperatures and pressures at altitudes from 70 kilometers to sea level, and to provide ionosonde measurements for the National Bureau of Standards. With a 7-channel 1750 MHz telemetry system, the HARP 16-inch vehicle also measured electron densities. The results compared well with similar data acquired by sounding rockets passing through the D-layer.

The Strongarm Project. The purpose of the Strongarm Project was to measure the density of free electrons in the ionosphere to an altitude of 1000 kilometers. Although good electron density measurements had been obtained from ten of the Ft. Churchill IGY rocket flights, only in one case did the flight attain an altitude approaching the F2 maximum layer at 300 kilometers. Thus, it was decided by BRL in 1959 that further attempts should be made to measure electron densities at higher altitudes.

A new solid propellant multi-stage rocket configuration, Strong Arm, was assembled for this purpose by the University of Michigan under contract to BRL. The five-stage rocket consisted of an Honest John Rocket, two Nike-Ajax boosters, a slow-burning Recruit (Yardbird) rocket, and a scaled Sergeant missile. The twenty-pound payload contained an oscillator, two transmitters, at 37 and 148 MHz, antennas, and a temperature measuring transducer (to measure the nose cone wall temperature beneath the ablating nose cover). The Strongarm rockets were launched by University of Michigan personnel aided by firing crews at NASA's Wallops Island Facility. Two firings were conducted at Wallops during November 1959. The first flight achieved an altitude of 1100 miles, for that time a record altitude for rockets launched from the Island. The flight provided excellent electron density data. Unfortunately the second flight was lost when the third stage failed to ignite.

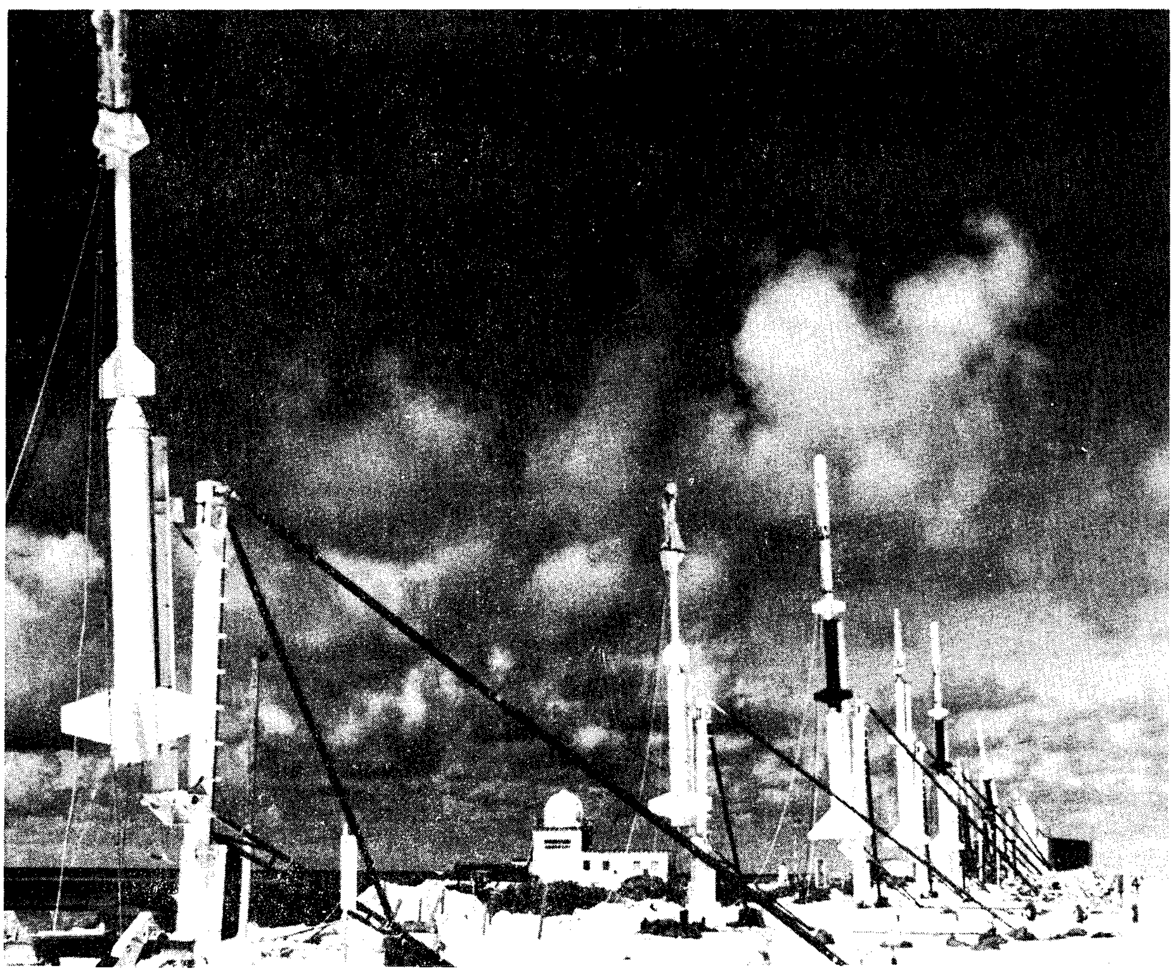
A second series of three Strongarm rockets was fired at Wallops Island in July and August 1960. Although none of the rockets in this series attained the desired altitude of 1000 kilometers because of failure of either the fourth or fifth stage (the highest altitude was 450 miles) valuable new electron density data were acquired in the still relatively unexplored region above the F2 maximum.

Defense Atomic Support Agency Project Fish Bowl (Operation DOMINIC). In 1962, under DASA sponsorship, BRL directed a large contractual effort and a considerable in-house program which culminated in the launching of 28 multi-stage sounding rockets to measure atmospheric characteristics and debris motions associated with three high-altitude nuclear bursts. These nuclear tests were carried out at Johnston Island in the Pacific Ocean.

The specific characteristics measured by rocket-borne instruments were prompt gamma radiation, delayed gamma and beta radiation from the debris, debris motion as determined by a gamma ray scanning telescope, electromagnetic emission at a wave length of 3914 angstroms from the first positive band of N_2^+, electron and ion density, electron temperature, ionospheric electron content, and positive ion composition. These characteristics were of particular interest in the D-region of the ionosphere (40–90 kilometers).

In addition to technically supervising the sounding rocket program, BRL made 3-frequency propagation beacons for 18 of the rockets. These beacons measured the integrated electron content in the ionosphere. The ground equipment needed for reception was designed and made at BRL, installed in trailers, and operated at Johnston Island by Laboratory personnel. The same ground stations received signals radiated from the Transit IV satellites (Omicron and Eta). Those signals provided means for measuring the total electron content between the satellite and the ground station; the results defined the long term effects of the nuclear explosions in the ionosphere.

Application of the Faraday-Doppler data reduction technique to the satellite data obtained gave independent determinations of electron content and ionosphere effective height profiles for forty passes of the Transit IV satellites. The three-frequency beacon propagation experiment provided electron density and content measure-



Sounding rockets at Johnston Island in 1962 ments for fifteen of the eighteen rockets that carried the beacon. Records of beacon signal strength permitted determinations of such parameters as blackout initiation and duration; post-burst absorption, rocket spin and precession, and antenna pattern and polarization. These data and the information on electron density and content constituted the major data base for weapons effects prediction codes developed in later years.

The International Year of the Quiet Sun (IQSY). BRL conducted a series of instrumented rocket firings at Fort Churchill, Canada during the International year of the Quiet Sun. The objective was to determine electron density profiles and earth magnetic field profiles in the auroral zone at a time of low sunspot activity. Knowledge of these ionospheric characteristics provides an understanding of electromagnetic propagation phenomena in northern latitudes. Measurements in the auroral zone are also important because it is a naturally disturbed region which can be used to simulate a nuclearly-disturbed atmosphere.

The field program was carried out in November 1964 when two Nike-Apaches instrumented with magnetometers and two Argo D4 rockets instrumented with two-frequency, phase coherent propagation beacons, magnetometers, and Langmuir probes were launched at Fort Churchill. The rockets were fired in mixed pairs, with an Apache preceding an Argo D4 by 90 seconds, followed by another Apache-D4 pair 36 hours later. The first rocket pair was fired at approximately local noon and the second pair at approximately local midnight, for the purpose of observing the diurnal variation in the parameters being measured. The near-simultaneous launching of the Apache and D4 in each pair was an attempt to resolve the ionosphere currents that might be encountered. Previous measurements of the geomagnetic field in the auroral zone ionosphere had revealed a complex variation of the field perturbations as a function of rocket flight time and position and very poor correlation of high altitude field variations with those at ground level. This lack of correlation indicated that the ionospheric current systems producing the most notable perturbations (as measured from the rocket vehicle) are quite small compared with the approximate 100 kilometer distance separating the rocket magnetometer from the ground magnetometer. Since the temporal characteristics of the high altitude perturbations cannot be determined from ground level measurements, it had not been possible to differentiate between spatial and temporal variations as detected by rocket-borne magnetometers. For this reason the Apaches instrumented with magnetometers were fired shortly before the D4's; thus the Apaches were essentially stationary at their apogee in the E-region as the D4's traversed a trajectory from the E-region to above the F-region.

Excellent electron density profiles from the propagation experiment were obtained on both the day and night shots. Of particular significance were the data from the rocket 8.19 DI fired at 1439 local time on 5 November 1964. The results provided dramatic evidence of the influence of the sun's activity on the earth's ionosphere.

From the standpoint of vehicle performance and data return, this was one of the most successful rocket programs that BRL has conducted. The vehicles performed as predicted, all instrumentation functioned as planned, and excellent data were obtained to D4 peak altitudes of 7.2 km and 855 km and to Apache apogee of 150 km. In addition to the scientific significance of the data obtained it should also be noted that these were the first D4 rockets to be launched from the Churchill Range; the use of this range for future firings of similar high altitude, long-range rockets was heavily dependent upon satisfactory (and predictable) vehicle performance.

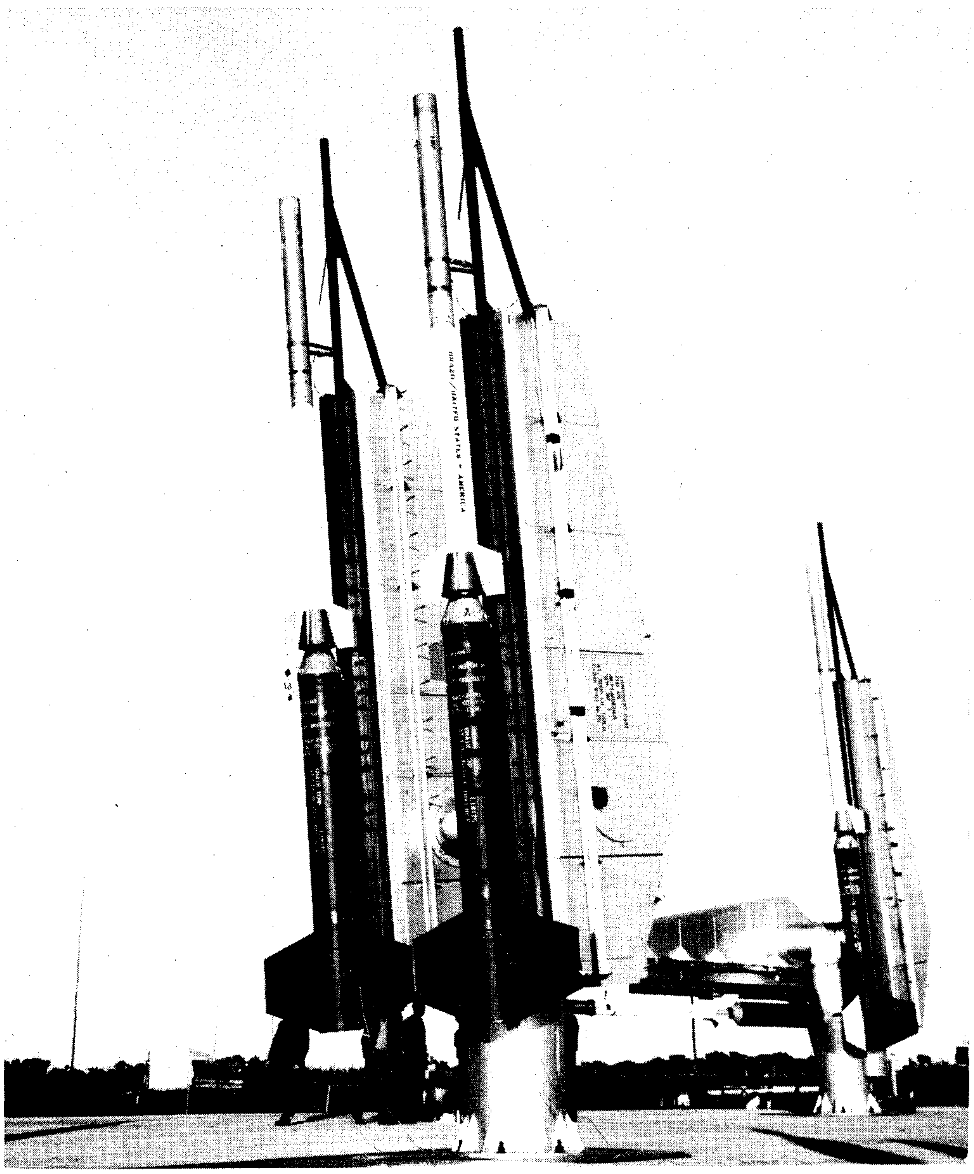
This program was partially supported both with funding and vehicle support by NASA. The Air Force handled launch procedures. The Space Physics Research Laboratory of the University of Michigan supplied the Langmuir probe instrumentation for electron temperature and reduced that data.

The Solar Eclipse, Brazil, 1966. The National Aeronautics and Space Administration, the Defense Atomic Support Agency, Sandia Corporation, and the Brazilian Space Commission (CNAE) cooperated in a sounding rocket program designed to study ionospheric changes occurring during the total eclipse of November 12, 1966.

For this program, fifteen two-stage rockets were launched from a site located within the path of the total eclipse, specifically at Cassino, near the city of Rio Grande, on the southeastern coast of Brazil.

Mr. Harold W. Zancanata, BRL, served as the technical coordinator for all DASA-funded ground-based and rocket-borne projects. BRL personnel also coordinated air and water shipment of equipment for all experimenters. Here the representatives of the Laboratories played an important part in the overall success of the various projects, for the field operations conditions were unusually severe and the passage of the eclipse imposed a rigid firing schedule for the rockets.

In addition to the coordination activities, BRL instrumented and launched five payloads carried on Nike-Javelin III rockets. One of these pay-



BRL Nike-Javelin sounding rockets poised for flight, Eclipse 1966, Brazil loads was launched a week before these eclipse to check range launching procedures, to certify the instrumentation payload and to provide reference data. The other four payloads were launched on the day of the eclipse.

Each payload carried a nose-tip Langmuir probe to measure electron density and temperature, two receivers to provide data for a partial reflection experiment and to measure differential absorption and a parachute-borne blunt-probe (ejected from the rocket at apogee) to measure positive and negative change conductivities.

Operation Polar Cap Absorption (PCA69). The objective of this project, sponsored by the Defense Nuclear Agency, was to determine the physical chemistry of the atmospheric D-Region while a high-absorption proton event was in progress. The measurements were made during the decay period of the solar proton event when there would be little change in the incoming energy distribution and the variation in the electron and ion content would be due essentially to the varying sunlight during sunrise, mid-day and sunset periods.

Thule Air Force Base, Greenland was selected initially as the site for the experiment; however, for various reasons, the site had to be changed to Ft. Churchill, Manitoba, Canada.

Seven Nike-Javelin rockets were each instrumented with a BRL six-frequency propagation beacon, a nose-tip Langmuir probe for electron detection, high- and low-frequency particle detectors, and photometers. Also included were aspect magnetometers and solar cells to determine the rocket's altitude.

One rocket was fired for payload certification in August 1969; the remaining six were fired during the period 2–4 November 1969. Electron density and radio-frequency absorption data were derived from the beacon-propagation experiment; electron current data were derived from the Langmuir probe measurements. North Carolina State University, under contract to BRL, was responsible for particle detector instrumentation and data reduction; similarly, the GCA Corporation was responsible for the photometer instrumentation and data reduction.

SECEDE II. This was one of several high altitude barium release programs sponsored by the Advanced Research Projects Agency, with participation by the Defense Nuclear Agency and the Atomic Energy Commission. Earlier programs in the series had been carried out near Puerto Rico in May 1968 (SECEDE I) and in Alaska, March 1969 (SECEDE III). Although SECEDE III is not discussed here, the Laboratories did play a major role in experiments for that project.

The experimental program for SECEDE II included a radio-frequency propagation experiment in which a rocket-borne, multifrequency beacon transmitted radio signals to ground based receiving stations. Signal processing provided dispersive phase Doppler signals that provided information regarding ionization along the propagation path.

During SECEDE II, four ground receiving stations were used; six rockets, programmed to release barium at altitude were launched from Eglin Air Force Base, Florida between 19 January and 2 February 1971. The RF beacon-bearing rocket was flown on a trajectory that would carry it behind the barium ion cloud, as observed from at least one of the stations. Following one of the releases, Event PLUM, all four of the receiving stations received RF signals dispersed as the rocket passed behind the cloud. In addition, the cloud was photographed from widely separated sites, including the four receiving station sites. To that date, PLUM was the only barium release event for which such extensive photographic coverage and dispersive phase Doppler data were available.

Thus, PLUM provided enough information to derive a computer model of an ionized cloud. The model, constructed by BRL personnel, covering the early time (2 to 3.5 minutes after the barium release) showed a developing cloud which agreed well with the photographs of the cloud. Moreover, the model reproduced the dispersive phase data to within five percent or better, for all four receiving stations.

Operation BARBIZON. This was another series of high altitude rocket experiments. The rockets were launched at Barking Sands, Kauai in the fall of 1971. Events CANUTO and DARDABASI of the series were high altitude barium release experiments implemented by BRL and sponsored for various purposes by the Advanced Research Projects Agency and the Defense Nuclear Agency. In each of these two tests, a rocket carrying a multifrequency propagation beacon, was to pass behind the "standard" barium cloud, relative to a ground receiving station at Dillingham Air Force Base, Oahu. The objective was to measure the radio frequency transmission effects and to determine the scale of striations in a striated barium ion cloud. Project SECEDE II had not been successful in obtaining the latter measurements.

The beacon rockets for both events did follow the intended pattern, but no evidence of the effects of irregularities or fine structure in the clouds could be determined from the data. However, fine quality dispersive Doppler data were acquired both at the Barking Sands station and the Dillingham AFB station.

The propagation path to the launch receiver was clear and unaffected by the barium cloud. Thus the data derived there defined ambient electron content and could be compared to the columnar electron content derived from the Dillingham data, for which the propagation path had been through the barium cloud.

Modeling the Chemistry of the Atmosphere. The purpose underlying the *in situ* measurements and laboratory experiments concerned with the chemistry of the atmosphere was to acquire sufficient information to construct a valid computer model which could predict the chemical processes occurring in the natural atmosphere and those occurring in an atmosphere disturbed by a nuclear burst. In the latter case, the code would provide the information needed to determine the influences on the propagation of electromagnetic radiation.

As BRL aeronomists acquired the data, it was applied to the construction of interim models which became research tools for detailed sensitivity studies to clarify those reactions which are most critical in the overall time evolution of the ionosphere. The determinations of the reaction coefficients corresponding to these reactions directed the emphasis in laboratory drift tube and afterglow experiments.

Concurrent with the development of models, resulting in AIRCHEM, to be discussed, the BRL investigators developed a numerical method for integrating the ordinary differential equations needed in the analytical study of ionospheric deionization processes. When applied to the AIRCHEM code, the method yields solutions that are sufficiently exact, yet requires minimum computational resources.

The ionized stratosphere or ionized mesosphere consists of many abundant chemical species. About sixty of these species are considered to be sufficiently abundant, or otherwise important because of their reactive properties, so as to require detailed computations to predict their dynamic concentrations and consequent effect on electromagnetic propagation. The various species found in the atmosphere interconvert through literally hundreds of chemical reactions. In addition to these chemical reactions forming and removing atmospheric constituents, various influences in the atmosphere—such as solar and cosmic radiation—cause ionization, excitation and dissociation. Following a nuclear detonation, x-rays, gamma rays, beta rays, and energetic neutrons are all available to interact with the atmospheric species.

The AIRCHEM code, combined with the numerical integration technique provides fast and accurate solutions describing the evolution as a function of time for the sixty or so important species; thus it provides a mathematical description of atmospheric deionization.

The AIRCHEM code has been applied by BRL to several studies of the atmospheric deionization outside nuclear fireballs at intermediate altitudes. The cases treated included a 5 MT burst at 30 kilometers altitude, and high yield bursts at 15, 20, 25, and 30 kilometers. Results from the first case were used to construct absorption contours for a north-looking radar 60 miles south of ground zero. The second group gave the number densities of the approximately 60 atmospheric species during the deionization process at various horizontal co-altitude ranges for times ranging from 1 microsecond to 1000 seconds.

Experiments in Reaction Kinetics of Atmospheric Chemical Constituents. As mentioned above, the determination of the reaction coefficients corresponding to the critical reactions occurring in the deionization of the atmosphere was the major thrust for drift tube and afterglow experiments. However, it was equally important to determine the equilibrium concentrations of electrons in the ionosphere. The laboratory program was successful in identifying the complex nitric oxide and water molecules important to the equilibrium concentrations.

Other investigations, emphasizing cluster reaction rates included, O_2 and He to Li^+; CO_2, N_2, and O_2 to NO^+; single and double clustering of N_2 to Li^+; CO_2 and K^+; and Ar to Li^+. Other research included work on experimental photodissociation and photodetachment of atmospheric negative ions.

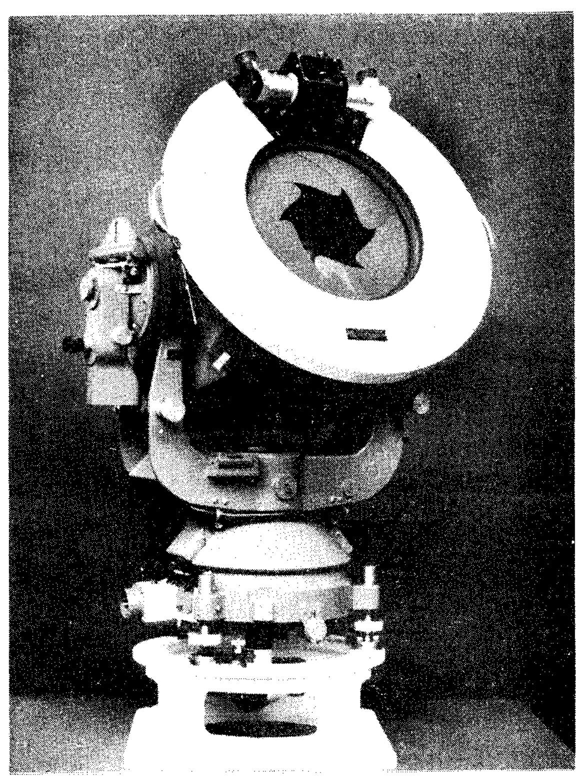
RESEARCH INSTRUMENTS AND FACILITIES

The design of instrumentation and data processing system had been a specific element of the mission assigned to the Ballistic Measurements Laboratory for many years. Among other factors, it reflected the responsibility which BRL had for developing the instrumentation and measurement techniques required for the Army missile program taking shape at White Sands Missile Range and Redstone Arsenal during 1950–1955. The challenges posed by the research and development of unique missile tracking optical and electronic instruments had been met for the most part by the early 1960's. The delivery of the Small Missile Telecameras to WSMR and of the Space Probe Optical Recording telescope and a similar, but larger model, to NASA essentially mark the end of BRL's involvement in the design and development of such instrumentation, *per se*. Henceforth, such development supported BRL's own research, permitting fiscal and manpower resources to be directed more towards upper altitude research and, more importantly, target acquisition, guidance and control.

Here, as elsewhere, space does not permit the description of all instruments and measurement techniques developed at BRL to support the missile ranges or for high altitude research. Thus only some important developments are described here; those instruments pertaining primarily to target acquisition, guidance and control will be found in that chapter.

At this point the reader may be helped by a brief description of optical systems used for ballistic purposes. In no particular order, they included the Askania, a cine-theodolite; the ballistic camera used to make multiple exposures on a single plate; and tracking telescopes which used astronomical telescopes of long focal length and motion picture cameras to track and record missiles in flight.

The BRL Ballistic Camera System. During the Second World War, BRL had developed optical (and electronic) methods and instruments to measure the trajectories and other flight characteristics of bombs, shells, and rockets; the data were used primarily for the construction of firing and bombing tables. After that war, the White

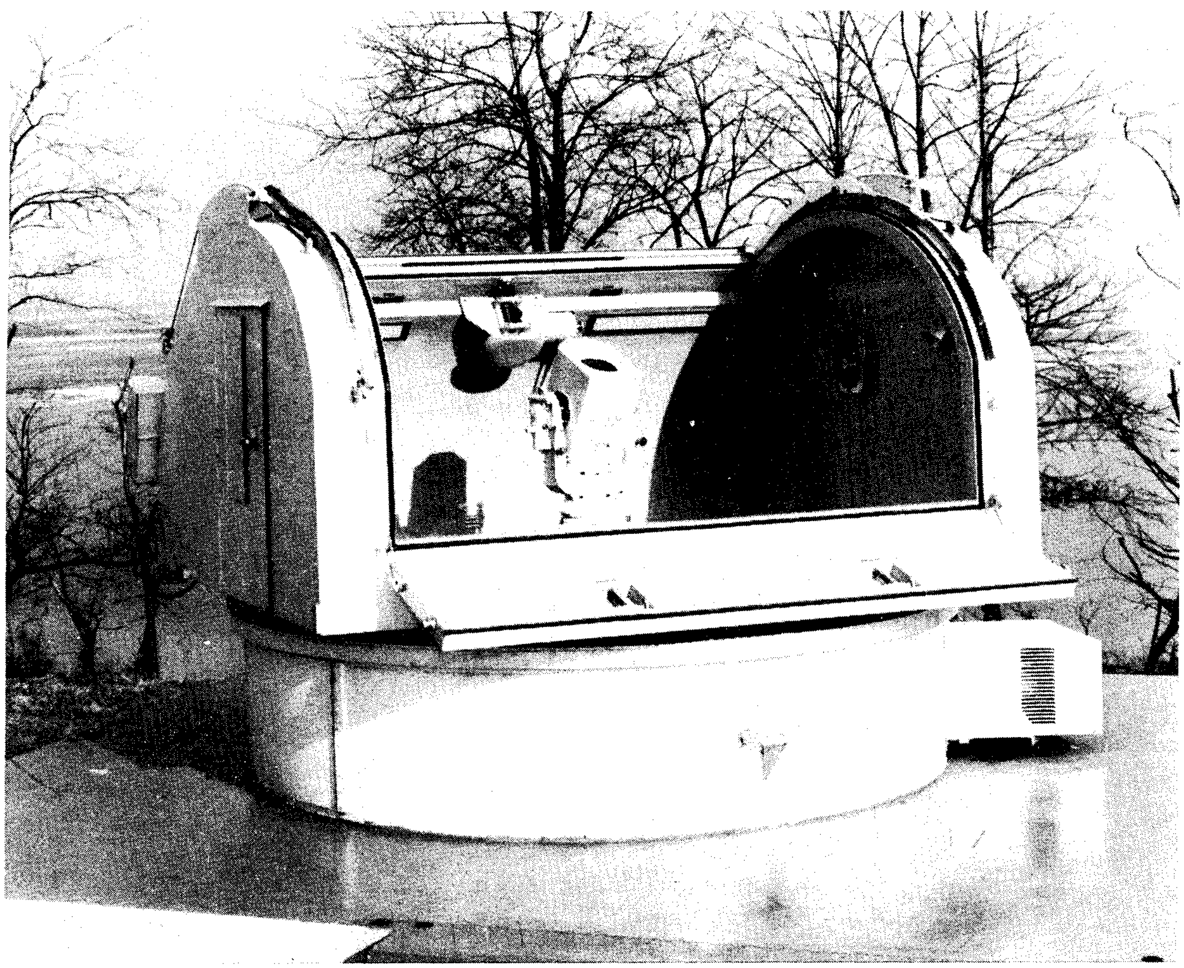


BRL Ballistic Camera

Sands Proving Ground (later White Sands Missile Range) was established and BRL was assigned the task of developing measurement methods and instrumentation, operating the instrumentation systems, and reducing the measured data. Although the systems were adequate to meet early requirements, BRL astronomers, physicists, engineers and mathematicians became increasingly aware of the need for a tracking system with high absolute accuracy. In addition to meeting specific test demands, the desired system would be the calibration standard for various range measuring systems.

A full scale experiment involving the comparison of ballistic camera and DOVAP (Doppler Velocity and Position) systems was carried out in the mid-1950's at White Sands Missile Range. The object tracked was a Corporal missile equipped with a flashing light and a DOVAP transponder. This single test, though not conclusive, showed the potential of the ballistic camera system as a calibration standard.

BRL, providing specifications, encouraged the Wild Instrument Company of Switzerland to design a special camera. The camera, actually a phototheodolite, became known as the BC-4. The major components of the precision system were the theodolite, an external capping shutter, an electronic shutter control synchronization system, and a skyscreen computer. Photographic images are recorded on glass plates with controlled emulsions and dimensions. The photo-



Ballistic Camera 4 (BC-4) station on Spesutie Island graphic records are read by a stereo-comparator and the output is processed by a high speed electronic computer. The computer program, of course, is the one designed to solve the general problem of photogrammetry.

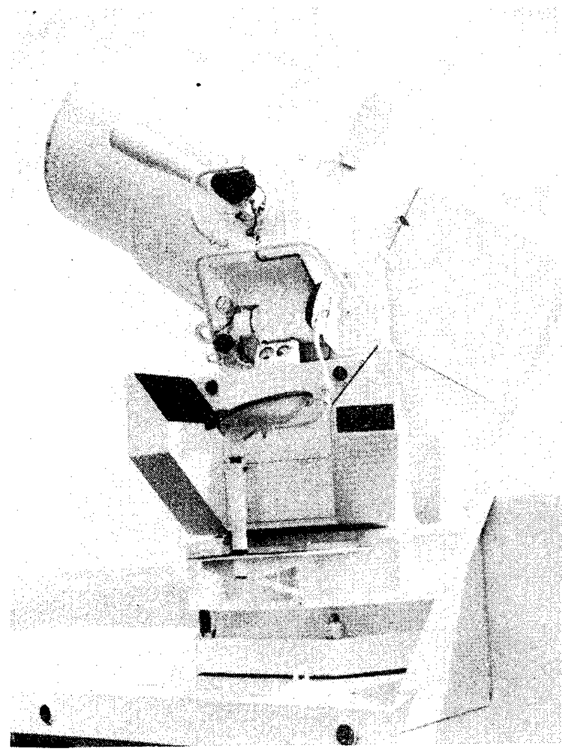
The camera was put into immediate use for night-time tracking of objects carrying flashing lights; it achieved its full potential through the development of a method for synchronously operating the shutters of widely separated cameras, and the development of the skyscreen which minimizes plate fogging caused by repeated exposures to background illumination during daytime operation.

The accuracy of the BC-4 system is limited by the random variations in atmospheric refraction, i.e., one-to-two seconds of arc. Under ideal conditions, the accuracy of shutter synchronization in a multi-station triangulation net has a mean error of 125 microseconds. Although the system is named after its specific application to ballistic problems, it has found use in many other applications.

The United States Coast and Geodetic Survey used the BRL system to establish a world-wide geodetic datum based on a satellite triangulation net. This marked the first time in the history of geodesy that a photogrammetric method was used to establish a geodetic datum. The method was equal in accuracy to that obtained by conventional geodetic triangulation for a continental datum and exceeded that obtained through the classical astronomical methods of triangulation for a world-wide datum.

The Small Missile Telecamera. As stated previously in the section describing the tracking of SPUTNIK II, the small missile Telecamera (SMT) was designed primarily to acquire trajectory data on small high speed missiles at great distances. It was intended for use at White Sands Missile Range, to where in fact, the laboratories eventually shipped four systems in 1958.

The design of this system represented a challenge—an exposure time of one five-thousandth of a second is required to halt the trailing (blurring) of the image to an acceptable amount, and an optical system of great light-gathering power is required because of the small amount of light



Small Missile Telescope

reflected from the missiles and the great distances at which trajectory measurements must be made. Thus, with a fast film emulsion, an aperture of at least thirty inches is required.

The optical system chosen was a thirty-inch, f/3.5 system, focal length 100 inches. The angular field average was 1°18′.

The missile image was recorded by a full-frame 70-mm camera running at 60 frames per second; timing marks were placed on the film at intervals of 0.01 seconds. Measurement of timing marks to a linear accuracy of 0.4 mm gave a timing accuracy in reduced data of 0.0001 second.

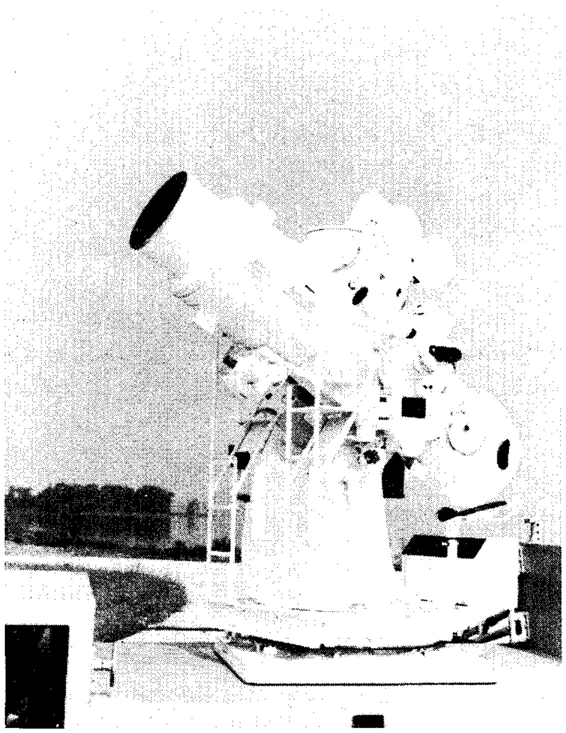
In use, the telecameras are calibrated and oriented by means of stellar observations and ground reference points.

The SMT engineering model undergoing tests at BRL in 1957, modified to use a Wild Ballistic Camera, was the system used to track SPUTNIK II. At the request of the IGY Technical Panel on Artificial Earth Satellites, BRL modified two other SMT's for satellite observations. Those instruments were installed at Smithsonian Institution Astrophysical Observatory Sites at West Palm Beach, Florida and the island of Curacao, Netherlands West Indies. They were operated at those sites for several months until they were replaced by Smithsonian systems.

The Space Probe Optical Recording Telescope. (SPORT) This tracking telescope and a companion larger version represent the final models in a series that began with "Little Bright Eyes", see Volume I. SPORT was designed specifically for research into the effects of the atmosphere upon the transmission of light. A particular subject for such research, for example, was quantitative data for stellar image excursions caused by random refraction under different atmospheric conditions.

The system used a corrector-reflector telescope with an aperture of 18 inches and a prime focal length of 82 inches. The primary recording camera was a full-frame 70-mm camera, but other types could be substituted. An auxiliary camera photographed azimuth and elevation angles from illuminated dials during tracking.

Apart from its use for basic research at BRL, the SPORT was used to support NASA in the ECHO satellite project. When the development of the larger version, known either as the Tracking Ballistic Telescope or Research Telescope TI, was discontinued for lack of funds, NASA provided funds to BRL to complete the system. Upon completion, the system was transferred to the NASA Wallops Island Facility.



Terminal Trajectory Telescope

The Sun Camera. When geodetic triangulations are done through aerial photogrammetry, an unfavorable accumulation of errors occurs in extended strip and block triangulations. Theoretical work, for some time, had indicated that the errors could be decreased appreciably through the use of independent, time coincident astronomical observations. A quantitative analysis by BRL led to specifications for the design of an optimum system in 1963—some thirty years after Santoni, of Italy, had developed an aerial camera that photographed the earth and the sun simultaneously. (The overall accuracy of his system reflected the state-of-the-art of aerial photogrammetric in that era).

The camera developed by BRL had two 100mm focal length, f/5.6 lenses installed in the camera body in such a way that the respective fields of view are diametrically opposed. A pulse-operated shutter system synchronizes exposures within 0.001 second for exposure durations of 0.002 to 0.010 second. This was to be the last photogrammetric instrument to be developed by BRL.

The DOPLOC Instrumentation System. The word DOPLOC is a contraction of two words, Doppler and Lock, it implies a phase-locked doppler system. The system was developed by BRL to obtain tracking data to determine satellite orbits, study radio-frequency electromagnetic propagation, and to measure electron densities at various altitudes.

The relatively weak radio signals expected from U.S. satellites required receiver band widths to be held to very low values to ensure adequate signal-to-noise ratios. Under contract to BRL, the Interstate Engineering Corporation developed a narrowband phase locked tracking filter to the Laboratories' design and specifications. Fortunately, the filter was to be the key element that enabled BRL to automatically track doppler signals from "dark" satellites.

In practice, the system detected signals reflected from satellites illuminated by electromagnetic radiation from a ground-based high power transmitter or signals actively transmitted by satellites. In either case, the signal passed through a high-gain receiver which detected the Doppler shift caused by the relative motion of the satellite with respect to the detecting system. After passing through the DOPLOC tracking filter, the signal was recorded on magnetic tape for processing on the ORDVAC computer.

Systems were operated in either active or passive modes. In the active mode, stations were operated only at specified times for launch or passage of satellites near the station. In the passive mode, stations were operated for 24 hours and required many more automatic scanning and alarm systems.

In the period October 1957 to June 1961, the DOPLOC station at BRL acquired launch and orbital data on numerous systems, including,

SATELLITES	*SPACE PROBES*
DISCOVER	LUNIK
EXPLORER	PIONEER
MIDAS	STRONGARM
SPUTNIK	SHOTPUT
TIROS	
TRANSIT	
VANGUARD	

The Ion Drift Tube. This facility is used for laboratory research in ion-molecule reactions. The results from such work find applications in the codes describing the ambient or excited states of the lower ionosphere.

In the drift tube, a heated alkaline source produces ions which, under the influence of an axial electric field, drift along an evacuated tube. The source runs continuously, but the drift of ions is controlled by two pairs of electrical grids called shutters. The first, or starting, shutter stops the drift of ions until it is opened for a few microseconds to allow a small group of ions to proceed down the tube. As the cloud of ions drifts down the tube, they diffuse, and the ions react with gas molecules in the tube to form other ions that have their own drift velocities and diffusion coefficients. Most ions strike the end plate of the tube, but some are swept through an aperture into a mass spectrometer. The mass spectrometer selects ions of one mass number from ions of other mass numbers that emerge from the exit aperture. The signals due to the arrival of those ions with the proper mass are sorted and stored in a multi-channel analyzer as a function of the time since the starting shutter was opened. Typically, fewer than one ion per group negotiates the drift tube and the analysis spectrometer chamber to be counted; so, the starting gate must be pulsed many times before statistically significant arrival times for the ions are accumulated. This tedious, time consuming experiment has been completely automated by BRL aeronomists. A computer program was designed in which the computer completely controls the experiment, changing the variables as results are obtained, starting a new sequence of drift tube events, processing and reducing the data, and so on. This was the first application at BRL of a microprocessor to control a complete experiment.

The Stationary Afterglow Facility. This facility, designed and constructed at BRL, measures ion-molecule, electron-ion, and electron-neutral reaction rate constants. Primary NO^+ ions are created by photoionization in their parent gas contained within a vacuum chamber. The chamber is an all metal, bakeable, cylinder eighteen inches in diameter and thirty-six inches long. A mass spectrometer, modified to accept either positive or negative ions, analyzes the ions that emerge from the afterglow. The ions transmitted by the spectrometer are then accelerated electrically and counted individually by an electron multiplier. Time resolved ion decay spectra are obtained from a multi-channel analyzer operating in a fast multiscaling mode. The afterglow facility is used with the BRL drift tube.

Antenna Research and Electromagnetic Propagation Range Facility. The facility consists of an Antenna Research Building, an anechoic chamber with a rotatable stand capable of supporting small missiles, an outdoor antenna testing range, a 100-foot oscillating, non-metallic tower for measuring radiation patterns of ground antennas, other mounts and towers for testing antennas, and the electromagnetic propagation range.

Built in the spring of 1963, the electromagnetic range facility was designed to support fundamental research in the near-earth meteorological environment. The purpose was to acquire meteorological information necessary for the design and evaluation of concepts for target detection and discrimination, tracking, guidance, and homing systems.

The propagation range, deactivated in 1970, was equipped with wind, temperature, humidity, and microwave refractive index sensors. The output from the various sensors was digitized and stored on magnetic tape. The sensors were mounted at variable heights up to 50 feet on five fold-down towers. The towers were spaced 500 feet apart. The facility occupied an area 750 yards long by 250 yards wide, flat to within ± four inches.

Given the extensive and well-established program in missile tracking and photogrammetric measurements that dominated work in the Ballistic Measurements Laboratory from the early World War II years and beyond, it's not surprising that in that program one first encounters BRL's interest in the propagation of electromagnetic waves. However, the interest was not directed towards application to target detection and signatures, or guidance and control; rather, it was focused on atmospheric effects on the transmission of energy at optical wavelengths, the visible portion of the electromagnetic spectrum. The phenomena were examined to quantify the effects upon the accuracy of tracking, photogrammetric and geodetic data. And much of this work was done to support other agencies.

This excellent work on the transmission characteristics of the atmosphere continued until the direct support provided by BRL in optical instrumentation and measurements to White Sands Missile Range and other agencies gradually tapered off in the 1960's, as the emphasis in the program was redirected to weapons applications.

This major change in direction occurred first during 1958–1960, when in support of the Army's Heavy Assault Weapon (HAW) Program, BRL examined the feasibility of using electromagnetic phenomena for identifying or illuminating targets and for transmitting control information to guided anti-tank weapons. Impetus for this change in direction came from BRL's growing awareness of the urgent need for fundamental data pertaining to targets and their environments as well as for new approaches to methods for detection, tracking and guidance. This awareness included the realization of the ultimate value in an integrated approach considering the basic phenomena as opposed to the expensive trial and error methods involved in *ad hoc* system development. Development of the TOW weapon system discussed in the chapter on Weapon System Evaluation, demonstrated the value of BRL's integrated approach.

In short, the BRL research program included basic definitions of target signatures, the effects of the atmosphere upon laser beams (coherent radiation) and other electromagnetic radiation (non-coherent radiation), and the physics and chemistry of the ionosphere. BRL's ionospheric research has been recounted in the previous chapter.

To expand, research in target signatures considered electromagnetic (visible, infrared, and millimeter and micromillimeter wavelengths) signatures of ground targets, starting with the premise that target signatures could be described by a complicated collection of simple physical processes. Thus the problems were attacked by making basic physical measurements of emissivities, reflectivities, atmospheric characteristics affecting transmission of electromagnetic waves, and so forth; this was followed by computer modeling, using information from the previous activities and introducing target correlation and pattern recognition techniques; the end product would be the creation of terminal homing and detection models that could consider the calculations of miss distances for homing systems and detection probabilities for surveillance systems.

Laser research in the effects of the atmosphere considered phenomena occurring in the near-earth atmosphere and was divided into two areas: the propagation of low energy laser radiation through the turbulent atmosphere and propagation of high energy radiation, treating both the effects of the naturally turbulent atmosphere and the effects induced by local heating of the atmosphere—caused by the laser beam.

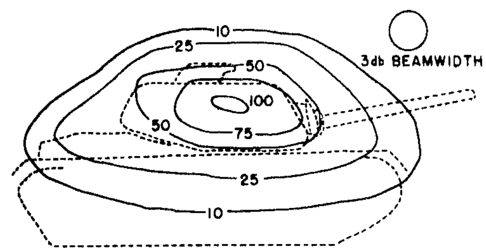
BRL's concern with millimeter wave technology centered on the application of active and passive radiometric techniques to Army systems for use in the near-earth environment against tactical targets. Passive radiometry uses a very sensitive, very wideband receiver to detect thermal radiation in the millimeter wave region. Because the emissivity of metal is very low in this wavelength region, targets such as tanks act as mirrors that (under proper conditions) reflect the radiation from the sky. The sky radiation is very weak, so the tank looks like a "hole" in the thermal radiation from the ground and foliage background. That is one of the few unique signatures for military vehicles.

Active radiometry is really a radar system that uses a wideband receiver and a matching wideband transmitter. Active radiometry was found experimentally to have a better rejection capa-

0.4 TO 0.7 MICRONS

0.68 TO 0.88 MICRONS

1.8 TO 15.0 MICRONS



3.06 TO 3.33 MILLIMETERS

Signatures of a tank illuminated at various wave lengths

bility of clutter (undesirable signals caused by reflections of returning signals) than narrowband conventional radar. Furthermore, it has much greater acquisition range, but poorer clutter rejection than passive radiometry.

It should be noted that BRL competence in the foregoing subjects did not result from a fortuitous set of circumstances; it was acquired deliberately through planning which included recruitment of young scientists qualified in optical and electromagnetic fields and the selection of key university scientists to assist the program. These latter were brought to BRL during the summer through the Cooperative Laboratory Research Program, sponsored by the Army Research Office, Durham, North Carolina.

It is equally important to note that BRL people, Victor W. Richards, Kenneth A. Richer, and Richard A. McGee, were the groundbreakers in millimeter radiometry, not only in theory but in the development of radiometer components and solid state devices. Not then available commercially, these parts, for example, semi-conductor diodes for millimeter applications, had to be made in-house. Other components were procured from contractors who followed specifications and design concepts generated by BRL scientists and engineers.

The formation of the Signature and Propagation Laboratory in 1968 provided a sharper focus to the target acquisition, guidance and control research that had been conducted for the last ten years.

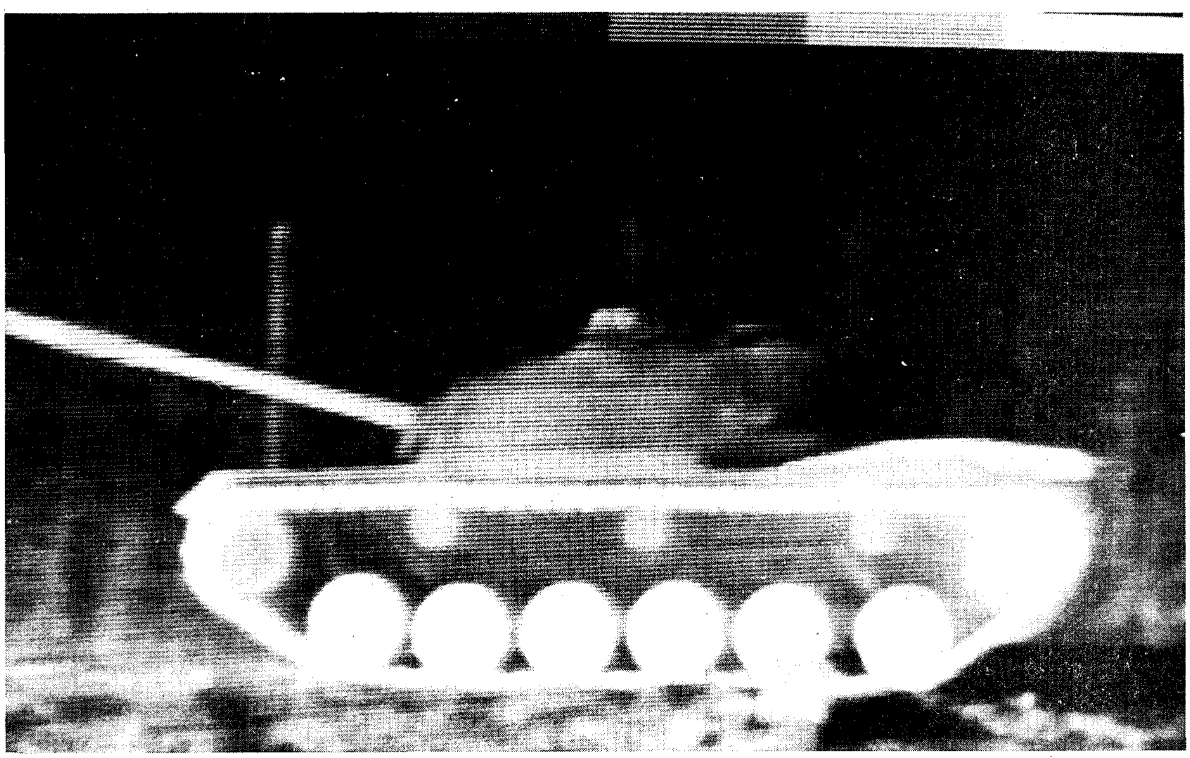
Under the aegis of the Army Materiel Command in 1971, BRL and several other AMC agencies began to coordinate their research in ground target signature measurement and analysis. Beginning in 1972, AMC provided funds specifically for a Target Signature Analysis (TSA) Program; before then, each agency had funded its own tasks which eventually became part of the TSA program.

The objective of the TSA program is to develop unified methods for target signature models which will provide the input information for target acquisition and terminal homing performance models.

TARGET SIGNATURES

The design of an acquisition and guidance system requires knowledge of the target and its environment, a method for sensing and tracking, some means for generating error signals (i.e. for determining whether the missile is on-target), and a method for using these signals to control the missile. In the program for this area, BRL emphasized research in those fields where information was lacking, but which fell within the realm of in-house competence. Thus, investigations of target and background radiation in the visible, infra-red, and millimeter portions of the spectrum were undertaken as a logical extension of the propagation work that had been carried out within the ballistic measurement program.

Infrared Observations. If not the first, BRL was an early investigator of the infrared signatures of tanks. As early as 1958, T. R. Bechtol had measured the infrared pattern presented by a tank and its background in the 2 to 15 micron wavelength regions. The infrared patterns were measured with the tank at various distances, at various aspects, with different backgrounds and with the tank partially obscured by foliage. So far as possible, actual tactical situations were simulated. The tank was observed parked, running, parked after running for various lengths of time, and after the gun was fired. The influence of diurnal and seasonal weather changes upon radiant output were analyzed. Experimenters used a thermal imaging camera to make black and white Polaroid prints in which shades of white through increasing grays to black were a



Infrared photograph of tank; temperatures of various areas of tank are inferred through comparison with gray scale at top of photograph measure of relative thermal radiance, rather than of light intensity as in normal photographs. The photographs were analyzed through visual comparison with a calibrated eight-step gray scale which appeared across the top of each photograph. Matching densities of the gray scale gave the radiance, and consequently the temperature of the area. The images provided by the camera were also recorded on an oscillograph from which quantitative radiance values could be determined. The oscillographic data were of higher accuracy than the photographic data, which provided excellent qualitative data. The infrared signature work terminated around the end of 1966. By that time many thermograms had been made of the infrared radiation patterns of tank targets in natural surroundings under various environmental conditions. Results were tabulated for the 2–15 micron region of the spectrum.

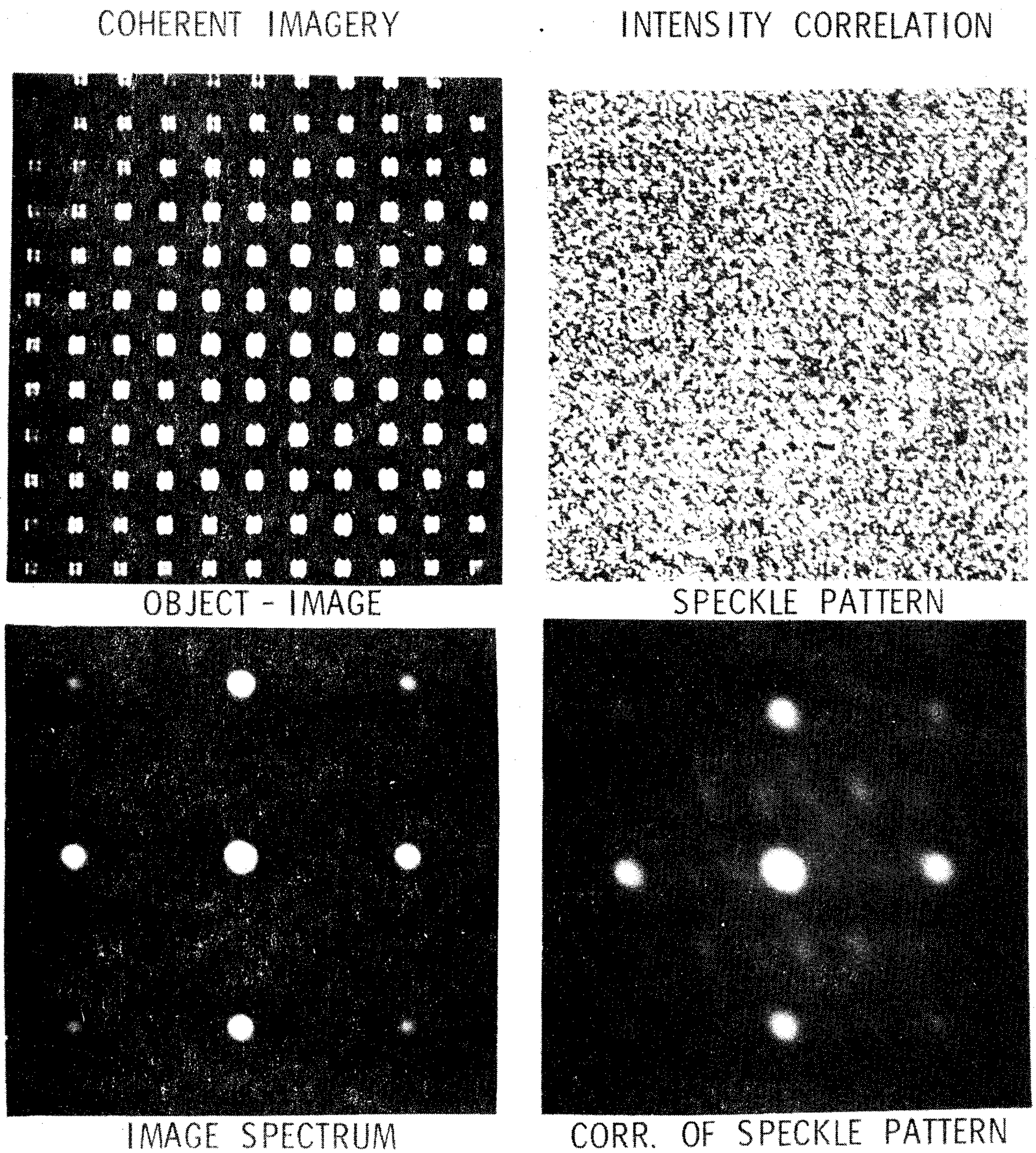
Acoustical Signatures. BRL activities in acoustic source identification began formally in the summer of 1970 when a small contract was let with the University of Michigan's Willow Run Laboratories (WRL) for collecting and analyzing acoustic and seismic signature data for some fourteen sources; for example, rain and hail, tanks and other tracked vehicles, jet and propeller aircraft, helicopters, and rockets, artillery shell and bombs. The initial effort was directed toward development of measurements and decision processes whereby acoustic/seismic noises could be classified and separated from background noises. By 1972, BRL with WRL and other consultants had determined that acoustic signals received at a remote sensor contained sufficient information to allow specific identification of helicopter sources, that the identification could be achieved accurately and automatically by some device.

At BRL, A. E. LaGrange constructed an experimental model of a helicopter classification system—after a computer simulation had substantiated the feasibility of using comb filters to detect and classify helicopter signals.

In field tests made in the winter of 1972, the classifier was tested against five different types of helicopters, and five different kinds of surface vehicles, including tanks, trucks and an Armored Personnel Carrier (APC). The helicopters were always identified correctly at a range of one kilometer; for 85 percent of the time and for 75 percent of the time the classifier identified targets correctly at ranges of one and one-half and two kilometers respectively. The maximum range in the test was more than six miles. For the ranges in the test, false alarms occurred less than four percent of the time.

Laser Speckle Interferometry. In another approach to target signature determination, P. H. Dietz investigated the use of statistical processing of laser-scattering patterns to infer information related to the irradiance distribution over the scattering object. This approach is a radical departure from standard imagery in which a lens is located in the far field of an object and used to form a real image. The image may then be processed by a number of modern optical information-processing schemes to derive various statistical measures such as correlation functions, power spectra, and other relevant values. However, in speckle interferometry, coherent radiation is scattered from a target, and the scattering (intensity) distribution is recorded in the far field of the object. This recorded pattern appears, in general, to be completely random. However, when the pattern is autocorrelated, the information derived is the power spectral density of the irradiance distribution over the target. The same kind of information is thus derived about the object of interest as in the previous approach, but the method of operation is different. Because of the nature of the process, noise introduced by transmission through atmospheric turbulence is less troublesome.

Radar Cross Section Measurements. Adequate radar cross section data are generally not available for helicopters because of the difficulty of making the measurements on full-scale helicopters. Cross section measurements made with helicopters in flight suffer from lack of correlation on helicopter attitude, ground clutter, and ground reflections. In somewhat analogous fashion, it is quite difficult to obtain such full-scale measurements on armored tanks as seen from guided missiles approaching from high altitude elevation angles, i.e., between 30° to 60° above the horizon.



Laser speckle interferometry: coherent image versus correlated speckle pattern

BRL solved both problems by using commercially available scale models of tanks and helicopters. Since radar cross section scales linearly with frequency, a 35 GHz signal illuminating a 1/32nd scale model will be equivalent to 1.094 GHz (the radar L-band) at full scale. Similarly, a 92.4 GHz signal illuminating a 1/32nd scale model will be equivalent to 2.89 GHz (the radar S-Band) at full scale.

The use of scale models at scaled frequencies, with attitude and background reflections controlled, permitted acquisition of data on radar cross section, angular radar glint, and radar amplitude scintillation power spectra.

During the same period research with scale models was being conducted, full scale tests were being run for several purposes. Radar cross section measurements were made by investigators using 70 GHz, 94 GHz, and 140 GHz systems. Typical targets were US and USSR armored tanks, and US helicopters, armored personnel carriers and trucks. Other tests provided data for analysis of the effects of foliage obscuration of targets and the effects of artificial obscurants such as smoke screens. For the latter case, BRL detectors were capable of tracking moving targets through smoke screens. (In later years, the experience gained by BRL researchers in obscurants, and aerosols and their effects was to be exploited in the design of obscurant systems.)

Signature Models. The development of a computer model for predicting thermal infrared signatures of a US M60A1 Tank marks a milestone for the BRL task to develop models for predicting the thermal emissive signatures of ground targets in typical backgrounds. Field measurements made by BRL validated the model's correctness. The methods and techniques used in developing the tank model are generally applicable to other vehicular targets.

A somewhat more complex model, also developed by BRL under the Target Signature Analysis program, provides intensity/irradiance ratios for electromagnetic radiation scattered from targets illuminated by lasers, search lights or flares. The method developed for artificial sources, but applicable to natural sources as well, generates two-dimensional images of simulated targets under various conditions of illumination. An algorithm based on combinatorial geometry techniques (originally developed for use in vulnerability analyses) generates the target models through the use of the digital computer. Several types of synthetic beams are used in the model to illuminate the target; radiation scattering is calculated by a submodel that generates the polarized bidirectional reflectance; the intensity/irradiance ratios of the scattered radiation are calculated for all positions from which the target can be seen; and the model also permits generation of a two-dimensional image of the illuminated area as seen from an arbitrary point.

Color photographs of a target tank can be produced by a computer-controlled device which paints the image in raster fashion, converting the radiance or temperature data provided by the signature model into prescribed colors. Each color corresponds to a 3° Celsius interval of effective black body temperature.

GUIDANCE AND CONTROL

To increase the first-round kill probability of anti-tank and assault weapons at extended ranges, two to three kilometers or beyond, requires some form of guided missile or projectile. A guidance system that requires external communication with the missile after it has been launched suffers from several disadvantages—interfering countermeasures, the need for skillful operators, increased vulnerability of the missile during flight, and exposure of the operator during the guidance phase. Thus passive homing guidance offers the most acceptable approach. But the problems in passive homing are quite severe: the target may not have a unique signature, its signature may be altered through camouflage, or there may be little contrast between a target and its background. Nevertheless, passive guidance research was a strong element in BRL's guidance and control program.

Photographic Image Correlation. Since many targets can be detected visually, it seems only natural to use contrast information for guidance. However, when only a small number of contrast points are used to "lock-on" a target, the problems in maintaining the lock-on are insurmountable. A guidance system must be able to use more of the available information.

One way to use more of this information involves pattern correlation; correlation of spatial patterns derived from target scene information may be used to determine when two views of the target are matched. The matching process then becomes the basis for a homing system. One of the most direct forms of correlation is by photographic image. This approach seemed particularly apt to BRL because of the Laboratories' experience in tracking, measurement, and photogrammetric research. Another factor that makes such an approach attractive, is the capability to separate essential information from non-essential information or "noise." Noise in this instance refers to all of the information that tends to make two images dissimilar; e.g., changing perspective due to changing range or angle.

BRL's first experiments to determine the feasibility of photographic correlation used photographs of typical target/background scenes. Experimental data were obtained with an optical correlator using both positive and negative image transparencies. The experiments considered autocorrelation of two identical images and cross-correlation of two non-identical images containing specific amounts of common information.

Research in photographic correlation techniques continued until the 1970's. The basic system required a missile-borne sensor which derived information from the target scene and then compared the target signature to a stored representation of the target's image. The comparison determined the attitude of the missile with respect to its on-course attitude and provided steering commands for correcting the missile's trajectory.

Experiment results showed that for tank targets, which can maneuver and pivot quickly, aspect changes present a formidable problem to a missile guidance system or tracker operating on an image correlation principle: the basic correlation function does not always attain maximum amplitude at the point of best image match. Thus, to overcome this difficulty, researchers investigated systems to "normalize" the function, i.e., to prevent large amplitudes at positions other than the time pattern match position.

Further evaluation consisted of determining the effects of image defocusing on the correlation functions and error signals generated by an experimental correlation sensor.

Millimeter Wave Radiometry. As the year 1960 began, the BRL program in millimeter wave research was strongly committed to obtaining basic data on the effects of the near-earth environment on the mm wavelength portion of the electromagnetic spectrum. These basic measurements included terrain reflection coefficients, radar cross sections of targets, antenna pointing errors (for pencil beams, conical scanning, and mono-pulse antennas) radiometric signatures of targets, and multi-path effects for various geometrical situations.

It soon became apparent that the applications of mm wave radiometry were limited by the lack of adequate millimeter systems or the operating characteristics of system components and the propagation characteristics of the atmosphere.

The former problem was overcome by a combination of in-house design and construction of components and systems, much of which can be credited to D. G. Bauerle, and the acquisition of components from contractors. For the most part, these components were one-of-a-kind, built to BRL designs and specifications and were essentially pushing the state of the art.

The second problem was eventually overcome by research coupling system operation frequency with favorable atmospheric characteristics. Millimeter waves are attenuated by: the molecular absorption of energy by water vapor and oxygen in clear weather, the absorption of energy by condensed water droplets in fog and rain, and the scatter from water droplets in rain. Also, rain drops scatter energy back into the radar antenna; the reflected energy appears as noise which can obscure the signal returned from targets. Research results showed that there are propagation "windows" at nominal frequencies of 35, 94, 140, 240, 360, 420, and 990 GHz. The atmospheric attenuation at these "window" frequencies, although less than at other frequencies, does increase with increasing "window" frequency except for the region of 240 GHz where attenuation is less than that experienced at 140 GHz. The clear weather attenuation at 34, 70, and 94 GHz is generally small compared with other radar system losses and propagation effects. Atmospheric attenuation is appreciable at 140 and 240 GHz; it is usually prohibitively large at 360 GHz and above, for all but extremely short-range uses.

It is this unique characteristic which enables mm wavelength radar to penetrate fog, dust, drizzle and light snow with very little attenuation and makes the system useful where good performance must be maintained through conditions of poor visibility.

Millimeter wavelength radar shows relatively little attentuation by rain as compared to that of optical wave lengths.

Quantitative relationships between rain characteristics and back scatter were determined experimentally for operating frequencies of 9.375, 35, 70, and 94 GHz, over a wide range of rain fall rates. The data were incorporated in attenuation and back-scatter models.

As early as 1960, the results of BRL analysis had shown the feasibility of radiometers, at very short wavelengths, for passive tracking and homing. At that time to confirm the analysis, BRL was acquiring a radiometer for use at 140 and 240 GHz (2.1 and 1.3 mm wavelengths.) Developed for BRL under contract, at that time the precision measuring equipment and special millimeter wave components constituted a unique facility for the newly-studied region of the radio frequency spectrum. This system as well as two others operating at 35 and 70 GHz were used to measure tank, sky, and background temperatures. Radio noise-temperature contours obtained by scanning across a tank tended to follow the physical outline of the tank. The results indicated that radiometric scanning could be considered a promising passive method for target detection and recognition.

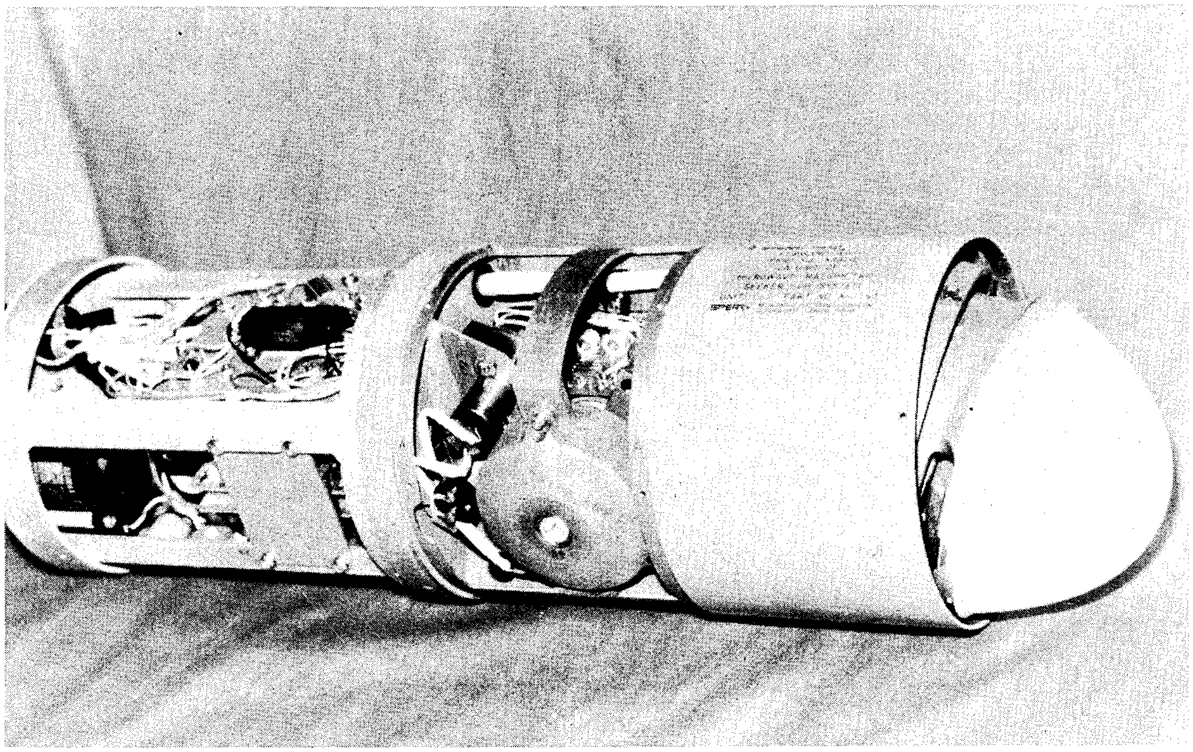
Note, however, before such application could be achieved, there was much further research to be done through the years. This included, for example, the effects of camouflage and target obscuration, analysis of performance at high elevation angles, methods for processing radiometer output and deriving guidance signals, selection of optimum frequency for operation, optimum antenna design, and techniques for enhancing target-to-background contrast. By 1969, most problems had been answered and a millimeter wave radiometer with a scanning antenna had demonstrated its ability to acquire a tank target in a complex background consisting of foliage, roads, and buildings. Around that time, BRL demonstrated a 35 GHz cold-seeking guidance radiometer which became the design basis for the millimeter wave seeker used in the Army Missile Command's TGSM (Terminally Guided Sub-Missile) Program. The Laboratories procured and tested this seeker for the Missile Command through an R&D contract with Sperry Microwave, Clearwater, Florida. This seeker used one of the first available Gunn oscillators and was the first example of a totally solid state millimeter wave seeker.

Also, millimeter wave radiometry techniques became a candidate for the SADARM (Sense and Destroy Armor), a concept to deliver a sensor and self-forging fragmenting munition to a target area. In that system, the sensor and munition are packaged in standard 155-mm or 8-inch projectiles fired from artillery. The package descends by a parachute, inclined to the vertical, spinning at a slow rate. (To the sensor, the tank appears as a cold target against a warm background.) The sensor scans an ever decreasing spiral with respect to ground surface until the sensor detects a tank on the ground. At that time the self-forging charge is fired to destroy the tank.

Research in active radar systems generally followed the same areas considered for passive systems. However, the emphasis in application changed in the 1970's to anti-aircraft fire control systems. This change came about through the desire to obtain the day-night, all-weather benefits of millimeter radar for anti-aircraft gun systems. The relatively short range of the millimeter systems is no handicap in anti-aircraft systems and their radiation characteristics render them relatively immune to anti-radiation missiles.

Target detection and guidance systems which operate in the near-earth region have many operational inadequacies related to the propagation phenomena of electromagnetic waves. For active, phase-coherent systems, multipath propagation, or interference results when the waves strike the terrain and are reflected in a direction different from the direct or primary waves. In a guidance system, such multipath propagation causes pointing errors; in target detection systems, multipath interference causes false targets and fluctuations in target signatures.

Efforts to offset multipath problems, and to exploit the attenuation "windows," led BRL to investigate signal frequencies extending from 35 GHz to 300 GHz—for active systems. At those signal frequencies antenna gains are high without



A 1972–1973 version of a millimeter wave radiometric seeker incorporating BRL-developed sensor design and signal processing algorithms derived through BRL target background information. (This very early prototype provided the basis for advanced systems used in the terminally-guided sub-missiles of the 1980's Assault Breaker.)

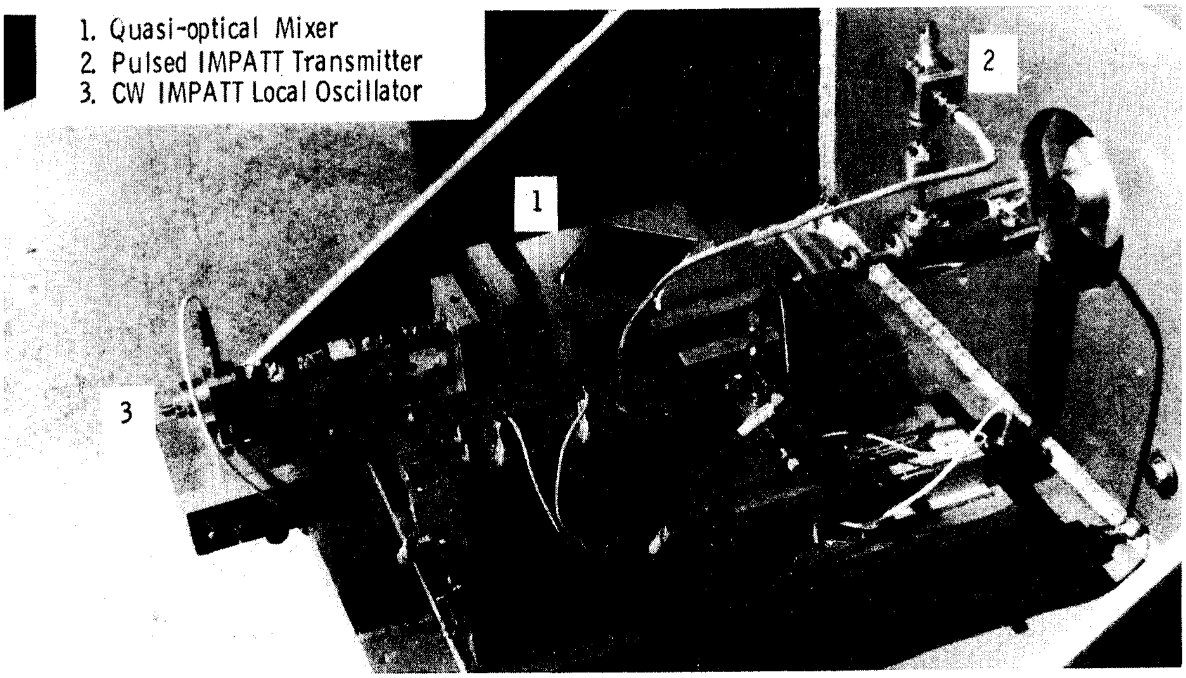
the necessity for large sized antennas normally associated with high antenna gains. For an antenna of reasonable size, antenna beam widths can be very narrow. The narrow beam width aids in discriminating against multipath and clutter signals.

Research in the active radar area included analyses of antenna pointing errors in the 140 GHz frequency region, range resolution capability for a 94 GHz frequency radar, and field measurements such as reflection coefficients, target cross sections, and background characteristics.

An important step forward occurred when BRL funded the development of an IMPATT (Impact avalanche transit time) device for use in active radiometric seekers. BRL designed and constructed an all solid-state 35 GHz radiometer, built around a pulsed IMPATT transmitter. The active radiometer, essentially a noise radar, transmits a wide-band noise modulated signal to illuminate a target. The signal is reflected back to the antenna and processed by a sensitive wide-band receiver of the same sort used by passive radiometers. The small size of the IMPATT and the associated antenna and circuitry permit packaging in a six-inch diameter munition.

Pulsed IMPATT diodes for operations at 94 GHz and 140 GHz were being developed by Hughes Aircraft Corporation under contract to BRL. The low voltages involved with the solid state IMPATT would permit easy access to this little explored region of the spectrum—a condition that existed as late as 1976. The use of very short wavelengths in the millimeter and sub-millimeter region and very narrow antenna beam widths offered many desirable features for Army weapon system applications. Standing at the very

target acquisition, guidance and control



Laboratory model of BRL 217 GHz solid state radar

forefront of this research, BRL was pushing the state-of-the-art to develop and improve components for use in active and passive systems. Using the results of in-house research, BRL developed laboratory demonstration models of the first all solid state radars operating at 35, 45, 140, 217, and 240 GHz.

SUPPORTING RESEARCH

The main thrust in Target Acquisition, Guidance and Control at BRL was the acquisition of fundamental information, primarily through in-house research, to define target signatures and the effects of the atmosphere upon laser beams and other electromagnetic radiation. The information would find applications in millimeter wave technology for active or passive terminally guided submissiles, missiles, and cannon launched guided projectiles.

BRL achieved its objectives in the target signature program. By 1976 target signature models had been developed and turned over to agencies who would be responsible for exploiting the results of the program; the laser reflection model for targets had been coded and validation of a radiance source model was under way.

That same year BRL decreased support to laser propagation research because of the changing nature of the work. Rather than conducting research on the fundamental process of laser propagation and atmospheric interactions, BRL researchers had been measuring beam intensities and providing micrometeorological information in support of the combined Army-Navy laser program—essentially a service. However, even so, BRL results were excellent, in particular the micrometeorological characterization of non-uniform terrain which can be applied to terminal homing problems or any problem involving propagation or imaging through the near-earth atmosphere.

The following examples illustrate the broad background accomplishments necessary to contribute to progress in target acquisition, guidance and control technology.

Rain Backscatter: Measurements and Model. The development of millimeter systems and research in attenuation and backscatter caused by rain appear to have gone hand-in-hand at BRL. For over almost the whole twenty-year span covered by this volume, experiments were made to measure such attenuation and backscatter. The definitive work on the latter subject appears to be that of V. Richard and J. Kammerer of BRL.

Rain reduces the range of millimeter wavelength radars by attenuating the target signal return and by masking the target signal with rain clutter—the noise-like signal backscattered from the raindrops. While both attenuation and masking are important in the performance of radar, their relative impact on performance degradation depends on the wavelength the radar parameters, and the rainstorm characteristics.

BRL planned an experiment to obtain complete and accurate data on rain backscatter as a function of rainstorm characteristics. Of particular interest were the amplitude and fluctuation of rain backscatter as a function of the rainfall rate as well as the associated raindrop size distribution, plus other metereorological parameters. Rain attenuation data would be inherently available from the radar output records.

The experiment conducted at McCoy Air Force Base, Orlando, Florida, August and September 1973, was unique. Rain backscatter measurements were made with pulse radars operating simultaneously at 9.375, 35, 70, and 95 GHz while continuous measurements of raindrop size and rate of fall were being made. The site had been selected because afternoon rainstorms occur almost daily during the season in Orlando.

The results showed that the reduction in range caused by rain backscatter is severe for frequencies in the region of 35 GHz when compared to the range reduction experienced with lower and higher frequencies, given a constant antenna size. Of particular significance was experimental verification of the expected decrease in the backscatter coefficient above 70 GHz. The experiment proved the long-standing theoretical prediction that radar could "see" a target above the rain clutter better at 95 GHz than a 35 GHz or 70 GHz, again for a constant antenna size.

The "weather-penetrating" capability of the millimeter wave systems enhances their attractiveness, thus increasing the importance attached to predicting the field performance of the system. As pointed out above, rain backscatter is a basic limitation to the performance of millimeter radar systems; the design of the systems requires accurate prediction of backscatter characteristics as a function of system and environmental parameters.

For an active millimeter radar system, the return signal can be displayed on a cathode ray tube where the image can be interpreted as an amplitude/range value. The basic problem, whether or not there is a human operator, is to extract information from the display. The presence of noise due to precipitation scattering causes problems in image interpretation. To develop image interpretation or noise rejection techniques, it is necessary that space and time characteristics of the return signal and the noise be expressed as usable functions of the various environmental and system parameters. In that way system optimization can be evaluated before hardware development; thus saving time and money.

Under the Target Signature Analysis program BRL had developed a radiative transfer model for visible and infrared radiation. Although millimeter wave lengths are 10,000 times longer than the optical and infrared wavelengths, the model was used, with appropriate wave length scaling, to construct a model to predict backscatter for 70 GHz radiation as a function of rainfall rate and distance from the antenna.

Laser Research. Laser research conducted within the frame work of target acquisition, guidance and control technology was concerned primarily with the transmission of laser beams through the near earth environment and the use of laser beams to illuminate or designate targets. Thus there was much emphasis upon the effects of turbulence, beam wander phenomena and the definition of the optical transfer function.

In an early experiment at BRL, a narrow beam of radiation from a ruby laser was projected over a grassy field in day time. The beam illuminated a white target which was photographed periodically to observe the effect of atmospheric turbulence on the distribution of radiation energy in the beam. The distributions were analyzed in terms of contrast and characteristic pattern size and compared with simultaneous micrometeorological measurements. The observers noted a gradual displacement of the beam as a whole. The displacement, on the order of 0.5 milliradian, was caused by refraction as the beam passed from a layer of air at one temperature to a layer of air at another temperature. This passage occurred as the beam passed over a rise or a dip in the ground.

The performance of many optical systems is limited by atmospheric conditions; for beams traveling long paths through the atmosphere the medium is not homogeneous, as demonstrated in the discussion of the preceding experiment, and the index of refraction varies along the beam path. This radiation can be characterized using statistical techniques. To study light propagation in the near-earth atmosphere, BRL physicists designed a system consisting of a helium-neon laser with an optical collimator, and a receiving system with a 24-inch aperture and a narrow bandpass filter. When coupled with a pulsed laser, the system was used in 1968 to determine the magnitude of scintillation as a function of range and strength of turbulence. The index structure coefficient, C_n, was measured by high speed thermal techniques at the same time the optical data were acquired. The final analysis of results produced a scientific "first"; the optical filter function (which is part of the atmospheric modulation transfer function) was derived and related to a new bounded beam theory. The system was used in later experiments in 1969 to gather data for extended optical filter functions.

The advent of operational, field-usable, pulsed laser illuminators enhanced the possibilities for semi-active missile guidance. The MISTIC system under development by the Army Missile Command in 1970 was designed to operate in a semi-active or passive mode or both. To enable the Missile Command to evaluate and compare operational characteristics of the various modes, BRL provided data from: field tests of an optical contrast seeker provided by the Missile Command, research in laser beam wander, and field measurements of laser reflectivity. The basic purpose was to determine the amount of energy entering a collector after reflection from targets such as tanks, armored personnel carriers, and cargo trucks for a number of laser-target-sensor geometric arrangements.

The characteristics of high power, narrow bandwidth lasers made coherent light sources attractive for use in long-distance, communications, guidance, and optical ranging systems. However, those same characteristics also create eye hazards for persons who may be illuminated by a beam. During 1969, BRL constructed a model which evaluates the likelihood of ocular damage occurring, considering atmospheric parameters. The analysis computes the area percentage of a transmitted beam cross section which lies above a chosen level of threshold energy density, with range as the independent variable. The threshold energy density is defined for incidence at the cornea. The model includes a factor which allows for lower beam energy density at a given range with increasing divergence, an atmospheric attentuation coefficient to account for the effects of Rayleigh and Mie scattering, and a pertubation factor for the effects of scintillation. A safety nomagraph is provided to facilitate an analysis of the probability of eye damage.

The results of laser research for target acquisition and guidance were incorporated in a digital computer model which could simulate a laser semi-active terminal guidance/homing system. Simplified functions represented elements encountered in the actual physical situation. The model simulates pulses of laser energy propagated along a path, considering the effects of the laser, atmosphere, aerosols, foreground, target, and background. The energy scattered by each of those elements is calculated and used to generate guidance and fuzing information for a homing missile. The calculations can be done repeatedly for a given missile flight simulation model under a wide variety of conditions.

RESEARCH INSTRUMENTS AND FACILITIES

The Antenna Research and Electromagnetic Range Facility, described in the preceding chapter, was used extensively by BRL for target acquisition, guidance and control research, particularly for millimeter wave research.

Laser research was supported by the Laser Propagation Research Facility, also located on Spesutie Island. The facility included transmitting and receiving instrumentation—a transmitted laser beam was received on a parabolic mirror which focused the beam, then transmitted it via auxiliary optics to a focal plane for still or motion picture camera recording. A graduated step wedge permitted conversion of beam densities to measurements for subsequent beam analysis.

Other indoor and outdoor laboratory areas with specialized equipment such as image correlation instrumentation, laser interferometers, and radiometers provided general support for acquisition and guidance research.

Thermal Imaging Camera. This camera (made by the Barnes Engineering Company) was used to measure infrared emissions from tanks and other vehicles. It was a mechanical scanning instrument that generated a television-type picture with a line raster containing enough elements per line so that each element corresponded to one milliradian, the field of view of the infrared detector. The varying electrical output of the scanning detector (radiometer) as it swept across the scene was amplified to modulate the brightness of a "glow tube." Synchronized with the scanning radiometer, an image of the glow tube, varying in brightness, swept across a Polaroid film. Successive sweeps drew a scene which visually represented the infrared characteristics of the tank and its background. At the same time, the detector output was recorded on an oscillograph. Data were collected, respectively, from the photograph through comparison of the image radiance with gray scales appearing on the photograph, and from the oscillogram by analyzing consecutive line scans.

BRL Infrared Camera. BRL developed a rapid-scan, infrared camera to operate in the 1–12 micron region. The camera met the need to analyze the behavior of high power 10.6 micron laser beam propagating through the real atmosphere. Further, this development provided instrumentation to perform output beam diagnostics for high power CW lasers. Existing IR Cameras were not suitable because of nonlinear representations of the object and slow framing speeds.

The IR Camera consisted of a rotating drum with a spiral set of holes that swept across an image formed by the telescope optics. A collecting lens on the opposite side of the drum focussed the illumination from each hole in sequence on a detector. With suitable electronics, a TV-type video signal was produced for magnetic tape recording and subsequent data processing. Individual line and frame decoding information was recorded similarly. Two cameras, each with a variable framing speed of 90–900 frames per second were used to photograph the image on the cathode ray tube.

The technique used to observe the spatial and temporal structure on high power laser beams was to image the diffuse reflection from a specular reflecting surface. This diffuse reflection represented the beam surface.

Methods for Measuring Atmospheric Clarity at Night. To support the target Signature Analysis Program, BRL researchers had to measure atmospheric clarity at night. Several problems were encountered in utilizing the known devices which obtain a measure of the visual range at night.

In order to maintain their accuracy transmissometers, with an accuracy of about 20 percent, require that their base line be changed as the visual range changes. Once the base line is changed a lengthy recalibration is required. The optical alignment of the source and receiver is critical, as well as maintenance of a constant output from the source. Backscatter measuring devices have accuracies generally less than transmissometers (20 to 50 percent) and are primarily limited to visual ranges less than 20 kilometers. Backscatter measuring devices also have problems of optical alignment and self calibration.

A number of methods for measuring atmospheric clarity were devised and implemented at BRL. These included monochromatic and white light transmissometers, backscatter measuring devices using collimated and non-collimated white light sources, forward scatter measuring devices, and combinations of back and forward scatter measurement devices. The primary method selected used a forward scatter technique, it was the only nighttime method which used a photometric technique.

The detailed studies were carried out by measuring the visual range during the afternoon using the "one black panel method." Starting about an hour before sunset and continuing for about an hour after sunset both the daytime method and the night method were used to obtain the visual range every three minutes. A graph of visual range versus the time of day, with both the daytime method and nighttime method plotted on the same graph, permitted a comparison of the two methods to be made. A value of the visual range for each method near sunset was obtained, and an error of the nighttime method was calculated using the daytime method as the basis.

An introductory discussion of interior ballistics research for this volume of BRL's history lends itself to division into two periods, 1957–1968, and 1969–1976. During the late 1950's and through the mid-1960's, there was much work directed towards the interior ballistics of rockets, particularly in propellant formulation, propellant combustion, analyses of combustion instabilities in rocket motors, the development of instrumentation and experimental techniques for such analyses, and development of corrective techniques to avoid unstable combustion in rockets. The Army Missile Command, Huntsville, Alabama, provided funds to BRL for theoretical and experimental investigations into the mechanical properties of rocket propellants. The work in interior ballistics of rockets was undertaken primarily to satisfy urgent needs; however, as capabilities to do such work developed elsewhere, BRL management deemphasized rocket research. Throughout the period however, BRL maintained a comprehensive program in the interior ballistics of guns.

A significant milestone in the first period was the work of P. G. Baer and J. M. Frankle which clearly defines the two eras in the development of interior ballistic mathematical models: before and after the high-speed digital computer. The digital computer permitted the interior ballistics analyst to consider approaches previously denied because of mathematical complexity.

Baer and Frankle introduced a method for providing, on a case by case basis, numerical solutions of the ordinary differential equations describing an interior ballistics trajectory, thus bringing the digital computer under the direct control of the user.

At the beginning of the second period, 1969–1976, interior ballistics research took a radical shift. Expanding computer capacity coupled with extensive employee training in computer programming made the shift possible. Dr. Joseph Frazer, Chief of the Interior Ballistics Laboratory since its inception in 1945, retired and Mr. Leland A. Watermeier became Chief of the Laboratory. Dedicated to the belief that contemporary and future ballistic research demanded the use of mathematical modeling and high-speed digital computers to the maximum degree, Mr. Watermeier and his staff formulated a comprehensive plan closely coupling modeling, experimental, and analytical programs to achieve an overall interior ballistics model. The goal was a model which could explain and account for the phenomena of ignition and combustion, wear and erosion, projectile/gun tube interactions, and for the effects of additives and changes in charge design parameters. Such a model would at long last provide a safe reliable method for the interior ballistician to design propulsion systems to meet the Army's continual demand for weapons with increased range, higher rates of fire, improved accuracy, greater payload, and longer life.

Dr. Joseph Frazer, Chief, Interior Ballistics Laboratory 1945 to 1969

To provide more coherent descriptions of the work performed in the various fields of interior ballistics, the detailed discussion following considers the period 1957 through 1976, as a whole, and occasionally considers research occurring before that period.

Mr. Leland A. Watermeier, Chief, Interior Ballistics Laboratory, received his AB from Blackburn College, his MS (Physical Chemistry) from the University of Delaware, and the Diploma of Imperial College (DIC) from the Imperial College of Science and Technology, London, England. Mr. Watermeier joined the Laboratories in 1951; he became Chief, Interior Ballistics Laboratory in 1969.

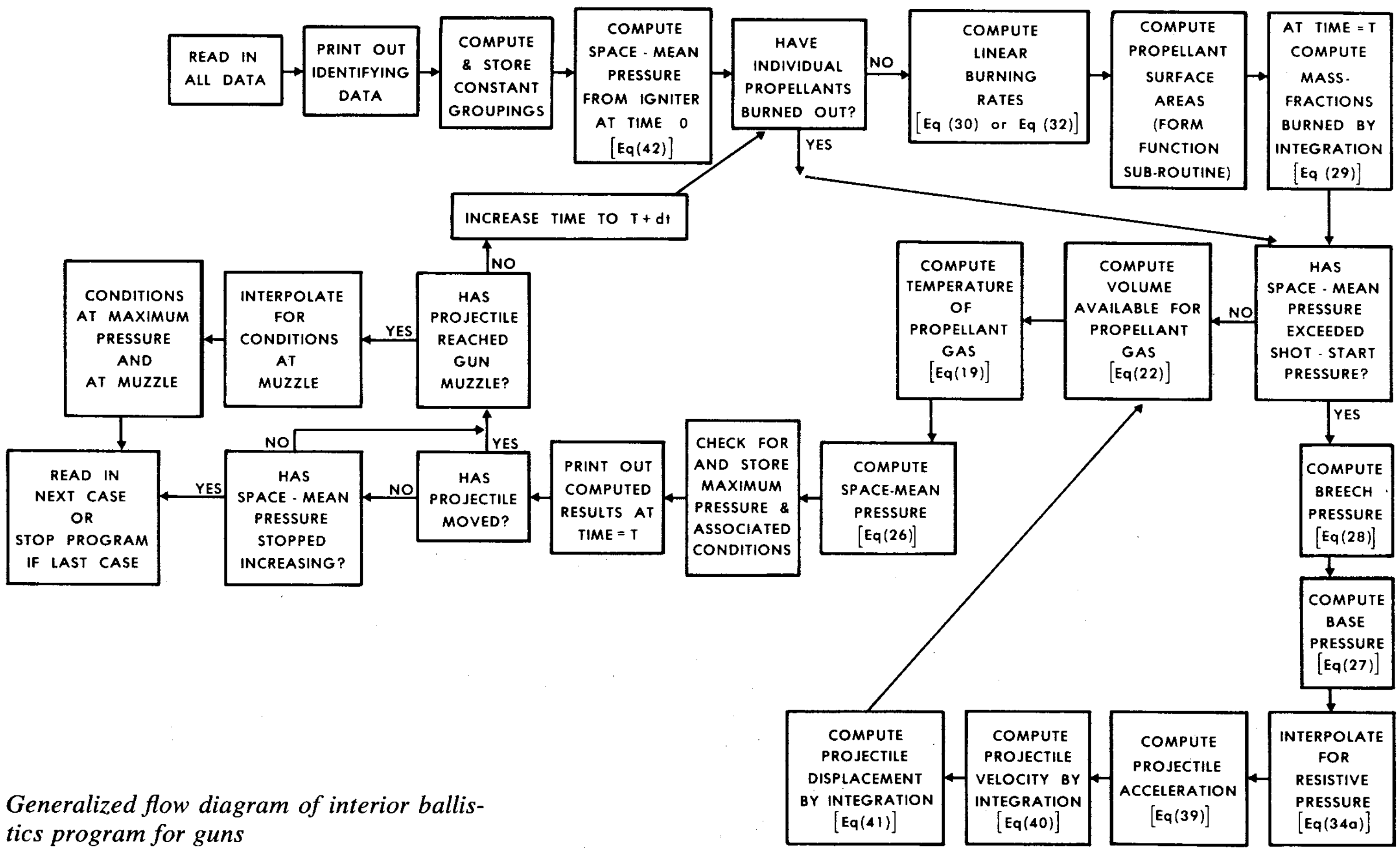
INTERIOR BALLISTICS COMPUTATIONS

Before the advent of the computer, all of the information useful for interior ballistics models consisted either of closed form solutions to the governing differential equations or tables of numerical solutions. At the Office of the Chief of Ordnance in 1921, Dr. A. A. Bennett at the suggestion of Col. William H. Tschappat compiled "Tables for Interior Ballistics," a set of numerical solutions computed by hand.

With the advent of the digital computer, the interior ballistician could consider approaches previously denied because of mathematical complexity and consequent burdensome computations. H. P. Hitchcock, BRL, made first use of the digital computer for solving the interior ballistics equations when he repeated and extended Bennett's work. The Electronic Digital Variable Computer (EDVAC) was used to compute the required interior ballistics trajectories (i.e. pressure vs. time and tube travel vs. time); the results eliminated some interpolations and extrapolations that had been needed previously to deal with more modern weapons and ammunition. Hitchcock's work was published in 1956. Around the same time, W. C. Taylor and others, also of BRL, used the computer to solve the differential equations; these solutions permitted the consideration of charges with arbitrarily described burning surfaces. Taylor's results appeared as graphs with dimensionless coordinates. Despite the progress that had been made, there yet remained a serious drawback; these tables and graphs required the user to reduce his particular problem to the dimensionless coordinates of the tables or graphs, derive his solution from the tables or the graphs, then convert his dimensionless solution back to engineering units. If the number of cases to be solved was large, then the solution process could be long. What was greatly desired of course was a method for obtaining direct numerical solutions in engineering units as a result of interactive, communication between the user and the digital computer. There was yet an intermediate step to be made at BRL: the reduction of interior ballistic data from artillery weapons by high-speed digital computers.

Like any science, the study of interior ballistics is based partly on theory and partly on observations. It is obvious, that whatever the idealized theory may be, certain empirical factors are usually needed in the practical case to correct the simplified theory so it agrees with the best available experimental evidence.

The development of new instrumentation for obtaining interior ballistic data from gun firings made possible a great improvement in the correlation of interior ballistic theory and actual gun performance. Now available from a single firing were projectile displacement versus time, pressure in the gun chamber and tube versus time, and the miscellaneous constants needed for in-



Generalized flow diagram of interior ballistics program for guns sertion in the interior ballistics model. In 1958, Baer and Frankle combined methods for rapid reading of gun instrumentation records with a digital computer program to process the readings. This was possible then because of improvements in data recording systems; the long-used and reliable cathode-ray tracing/photographic technique for recording gauge output was replaced by magnetic tape recording systems. Magnetic tape systems enabled the interior ballistician to convert analog data directly and easily to digital form. The ORDVAC (Ordnance Variable Automatic Computer) was used with printers and curve plotters to provide tables and graphs of projectile displacement, velocity and acceleration, engraving energy, bore friction losses, linear and mass propellant burning rates, and energy distribution, all as a function of time. These results were available within a few hours; previously, desk calculator methods had taken a minimum of two man-weeks to reduce the data from a single round. Moreover, techniques were now in place that could provide complete evaluation of the performance parameters for a large number of weapons—parameters that would be useful for validation of interior ballistic models.

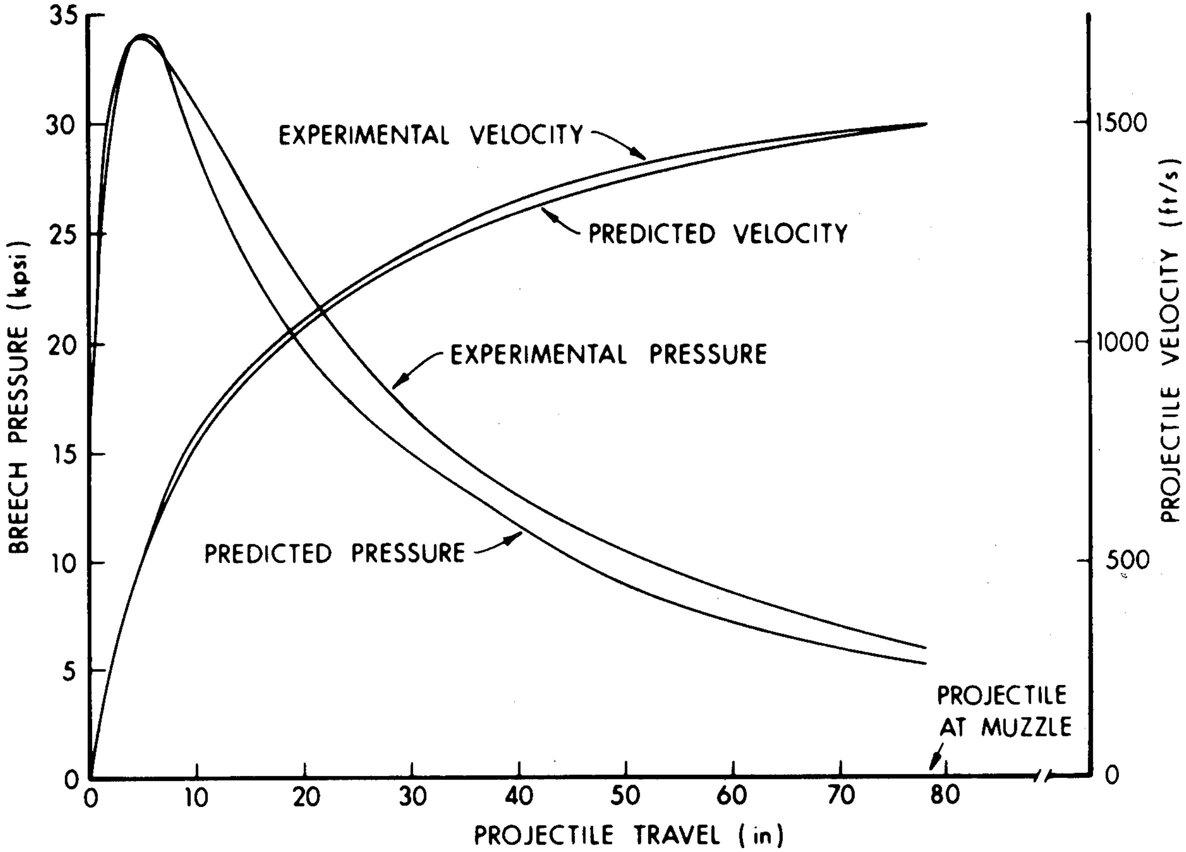
In 1962, Baer and Frankle constructed a digital computer program to simulate the interior ballistic performance of guns. Programming the interior ballistics equations for high-speed electronic computers eliminated the restrictions imposed by assumptions made only to facilitate the mathematical solution of the problem. The model also permitted the consideration of propellant charges made of several propellants with different chemical compositions and different granulations. Considerable versatility was built into the program; instead of stopping the computer during the last phase of computation, a new problem could be read automatically into the computer and solved. This multiple case feature could be used to advantage for any number of additional problems during a single computer run.

Tables of computed thermodynamic properties of military gun propellants were issued to assist in interior ballistic calculations. These tables were followed, in 1961 by the report "Notes on the Weights of Guns, Mortars, Recoilless Weapons and Their Ammunition," H. P. Gay. This outstanding report by Gay contained graphs showing the weights of existing mortars, artillery, and recoilless weapons and their ammunition. The graphs, combined with a graphical solution for the maximum range, provided a means for estimating the weight of weapon and ammunition required to deliver a projectile of given weight to a selected range. In mid-1967, a monograph was published for estimating the service life of a gun or howitzer; the estimate was based on fundamental interior ballistic parameters.

As interest in high velocity gun technology increased, the validity of existing interior ballistics theory for such guns was questioned. BRL carried out an experimental program to assess the validity of the theory. It appeared that the existing theory could be used to predict overall performance or muzzle velocity with reasonable success for guns with muzzle velocities as high as 5000 feet per second. However, it was not possible to calculate the detailed performance parameters needed for refined gun tube design. A result of greater importance was the revelation that there were insufficient experimental data to verify some of the simplifying assumptions made in the theory.

The standard procedure for obtaining data on the performance of weapons using propellants not at the standard temperature (70°) is to carry out an extensive firing program using propellants conditioned to predetermined temperatures. For most weapons this procedure consumes hundreds of rounds, is expensive, and takes much time and effort. The Baer-Frankle interior ballistics model was used to simulate the effects on weapons using propellants not at the standard temperature. When the results from model calculations were compared with data gathered from firings conducted with propellants at several discrete temperatures, it was found that the accuracy in predicting the changes in muzzle velocity at any given temperature fell within the round-to-round probable velocity variations at that same temperature. Thus, the model was sufficiently accurate to permit a significant reduction in the number of rounds fired for temperature effects, or to discontinue such firings entirely.

Throughout this period, interior ballistics models provided useful insight into many problems con-



Comparison of experimental and predicted interior ballistics performance of typical 105-mm howitzer

cerning the interior ballistician. For example, the objective of mounting a recoilless rifle on Army aircraft has been frustrated by the powerful back blast from the rifles. In contrast to a requirement that the back blast not exceed 1 psi overpressure at 60 inches, is the estimated actual 10 psi overpressure at that distance for a 105-mm rifle with a standard conical nozzle. Rigorous trade-off studies between weapon performance and aircraft safety required that flow from the nozzle be predictable with reasonable accuracy. Until 1973, empirical correlations were the only source for blast predictions. Existing analytical models were almost exclusively limited to steady-state models of rocket exhausts; a model was needed to evaluate the time dependent flow of the recoilless rifle. Consequently, BRL prepared a user's manual for the RIPPLE Code, developed by the General Atomic Division of General Dynamics Corporation under a BRL contract in 1967. The code was modified for analysis of back blast in the 105-mm recoilless rifle. Pressures were calculated for the nozzle inlet by using interior ballistics codes simulating performance of an assumed rifle/projectile combination; flows were computed for the input pressures for several nozzle shapes. Although experimental results were scarce with which to judge the computed solutions, it was believed that RIPPLE provided a credible solution to the pressure prediction problem.

A finite element code was used to define stresses on a 175-mm projectile in the gun tube and the axial resistance produced by the rotating band. The initial results of stress calculations with the finite element method disclosed the need for a consistent modeling process for both the interior ballistics trajectory and the stress analysis. The calculations showed a large force imbalance in the axial direction; the system of loads and accelerations was overspecified, hence system equilibrium was not satisfied. The difficulty was overcome by developing consistent equations of motion for the shell. Consequently, later stress analyses for other projectiles were more accurate.

PROPELLANTS

For most of this period in BRL history, efforts in propellant research were divided nearly equally into research in rocket propellants and research into liquid propellants for guns. As the period grew to a close however, research into rocket propellants had assumed a minor role and research in low vulnerability propellants for tube weapons was emerging as a major thrust. There were also new looks at the feasibility of fuel-air mixtures as propellants for small caliber guns and at the traveling-charge concept. Concerning the latter concept (See also page 80 of Volume I), a new effort was launched in 1976 to establish feasibility of a traveling-charge gun system using new high-burning-rate propellants. Computer simulations had indicated that it would be possible to design a traveling-charge gun capable of accelerating practical weight projectiles to 3 km/s with conventional military propellants. Design parameters had been determined for both tubular stick propellants and consolidated granular propellants. Tubular stick propellant, extruded at Radford Army Ammunition Plant, had been delivered to BRL. By the end of 1976, proposals for the fabrication of a 40-mm gun tube and provision of consolidated ammunition for the gun had been received and evaluated by BRL. An unsolicited proposal for the development of a series of high energy, ultra-high-burning-rate propellants had also been received and evaluated.

The work in propellants for rockets was directed toward the improvement of solutions for combustion instabilities in rocket motors; this work was to continue through 1976.

Research in liquid propellants centered on definition of the basic ignition and combustion processes and development of design criteria for liquid propellant guns.

Solid Propellants for Rockets. In the continuing effort to produce a significantly improved propellant, members of the Interior Ballistics Laboratory theorized that it should be possible to avoid the principal disadvantages of the currently used composite and double base propellants by combining typical ingredients of each in a balanced formulation. In this way it would be possible to compensate for the sometimes brittle characteristics of double-base propellant by adding the excellent elastic properties of the composite types. At the same time, the tendency of the composite types to flow and lose form would be counteracted by injecting into the system some of the rigidity of the double-base types.

Such a propellant would need less solid oxidizer than a conventional composite propellant; this would make it possible to add high energy ingredients to the formulation without affecting the physical properties adversely. Thus, it should be possible to develop a propellant which would be superior to existing propellant in both physical properties and in specific impulse.

BRL workers then decided to work initially with a mixture of nitroglycerine, nitrocellulose and polyurethane as the matrix with conventional ammonium perchlorate as the oxidizer.

When the intital work validated the feasibility of the approach, the next step was the formulation of a new propellant designated BRL-1, a high energy propellant combining the desirable features of both the composite and double-base types and possessing several unique features of its own. Crosslinking nitrocellulose with a polyester diol produced a high energy nitrato-urethane. The resulting elastomeric material possessed a combination of advantages over each material along—substantially improved mechanical properties, outstanding retention properties for nitroglycerine as a plasticizer, and a pronounced enhancement in thermal stability. BRL's successful research marked a watershed in the development of solid fuels for rockets.

This nitrato-urethane system provided a high energy propellant with low material costs. All the ingredients involved were readily available on the market in large quantities and no costly synthesis was involved. The nitrocellulose was a low cost material used directly without expensive extruding or particle-sizing processing. The processing techniques for the propellant were the same as those widely used in the composite propellant field.

The promise of the BRL-1 rocket propellant led to the development of new composite double-base propellants in which the ployurethane was replaced by other polymeric systems. The characteristic feature of these propellants was the binder which renders the mixture a pourable liquid before curing, and after curing, a solid with good mechanical properties. Polymeric systems other than polyurethanes were investigated because the latter have the disadvantage of reacting with moisture to produce carbon dioxide which forms bubbles in the final propellant grain, unless extremely dry materials are used and all mixing and pouring operations are done under vacuum. Encouraging results were obtained using commercially available epoxides and acid anhydrides which are compatible with the glycerol and cellulose nitrates and which, upon curing, react to form polyesters. Propellants having a composition of about 50 percent binder and 50 percent solid, with a theoretical specific impulse of 260 seconds at 1000 psi, could be made readily. Moreover, completely void-free grains were obtainable without resorting to vacuum mixing equipment or air conditioned surroundings.

Through a BRL contract, let initially in 1954, Wyandotte Chemicals Corporation had cooperated closely with the Laboratories in rocket propellant research areas of common interest, particularly in the work culminating in BRL-1 propellant. During 1959, BRL and Wyandotte conducted evaluation tests of 70- and 80-lb rocket motors using BRL-1 propellants. Held at the Canadian Armament Research and Development Center, the tests verified the predicted performance and the practicability of this then unique propellant concept. Responsibility for further development of BRL-1 propellant technology was given to the Army Ordnance Missile Command, Redstone Arsenal, Alabama.

Mechanical Properties of Solid Rocket Propellants. In addition to the efforts noted in the introductory paragraphs for the Missile Command, BRL conducted theoretical and experimental work on the mechanical properties of solid propellants to support the BRL-1 rocket propellant development. The theoretical work considered quasi-stable response, vibration theory and wave propagation. The experimental work involved measurement of bulk moduli and a firing program using model test rockets to define the interior ballistics performance and visco-elastic response of the propellant grains. The values obtained for the various mosuli were used in an application of stress function theory to determine the visco-elastic response of the propellant materials. Later work involved research to determine the effect of particle size on the attenuation and scattering of waves in solid propellant grains.

Combustion Instability in Solid Rockets. For nearly two decades before the advent of the 1960's, engineers and scientists in the field of solid and liquid propellant rockets had been concerned about pressure oscillations that occur sporadically during motor firings. These pressure oscillations occur in the frequency range of 100 to 100,000 cycles per second and may or may not be accompanied by unpredictable changes in burning rate and mean pressure within the motor cavity. When it occurs in solid rocket motors, the phenomenon is referred to as combustion instability or unstable burning. Severe combustion instability can result in destruction of the missile.

Although the subject is not discussed in Volume I of History of BRL, the Interior Ballistics Laboratory had been studying combustion instability for some time before 1957. Much of the evidence acquired by BRL pointed to the possibility that the oscillations might be acoustic in origin and might be initiated and amplified by the combustion process itself. In approaching the problem of combustion instability, BRL followed two basic programs. One program used an externally-driven sound source to produce pressure waves on a propellant surface as it burned under rocket chamber conditions; the other program involved self-excitation by the combustion process and thereby probably reproduced more nearly the actual operating conditions in a rocket motor burning unstably.

In the former program, when the oscillations provided by the sound source (a siren) reached a frequency that approximated the resonant frequency of the test chamber, the burning rate increased rapidly and large excursions (20–25 percent of mean pressure) occurred in the chamber pressure. These observations lent some support to the theory of acoustic interaction with the burning surface. It was also noted that for composite or double-base propellants containing aluminum, the flame zone appeared to be a zone of burning gases. In composites, some of the aluminum particles after melting, rolled about on the burning surface, picked up other particles, and eventually left the surface as large burning particles. Such behavior was believed to be one reason for instabilities reported when aluminum was present in the motor propellant.

In the latter case, experimenters investigated the frequency-dependent action of the combustion process of acoustic waves, which could be characterized by assigning a specific acoustic admittance to the burning-zone/product-gas boundary. Measurements of that property could then be compared with values predicted by acoustic theories. Results from experimental firings of three different types of propellants, which should exhibit combustion instability in varying degrees of severity, agreed with predicted performance.

An important conclusion from the first investigation was that powered aluminum, originally added to solid rocket propellants as a cure for combustion instability, actually contributed to or caused low-frequency combustion instability in some cases. The important result from the second, was that BRL was among the first three establishments in the United States to report actual measurements of acoustic admittance of burning propellant surfaces.

Changed emphasis in the rocket propellant combustion instability program occurred in 1968; at that time, following a meeting of the Army Rocket Propulsion Coordinating Group, BRL was asked to characterize families of rocket propellants according to their unstable burning tendencies and then, most importantly provide immediate, in-depth design criteria for resonance rods which had been determined to be a mechanical corrective for unstable burning.

Subsequently the effects of three major types of damping devices were explored. The types tested were: an area restrictor, a smooth rod, and a perforated rod. It was found that the area restrictor was a very effective suppressor, even at low frequencies. As dampers, perforated rods were strongly frequency-dependent, but their use was promising for high frequencies. Smooth rods were found to be ineffective. The researchers also concluded that control of unsteady combustion by "acoustic" design rather than "combustion" design appeared advantageous.

Low Vulnerability Ammunition. Contrary to what one might expect, it has been found, in work done at BRL and work done by contractors for BRL, that the propellant in large caliber ammunition can be more vulnerable than the explosive material in a shell or other warhead. This, of course, affects the overall vulnerability of a weapon system. What is needed then is a propellant with significantly higher thresholds for thermal and impact initiation, yet which provides the same ballistics performance.

The Army Small Arms Systems Agency had supported work to develop propellants which were less sensitive to initiation stimuli than conventional, single-, double-, and triple-base formulations. The objective of an "invulnerable" caseless small arms round was not met, primarily because of problems with ballistic and mechanical properties of proposed propellants.

It appeared that if some of the candidate propellants were considered for use in large caliber ammunition, the problems encountered in small arms applications could be overcome and their lower vulnerability properties utilized. To evaluate this concept, BRL embarked on a feasibility test.

The propellant selected for the test was a composite formulation, 75 percent HMX and 25 percent polyurethane, designated LOVA-X1A. The test included measurements of fragment and thermal initiation thresholds. Results showed that so far as thermal and impact initiation was concerned, LOVA-X1A was significantly less vulnerable than conventional M6 and M30 propellants.

Still pending in 1976, was the evaluation of the interior ballistics performance of LOVA-X1A.

Fuel-Air Propellants. As recently as the 1960's fuel-air propellants had not been considered seriously because of the relatively low density of loading (hence low energy content) required for practical application and the suspected complexity of a new weapon system. However, the potential advantages of fuel-air propellants—low vulnerability, elimination of the cartridge case, and decreased logistical demands—prompted interior ballisticians at BRL to re-examine the concept in 1973. The approach followed was identification and optimization of the constant volume pressure parameters which affect the rate of pressure rise and maximum pressure, and validation of the results through use of JP-4 fuel in a gun.

The approach was successful; a muzzle velocity of 2130 feet per second was achieved by a 560 grain projectile fired from a .50 caliber smooth bore barrel. These results indicated that with further optimization a .50 caliber 560 grain projectile with a muzzle velocity of 2330–2560 feet per second should be possible.

Liquid Propellants. The low flame temperature, reasonably flashless muzzle gases, and the potential for hydraulic loading are factors that have made liquid propellants interesting to interior ballisticians. However, the development of a bulk-loaded liquid propellant gun has long been hampered by erratic and unstable combustion.

Early gun firings gave unpredictable and, quite often, unexpected results. Combustion instabilities often caused extremely high pressures (60,000–80,000 psi) which exceeded the safe operating limits of currently fielded weapons. The trial-and-error method was used to obtain a workable weapon.

Eventually several experimental gun systems performed satisfactorily, but the results did not provide much information useful for understanding the fundamental processes of liquid propellant combustion in guns, nor were they very useful in establishing design criteria.

By 1957, BRL efforts to understand the combustion process and to develop at least a qualitative ballistic theory had progressed to the point where the behavior of burning mixtures of hydrazine, and hydrazine-nitrate and water, in a preloaded 37-mm gun could be described. When a column of liquid propellant was ignited radially by a pyrotechnic primer at the base end (end nearest the breech) a portion of the propellant (approximately one-third of the total charge) was ignited by the primer gases and was consumed during the engraving process and early projectile motion. The middle region or portion of the column was broken up, probably into droplets by the so-called "Taylor instability" effect and burned at an extremely high rate. This rate was sufficiently high that it increased the chamber pressure by about 50 percent or more, even though the chamber pressure was now double its initial value, and was increasing very rapidly (projectile velocity was 1200–1500 feet per second). The forward portion of the charge (now down to one-quarter of the initial total) followed the base of the projectile as in a traveling charge gun, and was consumed down the gun tube, a chamber length or more from its initial position.

These results indicated that liquid propellants could be used in a 37-mm gun to give a wide range of muzzle velocities (1800–4500 fps), and that chamber pressure could be controlled and kept well within the safety limits of the then-fielded weapons.

The semi-empirical explanation of the burning of the charge was improved in 1961 when the "Helmholtz Instability" effect was applied to the explanation. This type of instability arises when the combustion gas flows parallel to the surface of the liquid and generates waves and surface turbulence. The Helmholtz instability increases rapidly, and coupled with increased heat transfer, leads to a rapid increase in the rate of gas evolution sufficient not only to maintain the pressure, but also to increase it very rapidly and sometimes catastrophically. If the charge is completely consumed before the pressure rises catastrophically, and it usually is, a second maximum pressure occurs, typical of liquid propellant combustion in bulk-loaded systems.

The postulation that the Helmholtz effect was the mechanism that produces enormous combustion rates associated with the second pressure peak made possible construction of an interior ballistics model of a fully-loaded liquid monopropellant gun system. The model could explain, and in many cases predict, the predominant features of the complete firing cycle. It was proposed that the model was sufficiently valid to be the basis for semi-quantitative design analysis of a high velocity liquid propellant gun system for high muzzle velocity (5000 feet per second).

Research in liquid propellants continued, with varying degrees of emphasis, throughout the period 1957–1976. Among the activities was the computation of the thermodynamic properties of certain liquid monopropellants. Considered in these computations were monopropellants such as hydrazine, nitromethane mixtures, ethyl-propyl nitrate, and OTTO-II, all of which have been fired in guns; and isopropyl nitrate, LGPI, PL-13, JP4 and nitric acid, JP4 and air, N-neptane and hydrogen peroxide, JP4 and nitrogen tetraoxide, hydroxyl ammonium nitrate and dioxane and water, and hydroxyl ammonium nitrate plus isopropyl ammonium nitrate and water, which have been suggested for use in guns. Thermodynamic properties of these monopropellants summarized in tables and graphs include temperature, pressure, ratio of specific heats, internal energy, force, and entropy, for gun loading densities from 0.05 to 0.40 grams per cubic centimeter.

BRL also investigated a new class of liquid propellants originally developed by the US Navy for use as torpedo fuels. These propellant candidates are aqueous solutions of ionic salts with several desirable characteristics. They are stable, easily prepared, apparently non-toxic, and not unacceptably corrosive. In addition to having those properties, they have a calculated impetus of more than 300,000 ft-lb/lb and low vulnerability to weapon effects.

Firings in 38.8-mm bulk-loaded liquid propellant guns provided evidence that energy or pressure wave absorbers located at the breech and the projectile base may substantially reduce excess pressures in liquid propellant guns. Theoretically, the venting action (i.e., the intrusion of the primer gases into the liquid) from a pyrotechnic primer can produce severe pressure oscillations in a liquid propellant gun chamber completely filled with propellant where the loading density equals the propellant density of about 1.4 gm/cc. If measures are not taken to control the pressure waves by the use of pressure wave absorbers and to control the rate of primer venting, excessive pressures can be expected. Complementing the work with absorbers, BRL investigators developed a new type of radial venting pyrotechnic primer which provides, for the first time, symmetric and reproducible ignition. Given the past and then current difficulties in obtaining and storing chemically similar lots of monopropellant, and the observed variations in ignition required for different lots, these new primers and absorbers were expected to have major importance in reducing peak pressures encountered in liquid propellant guns.

Much of the research into the interior ballistics of liquid monopropellants at BRL during the 1970's had been initiated to support a small arms program at Pulsepower Systems, Inc. (PSI). The PSI program was funded by the Advanced Research Projects Agency, the Army Small Arms System Agency, and the Army Armament Command at Rock Island. A primer fabrication task at Frankford Arsenal and a liquid propellant development effort at the Naval Ordnance Station also contributed to the PSI program. However, so far as advancing the state-of-the-art in liquid propellant small arms was concerned, the PSI program emphasized hardware and automatic small arms development.

IGNITION AND COMBUSTION

Research in ignition and combustion became noticeably more sophisticated as the interior ballistician exploited the potentials of the digital computer, the capabilities of new instruments, and the flexibility of combinations of instrumentation and dedicated computers. An example of the depth and complexity of this research is an approach which attempted to link the quantum mechanics of chemical reactivity with the observable macroscopic processes of ignition and combustion. The development of interior ballistic models, their continual improvement, and the need for an all-inclusive, realistic interior ballistics model, placed an increasing demand on scientists to provide quantitative details of the extremely complicated phenomena that occur as a propellant ignites and burns. The broad scope of BRL research in ignition and combustion is revealed in the discussion which follows.

Ignition Research. Historically, igniter design has largely been an art based on cut-and-try approaches guided by previous experience. In the 1950's, BRL attempted to rationalize igniter designs through static tests in the laboratory and some modeling, but the origin of ignition anomalies were never fully understood. To attain this understanding, the BRL program set out to quantify: the response of an igniter material to external stimulus, characteristics of flame-spreading through the igniting material and the mode of energy transfer from the igniter, the mechanisms whereby igniter energy is introduced into the propelling charge, and the response of the propellant to that energy.

Resulting from that approach was a new ignition theory for solid base propellants which overcame the limitations imposed by previous ignition models. Those models oversimplified the chemical reaction kinetics and the thermodynamics of the ignition mechanism. The theory was formulated by combining individual models to form one comprehensive model which takes into account the chemical reaction kinetics and the physicochemical, diffusive, and hydrodynamic processes which occur during the ignition state of combustion in the solid phase, in the decomposition demarcation zone, and in the gaseous phase—processes responsible for the buildup to steady state combustion (and for the extinction of combustion already started).

About the same time, a theoretical microscopic model of ignition energy transfer in crystals was developed. An understanding of the mechanisms by which lattice vibrational energy is transferred into the internal degrees of freedom of molecules of organic propellants and explosives is necessary to explain how chemical reactions can be initiated. The coupling of this knowledge to the other steps leading to combustion can provide the capability for predicting the intrusive sensitivity of the material as well as the essential physical and chemical properties which new organic substances must possess to be useful as propellants (or explosives). The theory also accounted for the absorption of energy at ultrasonic frequencies.

Work was also undertaken to examine the electronic structure of nitrocompounds. The objective was to unravel experimentally the electronic intramolecular energy transfer mechanisms with a view towards understanding the contributions of excited electron states to the decomposition of energetic nitrocompounds.

Within the US Army Materiel Command, a research program in the fundamentals of ignition and combustion was established in 1971. This represented a unified Army program for which BRL was the program coordinator. It had become obvious, despite the progress that had been made in quantifying the ignition and combustion processes, that the ever increasing demands for higher performance specifications and operating characteristics in new weapons dictated even more rigorous understanding of the phenomena.

Combustion Research. The primary objective for research in propellant combustion is to obtain a complete, detailed, quantitative understanding of the chemical and physical phenomena involved. Quantitative understanding of these various mechanisms would lead to the development of a realistic mathematical model for predicting the combustion characteristics, and thereby the performance characteristics, of propellants. The development of this exact combustion model thus became the key technical factor for measuring progress in combustion research.

Early work in combustion during the 1957–1976 era emphasized study of the rates and mechanisms of gas reactions which control propulsion processes. This research considered three areas of reaction kinetics: High Temperature Kinetics, Explosion Kinetics, and Atom and Free Radical Reactions. The high temperature kinetics work was carried out in a high-pressure shock tube which permitted direct experimental study of chemical reactions at high temperatures (above 1500°K). The technique proved useful for measuring reaction rates at high temperatures, and is still in use at BRL. One early result was evidence that decomposition mechanism for NO_2 is unchanged over the temperature range of 700°K to 2500°K.

The study of atom and free radical reactions focused on the determination of the reaction rates, at room temperature and higher, for atoms and radicals in the gas phase or on surfaces. The measurement of atomic reaction rates was achieved by relating the intensity of an afterglow to its particular atom concentration. The afterglows were produced through a microwave discharge technique. Reaction rates measured for atomic oxygen and atomic nitrogen were extrapolated to the conditions of high temperature flame processes. Research in explosive kinetics gave results that clarified the thermal explosion of hydrazine vapor and the explosive reaction of H_2 and NO_2.

The chemistry of nitric oxide was thoroughly investigated because it is an important intermediate in the thermal decomposition and burning of propellant containing nitrate ester and nitro groups, and it is potentially useful as an oxidizer in liquid bi-propellant systems, although its potential may not be reached because of its slow reactivity with fuels.

Under the coordinated AMC program in ignition and combustion, referred to above, BRL carried out research in five areas: Reactions of Pyrolytic Fragments, Mass Spectral Analysis of Ballistic Combustion Products, Transient Burning of Nitrocellulose Propellant, Temperature Sensitivity of Gun and Rocket Propellants, and The Effect of Thermal Radiation on Solid Propellant Burning Rate.

During combustion, the propellant at the surface undergoes decomposition to form smaller reactive chemical fragments which subsequently react to give the flame in the gas phase. The objective of BRL work was to identify the nature and variations of the molecular fragments formed on the pyrolysis of homogeneous propellants and propellant ingredients. The pyrolytic products of nitrocellulose identified by BRL correlated with data published by others for fizz-burn products and dark-zone products (where under reduced pressures in inert atmospheres propellants burn without luminous flames) produced during the combustion of nitrocellulose propellants. When the data from the pyrolysis of nitrocellulose propellant and from an HMX propellant were compared, significant differences were noted in the amounts formed of nitrous oxide, hydrogen cyanide, nitric oxide and carbon monoxide.

Current interior ballistics models are based on a number of simplifying assumptions. One of the most basic and important assumptions is that of thermodynamic equilibrium throughout the interior ballistic process. This equilibrium assumption was to be tested under realistic interior ballistics, especially in the high velocity regime where time scales for equilibrium are short. A molecular beam sampling system was developed to study the transient species produced during the combustion process. Initial work studied the decomposition of ethylnitrate and n-propylnitrate.

Burning rate expressions used in gun codes are strictly valid for steady state combustion only. BRL undertook a task to determine the propellant properties that affect transient burning rate characteristics. The approach was both analytical and experimental. The analytical approach involved the extension of existing mathematical models or development of new models to generate data on transient burning rates. The calculated data would be compared to the results from strand burners and closed bombs in which both the static pressure and burning rate are increased simultaneously. Results of the analytical work showed that there is probably no significant enhancement of the burning rate for an idealized strand propellant in a closed burner for pressures greater than 500 psi. The experimental work, as expected, indicated that there was no burning rate enhancement for pressures greater than 2900 psi with pressure rise rates up to 2.9×10^5 psi/sec. The analysis indicated that the pressure transient effect could become significant for pressures greater than 500 psi for propellants with high surface to volume ratios. Supporting work suggested that the pressure transient effect could be significant for propellants burning at less than 2900 psi, but suddenly subjected to a pressure pulse.

Propellant combustion is sustained by several sources of energy release and feed back; one of the major sources is thermal transfer to the propellant surface. BRL developed a model that describes the theoretical interaction of an externally applied radiant energy flux with the combustion of a burning homogeneous solid propellant. It was presumed that the gas was transparent and that the radiation was absorbed within the condensed phase (the solid propellant). The burning rate was found to increase linearly with time as a function of flux for small intensities and less than linearly with time as the flux becomes larger. Identified were the necessary conditions for treating the radiation as an increase in initial propellant temperature, and the conditions at which such an equivalence principle would not apply. It was found that the effect of thermal radiation is strongly linked to the propellant parameter known as temperature sensitivity.

Pressure Waves in Gun Chambers. The occurrence of pressure waves, large pressure gradients which oscillate along the axis of a gun chamber, have been recognized as a cause of ballistic irregularities and gun system failures for some time. The first experimental evidence for their existence was found by R. H. Kent in 1935. Since that time a large body of empirical information on pressure waves has accrued and has been used, with uneven success.

To reduce the formation of pressure waves, BRL considered tailoring the propellant grain geometry to maximize the permeability of the propellant bed and to minimize the initial gas generation rate. This was done by using a 19-perforation propellant grain (as opposed to the usual 7-perforation grain). The results of test firings using 19-perforation grains and 7-perforation grains made of the same propellant formulation showed that at equivalent charge weights or equivalent velocities, the 19-perforation propellant showed a much smoother pressure-time history with smaller differential pressures than did the 7-perforation propellant.

As propellant charge weight is increased to obtain higher velocity rounds, a significant fraction of the total energy is expended in accelerating the solid and gaseous propellant. Classical ballistic theory predicts that this energy loss will produce a quadratic pressure distribution, with the projectile base pressure being a constant fraction of the breech pressure. That pressure oscillations do occur indicates that classical theory is not always correct. Test firings using a highly-instrumented 105-mm tank gun showed that sizeable discrepancies from classical theory do exist, particularly during the early motion of the projectile. Pressure oscillations, occasionally observed in the past during the development of a new round, were reproduced under laboratory conditions. These oscillations were hypothesized as arising from the non-simultaneous ignition of a fast-burning charge; they were subsequently eliminated by rearranging the charge symmetrically about a central tube igniter.

HEAT TRANSFER, WEAR AND EROSION

With the introduction of higher performance weapons, especially tank guns, came an ever increasing concern for gun barrel erosion. The concern became critical when it appeared that newly developed weapons would have tube life less than fatigue life. The causes of wear and erosion were known: thermal, caused by propellant burning and the projectile engraving process; mechanical, caused by combustion gases and the rotating band; and chemical reactions, caused by combustion gases and band material. The discovery of secondary wear in the M68 tank cannon, coming about through the addition of wear-reducing materials for the High Explosive Anti-Tank (HEAT) round, exposed a new problem.

Experimental methods were undertaken to measure the temperature distribution and total amount of heat transferred in gun barrels. The temperature distribution was obtained by placing small fine wire thermocouples at different depths and locations along the gun tube. The temperature-time history at each depth and location was obtained after firing a round. Data reduction and subsequent calculations resulted in a graph which could be used to determine the total heat transferred through the inside surface of the gun tube. The results of the experiment gave values of the total heat transfer approximately 25 percent higher than the values obtained by a previously used method that extrapolated the temperature reached by the outside of the tube.

The fine-wire thermocouple method was also used to measure heat transfer during firings made with and without wear-reducing additives. The results showed that 17 percent less heat was transferred to the gun tube at each location of the thermocouples when the additives were used than when additives were not used. Of more significance in this experiment than the simple fact of heat reduction was the conclusion that the location and manner of use of the additive, rather than its composition is more important so far as reducing total heat input is concerned. The additive is most effective wrapped around the forward end of the propellant with some of the additive folded over the propelling charge at the base of the projectile.

A two-dimensional finite difference/finite element code was developed to calculate the temperature profile within a gun tube. Most of the input data used in the code come from a revised version of the Interior Ballistics High Velocity Gun (IBHVG) program also developed by BRL. The values for peak temperatures at the origin of tube rifling after two milliseconds agreed with experimentally determined values. Subsequently, this finite-element program was complemented by a program using Monte Carlo techniques to determine temperature profiles in a 37-mm gun as a function of time and space.

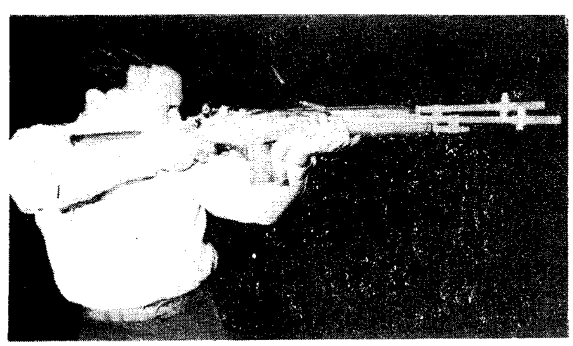
Positive ion beam techniques were used to measure wear in gun tubes and to examine composition changes in gun steel surfaces. These techniques are described below in the section on instrumentation.

Erosion has been drastically reduced for large caliber guns by the use of rayon propellant liners coated with mixtures of titanium dioxide or talc (magnesium metasilicate) and wax. Developed semi-empirically in 1962, by S. Y. Ek and D. E. Jacobsen of Sweden, the wear-reducing characteristics of these materials (additives) continued to be investigated. BRL completed a survey which presents in one document all the salient information collected on wear-reducing additives.

GUN TUBE MOTION AND WEAPON KINEMATICS

Theoretical and experimental tests were made to determine the effect of tube bending (droop) and gun vibrations on the accuracy of tank guns. The results of the tests, made using a 90-mm gun, indicate that the effects of droop, initial crookedness of the tube and the tube bend associated with thermal gradients could largely be eliminated by using muzzle bore sights to aim the gun. The number of rounds fired in the tests was not sufficient to establish a statistically significant measurement of the projectile "jump" associated with the whip of the tube. However, theoretical work showed that this jump will be different for different types of projectile.

Somewhat later during a BRL Tank Gun Firepower Study, the most salient finding to emerge was the importance of variable bias in the accuracy of tank guns. Briefly, when small uniform series of shots (5–10 rounds each) were fired, seemingly excellent dispersion of 0.2–0.3 mils standard deviation was achieved for each group. However, dispersion of the centers of impact for several such groups was about 0.7 mils, about three times as great. This shift, or variable bias, in the center of impact from occasion to occasion frustrates the tank gunner's attempts to permanently zero his sights; more importantly, it gives an unacceptably low first round hit probability at ranges greater than one kilometer. Results from environmental tests at BRL showed the overriding importance of thermal distortion from natural causes in producing variable bias in gun tubes. On a sunny day, the gun bent as much as 1.8 mils, seven times the normally expected round to round error for the 105-mm M68 Tank Gun. Mr. Billy D. Sissom, Materiel Test Directorate,



Man-weapon system in automatic fire

Aberdeen Proving Ground, should be credited for his early and valuable research into the causes of variable bias.

Two important results of BRL work that would have broader applications in the evaluation of weapons kinematics were the development of an analog simulation of the mechanism of the M16AI Rifle, and a hybrid computer model of the 30-mm XM140 Automatic Weapon System. The former provided the ordnance engineer with the basic techniques, or if you will, tools for modeling the operations of self-powered automatic weapon mechanism. The latter provided the techniques for modeling externally powered automatic weapon mechanisms and operations; in addition it combined the advantages of digital computer accuracy and programmability with analog time-scaled simulation and convenient man-machine interaction.

The M16AI Rifle Model constructed by H. P. Gay and E. M. Wineholt deserves more extensive discussion since it represents a significant and useful accomplishment, theoretically in its own case and for subsequent kinematic models, and practically in its application to the M16AI Rifle.

Extensive use of the M16 Rifle in Southeast Asia led to allegations that it was not reliable. In November 1967, the Army's Weapon Systems Evaluation Group became responsible for directing tests to determine the operational reliability of the 5.56-mm M16AI Rifle. Test results revealed several malfunctions, some of which could be linked to the propellant used in the ammunition.

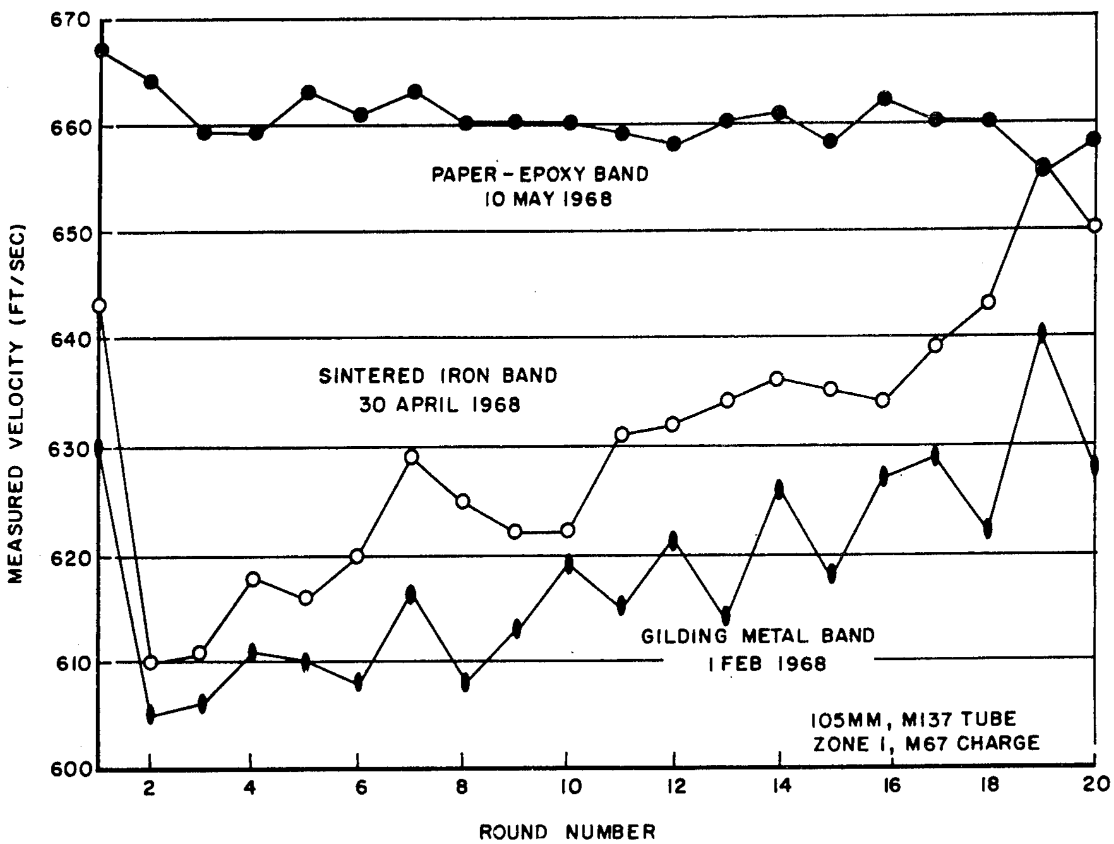
The AMC Project Manager for Rifles organized an M16 Advisory Group to coordinate efforts of AMC agencies participating in improvement efforts and production of the rifle and its ammunition. At the first meeting of the Group, February 1968, BRL was given responsibility for investigating the interior ballistics and kinematics of the weapon. It was soon evident that the original scope of work at BRL needed extension. For example, a detailed analysis of the gas operating system needed to be made to define interactions between the interior ballistics and the dynamics of the rifle. And, at the request of the Project Manager, BRL conducted several *ad hoc* analyses, such as the effects of cyclic rate on parts breakage and the performance of mechanisms at extreme temperatures.

Believing that a physical-mathematical model of the rifle mechanisms was essential to an understanding and evaluation of the weapon's performance, BRL interior ballisticians H. P. Gay and E.M. Wineholt (see also Flow in Gas Operated Weapons, Exterior Ballistics) initiated a four-phase program that included:

- measurements of masses, moments of inertia and distances—to provide basic input to the model,
- firing tests to measure gas pressures in the firing chamber, at the gas port, and in the carrier cavity and to provide data for displacement-time curves for the main components of the weapon. (Displacement-time curves would represent the forcing functions in the model.)
- development of mathematical or physical models so that the operation of the mechanisms could be simulated on an analog computer, and
- comparison of the calculated (simulated) velocities and displacements with those observed in the firing tests—to assess the validity of the model.

The output of the model simulating operation of the M16AI Rifle mechanism agreed well enough with the corresponding observations for the researchers to conclude that the model was accurate in evaluating the effects of changing masses and forces of the system.

In 1970, BRL initiated investigations into non-metallic rotating bands for two reasons: to correct known deleterious ballistics effects, and to find a substitute for an often critical rotating band material—copper. The effects to be corrected were "the first round effect" which is a marked variation in muzzle velocity between the first round fired from a cold or unconditioned gun, and the "creep effect" which is a slow upward trend in muzzle velocity during the firing of a series of rounds from an initially cold gun. Nine different non-metallic materials were used as substitutes for gilding metal or copper rotating bands. The results demonstrated that first round and creep effects would be eliminated, or at least, drastically reduced when non-metallic rotating bands were used with a 105-mm howitzer. The



Effect of non-metallic rotating bands on the initial velocity of 105-mm rounds

use of non-metallic rotating bands also offered a potential for attaining lower muzzle velocities in a given weapon than are possible when metallic bands are used. It also promised lower costs and a reduction in barrel wear as a result of decreased engraving force, band pressure and coefficients of friction.

RESEARCH INSTRUMENTS AND FACILITIES

One problem, common to many laboratory instruments and to field firings of instrumented guns, is the large volume of analog data that is acquired in the course of an experiment or a gun firing. A disproportionate amount of the researcher's time, or that of his technical assistants, must be spent in the repetitive task of reducing the data to usable form. That time could more profitably be spent on interpretation of the results and optimization of the experiment.

It was soon realized by interior ballisticians at BRL that the digital computer, either a central system or a dedicated minicomputer, could relieve some of the burden of data reduction and in the case of a dedicated computer actually repetitively control an experiment. This exploitation of the computer and the increasing sophistication of instruments and experiments characterize instrumentation techniques and facilities used at BRL during the period. Advances in magnetic tape data-recording systems and the development of analog to digital conversion techniques, both the results of the Laboratories' in-house research, made such exploitation possible. The paragraphs that follow describe some of the techniques and facilities used for interior ballistics work.

Microwave Interferometer. This experimental tool developed at BRL in the late 1950's ranks high among advances in experimental interior ballistics. The instrument measures the early displacement of projectiles within the gun tube or an artillery rocket within its launch tube. It does this essentially by counting the Doppler beat frequency as a function of time between a microwave beam propagated down into the gun tube and the beam reflected by the moving projectile. The experimental problem then shifted from the measurement itself to the digestion and interpretation of the now abundant data. This problem was solved in 1960, through the development of a data recorder-reproducer which could play back information into a card punch for direct use in a computer. The microwave system was subsequently modified to provide pressure measurements on the base of the projectile. Pressure gages installed on the base modulated an oscillator which through a semi-conductor diode modulated the amplitude of the microwave beam.

Molecular Beam Sampling System. This apparatus is used to study transient and stable chemical species formed during the pyrolysis and combustion of energetic compounds and propellants over the pressure range from a few Torr to 13.8 milli-Pascals. The system is also used to examine chemical phenomena in the various zones in flames and to determine the effects of additives on the chemical profiles of the zones. Its third use is in the study of rapidly changing chemical phenomena under transient conditions such as those that occur during the ignition process.

Integrated Mass Spectrometer/Computer System for Analysis of High Energy Materials. The system is used to identify samples obtained from either liquid or gas chromatography separation processes. To meet the restraints of high-speed, background subtraction, and background scaling and the need for rapid data reduction and presentation of the results, an interactive computer system controls the operation of the mass spectrometer and acquires, stores, and manipulates data. The results are made available instantly on a cathode ray tube. The system allows identification of a wide range of high-energy materials, including those with low thermal stability or volatility:

High-Speed Liquid Chromatographic Techniques for the Analysis of Energetic Materials. This technique developed by BRL provides a new method for the separation and analysis of thermally unstable and nonvolatile energetic materials. Combined micro-infrared techniques were developed to aid in the identification of separated fractions. The system is used to study intermediate species formed during radiolysis of propellants, condensed-phase chemical changes caused by propellant aging, and catalytic effects on condensed-phase decompositions. The techniques have proven to be extremely effective for the routine analysis of propellants and explosives.

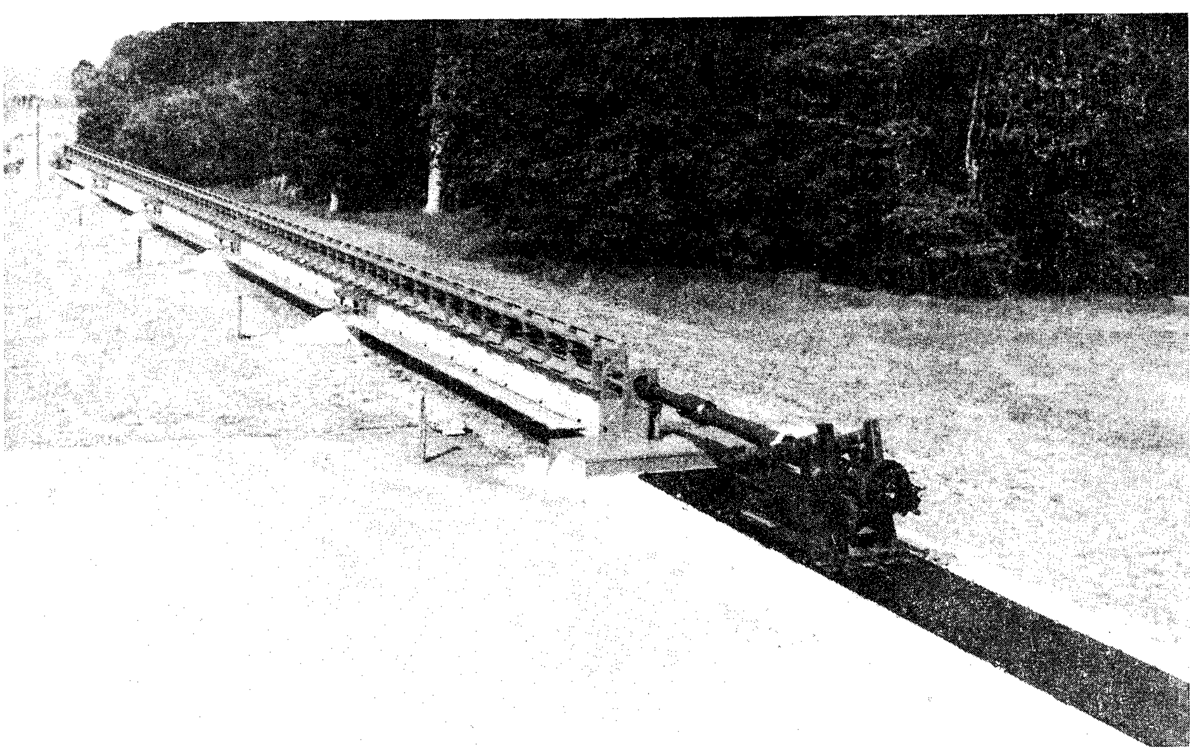
Activation Technique for Erosion Wear Measurements. The basis for this technique is the transformation of stable materials into radioactive isotopes by nuclear reactions produced by energetic positive ion beams. The characteristic radiations emitted by the radioisotopes provide a means to monitor charges in the characteristics of the activated area of the surface. Activation to a prescribed depth of a small area of a gun tube allows wear in the region to be measured by monitoring the decrease in radiation due to the removal of surface material. The advantages are that single-shot tube wear can be measured to submicron accuracy, *in situ,* without bore cleaning.

Ion Beam Technique for Examining Composition Changes in Gun Steel Surfaces Due to Propellant Erosive Burning. BRL developed an ion beam technique by which the outer micron layer of an eroded surface may be examined quantitatively for concentration and depth profiles of carbon, nitrogen, and oxygen. These elements are of great interest because all but a small percentage of a given propellant is made up of their compounds. As the propellant combustion products interact with a gun tube surface, various chemical reactions take place. Driven by high temperatures and high pressures, these reactions attack and erode the surface. Some of the products of these reactions will remain in the surface; thus, measurement of the carbon, nitrogen, and oxygen concentrations yield information about the importance of chemical processes involved in the combustion. In addition, any film layer or other substance containing carbon, nitrogen, and oxygen which might be effective in retarding erosion would be identified through the ion beam analysis.

Shell Pusher. This device, developed at BRL, pushes projectiles through large caliber gun tubes, 105-mm, and 175-mm. The pusher can exert a force of up to 250,000 lbs. on the base of a projectile through a continuous stroke of sixty inches at a rate of one inch per minute. The shell pusher is the only Army apparatus available with a continuous stroke capability.

The system is used for experiments in the study of projectile resistance profiles, projectile-induced tube strains, rotating band induced projectile strains, effects of rotating band geometry and materials on resistance profiles and shot start, and in-bore radio propagation phenomena for telemetry applications.

Large-Caliber Soft Recovery System. To measure the behavior of a projectile and products of combustion during the interior ballistics cycle, on-board telemetry or self-recording instrumentation often is packaged in the projectile. The stringent operating specifications imposed by the ballistics environment and the need for measurement accuracy make such measuring devices expensive. One way to reduce costs significantly is to recover the instrumentation package so that it may be re-used several times. Honeywell, Inc. has designed a soft recovery system to do that. The system is designed to fire the 105-mm (tank gun and howitzer), and 155-mm and 8-inch cannon. Four-and eight-channel telemetry packages will be used to obtain data which will be stored on an on-line digital system. Fully operational status was achieved in 1978.



Large caliber recovery system

THE STATUS OF INTERIOR BALLISTICS

In late 1976, the Interior Ballistic Laboratory of BRL was the focal point for a review of the Army Gun Technology Program (AGPTP). In response to a request from the Department of Defense, Office of Research and Development (ODDR&E) a team chaired by a member of BRL had prepared a description of the Army's Gun Propulsion Technology Program for the current fiscal year 1977 (1 October 1976 to 30 September 1977), and projections of technological gaps that would face the interior ballistics community in the future. The team had responded also to a similar request made by the Director of BRL on behalf of the newly formed Army Armament Research and Development Command (ARRADCOM). However, the Director's broader request asked for the Army's total planned basic and applied research, and development program in gun propulsion technology for all systems for the current and future fiscal years.

The group assembled under BRL's chairmanship consisted of representatives from BRL and Frankford, Picatinny, Watervliet, and Rock Island Arsenals (all of which, including BRL, became completely or partially part of ARRADCOM). To ensure that no facets of an integrated program would be overlooked, representatives from the Defense Advanced Research Projects Agency, the US Navy and Marines, and the US Air Force were involved in the team's work.

The gun propulsion technology area was defined to include solid and liquid propellants, ignition and combustion, charge design, gun tube wear and erosion, projectile/tube interfaces, and materials, but only as these subjects directly influenced propulsion or the interior ballistics cycle. The Technology Program covered five categories of systems: artillery, medium caliber automatic cannon (20- to 90-mm), recoilless rifles and mortars, small arms, and tank cannons. Within each of those categories, the Program charted a deliberate approach for improving the state-of-the-art and carefully identified and defined those areas in which technological information was lacking. The following provides a very brief overview of the Gun Propulsion Technology Program as it was constructed at the end of 1976.

- Artillery: characterization of the phenomena of dynamic combustion in stick propellants, muzzle flash phenomena, evaluation of the effect of non-metallic rotating bands on tube wear, optimization of ablative coolants, consolidated charges, and exploitation of combustible cases with novel grain configurations.
- Medium Caliber Automatic Cannon: muzzle velocities greater than 2 km/s; determination of the effects of repetitive firing on the dynamics of the projectile and gun tube, projectile and fuze integrity during launch and flight; sabot design; liquid propellants that do not produce toxic vapors, that are not detrimental to barrel and weapon materials, and that have acceptable combustion cycles; better understanding of molded/consolidated propellants; and improvement in interior ballistic characteristics of standard propellants.
- Recoilless Rifles and Mortars: for Recoilless Rifles—propellants, igniters, and design configurations that will give uniform muzzle velocities and the necessary muzzle exit energy to allow accurate, long-range delivery of efficient anti-tank payloads; for Mortars—reduction in signatures and in ballistic sensitivity to temperature.
- Small Arms: effects at high volumetric impetus, muzzle devices to reduce weapon noise levels to prevent user ear damage, gas operating systems with minimum sensitivity to unavoidable variations in ammunition, and a good, workable, simple interior ballistics model.
- Tank Cannon: cartridge case design methods for high pressure tank cannons, controlled-progressivity propellants, low-vulnerability propellants, reduced parasitic mass on projectiles, evaluation of residual stresses caused by variations in auto-frettage and electroplating processes, improved wear and fatigue life, thermal jacket technology, and first round effects on accuracy.

Thus, despite the progress made at BRL (and elsewhere) during the twenty years from 1957 to 1976, there still existed major areas of technological unknowns in familiar subjects.

As this era in BRL's history opened, the Nation's defense and space priorities were mirrored in the activites of the Laboratories wind tunnels and ranges. More than one-half of the firings in the free-flight ranges were for the Air Force intercontinental and intermediate range ballistic missiles; the wind tunnels were providing most of the subsonic development tests for the then new Army Ballistic Missile Agency. And wind tunnel tests for the Navy were establishing the basis for the aerodynamic and structural design of the rocket to be used with Vanguard, proposed to be the United States' first satellite.

When somewhat later, in 1961, President Kennedy announced that manned lunar landing "in this decade" was a national objective, BRL aerodynamicists lent their competence and facilities to support the Mercury, Gemini, and Apollo Projects.

Despite the heavy demands for applied research placed upon the BRL exterior ballistics staff and facilities by those programs, the Laboratories continued extensive research in aerodynamics and other branches of fluid mechanics, missile dynamics, and developed new experimental facilities. Interestingly enough, changing Army requirements and the availability of test facilities elsewhere led to the closure of one of these facilities, the hypersonic wind tunnel only a few years after its construction.

As the demand for support to the missile and space programs decreased, BRL began about 1968 to devote a larger fraction of its manpower and resources to conventional artillery and small arms research. The current Army doctrine calls for greater mobility of weapons; this creates a preference for mobile howitzers with shorter tubes, or if necessary, for intermediate caliber cannons with medium length tubes. However, artillerymen still call for longer ranges and heavier payloads. The answer by shell designers and ballisticians has been shell with larger interior volumes and more aerodynamically streamlined external surfaces. These shell usually have long ogival noses, conical boattails, and length-to-diameter ratios greater than 5.5. The increase in exterior and terminal ballistics performance by these new shell was achieved, however, at the expense of gyroscopic and dynamic stability margins compared to those of older shell. Magnus moments and their consequent effect, yaw, were particularly troublesome.

BRL had begun a large-scale investigation on Magnus effects as early as 1946; some of this work was devoted to measuring velocity distributions in the boundary layers around a spinning body in subsonic flow in order to obtain data to be compared with small-yaw predicted behavior. Considerable insight to the Magnus problem was provided by J.C. Martin in 1955. Martin presumed that the effect had its origin in the boundary layer about the shell. He found good agreement be-

Dr. Frederick D. Bennett, Chief, Exterior Ballistics Laboratory 1963–1970, received his AB from Oberlin College, and his MS and PhD (Physics) from Pennsylvania State College. Before joining the BRL staff as a physicist in 1948, Dr. Bennett had been an Associate Professor of Electrical Engineering at the University of Illinois. Dr. Bennett retired from the Laboratories in 1970.

tween his analytical approach and experimental data obtained at BRL. However, at the end of 1956 there was no aerodynamics theory available to predict or provide reliable estimates of this important phenomenon.

Although by the beginning of 1957, Dr. R. Sedney of BRL had developed a method for computing the Magnus force on a slender spining cone with a laminar boundary layer and a small angle of attack, the method predicted a much smaller force than that actually observed on slender cones in flight. The Magnus problem was to occupy BRL aerodynamicists throughout the period covered by this Volume.

Another ordnance problem that also was far from solution at this time was the stabilization of liquid-filled shell. Proposed theoretical solutions had very little success in predicting the behavior or projectiles in actual flight. *Ad hoc* engineering modifications for stabilizing particular shell were at times very successful, but no reliable theory was available for designing stable, liquid-filled carriers.

Around this time also there was renewed interest in an experimental technique using exploding wires because certain related phenomena had become important. These phenomena were associated with high speed flight and ionized gases or plasma. Analysis of the shock waves and other patterns of flow around exploding wires could provide information about analogous disturbances produced or caused by missiles (projectiles), meteorites and other high velocity objects traveling through the atmosphere. Practical problems in space technology and in the field of thermonuclear power created great interest in plasmas and their behavior in magnetic fields. Plasmas can be produced in wire explosions; such explosions create free radicals and unusual short-lived molecules. By 1958, improvements in streak camera photography enabled researchers to determine that the shock wave left the luminous plasma far behind. Several years later, research extended to the nature of the plasma itself. Here the work emphasized the behavior of metals at high temperatures, where thermodynamic data beyond the melting point and in the two-phase regime were lacking. Results could find application in shaped charge jet theory.

As part of the general BRL program in high altitude atmospheric physics research, and probably more importantly, efforts towards the extension of the frontiers of interior and exterior ballistics, much attention was given to developing guns to replace rockets for propulsion of atmosphere probes to moderate altitudes. Guns have a great advantage because projectile impact points can be predicted with reasonable accuracy and they can be used in many locations where sounding rockets would be out of the question. Thus, BRL developed a 5-inch gun with an instrumented projectile (probe) and a 7-inch gun with a probe system capable of achieving an altitude of 350,000 feet. With Gerald Bull of McGill University, BRL exterior ballisticians designed and installed a 16-

Dr. Charles H. Murphy, Chief, Exterior Ballistics Laboratory, has been at BRL since 1948. He received his BS, Cum laude (Mathematics) from Georgetown University and his MA (Mathematics), MS (Engineering and Aeronautics), and PhD (Aeronautics) from The Johns Hopkins University.

inch extended gun in the Barbados. In 1966, BRL directed modification of a second 16-inch gun at Yuma Proving Ground, Arizona. That gun fired a 180 pound projectile to a record height of 111 miles. (Subsequently, high acceleration-proof instrumentation developed for a High Altitude Research Program (HARP) would be exploited in the COPPERHEAD 155-mm guided projectile).

Before the advent of the digital computer, firing tables were prepared by human "computers" using desk calculators. For the firing table data, therefore, relatively few trajectories were computed and intermediate values were obtained by interpolation. The introduction of the electronic digital computer made it easier to include differential corrections (for meteorological conditions other than standard) in detail limited only by the size and complexity of firing tables acceptable to the using services. With no increase in the number of personnel, by automation of calculations, firing table production increased from an average of two major tables per year during 1950–1959, to about six per year in 1960, and about twelve per year by the end of 1976. Also, by that time BRL was producing 30–40 published documents containing input data for artillery computers.

The transfer of the Firing Tables Branch from the Computing Laboratory to the Exterior Ballistics Laboratory in 1968, permitted consideration of ballistics problems encountered in the preparation of firing tables within the context of the broader exterior ballistics program. For example, experimental measurements of missile stability over an entire real trajectory could contribute intermediate values of position and yaw angle for comparison with values derived from ballistic models used in firing table computations.

The need for initial data for firing table and trajectory calculations spurred a cooperative effort between investigators in exterior ballistics and interior ballistics beginning in 1968, to remove conjecture from ascribing precise value of velocity, angle of yaw, and rate of change of yaw of shell emerging from the gun. This domain of ballistics, known variously as Intermediate or Transitional Ballistics received increased emphasis through 1976 and beyond. It was known that erratic launching conditions could cause premature tumbling and disastrously short trajectories for projectiles that might be initially only marginally stable.

Some of the efforts discussed in this introductory section as well as other subjects are covered in greater detail in the following sections.

MAGNUS FORCE RESEARCH

The Magnus force is a side force that occurs on a spinning projectile in flight at an angle of attack with respect to its trajectory. Although its magnitude is low, typically one-tenth to one-hundredth that of the normal force acting on a projectile, Magnus effects are important because the Magnus moment acts to undamp the projectile over its entire flight. Magnus effects have been of concern in the design of artillery projectiles for many years.

Army interest in achieving longer range and greater payload capacity in conventional artillery projectiles led to the design of long, slender projectiles with boattailed afterbodies. Those design characteristics have resulted in reduced gyroscopic stability and increased Magnus moment; thus the new shapes are more susceptible to Magnus induced instability.

A rational theoretical approach for predicting the Magnus forces and moments on a spinning yawing projectile—to a degree necessary to satisfy engineering design approximations—depends upon a realistic, theoretical model describing the three dimensional boundary layer and the inviscid crossflow interaction with surface spin. Such a model was not available at the beginning of this period in BRL's history; however, between 1970 and 1976, substantial progress was being made in the development of a numerical technique for solving the three-dimensional laminar and turbulent boundary layer equations for supersonic flow over a yawed spinning cone.

Even so, extensive wind tunnel and free-flight range testing was still required to determine the Magnus characteristics of a specific configuration.

Initial insight into the Magnus problem was provided by John C. Martin, BRL, in June 1955. Experiments show that for small angles of yaw;

Magnus effects do exist and they are sufficient to have a strong effect on the dynamic stability of projectiles. Because perfect fluid theory predicts no Magnus effects in that range of yaw, Martin presumed that the efect had its origin in the boundary layer. His analysis indicated that the Magnus force for boundary layers is a function of the displacement thickness at the base for zero yaw. When he extended his analysis to turbulent boundary layers, he found good agreement between the analytical results and experimental data obtained at BRL. However, his analysis was limited to very small angles of yaw and was applicable only to bodies with long cylindrical portions.

As noted above, by the begining of 1957, Dr. R. Sedney of BRL had developed a method for computing the Magnus force on a slender spinning cone with a laminar boundary layer and a small angle of attack. The method predicted a force much smaller than that observed on slender cones in flight, but no free-flight experimental data were available for cones with completely laminar flows. Attempts to extend Sedney's theory to more complicated shapes and to turbulent boundary layers were unsuccessful.

In January 1959, Anders S. Platou reported on the results of wind tunnel tests on a short body at supersonic speeds. His experimental investigations of the Magnus force on bodies of low fineness ratios, i.e., where the body length to diameter ratio is low, led to the following conclusions:

- Within its expected accuracy, Martin's theory agrees with the data obtained for laminar flow.
- Magnus force generated on the basic body with laminar flow is less than the Magnus force generated on the same body in turbulent flow.
- A rounded base creates a negative, nonlinear Magnus force; a square base body has a positive force, linear with spin, at an angle of attack at least up to five degrees. A blunt nose, a rotating band, or a crimping groove modifying a streamlined body, all influence the Magnus force, but to a lesser degree than does a rounded base.

While carrying out Magnus tests on various bodies of revolution in transonic cross flow, it became obvious to BRL researchers that the Magnus force was increasingly dependent upon the Mach number of cross flow as the cross flow Mach number approached sonic speed. Above a cross flow Mach number of 0.6, the Magnus force decreases linearly as the cross flow Mach number increases. Since it was known that the Magnus force on a body at a high angle of attack depended mainly upon the cross flow, it was quite natural to presume that such a Magnus force would correlate well with the Magnus force developed on a cylinder mounted perpendicular to wind tunnel flow. Such correlation was shown to exist and the data from the test could be used to predict the Magnus force on a body of revolution in transonic cross flow.

To overcome manufacturing asymmetries in the body and fins, many finned projectiles are designed to spin in flight. While it tends to nullify the effects of fin asymmetry, the spin introduces Magnus-like forces which can have a significant effect on the trajectory. This prompted BRL to analyze the flow over a slowly spinning finned projectile in a wind tunnel. The most significant result was to demonstrate that the lateral forces and moments on a slowly spinning finned projectile can be of the same magnitude as those on a rapidly spinning projectile without fins.

As BRL entered the 1970's, despite the slow but sustained progress in Magnus research, a method for predicting Magnus characteristics of spinning projectiles, for all shapes at all Mach numbers and Reynolds numbers was still elusive. The M549 Projectile Study, conducted in 1970, provided impetus for a more extensive, concentrated theoretical and experimental program to evaluate the Magnus characteristics of spinning projectiles. For that study, extensive wind tunnel and free flight range tests were conducted to determine the effects of mach number and Reynolds number on the Magnus force and moment. These data and other aerodynamic information were needed to explain the unusual behavior of the shell under certain conditions. Wind tunnel tests of an M549 configuration showed large changes in pitch and Magnus characteristics at transonic speeds. Tests using the same shape without a boattail indicated that the large changes were caused by the boattail configuration. Since it was believed that the data were insufficient to verify that conclusion, additional wind tunnel tests using the Army-Navy Spinner Rocket (a standard shape for wind tunnel tests) were carried out to determine the influence of body fineness ratio and of base configuration of a projectile at subsonic and transonic speeds. The tests confirmed that the conical boattail has significant influence on the aerodynamic properties of the projectile: the Magnus force and moment increase, particularly at high subsonic speeds. Particularly significant is the large variation in Magnus force and moment over the transonic speed range, directly attributable to the conical boattail. The results also showed that Martin's theory gives acceptable estimates of the Magnus force and the location of the center of pressure for high fineness ration projectiles with square boattails at low subsonic speeds; however, the theory tends to overestimate the Magnus force on bodies with low fineness ratios.

Another aspect of the Magnus effect investigated by BRL was the "spin mismatch Magnus moment." A bullet has "match spin" as it leaves a stationary gun barrel and then becomes "overspun" down range as it slows faster in velocity than it does in its spin. Wind tunnel and free-flight range tests of Army-Navy Spinner Rockets, with bullet-like engraving, fired at high subsonic and supersonic speeds showed no significant Magnus non-linearities caused by spin mismatch. The effect of grooves on stability is appreciable when the projectile is sufficiently "underspun."

It appeared by 1976 that the Magnus problem would at long last become tractable; BRL exterior ballisticians had available a numerical technique to compute the three dimensional turbulent boundary layer development over yawed, spinning bodies of revolution. This technique would be the key for predictive Magnus modeling.

LIQUID-FILLED SHELL

It had long been observed that some spin stabilized shell, when filled by a liquid, become dynamically unstable in flight. Even when the instability is moderate, if it lasts for a long enough time, the shell becomes wildly unstable and useless. Of course, the problem of instability in liquid-filled shells had been under investigation for many years; however, in 1962, where this discussion begins, there was still no definitive theory which could predict the performance of such shell. It was known however, through experiment and theoretical analyses that the following influenced the dynamics of liquid-filled shell: the shape of the cavity, the unfilled space (ullage) left in the cavity (the percentage of the cavity filled), the specific gravity and viscosity of the liquid and the spin rate of the shell.

In 1940, E.A. Milne, of the British Ministry of Defence, made a thorough theoretical analysis of a mathematical model of the stability of a shell having a spheroidal cavity completely filled with an inviscid fluid, rotating with the full spin of the shell. Employing the model, he derived a set of inequalities which defined the region of instability. Using a large sample of results from firings of liquid-filled shell, Milne analyzed each shell according to the fineness ratio of the cavity, the mass of the liquid, and its transverse and axial moments, then according to its actual behavior, categorized it as either stable or unstable. When he plotted his data, he found a fairly well defined curve separating the stable data from the unstable. While the curve was only tangential to the theoretical instability boundary and was purely empirical elsewhere, it proved to be useful. Milne did look at the effect of viscosity and of airspace, but could not treat these variables adequately in the theory then available.

K. Stewartson, Great Britain, extended Milne's analysis in 1959 to consider a cylindrical cavity partially filled with an inviscid fluid rotating as a rigid body with the spin rate of the shell, a more realistic treatment and of course considerably more complicated. Stewartson showed that instability results only when the poles of a complicated non-dimensional function, defined by the dimensions of the cavity and the fluid mass, approach the nutational frequency of the shell. The theory appeared to be fully confirmed through tests at the British Proving Ground at Porton; the liquid-filled shell problem appeared to be solved.

Such was not to be, during contemporary test firings of developmental shell at the Proof Division at Aberdeen Proving Ground, the shell became violently unstable under all test conditions. According to Stewartson's analysis the shell should have been stable, but it was not.

Because detailed experimental data on the dynamics of liquid-filled shell were lacking, BRL ballisticians decided to obtain such information. They were aided in their decision by the availability of the BRL Free Flight Aerodynamics Range which made the acquisition of such data feasible.

According to Stewartson's theory, the stability of a shell with a liquid-filled cylindrical cavity can be predicted if the liquid is in rigid body rotation. However, for a liquid of low viscosity, a relatively long time is needed for the liquid to achieve full spin; during the transition period from less than full spin to solid body rotation, a shell could become dynamically unstable even though it might be stable at its final state. In the course of experiments at BRL in 1962, Boris Karpov found severe dynamic instabilities in shell where the shell should have been stable following Stewartson's theory and the presumption of rigid body rotation.

To extend the capability to predict instabilities for such cases as those encountered by Karpov, Eric H. Wedemeyer, also of BRL, derived a theoretical analysis of the unsteady flow within a cylinder started from rest and spun about its axis of rotation. His analysis was confirmed through comparison with experimental data obtained from spin decay data of liquid-filled shells and direct observation of the secondary flow within a spinning transparent cylinder.

As research in liquid-filled shell phenomena continued, it became quite evident that instability during spinup arose from resonance as time-dependent eigenfrequencies (the frequencies of free oscillations of the fluid) coincided with the nutational frequency of the shell. The next step in research was experiments with liquid-filled shell in free flight and with a liquid-filled gyroscope where, for each case, the internal cavity was designed to give a principal fluid frequency that was equal to the nutational frequency of the respective system. Comparison of the results with predictions provided by Stewartson's inviscid theory showed that the nutational amplitude at resonance and the width of the resonance band are Reynolds number dependent. There was also a small shift in resonance frequency. The experiments suggested that for very large Reynolds numbers, the inviscid theory gives reasonable predictions. The final conclusion, however, was that shell designers would do better by accounting for the effects of their fluid viscosity; for liquid viscosity is responsible for the observed discrepancies in Stewartson's theory. This conclusion led Wedemeyer (in a most elegant mathematical treatment) to introduce viscous terms into Stewartson's equations, terms that Stewartson had neglected. The modified theory explained the broadening of the resonance band width and the frequency shift due to viscosity. The results were confirmed experimentally for large nutation amplitudes and Reynolds numbers greater than 10^3, but less than 10^6. Inconsistencies were attributed to a change in the cavity boundary layer structure as a result the yawing motion of the test gyroscope.

Although most practical cavities for liquid-filled shell are approximately cylindrical, some deviate sufficiently from exact cylindrical shapes to introduce doubt that treating them as cylinders is still a good approximation. Stewartson had shown for the case of the cylindrical cavity that instability occurred when any of the eigenfrequencies falls within a certain band width about the nutational frequency of the shell. Wedemeyer took the theory a step further by computing the eigenfrequencies of liquid oscillations in non-cylindrical cavities. His approach reduced the problem of finding the eigenvalue to a simple mathematical integration which can be performed by hand when the diameter of the cavity varies slowly.

Although the discussion here has summarized theoretical and experimental progress in liquid-filled shell phenomena, one should note that BRL also emphasized the practical applications of the research results. For example, in Army Materiel Command Pamphlet (AMC-706-65) "Dynamics of Liquid Filled Shell," 1963, Karpov gave recommendations and aids for use by designers of liquid-filled shell; he stressed that Stewartson's analysis was the best *a priori* method for avoiding steady state instability in spinning shell. Karpov's report also included extensive numerical tabulations of the values of variables needed for quantitative design. Although Karpov's tables were useful and the pamphlet provided a complete summary of the state-of-the-art for liquid-filled shell design, designers experienced some difficulty in applying the contents of the pamphlet to the design of shell. The designer's need was met by BRL's report "Dynamics of Liquid Filled Shell," John T. Frasier, 1967. Not only did Frasier extend Karpov's previous work, he summarized the recent work at the Laboratories to point out the significant advances that had been made in understanding liquid-filled shell problems since the publication of Karpov's work in 1963. Frasier also described Stewartson's Theory, emphasizing the physical significance of the assumptions and results of the theory, rather than its mathematical detail. His intention was to give the novice designer of liquid-filled shell an appreciation of and firsthand working knowledge of the analysis so that quantitative design should be simplified. The effects of non-cylindrical cavities, rodded interfaces, and viscosity were further clarified by Frasier and W.P. D'Amico in 1970.

Instability in liquid-filled shell remained a persistent problem, however; instabilities occurred in a 4.2 inch mortar round with white phosphorus in 1968 and a 155-mm binary shell in 1972. In both cases, the instabilities were attributed to the effects of liquid spinup and corrective measures solved the problems.

As a result of the BRL's work in liquid-filled shell, by 1976, BRL ballisticians were able to calculate the frequencies of free oscillation of the liquid during spinup time. A serious gap in shell design had been filled and remaining work consisted of investigating non-linear, large-amplitude effects, analyzing the effects on liquid-filled shell at low Reynolds numbers, and solving *ad hoc* unique payload problems.

PROJECT HARP (High Altitude Research Program)

In the latter part of 1959, informal discussions between the Armour Research Foundation and the Canadian Armament Research and Development Establishment (CARDE) considered the use of gun-fired probes to obtain ultraviolet background emission data above 100,000 feet altitudes. During a visit to CARDE, Dr. Charles H. Murphy, Jr. of BRL learned of this discussion from Dr. Gerald V. Bull, (later Director, Space Research Institute, McGill University), who was directing the CARDE effort.

Subsequently, in late 1959 and early 1960, BRL and CARDE independently carried out feasibility studies, in both cases for guns using sub-caliber projectiles. In early March 1960, Lt. Gen. Arthur Trudeau, Chief of Army Research and Development learned of BRL's interest in gun-launched probes and, realizing that such probes might provide low cost probes for high altitude research, encouraged the project. By July, BRL had demonstrated feasibility of a carrier vehicle in horizontal firings and had designed and conducted static tests of probe packages. Around the beginning of 1961, HARP became a program of engineering and scientific research and development sponsored by the US Army and the Canadian Department of Defense Procurement. Engineering efforts were devoted to developing the launching system—guns, vehicles, and payloads—to achieve maximum payload/mission potential. Scientific efforts were devoted to synoptic studies of the upper atmosphere.

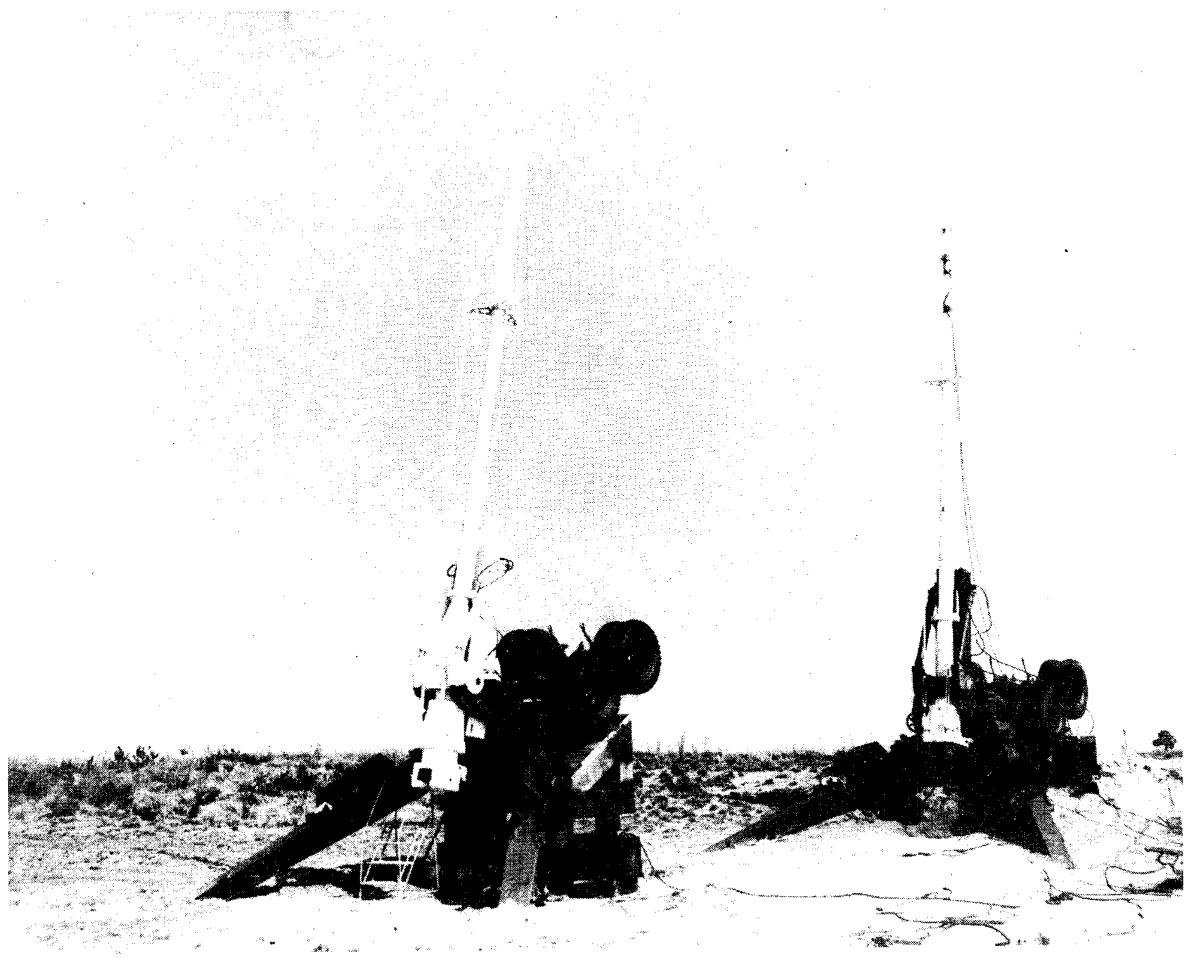
BRL was the center for the Army program, with participation by the Harry Diamond Laboratories for in-flight telemetry systems, Yuma Proving Ground, Arizona, for launch site support, the National Aviation and Space Agency, Wallops Island, Virginia for cooperative high-altitude research projects and launch site support, and Picatinny Arsenal and the Naval Ordnance Laboratory for package ejection devices. The Space Research Institute, McGill University was the center for the joint Army/Canadian Defense research program; the program was monitored by a Joint Steering Committee consisting of members of the Army Research Office, the Army Materiel Command, the BRL, and the Canadian Department of Defense Production.

The first flights, fired to demonstrate apogee/payload and dispersion performance, took place at the Edgewood Area of Aberdeen Proving Ground in June 1961. Fired from a standard service gun modified to a smooth bore, a 21.5 pound, saboted, fin-stabilized five-inch diameter carrier achieved a maximum altitude of 130,000 feet for a muzzle velocity of 5300 feet per second. Chaff payloads were deployed successfully during a second series in August. In June 1962, the five-inch vehicle achieved an altitude of 250,000 feet.

The first series of firings with the smoothbore five-inch gun indicated that the projectile was mechanically weak and powder charge erosion was unacceptably severe. The projectile was redesigned and M17 powder composition was substituted for the M2 charge used originally. At the same time the gun tube muzzle was extended by ten feet. Flare and parachute packages and 250 megahertz in-flight telemetry systems were developed for the five-inch gun system during 1962 and 1963.

A seven-inch gun system similar to the five-inch system was developed during 1963–1964. While retaining the mobility of the five-inch system, the new system extended the apogee to 400,000 feet. It also provided more space for electronic instrumentation such as sun sensors and Langmuir probes as well as meteorological sonde parachute packages which could measure pressure and temperature from 250,000 feet altitude to sea-level.

In 1962, having acquired two surplus US Navy 16-inch gun tubes, McGill University began in-



Extended 5-inch and 7-inch guns used in High Altitude Research Program stallation of a 16-inch HARP system on the island of Barbados, British West Indies. One tube was smoothbored to 16.4 inches and a second tube attached to give an approximate overall length of 85 calibers. In March 1964, a 185-pound vehicle was fired to 430,000 feet. This altitude was exceeded in November 1966 by a projectile which reached 468,000 feet; the achievement was made possible by modifying the sabot and the powder charge and by evacuating air from the gun tube before firing.

The first gun-boosted rocket to be flown successfully from a HARP gun was a five-inch diameter aluminum body, fixed-fin, subcaliber solid propellant rocket fired from the 16-inch Barbados gun in September 1963. That test as well as ensuing tests showed that engineering development was needed to provide rocket propellant grains that would not break up during launch from the gun.

Until late 1966, the primary development firings of the five- and seven-inch systems were made at Wallops Island; the only vertical firing 16-inch gun was located at Barbados. Since firings at these two locations meant water-impact of projectiles, recovery of developmental payloads was difficult if not impossible. Thus, it was decided in 1965 to establish a second 16-inch gun system where projectiles would impact on land. The availability of a 16-inch Navy Mark 7 rifle and mount at Yuma Proving Ground prompted BRL to request permission from the Test and Evaluation Command, (TECOM) to modify the gun and to fire it at vertical elevation. The request was approved by TECOM as well as was a request to install a 5-inch vertical gun system adjacent to the 16-inch gun site.

The first payloads flown in the 5-inch system were radar chaff and aluminized parachutes; the deployed payloads were tracked by radar to define wind velocities between 100,000 and 80,000 feet. Later payloads included telemetry systems with accelerometers and sun sensors to provide information on missle dynamics.

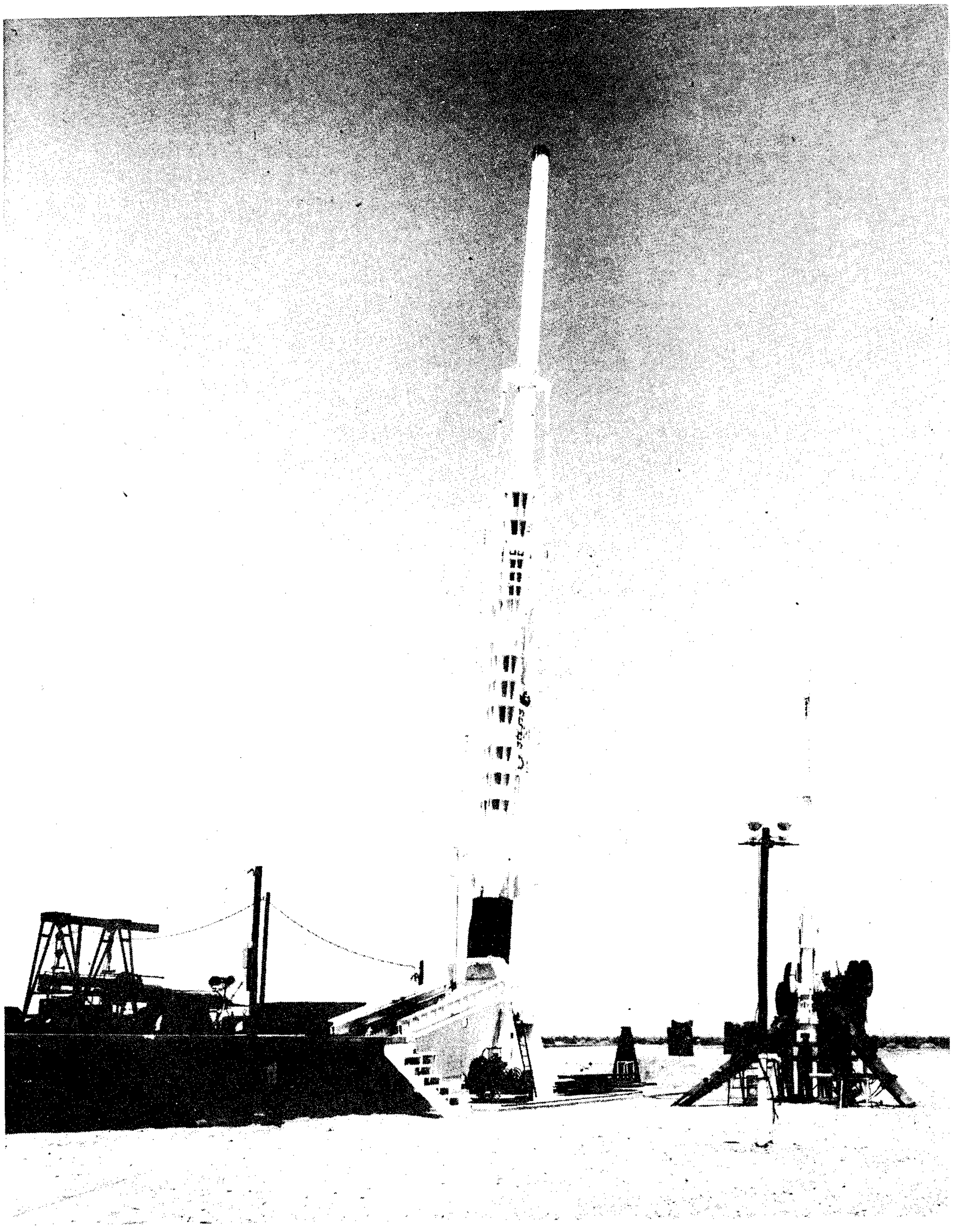
The 7-inch missiles also carried chaff and aluminized parachutes for wind sensing; however, winds could be measured at a higher altitude—above 210,000 feet. The additional payload volume in this larger missle permitted use of chemical payloads such as cesium nitrate with high explosive to generate electrons at 330,000 feet. The ability of the missile to reach through the D-layer into the lower E-layer of the ionosphere led to the development of a Langmuir probe and associated telemetry to make direct measurements of electron density.

While the chaff and aluminized parachute payloads were flown from the 16-inch gun, the payloads in most cases could be fired from the smaller guns. The 16-inch system was used to place chemical payloads above 300,000 feet. These included liquid trimethyl-aluminum, a pyrophoric compound, to produce luminous night time trails from 300,000 to 460,000 feet to measure ionospheric winds, and a cesium compound exploded at 330,000 feet to produce an artificial electron cloud which was observed by a ground-based ionosonde. Sixteen-inch flights with 250 MHz and 1750 MHz telemetry sytems carried instrumentation such as magnetometers, sun sensors, pressure gages, and Langmuir probes.

The development of the gun probe system provided a means to collect considerable scientific data on the upper atmosphere. However, greater benefits will probably be derived through the information gained in the design of gun tubes and powder charges for high muzzle velocity, long range guns and instrumentation capable of withstanding the high accelerations experienced by the HARP vehicles.

Under the aegis of HARP, gun-launched rocket systems had been developed extensively. An attractive application of the gun-launch concept was to cost-effective systems to place substantial payloads at very high altitudes, or even in low earth-orbits. For such applications, a gun-caliber of 16-inches or greater was indicated, with a single- or multiple-stage rocket fired from the gun. The gun-launcher itself would act as the first stage of a multistage system.

Using results from a series of exploratory firings, the Space Research Corporation, North Troy, Vermont and the Space Research Institute, McGill University, developed a 16.7-inch smoothbore gun-launched system designated GLO (for Gun-Launched Orbiter) socalled because of its orbiting potential. An advanced version of the system GLO-1A was capable of placing a 150-



Extended 16-inch smoothbore gun at Yuma Proving Ground, Arizona. In November 1960, BRL researchers fired a 180 lb projectile from this 119 ft long gun to an altitude of 111 miles above the Arizona desert pound payload to an apogee of 1000 nautical miles and 500-pound range payloads to an apogee of 500 nautical miles. However, so far as placing small earth satellites in orbit, the system yielded payloads too small to be of interest, other than the possible case of inflatable balloons.

In cooperation with the Space Research Corporation in the early 1970's, BRL designed a number of follow-on systems to the GLO-1A. A large amount of development engineering was completed, including launching of critical elements such as the large first-stage motor guidance packages, and control packages. The 16.7-inch system was considered to be the lowest size of interest; studies were conducted of scaled-up versions (24-inch and 32-inch). Conclusions of the engineering studies were that gun-boosted rocket systems were cost-effective, all sounding altitudes could be reached with significant payloads, and 100-pound payloads could be inserted in low earth-orbits.

FIRING TABLES

Before the advent of the high-speed electronic computer, relatively few trajectories were calculated to provide data for firing tables, and intermediate data were obtained through interpolation. The introduction of the computer machines made it easier to include many more differential corrections, for meteorological conditions other than standard, in firing tables. The detail of such corrections was limited only by the size and complexity of firing tables acceptable by the using service.

The high speed capability of the computer coupled with improvements in programming significantly increased the productivity of the Firing Tables Branch, without an increase in personnel—actually in later years the number of personnel in the Branch decreased. Firing table production increased from an average of two major tables per year during 1950–1959, to about six per year in 1960, and to about twelve per year by the end of 1976 when both BRLESC I and BRLESC II were on line. Moreover, by that time, BRL was also publishing 30–40 documents containing input data to be used with artillery field digital computers.

At the same time productivity was being improved, new techniques for calculating trajectories were being developed; these techniques discussed below, led to much more accurate tables. The accuracy in these tables was also improved as the new International Civil Aviation Organization (ICAO) Standard Atmosphere was adopted; the new standard atmosphere gave more realistic values of density at higher altitudes.

The transfer of the Firing Tables Branch from the Computing Laboratory to the Exterior Ballistics Laboratory in 1968, permitted integration of ballistics problems encountered in the preparation of firing tables into the broader exterior ballistics program. For example, newly developed techniques to measure missile stability over an entire trajectory of a projectile in flight, could contribute intermediate values of position and yaw angles for comparison with computed values used in preparing firing tables.

Responsibility for computing bombing tables was transferred to the US Air Force in July 1956; the transfer was made at the Air Force's request (they also took over the bomb test drops and reduction of the data from the drops). However, BRL continued to support bombing tables and aircraft gunnery work for several years until an Air Force group being developed at Eglin Air Force Base, Florida, acquired adequate competence.

BRL's long-term interest in the cross-wind problem and other problems encountered when guns are fired from aircraft lapsed when the Bombing Tables Group moved to Eglin. Interest was renewed again in the 1960's when Army helicopters took an increasingly active role in combat. Aiming information was urgently needed because pilots essentially were using "seat-of-the-pants" techniques to direct their weapons at targets. BRL began to provide aiming data for use in air-borne computers—a task that was notably difficult because of the number of parameters that had to be considered; for example, air speed, helicopter aspect, blade downwash, and so forth.

Unusually significant, with outstanding contributions on BRL's part, was the Firing Tables Branch's involvement—particularly that of its Chief, Mr. Charles H. Lebegern, Jr.,—with NATO committees responsible for preparing standardization agreements on items relevant to firing tables. This involvement began in the late 1950's when BRL responded to a call from the Office, Chief of Ordnance to attend a NATO meeting where an attempt was to be made to get the NATO organizations to agree to use the same standard atmosphere for ballistic purposes. From that small beginning, a foundation was laid which permitted, by the mid-1970's, a high degree of standardization in firing table operations among the NATO countries. [Accomplishments, over the years, followed one on the other in such a logical manner, that by the 1980's, NATO was well on the way to achieving ammunition interchangeability.] Briefly, some of these standard agreements and their significance are:

- Standard Atmosphere for Ballistic Purposes, 1958. The adoption of the ICAO Standard Atmosphere as a NATO Standard meant that the countries were on the path to a common artillery firing table format.
- Standard Ballistic Meteorological Message, 1960. A standard format for the "met" message with newly computed weighting factors permits NATO artillery forces to exchange meteorological data.
- Requests for Meteorological Date for Ballistic Purposes, 1967. This agreement set procedures on how to ask the (friendly) foreign artillery fighting on your flanks for "met" data.
- Standard Artillery Computer Meteorological Message, 1969. With the introduction of field computers used with artillery, BRL saw the need for a standard (unweighted) "met" message for use with computers.
- Procedure for the Determination of Exterior Ballistics Performance of Shell. This agreement gives the minimum firing program that BRL believes will produce firing tables with acceptable accuracy.
- Adoption of a Standard Firing Table Format, 1970. This is an outstanding agreement; it permits an artilleryman to use firing tables in a language he does not understand! Without this agreement, too, there would be no ammunition interchangeability.

Other agreements defined terms and listed gauges and velocity measuring instruments that were NATO approved. The approval resulted from tests carried out by BRL.

A Standard Atmosphere for Ballistic Use. Since 1948 BRL had been attempting to get a new standard atmosphere model substituted for the American Ordnance Standard Atmosphere (AOSA), which had been established in 1918. Despite physical inconsistencies, in particular the inability to satisfactorily represent air density at high altitudes, the AOSA served the Army's purposes for forty years.

A Tripartite (United States, United Kingdom, and Canada) Conference on Bomb Ballistics held at the Ballistic Research Laboratories in September 1950, established requirements for a new standard atmosphere for bomb ballistics which would replace both the American Ordnance Standard Atmosphere and the British Standard Ballistic Atmosphere. Subsequently, BRL constructed an atmosphere meeting those requirements, but it did not have the complete approval of a Tripartite Working Group on Exterior Ballistics, which met at BRL in 1951. That group established another set of requirements for the proposed atmosphere.

Wrestling with the dilemma, BRL took the lead in determining which sort of atmosphere would be acceptable, and canvassed agencies in the Tripartite countries for their opinions. The results showed that most agencies favored an atmosphere with characteristics similar to those of the ICAO standard atmosphere. Consequently, BRL proposed that the ICAO standard be adopted; it was, and unification was achieved in the standard atmospheres used by the various services of the Tripartite nations. Ultimately, as pointed out above, it became the standard for NATO.

The significance of the results achieved through BRL leadership here cannot be overestimated. Before the adoption of the new standard atmosphere, the Army, Navy, and the British and Germans had all used their own versions of atmosphere characteristics. To say the least, this made inter-service and international comparisons of trajectories and firing tables difficult. Once the standard atmosphere had been adopted, comparisons could be made and the door was opened to standardization of US and NATO firing tables and ammunition.

The Preparation of Firing Tables. In 1964, Robert F. Lieske and Robert L. McCoy of BRL programmed, for use on the BRLESC, the equations of motions for a rigid body in free flight, specifically for a rocket during the burning phase. Incorporating all six degrees of freedom for the body, it is a general and flexible model for simulating the trajectory of a rigid body. The basic aerodynamic theory and the concise vector notation used by Lieske and McCoy were first developed by Fowler, Gallop, Locke, and Richmond in 1920, and augmented by R.H. Kent's theory on spinning shell. The work of Fowler, *et al,* was modified by K. L. Nielsen and J. L. Synge in 1946. E. J. McShane, J. L. Kelley, and F. V. Reno extended the work of Nielsen and Synge and developed the basic aerodynamic hypotheses used by Lieske and McCoy. One should note Hitchock, Kent, *et al,* were quite familiar with the detailed six-degree-of-freedom model; however, they were not able to use it because of computing complexity. The force-moment equations describing rocket motor performance were obtained by Lieske and McCoy by collecting the basic principles expounded in "The Mathematical Theory of Rocket Flight", Rosser, Newton and Gross and "Exterior Ballistics of Rockets", Davis, Follin, and Blitzer.

The aerodynamic hypothesis with representative equations and the rocket motor force-moment equations were all brought into logical consistency and expressed in the vector notation by Lieske and McCoy. When compared to the results of physical experiments over a wide range of test conditions, simulations of free rocket trajectories over a wide spectrum of test conditions, demonstrated the correctness, accuracy, and usefulness of the six-degree-of-freedom model. The model is also useful for conventional spin stabilized projectiles.

However, the six-degree-of-freedom model procedure is a very lengthy one, even on the BRLESC. Averge computing time would be four seconds per one second time of flight. For preparation of cannon artillery tables, that length of computer time is prohibitive. Preparation of firing tables for a howitzer requires BRL to compute about 200,000 trajectories which have an average time of flight of about 50 seconds. Such computations with the six-degree-of-freedom code on BRLESC would require 10,000 hours of computer time. However, they would offer the utmost in accuracy.

Until 1966, economy in computations with an acceptable degree of accuracy had been achieved through the use of the equations of motion for a particle (point mass trajectory theory). Computer time needed with that approach was one second per one hundred and sixty seconds of time of projectile flight. For the same howitzer table used in the example above, only about two hours of computer time would be required.

Although the trajectory computed by the point mass theory does not give an exact match along an actual trajectory, it does match the end points. But, for many years, this degree of accuracy was considered adequate for artillery tables.

In 1966, R. F. Lieske and M. L. Reiter derived a mathematical model, the modified point mass model, which is not as time consuming to run as the rigid body model, but which represents the center of gravity motion of the projectile (trajectory) much more closely than the original particle model. The improvement in the model is achieved by introducing a descriptive force system, axial spin values, and estimates for the yaw of repose.

The modified point mass model accounts for better than 90 percent of the discrepancies in the dependent variables (range, height, and deflection) between the point mass representation and the rigid body model, which is the most complete representation available. The improvement in accuracy is attained at a cost of only about twice the computational time of the old point mass solution. (The rigid body solution requires 100 to 1000 times that of the point mass solution.)

The modified point mass solution has become the standard technique used by BRL in the construction of firing tables. It has also become the standard model for NATO computations; in Europe it is known as the "Lieske Model." (Experience was to show later that even when the powerful Cyber computer system became available to compute six-degree-of-freedom trajectories, the modified point mass model still

CHARGE 7W — TABLE F — FT 155-AK-2

BASIC DATA — PROJ, HE, M483A1 FUZE, MTSQ, M577

1	2	3	4	5	6	7	8	9
RANGE	ELEV	FS FOR GRAZE BURST FUZE M577	DFS PER 10 M DEC HOB	DR PER 1 MIL D ELEV	FORK	TIME OF FLIGHT	AZIMUTH CORRECTIONS DRIFT (CORR TO L)	AZIMUTH CORRECTIONS CW OF 1 KNOT
M	MIL			M	MIL	SEC	MIL	MIL
7000	192.7	18.3	0.12	24	2	18.2	4.2	0.36
7100	196.9	18.6	0.12	24	2	18.6	4.3	0.37
7200	201.1	18.9	0.11	23	2	18.9	4.4	0.37
7300	205.4	19.3	0.11	23	2	19.3	4.5	0.38
7400	209.8	19.6	0.11	23	2	19.6	4.6	0.39
7500	214.2	20.0	0.11	23	2	20.0	4.7	0.39
7600	218.6	20.4	0.11	22	2	20.3	4.8	0.40
7700	223.1	20.7	0.10	22	2	20.7	4.9	0.40
7800	227.7	21.1	0.10	22	2	21.0	5.0	0.41
7900	232.3	21.4	0.10	22	2	21.4	5.1	0.41
8000	236.9	21.8	0.10	21	2	21.8	5.2	0.42
8100	241.6	22.2	0.10	21	2	22.1	5.3	0.42
8200	246.4	22.5	0.10	21	2	22.5	5.4	0.43
8300	251.2	22.9	0.09	21	2	22.9	5.5	0.43
8400	256.1	23.3	0.09	20	3	23.2	5.7	0.44
8500	261.0	23.7	0.09	20	3	23.6	5.8	0.44
8600	265.9	24.0	0.09	20	3	24.0	5.9	0.45
8700	270.9	24.4	0.09	20	3	24.4	6.0	0.45
8800	276.0	24.8	0.09	20	3	24.7	6.1	0.45
8900	281.1	25.2	0.09	19	3	25.1	6.3	0.46
9000	286.3	25.6	0.08	19	3	25.5	6.4	0.46
9100	291.6	26.0	0.08	19	3	25.9	6.5	0.47
9200	296.9	26.4	0.08	19	3	26.3	6.6	0.47
9300	302.2	26.7	0.08	19	3	26.7	6.8	0.48
9400	307.6	27.1	0.08	18	3	27.1	6.9	0.48
9500	313.1	27.5	0.08	18	3	27.5	7.0	0.49
9600	318.6	28.0	0.08	18	3	27.9	7.2	0.49
9700	324.2	28.4	0.08	18	3	28.3	7.3	0.50
9800	329.9	28.8	0.07	18	3	28.7	7.5	0.50
9900	335.6	29.2	0.07	17	3	29.1	7.6	0.50
10000	341.4	29.6	0.07	17	3	29.6	7.8	0.51
10100	347.3	30.0	0.07	17	3	30.0	7.9	0.51
10200	353.2	30.5	0.07	17	4	30.4	8.1	0.52
10300	359.2	30.9	0.07	17	4	30.8	8.2	0.52
10400	365.3	31.3	0.07	16	4	31.3	8.4	0.53
10500	371.4	31.8	0.07	16	4	31.7	8.5	0.53

FT 155-AK-2 — TABLE F — CHARGE 7W

PROJ, HE, M483A1 FUZE, MTSQ, M577 — CORRECTION FACTORS

1	10	11	12	13	14	15	16	17	18	19
RANGE	RANGE CORRECTIONS FOR									
	MUZZLE VELOCITY 1 M/S		RANGE WIND 1 KNOT		AIR TEMP 1 PCT		AIR DENSITY 1 PCT		PROJ WT OF 1 SQ (4 SQ STD)	
	DEC	INC	HEAD	TAIL	DEC	INC	DEC	INC	DEC	INC
M	M	M	M	M	M	M	M	M	M	M
7000	18.8	-18.4	4.7	-4.2	-2.6	0.4	-22.3	22.0	-20	20
7100	18.9	-18.5	4.8	-4.3	-2.5	0.2	-22.8	22.5	-20	20
7200	19.1	-18.7	5.0	-4.4	-2.4	0.0	-23.3	22.9	-20	20
7300	19.2	-18.9	5.2	-4.6	-2.2	-0.2	-23.8	23.3	-19	20
7400	19.4	-19.0	5.4	-4.7	-2.0	-0.4	-24.2	23.7	-19	20
7500	19.5	-19.1	5.5	-4.9	-1.8	-0.7	-24.7	24.1	-19	20
7600	19.6	-19.3	5.7	-5.0	-1.6	-0.9	-25.2	24.5	-19	20
7700	19.8	-19.4	5.9	-5.2	-1.4	-1.2	-25.6	24.9	-19	19
7800	19.9	-19.6	6.1	-5.3	-1.2	-1.4	-26.1	25.3	-19	19
7900	20.0	-19.7	6.3	-5.5	-1.0	-1.7	-26.5	25.7	-19	19
8000	20.2	-19.8	6.5	-5.7	-0.8	-2.0	-27.0	26.2	-19	19
8100	20.3	-20.0	6.7	-5.8	-0.5	-2.2	-27.4	26.6	-18	19
8200	20.4	-20.1	6.9	-6.0	-0.2	-2.5	-27.9	27.0	-18	19
8300	20.5	-20.2	7.1	-6.1	0.0	-2.8	-28.3	27.4	-18	19
8400	20.6	-20.3	7.3	-6.3	0.3	-3.1	-28.7	27.7	-18	18
8500	20.8	-20.5	7.5	-6.5	0.6	-3.4	-29.2	28.1	-18	18
8600	20.9	-20.6	7.7	-6.6	0.9	-3.7	-29.6	28.5	-18	18
8700	21.0	-20.7	7.9	-6.8	1.2	-4.0	-30.0	28.9	-18	18
8800	21.1	-20.8	8.1	-7.0	1.5	-4.4	-30.5	29.3	-17	18
8900	21.2	-20.9	8.3	-7.2	1.9	-4.7	-30.9	29.7	-17	18
9000	21.3	-21.1	8.6	-7.3	2.2	-5.0	-31.3	30.1	-17	17
9100	21.4	-21.2	8.8	-7.5	2.6	-5.3	-31.7	30.5	-17	17
9200	21.5	-21.3	9.0	-7.7	2.9	-5.7	-32.2	30.9	-17	17
9300	21.6	-21.4	9.2	-7.9	3.3	-6.0	-32.6	31.3	-17	17
9400	21.8	-21.5	9.5	-8.1	3.6	-6.3	-33.0	31.7	-16	17
9500	21.9	-21.6	9.7	-8.2	4.0	-6.7	-33.4	32.1	-16	17
9600	22.0	-21.7	9.9	-8.4	4.4	-7.0	-33.8	32.6	-16	16
9700	22.1	-21.8	10.2	-8.6	4.8	-7.4	-34.3	33.0	-16	16
9800	22.2	-21.9	10.4	-8.8	5.2	-7.7	-34.7	33.4	-16	16
9900	22.3	-22.0	10.7	-9.0	5.6	-8.1	-35.1	33.8	-15	16
10000	22.4	-22.1	10.9	-9.2	6.0	-8.4	-35.5	34.2	-15	16
10100	22.5	-22.2	11.1	-9.4	6.4	-8.8	-35.9	34.7	-15	15
10200	22.6	-22.4	11.4	-9.6	6.8	-9.1	-36.3	35.1	-15	15
10300	22.7	-22.5	11.6	-9.7	7.2	-9.4	-36.7	35.5	-15	15
10400	22.8	-22.6	11.9	-9.9	7.6	-9.8	-37.2	36.0	-14	15
10500	22.9	-22.7	12.1	-10.1	8.0	-10.1	-37.6	36.4	-14	15

Pages from automated Firing Tables

provided the necessary accuracy for computations. The more complex model offered no advantage; consequently it was little-used except for rockets and air-craft-launched projectiles and as an analytical/diagnostic tool.)

Since computer time is expensive, it was only natural for firing tables personnel to examine the efficiency with which the numerical integrations of the equations of motion were being solved. Efficiency was improved when H.J. Breaux added a sub-routine which varied the time interval for integration—shortening the interval for particularly important segments of the trajectory and lengthening them where accuracy would not be affected. His work was followed by that of B.J. Matts. By changing one of the equations in the numerical algorithm, Matts developed a scheme that reduced trajectory computation time by thirty percent and gave improved accuracy.

Field Artillery Computers. The work of the firing tables groups at BRL also found applications in several types of artillery fire control systems now used by the Army. Representing one type are the Field Army Digital Automatic Computer (FADAC) and the Battery Command System (BCS). Representing a second type is TACFIRE, a tactical control system which is used at the Army Corps Center to control artillery tactics, i.e., to make decisions on types of rounds the battery should fire and where they should be used. Essentially a decision aiding device, TACFIRE analyzes targets, keeps track of ammunition expenditures and thus of ammunition levels, and so forth. It can, however, when necessary be used to provide trajectory information to an artillery battery. TACFIRE, using older computer technology is housed in two large semi-trailer vans.

FADAC, which uses the original point mass model as the basis for its computations, is rapidly becoming obsolete. Spare or replacement parts are no longer being manufactured and existing units are kept in repair only through cannibalization of unrepairable units.

The BCS, which replaces FADAC, uses the modified point mass model; all computational algorithms and directions were provided by BRL. The BCS computer is about half the size of an office desk; it incorporates the computer hardware of the early 1970's.

The need for firing tables for guided missiles first arose when the US Army introduced the Redstone Missile into its arsenal of weapons. The repetitive nature of such computations, their continuing requirement, and turnover in personnel created a need for the systemization of computations, applicable to different missile systems, but at the same time not requiring extensive analysis, new computer program, and intensive training for personnel. Breaux devised a technique, which after mechanization, makes the computations routine. Breaux used stepwise multiple regression, essentially a smoothing operation, to solve the equations giving information on the pre-settings required in a missile's guidance system so that the missile will pass through a desired target point (this, despite the fact that a missile system might have "on-board" guidance).

Since the missile, when fielded, must be capable of being fired from any point on the earth, in any direction, and to any range within its capability, some method is required to predict the flight of the missile in situations different from the conditions and locations during the original development and testing phase. This capability is provided by the mathematical model which can be used to generate a trajectory. Breaux's model is useful for providing the fundamental input data needed for the small field computers which were or are part of weapon system such as the Redstone, Jupiter, Pershing, and Sergeant, and for general purpose field computers.

Artillery Shell Drift and the Effect of Wind on Flat Fire Trajectory. Although not related, these two subjects provide interesting examples of instances in which the availability of the computer and improved trajectory models gave definitive answers to questions that had been asked intermittently for many years.

The first instance has to do with the deflection of artillery shell. The yaw of repose is the steady state angle of attack caused by gravity-induced curvature of a shell's trajectory. When trimmed at this angle, the nose of a spinning shell is to the right of its flight path (for shell with righthand spin). Associated with this equilibrium angle is a lifting force that causes the shell to drift or deflect to the right.

Even as late as the beginning 1970's, ballisticians believed right deflection was characteristic of all spin stabilized shell. However, over the years there had been reports from artillerymen that shell fired at high quadrant elevations (higher than the tube-limited elevations considered in the firing tables) and at low velocities drifted to the left. Theoretical analyses at BRL showed that for the 105-mm howitzer, shells fired at standard elevations would have the expected deflection; at elevations greater than 1300 mils, the shell would drift to the left. The results led to an experiment using 105-mm shells equipped with sun-sensors to determine the attitude of the shell during its flight. The experiment showed that a quadrant elevation of 1350 mils close to the maximum to which the howitzer could be elevated using the elevation mechanism alone, represented the point for onset of the left deflection phenomenon. For quadrant elevation less than 1350 degrees, the shell experienced right deflection; for elevations greater than 1350 mils, the shells experienced left deflection. Moreover, the sensor data showed that projectiles deflecting to the left traveled base-forward during descent; after reaching their summit, the shell did not turn over. The persistent, fragmentary, often unscientific reports of left deflection had been confirmed.

The second instance had to do with the validity of the formula used by marksmen to calculate the deflection caused by a cross wind. The formula has been used for years, but questions as to its accuracy had been received by BRL continually from marksmen, rifle teams, and systems developers. The answer usually given was that the formula is more accurate than the rifleman's ability to estimate wind speed. The answer is undoubtedly technically correct for most cases, but the persistence of the question suggested that BRL provide a more quantitative answer.

Through rigorous, elegant mathematical investigation, R. L. McCoy demonstrated the correctness of the classical crosswind deflection formula and that the effects of head or tail winds were insignificant compared to the cross wind effect.

EXPERIMENTAL AND FULL-SCALE FLIGHT TESTS

The expanding US ballistic missile program, the developing interest in earth-satellites (spurred by plans for the International Geophysical year, and later by the deployment of SPUTNIK I), and the nation's man-in-space program were reflected in the extensive support provided by BRL's unique aerodynamic research facilities. By 1957, more than half the test time in the Transonic Range and Wind Tunnels was being devoted to tests of nose-cones, re-entry bodies, missile structures and components, and special configurations for ICBM's, and of other missiles. A smaller portion of the Aerodynamics Range test time was spent in similar tests. While conventional weapon projects were being given relatively low priority, the needs of arsenals developing weapons and ammunition were still being met.

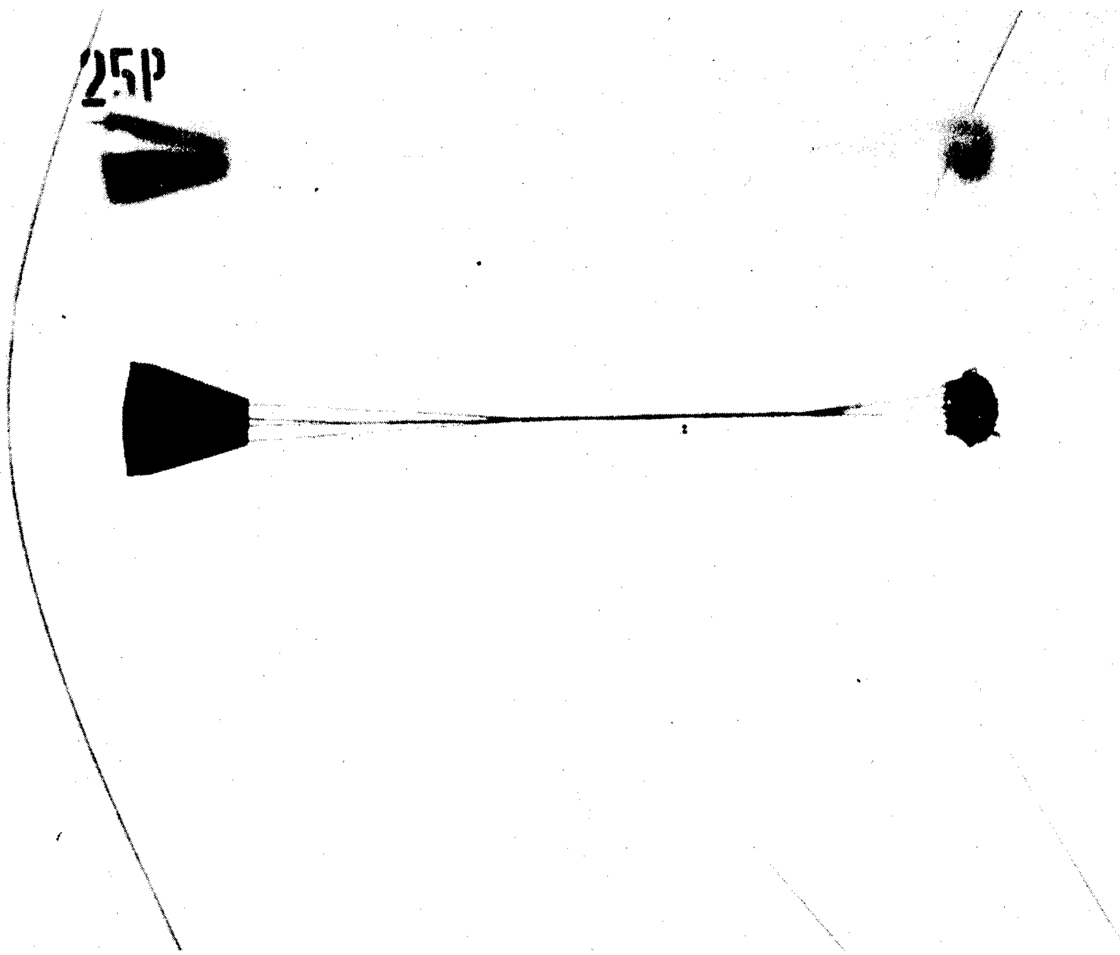
Until 1970, the wind tunnels and ranges were used extensively to support, directly or through their contractors, Army, Navy, Air Force, and NASA system developers. The contractors with whom BRL cooperated closely included, for example, the Glenn L. Martin Company (later Martin Marietta Corporation), the Research and Development Division of AVCO Manufacturing Corporation, the Lockheed Aerospace Division, the Missile and Space Vehicle Division of General Electric Corporation, and the Marquardt Aircraft Company.

For the Army, BRL provided support in the development of the Redstone missile series, the two-stage solid-propellant Pershing tactical missile, the initial Saturn booster (which was later to be used in the country's space program), the Hawk and Lance ground-to-air missiles, the Little John and Davy Crockett tactical systems, and the Willow Project missile (a Redstone missile modified for standby high-altitude nuclear weapon tests). The results of tests on the Redstone vehicle brought about a radical change in the concept for the re-entry mode and in the missile's configuration. Besides increasing the reliability of the system's performance, the new concept provided greater range for the missile. In a separate series of wind tunnel tests, the Nike-Zeus, Hawk and Pershing missiles were examined to determine the optimum location of pressure sensors needed as part of aiming and self-destruct systems.

Air Force systems for which BRL provided aerodynamic research support included the Atlas, Titan and Minuteman ballistic missiles, and the SAMOS re-entry system. An interesting adjunct to the Atlas work, was the analysis of the problem of ejecting a data capsule through the trailing wake of a nose cone. Although the study specifically considered the case of a capsule ejected from an Atlas re-entry nose cone, the results found applications in the general subject of recovery system deployment.

Support to NASA's space program can be considered to have begun when BRL facilities were used in testing scale models of two-and three-stage Saturn configurations for the Army Ballistic Missile Agency in 1959. That support continued when responsibility for further Saturn development was shifted from ABMA in 1960 to NASA. In 1963, BRL personnel in cooperation with members of the Marshall Space Flight Center of NASA tested several models of the Saturn V in the hypersonic wind tunnel. During the same year, BRL conducted wind tunnel tests on the Mercury Redstone vehicle used for the preliminary man-in-space flights.

As noted above, BRL still continued to meet



Mercury re-entry capsule with parachute in free-flight

the needs of weapon and ammunition designers during this period. The testing support provided by the wind tunnels and ranges was augmented through the years by full-scale, full-range, firing tests directed or supervised by BRL's exterior ballisticians. Typical of such activity was the 1973–1974 dispersion test of 155-mm rounds fired at the Proof and Experimental Test Establishment, Nicolet, Quebec, Canada. Previous launches at BRL of a rocket-assisted M549 shell showed significantly increased dispersion when fired at transonic velocities in cold weather. Calculations considering cold temperature and high air density with the six-degree-of-freedom model predicted large yaws and neutral damping. The predictions were confirmed, demonstrating the need for additional development.

The development of sensors and telemetry systems capable of withstanding very high accelerations made it possible to validate the binary shell concept. The 8-inch and 155-mm binary shells each carry two normally non-toxic liquid agents, stored separately in the shell before firing. When mixed in flight, these agents become a lethal compound. The shell developers were concerned whether the two reagents would mix in flight to produce a chemical reaction with an adequate yield of lethal agent. The design concept was for the launch set-back force and the pitching-yawing environment of the projectile to, respectively, rupture a separating diaphram and permit sufficient agitation to give good mixing. Because of the ban on open-air testing of chemical weapons, the actual military reagents could not be tested during firing. Thus, reagent simulants were developed. When mixed in-flight, these reagents would produce an exothermic reaction which could be measured by a temperature sensor. Responding to a BRL suggestion for an experiment, the Munitions Division, Edgewood Arsenal requested BRL to develop a temperature sensor-telemetry system to monitor the reaction temperatures in flight. Telemetered data from projectiles in flight showed that mixing and chemical reaction to the desired extent did take place.

RESEARCH IN FLUID MECHANICS

Mach reflections, triple shock waves, occur in shock wave phenomena which may have practical implications. For example, they occur in nuclear bomb shock waves when the shock waves interact with the ground. Understanding the laws governing the flow in triple shocks becomes important because the details of the flow at the intersection of the waves govern the pressures and velocities of the flow behind the intersection. For nuclearly-induced shock waves, predictions of damage require understanding of the triple shock flow. Until 1957, the theory of Mach reflections had been in an unsatisfactory state.

In that year J. Sternberg of the Exterior Ballistics Laboratory developed a new treatment of the triple shock phenomenon which apparently removed the theoretical difficulties. His approach constituted an important advance in understanding a difficult problem in fluid mechanics, which for more than a decade had thwarted efforts in theoretical fluid mechanics research. Computations using his theory gave flow patterns consistent with the most accurate measurements of flow properties near triple shock intersections in shock tubes.

Flow in Gas Operated Weapons. By the mid-60's, the ordnance engineer had been provided the basic tools for modeling the operations of self-powered automatic weapon mechanisms. BRL had developed analog simulations of the mechanism of the M16A1 Rifle. This strictly kinematic approach was supplemented in 1970 by an analysis delineating the details of gas flow in gas-operated weapons, specifically for the M16 Rifle. Developed by J. H. Spurk, the analysis describes the process whereby gas with time-varying pressure flows through a duct from a port in the barrel to the bolt cavity where the pressure of the propellant gas is used to unlock the bolt, extract the cartridge, and supply sufficient momentum to the bolt carrier so that the next loading cycle can be completed. The analysis applies equally well to other gas operated systems and could find application in control systems where high pressure gas is used to operate jet or surface controls. Spurks's model is a benchmark in the theory and design of gas-operated weapons.

A year later, N. Gerber analyzed the sensitivity of Spurk's model to variations in input data—concentrating on several of the more notable effects caused either by a change in conditions inside the gun (e.g., friction in the gas duct, change of ammunition), or uncertainties resulting from experimental measurements (e.g., selection of operation zero time, and peak pressure at the gas duct entrance). Gerber's work showed that thermodynamic variables in the bolt carrier cavity are only weakly sensitive to variations in the pressure and temperature in the gun barrel when the bullet passes the port, friction in the gas duct, and frictional resistance to bolt carrier motion. However, the computational results are sensitive to the choice of zero time.

Aerodynamic Drag. In considering subsonic aerodynamics, ballisticians normally divide drag into two components: form drag, attributed to pressure, and viscous drag, attributed to skin friction. Because the latter drag is usually relatively small, use of a streamlined shape for a shell can reduce the drag to very small values, nearly zero in some cases. However, such shapes introduce stability problems; therefore shell designers resort to shapes with relatively high drag.

For the supersonic case, the ballisticians consider four components of drag: forebody drag, attributed to pressure, viscous drag, boattail drag and base drag, both attributed to pressure phenomena. For many years, shell design practice was to decrease forebody and skin friction drag as much as practical, then accept the remaining base drag. In a survey reported in 1966, R. Sedney concluded that there was not strong interest on the part of shell designers in attempts to solve the base drag problem through theoretical and semi-empirical approaches. He based his conclusion in part on the lack of information concerning the relative magnitude of base drag compared to total drag. This state of affairs as well as the Army's requirements for shell with longer ranges prompted BRL to renew research into drag phenomena, particularly for base drag. This applied research included investigations of "fumers," tracer-like compounds which in burning provided a gaseous mass to the low pressure region of the base; analyses of optimum bullet shapes, particularly for small arms; and improved non-conical boattails for projectiles.

The main purpose of a projectile boattail is to reduce aerodynamic drag thereby increasing the range of the projectile. In the past, various geometric shapes (a conical boattail has been the most useful) have been used to form the boattail; these have all depended on the reduced base area to reduce the drag. While the boattails do reduce the drag, they also develop a negative lift which increases the unstable pitching moment and reduces the gyroscopic stability of the shell. These various boattails, particularly the conical shapes, also generate large Magnus forces at transonic speeds, which can adversely affect the dynamic stability of the projectile.

In the 1970's, BRL experimented with several radically different boattails which do not have axial symmetry, but which appear to have several advantages over the normally-used axisymmetric shaped boattails. These boattails are formed by cutting the main projectile cylinder with planes inclined at a small angle to the main projectile axis—so that flat surfaces are created on the boattail. The flat surfaces increase the boattail lift so that the unstable pitching movement is decreased and the drag is reduced as a result of the smaller base area. Also, elements of the main cylinder extending to the base increase the overall length of the projectile in contact with the gun tube. This increased "wheelbase" should reduce in-tube balloting and possibly reduce muzzle jump.

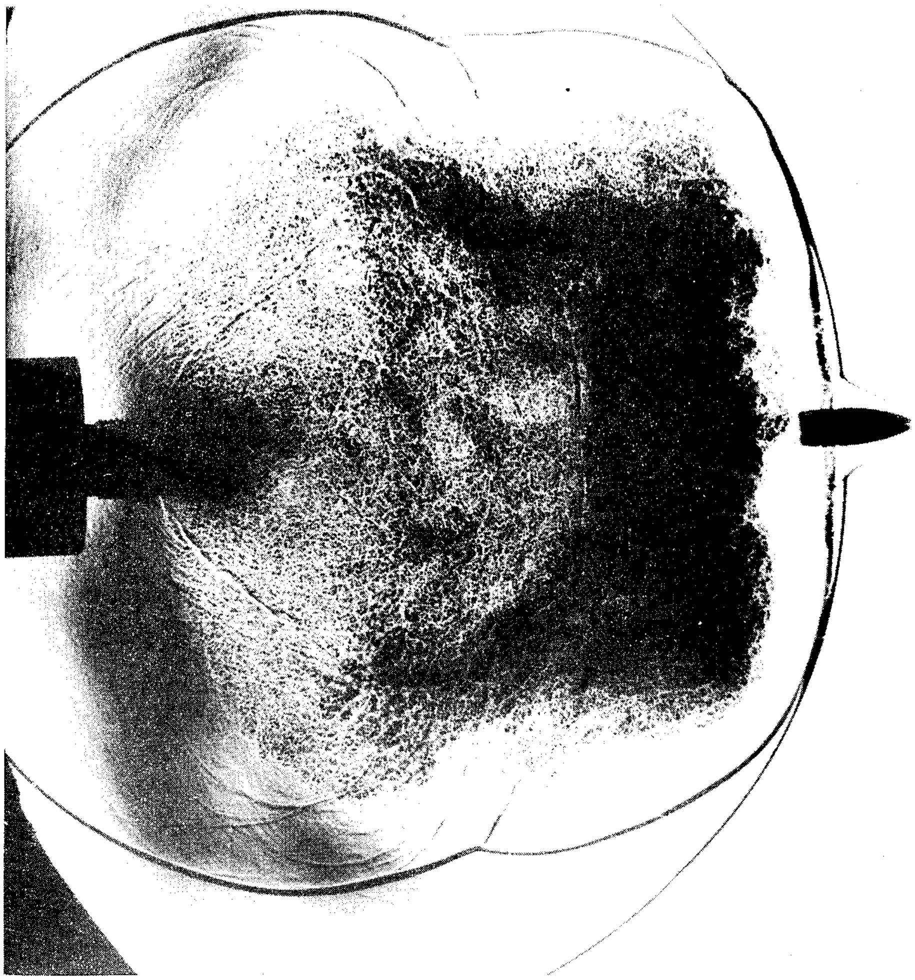
Wind tunnel tests demonstrated that a twisted triangular boattail improves the aerodynamic properties of the projectile at transonic and low supersonic speeds. In 1976 full-scale firing tests were being planned for 155-mm M549 shell with this boattail.

Turbulent Boundary Layers. The Magnus effects, covered in detail above, are of very real concern in the design of artillery projectiles. To compute Magnus effects, one needs an accurate flexible technique for computing the three-dimensional boundary layer development, because the Magnus effect is a viscous phenomenon. At the end of 1976, BRL had developed a finite difference scheme to solve the basic three-dimensional compressible turbulent boundary layer equations.

TRANSITIONAL BALLISTICS

Re-emphasized by BRL at the beginning of the 1970's, this branch of ballistics considers the phenomena that occur during the phase in which a projectile loses contact with its launcher and becomes affected by the transient jet flow just outside the muzzle. Erratic launching conditions increase the probable error in the round's impact and may cause premature tumbling and disastrously short trajectories, particularly for projectiles that may be only marginally stable. Some degrading effects introduced during the transitional phase can be attributed to muzzle whip, tip-off, in-bore transverse angular momentum caused by worn tubes, muzzle jet flow, and sabot separation. The first three of these effects occur while the projectile is still in contact with the launcher; the motion and orientation given to the projectile is in the transient flow just outside the muzzle.

BRL work in what was becoming an increasingly important field included correlation of interior ballistics performance with muzzle blast effects, description of the exterior environment around weapons, and description of the initial aerodynamics of the shell—in terms of linear, quasi-steady aerodynamic interactions.



Bullet in gas bubble at rifle muzzle

Spark shadowgraphs and x-ray photographs were taken to define the development of the blast flow field as a projectile emerges; experiments using these optical techniques were complemented by pressure measurements made in the vicinity of the muzzle of an M-16 rifle firing ball ammunition. The effects of muzzle jet asymmetry on projectile motion were determined through other experiments. An analysis of initial launch dynamics for a saboted flechette related the initial conditions to the subsequent dispersion at the target. By 1976 it was possible to apply a computer code to the quantitative analysis of two dimensional, compressible, time dependent flows with a moving projectile in the vicinity of an M16 rifle with a flash-hider and a 155-mm howitzer with a muzzle brake. The results gave a complete history of the flow field and values for the impulse on the muzzle device.

NON-LINEAR FLIGHT DYNAMICS

During the first half of the 1950's, one of the most challenging problems in exterior ballistics was the prediction of the motion of bullets (missiles) flying at large initial angles of yaw. The advent of the supersonic aircraft had brought this problem to the forefront of research; by 1955, what had been a difficult low-priority research problem became an equally difficult problem of utmost current (then) engineering importance. The practical problem was to describe the projectories of bullets fired from aircraft with sufficient accuracy to design fire control equipment. Adequate description of the missile's flight involves consideration of two degrees of freedom (vertical and horizontal components of yaw); thus the equations describing the motion are nonlinear and cannot be solved by simple ordinary mathematical methods. Solutions require painstaking numerical methods. However, late in 1956, C. H. Murphy, BRL, constructed a simpler set of equations describing the motion of missiles with large yaw. His method of approximation was substantiated by data from numerous firings on free-flight ranges and by numerical integration of the exact equations of motion. Dr. Murphy's method is based on the assumption that the actual non-linear motion over short portions of a trajectory can be approximated by the solution of a linear equation whose coefficients are functions of the amplitude of the motion. Murphy's theory was applied to give a mathematical solution to the anomalous behavior of the Navy's 12.75-inch fin-stabilized antisubmarine rocket. (While the theory gave the first rigorous mathematical treatment of the rocket's problem, note that the essential causes of the weapon's misbehavior were well enough understood by Navy scientists to permit development.) Murphy's theory was a major theoretical breakthrough and, because of its generality, has broad applicability in aerodynamics.

About a year later, H. L. Reed, also of BRL, developed a new method of handling non-linear dynamics through the application of Hamiltonian perturbation techniques. His method supplemented the Murphy theory and established a test of the conditions under which the Murphy techniques could be applied. Subsequently, Murphy examined the effect of strongly nonlinear static moment on the combined-pitching and yawing motion of a symmetric missile. He re-phrased the perturbation approach used by Reed and suggested by L.H. Thomas at BRL in 1952 to a simpler, more convenient form making use of the amplitude plane proposed in his initial approach. By 1965, Murphy had consolidated the results of ten years development of the analysis of linear and nonlinear angular motion of symmetric missiles. (By 1976 more than 300 aerospace engineers had attended Dr. Murphy's course, "Free Flight Motion of Symmetric Missiles," sponsored by BRL.)

RESEARCH INSTRUMENTS AND FACILITIES

Throughout the twenty-five years following the introduction of the supersonic wind tunnel at BRL late in 1944, the Exterior Ballistics Laboratory was the Army's major activity for aerodynamic and missile dynamic testing. To meet its consequent responsibilities, BRL had to develop, maintain, operate, and improve major range and wind tunnel facilities. The bulk of the manpower and money allotted to the Exterior Ballistics Laboratory was spent in the development of experimental facilities whose equivalent capital investment, in 1970, represented 15 to 20 million dollars.

Financial support for the wind tunnels began to falter in the mid-60's when the Army Materiel Command decided to put them on a pay-as-you-go basis, requiring project officers or managers to pay for their tests. However, it became clear that project managers were not major sources of funds for the types of tests then being carried out at BRL. Funds were then provided by AMC, but eventually the costs for wind tunnels operation placed unbearable pressure on the funds and manpower allotted for overall BRL operation. Regretfully, the Director of the BRL decided to close the four tunnels in 1976. (One should note that the BRL wind tunnels were outstanding facilities, the best small supersonic tunnels in the nation, and the associated work was of the highest quality.) However, the Director's regret was tempered by the knowledge that adequate wind tunnel support was available elsewhere for BRL's continuing work in transonic aerodynamics.

The section below describes those wind tunnels, as well as other facilities used in exterior ballistics research.

Wind Tunnels. In July 1960, BRL had two supersonic wind tunnels available for research and development testing; a third supersonic tunnel was available for research projects only. All three tunnels had flexible nozzles and operated in the Mach number range from 1.25 to 5.0. A hypersonic wind tunnel was added to the complex during 1961–1962; it extended the Mach number range from 5.0 to 10.0. The tunnel had three axisymmetric nozzles, giving a range of Mach 6.0, 7.5, and 9.2.

Tunnel No. 1 was a continuously operated, variable density, closed circuit tunnel, with a test section 15 inches high by 13 inches wide. The normal range of angle-of-attack for models in the tunnel was from −10 degrees to +15 degrees, adjustable by means of a crescent shaped mount. The range could be extended by using offset struts. The tunnel had been calibrated for operation at 15 Mach numbers between 1.5 and 5.0

Tunnel No. 2, used only for research, was also a continuously operated, closed circuit tunnel. The air density was variable. The tunnel design permitted great flexibility so that many types of research programs could be accommodated. Ordinarily Tunnel No. 2 was operated on a non-interference basis with the other tunnels. However, either Tunnels No. 1 and No. 2, or No. 2 and No. 3 could be operated simultaneously if the flow in either pair was at a sufficiently low Mach number.

Tunnel No. 3 was a continuously operated, closed circuit tunnel similar to Tunnel No. 1. The test section was 20 inches high by 15 inches wide for Mach numbers 1.25 to 2.0 and 13 inches high by 15 inches wide for Mach numbers 2.17 to 4.89. Most models were sting-supported from an angle-of-attack crescent, adjustable from −10 degrees to +15 degrees. As in Tunnel No. 1, the range could be extended by using offset struts.

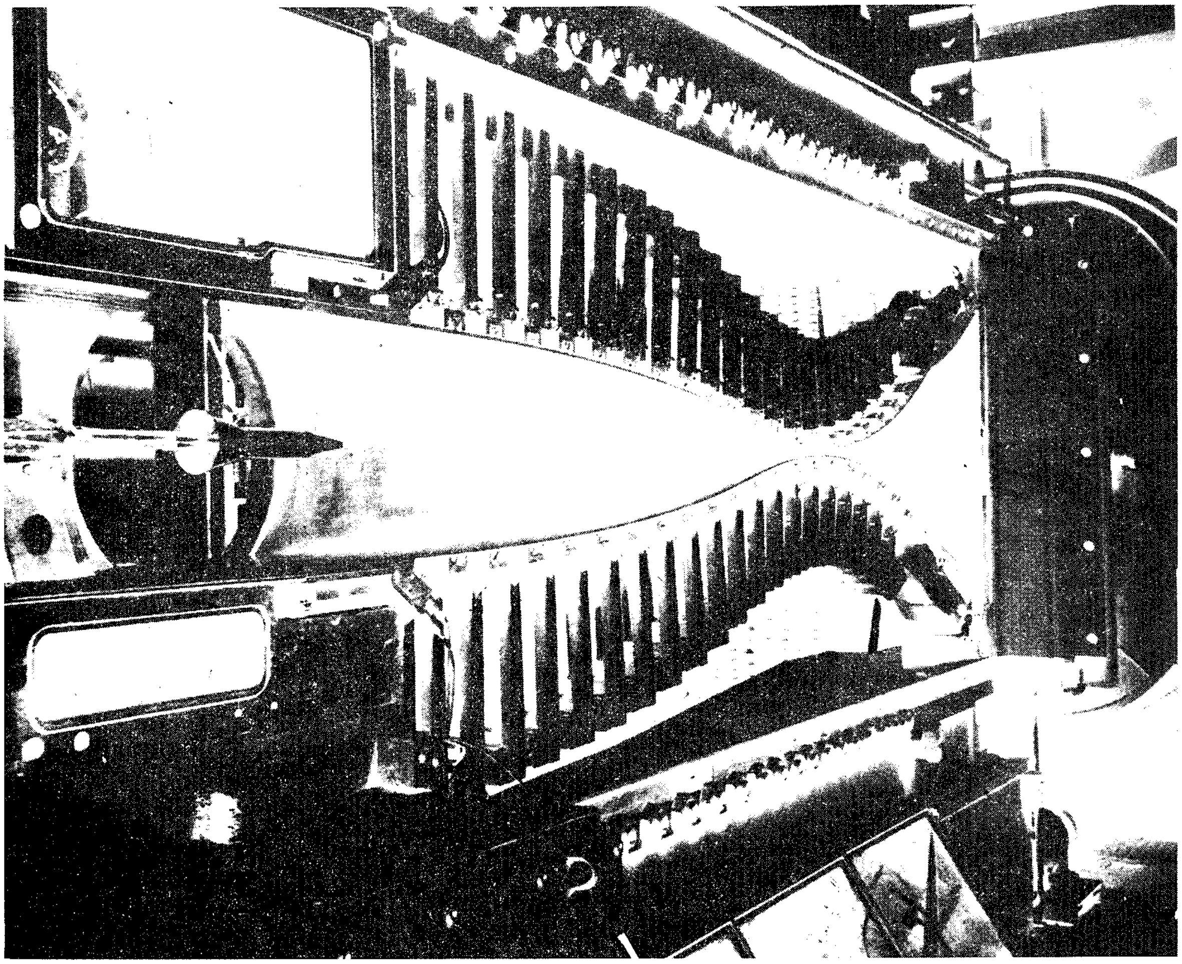
Tunnel No. 4 was a hypersonic tunnel, a continuously operated, variable density, closed circuit type capable of operation up to Mach 10. The approximate maximum supply pressure and temperature were respectively, 2200 psia and 1960° Rankine. Air coming from the compressors was heated in a combustion heater and an electric air heater. After heating, the air passed through a stilling section, an axisymmetric nozzle, an open-jet test section, supersonic and subsonic diffusers, and an aftercooler back to the compressors. All parts of the tunnel exposed to the heated air were water cooled. Mach numbers were achieved by interchanging three axisymmetric nozzles; Mach numbers were 6, 7.5, and 9.2.

Sting-supported internal-strain gages, temperature compensated, measured aerodynamic forces on models. Flow around models was recorded by Schlieren and spark photographic techniques. Each tunnel was equipped with a conventional two-mirror Schlieren system capable of either sustained or spark illumination. Mercury or silicone manometers and pressure transducers measured tunnel and model pressures. Supply pressure, tunnel temperature, and humidity level were monitored constantly during a test. The regulation of the supply pressure, to ± 2mm of mercury, was indicated by a pressure transducer built at the Laboratories.

Raw force and pressure data were recorded and reduced manually or automatically. For automatic recording and data reduction, the data readout system was coupled to an electronic computer. The final data acquisition system installed in 1971 had 50 analog channels and 20 digital channels; the system acquired data at a rate of 12,000 samples per second. Data could be acquired in several modes; continuous, periodic scan, single scan, and so forth.

Throughout the lifetime of the wind tunnels the operating staff and other scientists and engineers of the Exterior Ballistics Laboratory continually improved and upgraded the instrumentation and ancillary equipment for the tunnels. The development of the technique for launching test models in the supersonic and hypersonic tunnels serves as a particularly good example of such activities. Through this technique, developed in the 1960's, the behavior of the models in free-flight could be monitored by high-speed photography. The problem of sting-test model interference was overcome and a capability was provided for testing many model configurations which could not be tested otherwise. The free-flight launch was very valuable for studies of stability and Magnus moments on high fineness-ratio bodies.

As late as 1975, BRL scientists were applying new technology and instruments to combine optical, tracer, and surface indicators to improve



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Missile model in flexible throat of supersonic wind tunnel

flow visualization; for example, shadowgraph/Schlieren oil flow techniques, a vapor screen system using a continuous wave laser, and reversible dye technique.

The Aerodynamic Range. The development of the Aerodynamic Range is described at some length in the first volume of BRL's history. In brief, it is the world's first large-scale, fully-instrumented ballistic range providing data on the aerodynamic characteristics of projectiles in free flight. The unique technology represented by the facility became the foundation of similar installations worldwide. (In 1982, the range was to be designated a "National Historic Mechanical Engineering Landmark," by the American Society of Mechanical Engineers.)

The Aerodynamics Range is a fully enclosed facility equipped to launch a projectile in free flight and to record its motion over a 285-foot trajectory. The range consists of a firing room, containing a launcher, a blast chamber to protect instruments, and a photographic gallery for recording the flight of the projectile. The Range gives the capability for accurately measuring the history of projectile motion and the detailed structure of the transient flow over a body in high speed flight.

The Transonic Range. The design and construction of this facility is also discussed in the first volume of this history. Like the complementary Aerodynamics Range, the Transonic Range was originally a unique facility. Because of its size, the Transonic Range avoided the "choking" effect produced in other facilities when shocks reflected from walls or photographic stations interfered with normal air flow over the projectile. When it was completed in 1950, there were essentially no other transonic test facilities of laboratory or semi-laboratory quality available. Actually the Range was used before it was completely equipped in order to assist in the development of fin-stabilized rounds for the Korean Conflict. At the time of its activation, the Transonic Range provided, as it still does, capabilities for: full-scale tests of shell at subsonic, transonic, and supersonic speeds under realistic conditions; tests of model bombs or missiles at transonic speeds and high Reynolds numbers; tests of model bombs or missiles at high supersonic speeds, Mach7, at high Reynolds numbers and high stagnation temperatures, and accurate measurements of rocket (up to 105-mm diameters in size) positions and attitude.

These capacilities led to the almost routine inclusion of the facility in development test plans for nearly all nuclear bombs and shell through the 1950's and into the 1960's. The scope of range paramenters—high Mach number/high Reynolds number and down to transonic speed—led to tests of scale models of most of the re-entry vehicle designs associated with the Atlas, Titan, Minute Man, Polaris, and Skybolt ballistic missiles, as well as SAMOS, Discoverer, Mercury and Apollo systems.

Later in the 1960's, NASA and the US Airforce developed other facilities capable of providing transonic and high Mach number test conditions; France and Canada also developed aeroballistic ranges. However, BRL's Transonic Range remains the only US range of its type, the only large scale transonic test facility directly under Army control. Although competitive, alternative testing methods now exist, for many tests the aeroballistic range still provides the most realistic simulation.

The BRL Transonic Range consists of a building, enclosing a free-flight space, about 1000 feet long and 24×24 feet in cross section, a firing station at one end of the building, and an instrument building several hundred yards away. Screens and cameras, in groups of five, are spaced throughout the range. Typical records are spark shadowgraphs on glass photographic plates and microflash photographs. High-speed computers reduce the data obtained in the range. The computations provide ballistic information such as coefficients of moments, spin decelerations, lift, damping moment, and Magnus force.

Projectile-Borne Instrumentation. Dr. G. H. Murphy, in 1961, encouraged scientists at the Exterior Ballistics Laboratory to begin a long-term effort to equip projectiles with on-board sensors and telemetry systems to measure shell dynamic behavior under actual trajectory conditions. Desired measurements included projectile yaw, heat transfer and surface pressures, and the performance of the projectile's internal components. The effort was stimulated by and interacted strongly with the HARP project mentioned earlier.

The development of an improved yawsonde by W. H. Mermagen, BRL, during the late 1960's was a significant advance in methods for remote measurement of projectile behavior. The yawsonde is a projectile-borne device used to measure the spin, nutation and precession of a shell in flight. First developed by I. O. F. Amery and his associates at the Royal Armament Research and Development Establishment, Kent, England, the device uses solar sensors to determine the orientation of the shell. Amery's model was the basis for a yawsonde developed by Harry Diamond Laboratory and defense contractors.

Developed in 1959, Amery's yawsonde consisted of a pinhole viewport in the projectile and a silicon photodetector. Mermagen adapted the concept to, first, a dual-sensor, slitted optical system, then later, to a multi-sensor yawsonde capable of determining pitching and yawing motion even in the resonant frequency regime. Capable of measuring the yawing and spinning motion of a projectile along its entire trajectory, by 1970 the BRL Yawsonde had undergone miniaturization and modifications which permitted it to fit within the confines of an artillery-shell fuze. Having the same physical properties as a standard mechanical time fuze, the yawsonde was an "off-the-shelf" item that could be fitted to an artillery shell in lieu of the fuze normally attached and used routinely to provide ballistic data during gun firings. (During the decade of the 70's, the BRL yawsonde was to be the routine device for analyzing long-range flight stability. It would be used during the development of every major artillery weapon then.)

BRL research in projectile-borne instrumentation resulted in several breakthroughs in the technology of on-board instrumentation. In 1962, a model of the General Electric RVX nose-cone instrumented with 250 MHz telemetry and a stagnation-point heat transfer sensor was launched from a 105-mm gun. Although experiencing a launch acceleration of 250,000 g, the system measured and transmitted useful stagnation temperature data. Even to date, that launch condition represents the most severe environment withstood successfully by an electronics payload.

The yawsonde was used with great success to analyze the stability of the M422 nuclear shell, an analytical problem that had vexed the Army since 1950, and to validate the method used to correct the flight instability that had been detected in the shell.

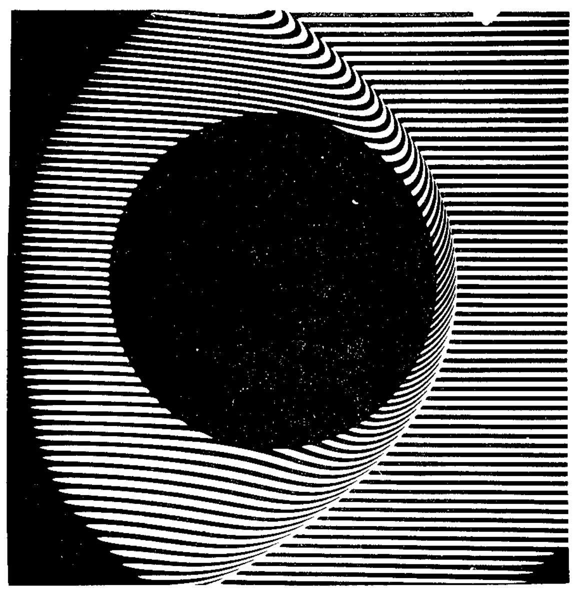
During the mid-1970's, specialized telemeters were developed to provide in-flight information on the functioning of nuclear payload components, the accuracy and occurrence of events in mechanical time fuzes, and the performance of HEAT munitions.

With R. H. Whyte of the General Electric Company, Mermagen complemented his instrumentation development with work to develop numerical integration analyses for determining aerodynamic coefficients from yawsonde and radar data.

The results of BRL's work in projectile-borne instrumentation encouraged Picatinny Arsenal, Sardia Laboratories and other government research agencies to undertake similar investigations. The need for on-board systems spurred industrial interest and commercial development so that high-g telemeters, sensors, and systems are now available from commercial sources.

Light Gas Guns. The demand for aerodynamic and aerophysic information for hypersonic flight led BRL to mount a major effort between 1950 and 1965 to develop experimental facilities for such work. The objective was to develop launchers for reaching 17,000 feet per second for models up to 3 inches in diameter. By 1960 BRL had two small single-stage hydrogen-oxygen-helium guns in routine operation; model velocity was about 12,000 feet per second. By 1962 BRL also had a two-stage light-gas gun facility available. Model velocities and weights available were: 17,000 ft/sec. for a 2.3-gram cylinder, 25,000 ft/sec. for a 5-gram projectile, and 13,500 ft/sec. for a 1.25 lb projectile. These facilities were phased out in 1969 because of decreased interest in re-entry physics.

Controlled Temperature and Pressure Range. Completed in 1956, this range was used from then until 1963 to provide hypersonic aerodynamic data. Basically the controlled temperature pressure range was a refrigerator with pressure control. When the temperature inside the refrigerated section was lowered, the speed of sound in air was lowered. Thus for a model tested at a



Interferogram of 90-mm sphere in Controlled Pressure Range given speed, the Mach number would be higher than that reached in a corresponding atmospheric test at normal pressure and temperature. Desired values of Reynolds number could be obtained by varying the density of the range atmosphere which could be achieved by controlling the pressure within the range. Models could be tested at Mach 10, a value twice the mach capability of any other free flight range. Unfortunately, the CTP Range never achieved its apparent potential.

Expansion Tube. The need for a facility capable of producing a high-velocity, high stagnation temperature air flow having a low free-stream level of molecular dissociation prompted BRL in 1962 to analyze the feasibility of an expansion tube. Such a facility could bridge the gap between tunnels which could not provide the needed enthalpy multiplication and shock tubes which provided flows with a high degree of molecular dissociation. The promising results of theoretical work led, in turn, to the construction of a pilot model in 1962 to further demonstrate feasibility.

Constructed from surplus 90-mm gun tubes, the expansion tube had a test section 6.5 inches by 6.5 inches, which permitted use of relatively large models. Mach numbers in the range of 10 to 20 were achieved with test times on the order of 50 to 100 microseconds. Fluid flow was analyzed by means of simultaneous streak and frame interferometry using green and blue monochromatic light respectively. The expansion tube was used for hypersonic non-equilibrium flow research until the mid-1970's.

In the closing years of the 1950's, Terminal Ballistics encompassed a broad program of basic and applied research.

Basic research covered virtually all aspects of ignition and detonation of gaseous and condensed phase explosives, and of shocks in fluids. Various parts of the program were directed toward the development of general mathematical models and computer programs to predict the behavior of a system containing chemical reactants subject to high-energy exothermic reactions, using only the chemical and physical properties of the components. Non-steady behavior such as build-up to chemical reactions, transitions from deflagration to detonation, and periodic or aperiodic instabilities, as well as steady-state conditions were phenomena to be considered. The ultimate goal once such predictions could be made from the model was to evaluate, by computational means, the feasibility and effectiveness of new physical arrangements and new chemical compounds for use in warhead devices.

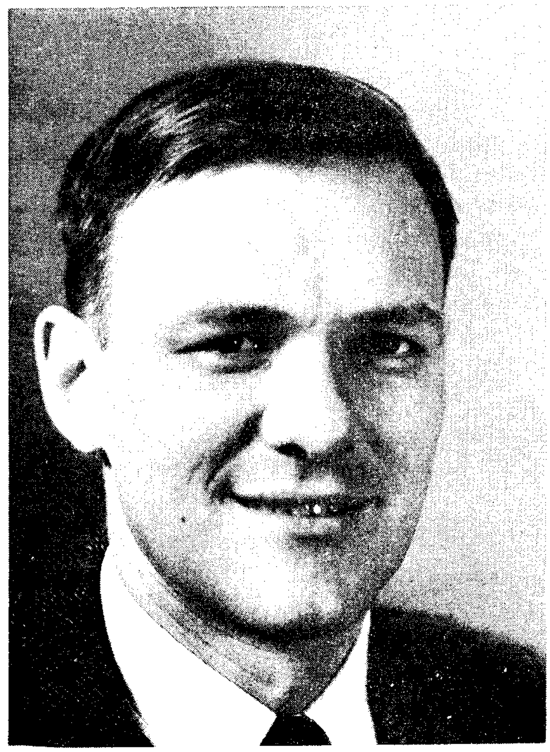
Broad fundamental investigations were under way on the effects of intense pressure waves in solids. In this work were considered the effects of extreme, transient pressures on electrical, magnetic, and crystalline properties, as well as the mechanical-fluid dynamic responses, meaning that the whole field of solid physics was involved. The purpose here was to construct a mathematical description that would predict for multi-dimensional configurations the details of wave propagation, deformation and fracture, and changes in crystalline, electric and magnetic properties of solids subjected to intense pressure pulses. It may be noted here that early in this particular research, BRL scientists made two important discoveries. The first of these was that the conductivity of several insulator materials changed under severe transient stress. The behavior of sulphur was particularly interesting; its resistivity decreased smoothly from more than 10^{15} ohm-centimeters at ambient pressure (zero stress) to less than one ohm-centimeter at 200 kilobars pressure. The phenomenon was exploited to develop a pressure transducer capable of sensing pressure pulses in the megabar range. The second discovery was that plastic dielectrics, such as plexiglass and polystyrene, subjected to an explosively produced shock wave, generated a displacement (polarization) current. Not only was the phenomenon of basic scientific interest in the physical characterization of plastics, it was of considerable practical interest because it could be exploited to produce electrical pulses with very precisely controlled parameters.

Dr. Edward E. Minor, Chief, Terminal Ballistics Laboratory, 1959 to 1971

By 1962, considerable strides had been made towards the quantitative understanding of the mechanical behavior of solids subjected to one-dimensional compressive stresses under extreme pressure; some mathematical descriptions of one-dimensional wave propagation had been derived; and rudimentary treatments of two-dimensional deformations and one-dimensional fractures had been constructed. However, the problems of elastic-plastic deformation in more than one dimension, strain-rate effects, and anisotropic behavior were only qualitatively and incompletely understood. This state of affairs demanded that a major effort be undertaken to develop the appropriate constitutive equations and the mathematical procedures to exploit them.

The continuing emphasis in terminal ballistics research upon mathematical modeling fit well with the dominant theme of overall research at BRL during the late 60's and 70's,—the attainment of predictive models that would make *ad hoc* testing unnecessary and provide the basic information for inclusion into vulnerability studies and ordnance design.

The advent of tactical nuclear weapons emphasized the importance of providing the Army with equipment capable of surviving and operating effectively in a nuclear environment. Consequently, BRL followed several avenues at the fundamental level to provide procedures and data whereby the capability of current ordnance equipment to survive the effects of nuclear weapons could be predicted and optimum designs for new equipment be made *a priori,* that is, without recourse to cut-and-try approaches. Subsequently in 1959, the 3-MeV Van de Graaff positive ion accelerator at BRL was used to study neutron transport through composite slabs representing armor; this work was part of the Army's radiological armor program. Although the Van de Graaff accelerator could be useful for making in-laboratory studies of the mechanisms of radiation damage and in developing and calibrating radiation measuring instruments, it could not provide nearly enough neutrons to simulate the nuclear effects produced by nuclear weapons. Since there were then no facilities available that could simulate the transient effects of the prompt radiation from a nuclear weapon, BRL was given the responsibility for planning a pulsed reactor facility to be located at Aberdeen Proving Ground. During 1963, Congress approved the funding and construction of the Army Pulsed Nuclear Radiation Facility. The Reactor became operational in late 1967.



Dr. John T. Frasier, Chief, Terminal Ballistics Laboratory 1971 to 1976, received his BS (Engineering Mathematics, Physics) from Virginia Polytechnic Institute and his PhD (Engineering) from the Pennsylvania State University. Following two years of active Army duty at BRL, Dr. Frasier was an Assistant Professor of Engineering at Brown University. He returned to BRL in 1962. Dr. Frazier became Director, Large Caliber Weapon Systems Laboratory, US Army Armament Research and Development Command, Dover, New Jersey, in 1976.

BRL gained another facility useful for radiation experiments when the Nuclear Defense Laboratory, changing its name to the Nuclear Effects Laboratory, became part of the Ballistic Research Laboratories in January 1969. This was the Ralph J. Truex Tandem Van de Graaff Accelerator Facility, for which more about, see below.

Until the cessation of atmospheric testing of nuclear devices, BRL played an active role in the design and conduct of projects for measuring free air blast and the effects of blast upon Army materiel. For these tests, BRL designed mechanical self-recording pressure and acceleration gauges that complemented electronic devices emplaced to make similar measurements. Later, a much-improved version of the self-recording pressure gauge was used at Cape Canaveral to record pressures in the event of an explosion during launch of a space vehicle.

At the same time that the US entered into the

Nuclear Test Ban Treaty, provisions were made for achieving and maintaining a readiness-to-test capability in the event that resumption of testing would be required. The Laboratories had several projects under the program which was known as Operation Blue Rock. Also, there was a shift in emphasis to experiments in which the effects of nuclear weapons were simulated. As mentioned above radiation effects were simulated through the use of the pulsed reactor and the accelerators; blast phenomena effects were simulated through the use of large quantities of conventional explosives and shock tube experiments. Experiments carried out by BRL concerned air blast and ground shock phenomena and their effects, including blast loading and response of military equipment, protective structures, and other items. Experiments using scaled models of structures were carried out in BRL's 24-inch shock tube; the Nike-X Dual Shock Tube completed at BRL in 1968 was used for full-scale tests. The Nike-X tube had been constructed specifically to test the large diesel and turbine electrical generators used to provide power to Nike-X installations.

Mr. Richard Vitali, Chief Detonation and Deflagration Laboratory received his BS (Physics) from the St. Lawrence University. He also completed extensive postgraduate work at the Carnegie-Mellon Institute and the University of Delaware. Mr. Vitali joined the BRL staff in the mid-1950's and became a Laboratory Chief in 1971.

During the latter part of 1961, personnel of the Terminal Ballistics Laboratory conducted a survey of the existing knowledge and current activities relating to the destruction of all sorts of material and equipment in unconventional (guerilla) warfare (UW). The assignment had first been given to the Special Projects Group (the former Future Weapons System Agency); however the Terminal Ballistics Laboratory assumed the task when the Special Projects Group decided to concentrate their efforts in target acquisition, guidance and control. The survey disclosed that no systematic, comprehensive study of UW targets and their vulnerability to feasible destructive devices existed. Consequently, near the end of 1962, BRL initiated Project WOODEN SHOE to study methods for destruction of material in unconventional warfare. The purpose of the project was to provide information regarding the most profitable targets and practical means for their destruction to: agencies involved in unconventional warfare training and operations, agencies concerned with the protection of US assets against subversive activity and, groups involved in development of items for special warfare applications. Upon the formation of the Vulnerability Laboratory in 1969, the WOODEN SHOE Project was transferred to that Laboratory.

Modern trends in military and non-military scientific development made imperative the extension of fundamental knowledge concerning terminal ballistic effects to much higher velocities than had previously been studied. Relevant problems included the effect of a collision between an ICBM traveling at 25,000 feet per second and a fragment traveling at a comparable velocity, or a satellite circling in space struck by a meteorite at a relative velocity of several hundred thousand feet per second. To satisfy this need for basic information in the field of high velocity terminal ballistics, in 1957 BRL instituted a program of theoretical and experimental research to determine the laws governing crater formation under "hyper-velocity" impact. Techniques were developed to project finite particles at velocities as high as 80,000 ft/sec. and micron-sized particles at velocities up to 50,000 ft/sec.

Like many other military organizations, BRL embarked upon a laser research program. In 1962, at the Laboratories it consisted of two parts; the part of interest here was devoted to the terminal effects of intense beams of coherent electromagnetic radiation. The other part was devoted to the production and transmission of laser beams, ultimately for evaluation as means for target acquisition, guidance and control.

The frequency of defeat of trucks and tanks by fire and explosion during combat led BRL to establish a program to investigate the basic parameters in ignition and flame spreading in fuels. There were several very interesting results from this work: one was the synthesis of fire-safe fuels; another was the identification of less volatile but equally efficient fuels for jet aircraft. With respect to ammunition explosions in tanks, a system for isolating such explosions from crew members came about through a concept for special ammunition compartment.

There is a constant duel between armor designers and anti-armor weapons designers. Supremacy of armor is soon overcome by improvements in K.E. penetrators and shaped charges, and vice versa. Similar competition existed between scientists at BRL working on armor and on penetrators. By the early 1950's, tank armor was at a great disadvantage versus the available improved anti-tank rounds. To offset the vulnerability of American armor, researchers at BRL concentrated on approaches that considered active armor systems to detect and destroy an incoming projectile, reactive armors that have an array containing explosive material that would detonate and destroy an attacking penetrator or shaped charge, and passive armors consisting of ceramics or glasses laminated with steel and aluminum and spaced armors. Much of the work on laminates was applied to concepts for the Main Battle Tank of the 70's (MBT70), a joint effort between the United States and Western Germany to develop a tank. The attempt was ended in 1970 by the US Congress, apparently on the grounds that the tank was not cost effective.

Work on composite spaced and ceramic armors continued at BRL for about twenty years—from 1953 to 1973. While some of these armors provided equivalent protection against shaped charge warheads at approximately half the weight of that of monolithic armor, they were still much too vulnerable to kinetic energy penetrators.

A notable lead in the armor-penetrator race was achieved when armor workers at the Military Vehicles Engineering Establishment, Chobham, England discovered the basic principles of a new armor. Chobham armor promised a high degree of protection against both types of penetrators. Both the US and Great Britain subsequently independently developed armors based on the Chobham principles. By incorporating the principles that made Chobham armor successful into the extensive armor technology base at the Laboratories, BRL was able to develop an armor for use in the XMI tank (known now as the Abrams Tank) being developed during the 1970's. Somewhat later the British developed Chobham technology and applied it to the design of armor for the Challenger Tank. This remarkably efficient armor is currently believed to be impervious to all threats existing at the time of its design.

Details about some of these foregoing subjects will show the broad range of BRL in terminal ballistics research during the twenty years following 1956.

AIR BLAST PHENOMENA

To a very large measure, the need to characterize the air blast produced by nuclear detonation dominated research in air blast during this period. After 1958, except for a brief period in 1962, such characterization relied upon simulations provided by conventional explosions. Nevertheless, the research in air blast from conventional explosives *per se* was not insignificant.

Blast From Conventional Explosives. By 1956 the details of what actually happened when a high explosive projectile detonated in free air had been established definitely. The character of blast waves, the nature and role of the shock front, positive impulse, peak pressure (both face-on or stagnation, and side-on or static) at any point which a shock wave passes, and the effects of temperature and ambient pressure on shock waves, had all been thoroughly investigated. The findings had been analyzed systematically to provide a coherent explanation of blast phenomena. Nevertheless, research into the response of structures and aircraft was governed by empirical tests using various explosives against target materiel. Lacking were analytical treatments that would obviate the need for testing, a standard explosive against which the performance of other explosives could be measured, a reliable treatment of the effect of altitude upon blast parameters, and final definition of the directional effects of charge motion on shock formation.

A Standard Explosive. In June 1956 BRL had compiled extensive air blast data on shock front pressure and positive impulse for about thirty different bare explosives fired in free air. Of the various parameters affecting the blast wave, charge composition, shape, and orientation of the charge relative to the measuring instrument were the three considered. When the data were used to construct overpressure curves, an analysis showed that the order of effectiveness could not be determined by comparison of pressure or impulse only, overpressure at one distance or within a small range of distances, or odd-shaped charges. The conclusion was that measurement of relative effectiveness of different explosives to cause damage required knowledge of pressure and impulse values of the shock wave as functions of distance from the source of the explosion. Also, the explosive chosen as a standard should be an explosive easily handled, with easily controlled density and composition, and with explosive properties that did not vary greatly from charge to charge. Although to that time TNT had been commonly used as a standard, Pentolite (a mixture of TNT and PETN) appeared to be a better choice.

Spherical charges of 50/50 Pentolite had been used often in air blast measurements because of the reproducibility of the resulting shock wave parameters. In February 1960 analytic expressions for side-on pressure, side-on positive impulse, and normally reflected impulse had been developed by fitting least squares polynomials to all currently available data from Pentolite charge detonations, except for those before 1945. Those earlier measurements were omitted because of improvements in measuring techniques which had been made since that time and because many of those measurements had been made under possibly less-controlled war time conditions. Again the conclusion was that Pentolite should be used as a standard explosive when the side-on or static peak pressure in a blast wave is considered. The conclusion was based on the excellent agreement of measurements by various investigators and the large number of observations available.

The availability of the high-speed computer made it possible to solve the problem of a spherical Pentolite charge explosion; i.e., knowing the detonation process and the properties of the explosion products to calculate the flow parameters in the explosion gases and in the region of the disturbed air. The results were, for the first time, presented as tables of pressure, density and internal energy for the explosion products of Pentolite calcuated as functions of temperature and entropy.

Air Blast at High Altitudes. The advent of high altitude aircraft, missiles, and satellites generated much interest in the vulnerability and defeat of such structures by air blast at co-altitude. The extent to which the current scaling techniques of the late 1950's could be used to predict the quantitative characteristics of explosively generated blast, and consequently the transient loading on such structures was of particular concern. There was a large amount of published experimental data on blast waves obtained at sea level conditions; however, even as late as 1964–1965, there were relatively little data that had been obtained at simulated high altitudes under conditions of reduced ambient pressure. Adequate scaling was needed and would facilitate many ongoing investigations in the response of materiel at high altitudes.

Scaling methods developed by Sachs (see Volume I) were used to predict blast characteristics at high altitude, but the maximum altitude and minimum distance from an explosive charge for which the Sachs laws were valid had not been experimentally determined. The High Altitude Simulating Blast Sphere Facility at BRL was used for research to determine the extent to which the scaling laws applied and to establish values of blast close to the charge. Quantitative data were obtained for simulated altitudes up to 175,000 feet by the end of 1965.

In 1971 data were obtained for three military explosives, Pentolite, Composition-B, and HBX-6 detonated at ambient pressures corresponding roughly to an altitude of 66,000 feet. When the new data were combined with existing published data at BRL they led to the conclusions that Sach's scaling was only approximately valid for peak pressure and that deviations between predicted scaled values and actual values increased rapidly as ambient pressure decreased.

Directional Effects of Charge Motion. Motion of an explosive may increase blast effectiveness in the forward direction. Estimates of the magnitude of the effect had been made in 1958 and earlier by assuming particular shock forms or energies. Established methods for calculating shock strengths had not been readily applicable because two space variables were needed to describe the flow. However, the problem of shock formation along the line of flight was soluble because the flow conditions there could be described readily. Along that line, air flow is perpendicular to the surface and the entropy is that behind the ballistic shock.

For a spherical charge moving at supersonic speeds, a detached shock forms ahead of the charge. Since no disturbances exist outside the ballistic shock and properties of this shock could be detailed, theoretical approximations of the flow properties along the normal streamlines of the charge surface could be made. Calculations showed that the effect of the ballistic shock formed by an explosive sphere traveling at Mach 10 was to increase the initial shock pressure at the charge surface as much as 6.6 times. However, at the point of intersection with the bow wave, the increase in pressure lowers to about 1.5 times that produced by a stationary charge. The large decrease in pressure from its initial value to that at the intersection agreed with experimental evidence. In the rearward direction, i.e., opposite the direction of motion, the explosive shock forms in a less dense medium; thus the initial pressure at the shock surface is less than the pressure would be at the surface of a stationary charge.

Fuel-Air Explosives. Beginning in the late 1960's, BRL conducted research to characterize the blast parameters associated with detonation of a fuel-air explosive cloud. A Fuel-Air Explosion (FAE) results from the dissemination of a detonable fuel into an aerosol cloud which is then initiated to produce an explosion that will subject a large area to a high overpressure, 2800 k.Pa. (400 psi).

In 1972 the BRL assisted the Mine-Countermine Laboratory at Fort Belvoir in documenting the peak overpressure and impulse loading on ground emplaced anti-tank mines from the detonation of a FAE cloud. Other research related to mine neutralization led BRL in 1975 to develop a concept whereby the fuel could be sprayed over a mine field from a modified flame thrower tank. When the resulting aerosol cloud was detonated the airblast would neutralize anti-tank mines. This concept was called SPRAYFAE and was successfully tested over a live minefield.

In 1975 the effectiveness of FAE in an air defense role was investigated by testing the blast output and detonability of dispersed FAE clouds at simulated high altitudes using the BRL high altitude blast sphere.

Blast from Nuclear Weapons: Atmospheric Tests and Simulations. As early as the end of World War II, a Nuclear Physics Section was organized in the Terminal Ballistics Laboratory to do fundamental research in nuclear weapons effects and to develop techniques to measure the effects and the response of materiel to them. (See Volume I). As a consequence, BRL participated in most of the nuclear tests at the Nevada Test Site and the Marshall Islands in the Pacific Ocean. This participation, at first primarily stressing free field blast measurements and the response of Army materiel but later extending to analyses of other phenomena, continued in 1957 during Operation Plumbbob in Nevada, and in 1958 during Operations Hard Tack and Fish Bowl, respectively in the Marshall Islands and at Johnston Island near Hawaii. In 1962, when atmospheric tests were resumed briefly at the Nevada Test Site, BRL took part in Operation Sunbeam. That was a test series emphasizing low-yield nuclear weapons.

The activities of the Laboratories during Operation Plumbbob—representing the largest and most varied program undertaken by a single laboratory in a nuclear test operation to that date—were typical of the Laboratories' role in nuclear weapons tests. In addition to conducting basic blast and effects experiments, BRL provided essential instrumentation service and support to the Armed Forces Special Weapons Project, the Federal Civil Defense Administration, and the Civil Effects Test Group of the Atomic Energy Commission.

Particularly valuable results from the Plumbbob Operation were the data on free field air blast parameters and precursor shock wave formation and shape (this latter was a subject of intense interest at the time) as a function of weapon yield, height of burst, and terrain irregularity.

Response measurements made on above ground and underground structures such as missile silos, embraced measurements of strain, displacement and accelerations. These measurements were correlated with concurrent measurements of blast and shock propagation in the surrounding or supporting medium (air and earth). Not only were U.S. domestically-designed underground structures tested and analyzed, but similar structures designed by France and by the Federal Republic of Germany.

Under the Desert Rock Operation, attached to Plumbbob, BRL determined the effects on performance of many sorts of military vehicles and some mine fuzing components exposed to nuclear weapons. (Radiological shielding measurements were made on various vehicles with the help of the Nuclear Radiation Laboratory of the Army Chemical Center.)

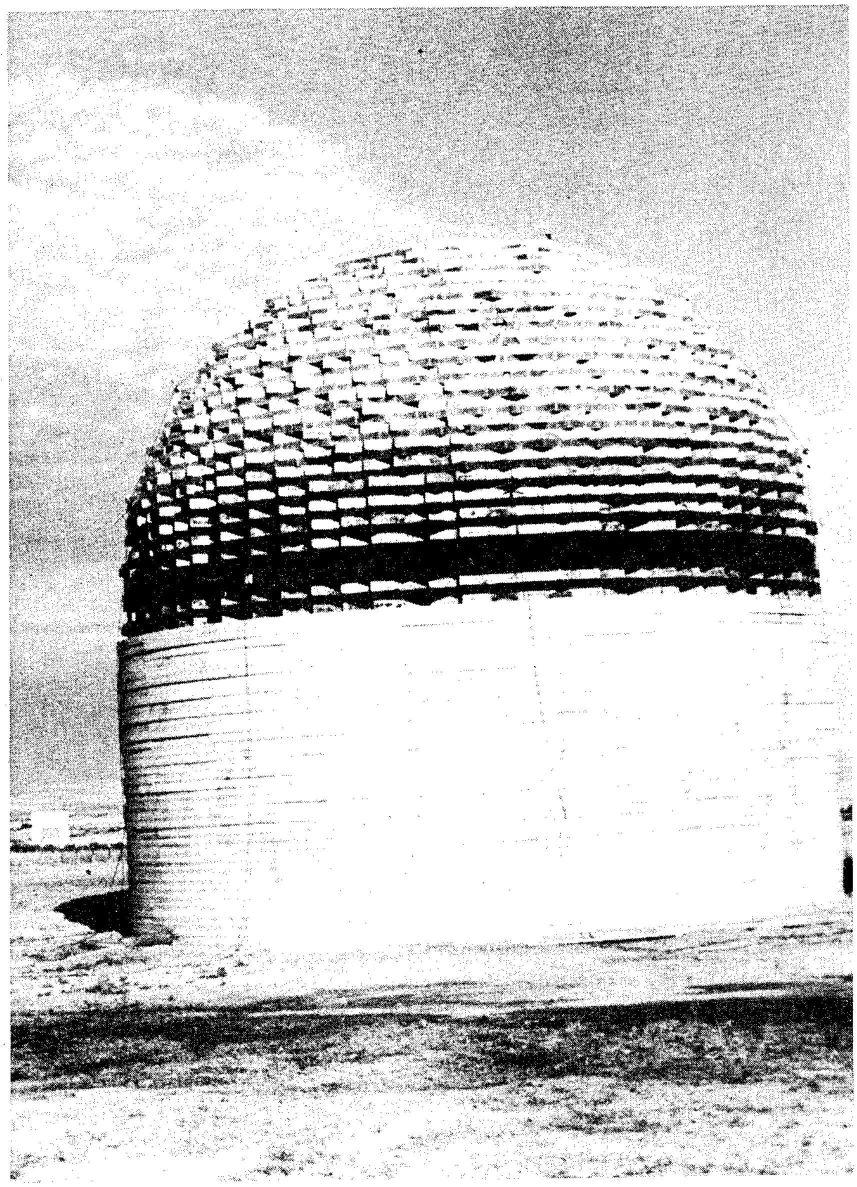
As was the case for the fundamental air blast and response research, the general problem of blast flow and overpressures in protective shelters, tunnels, and entrances was to be of interest for many more years. In the latter work BRL had the close support of the Federal Civil Defense Administration (later the Office of Civil Defense) and the Civil Effects Test Group. In that endeavor experiments encompassed full scale field tests as well as closely coupled scaled model experiments in the BRL shock tube.

Simulations by Conventional Explosives. The provisions of the Limited Test Ban Treaty meant that atmospheric nuclear testing had to cease. However, there was still a great need for data on target response to nuclear blast and shock and for use in confirming empirical predictions and theoretical calculations for blast parameters. (The same could be said, of course, for target response to the thermal, radiative, and electromagnetic effects.) Thus, conventional, and some not so conventional explosives began to be used to simulate the blast from nuclear explosions.

The Canadian government, through its Defense Research Board, had begun a program in 1957 to measure blast phenomena produced by detonation of large charges of TNT. These high explosive tests were conducted at the Suffield Experimental Station (SES), located at Ralston, Alberta, Canada. The Ballistic Research Laboratories began, in 1959, to participate in this series of multi-ton TNT experiments at Suffield. In those experiments BRL, in addition to conducting various effects and target response projects, instrumented a "blast line" to measure the pressure-time history of the blast wave at selected distances from "ground-zero", that is from the center of the explosive mass.

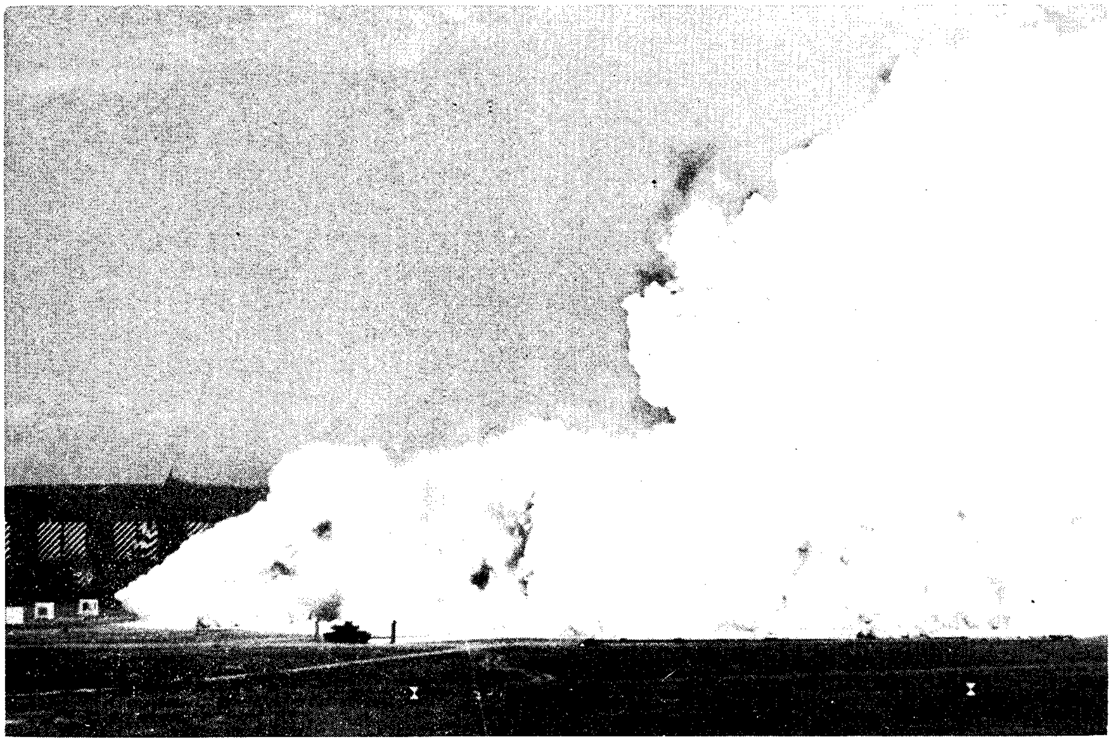
The Laboratories took part in a 5-ton test in 1959, a 29-ton test in 1960, a 100-ton test in 1961, and a 500-ton test (Operation Snowball) in 1964. For the last three tests, the Defense Atomic Support Agency (DASA) sponsored the US experiments, and agencies from the US, the United Kingdom, and Canada carried out a coordinated program under the guidance of The Technical Cooperation Panel (TTCP).

Using the pressure-time measurements made during those four shots, BRL researchers constructed empirical curves giving peak overpressure, arrival time, positive phase duration and



500-ton stack of high explosive, Operation Snowball

impulse versus scaled distance for a yield of one-pound of TNT at sea level. The data from the surface detonations varying from 5-tons to 500-tons had of course been scaled to the one-pound weight of high explosive. These standard TNT performance curves were then compared to similar curves for blast yield from sub-kiloton nuclear detonations. In the process, because of the differences in yield between chemical and nuclear detonations, the TNT parameters were scaled to an 0.5-kiloton yield at standard sea level conditions while all nuclear points were scaled to a 1.0 kiloton yield under the same conditions. It was then concluded that explosions from TNT hemispheres did indeed make an ideal technique for the simulation of air blast from low yield



Detonation of 500-ton stack of high explosive. Refraction due to shock wave distorts images of diagonally striped targets.

nuclear weapons. It also appeared that the high explosive (H.E.) detonations would also simulate the general pressure-versus-time wave shape recorded from large scale nuclear detonations (but only where a precursor would not be expected). The TNT blast parameter curves constructed by BRL were accepted by the Department of Defense Explosives Safety Board and the NATO countries as the standard for Quantity-Distance Tables and for establishing TNT equivalence of other explosives and munitions.

When for the 100-ton test in 1961 DASA asked BRL to coordinate the field activities of all U.S. projects participating, they were setting a pattern to be followed by BRL during many subsequent large-scale explosive tests. The Laboratories involvement with these large scale high explosive tests continued through 1976. Some representative tests were:

- Clustered Atomic Warheads (CLAW) and Project White Tribe. In March 1960, representatives of the Air Force Special Weapons Center, Kirtland Air Force Base, Albuquerque, New Mexico, visited BRL to discuss enhancement in air blast that might be obtained from simultaneous detonations of a cluster of nuclear weapons—compared to that obtained from the detonation of a single large-yield warhead. Should it be demonstrated that significant overpressure enhancemnent could be achieved with such a scheme, the Air Force would then consider substituting clusters of smaller atomic weapons for the single large warhead being considered then for several missile systems. The concept was given the code name CLAW.

The Laboratories suggested that a comprehensive series of experiments with spherically shaped charges of moderate weights (one pound and eight pounds of bare explosive), with a complementary theoretical treatment, could provide the necessary information. From the results of experiments in which charges located on the vertices of an equilateral triangle were detonated simultaneously, it was concluded that simultaneous detonation of a cluster of explosive would yield greater area coverage (for any specified minimum peak pressure) than that of a single large charge—provided that the distance between the clustered charges was optimized. Classical shock theories were used to predict the interaction effects of multiple shocks.

However, several phenomenological aspects of the blast behavior of simultaneous detonations remained unanswered at the end of the experiments. Therefore, the Special Weapons Center and BRL considered a larger scale test, intermediate between the small scale experiments and the nuclear case. After determining the feasibility of the large scale experiment, BRL initiated a series of three trials using trios of 10,000-pound charges of Pentolite explosive. The tests were supported by the Air Force Special Weapons Center. The test site selected was White Sands Missile Range, New Mexico. The name White Tribe, given to the operation, is an acronym derived from *White* Sands *Tr*iple *B*urst *E*xperiment.

The air blast data collected during White Tribe substantiated the results of the previous small scale tests. Reliance on scaling laws used in predicting the blast parameters was justified.

- Operation Blowdown, 1963. This experiment sponsored by the Australian Ministry of Supply investigated the effects of a 50-ton charge of TNT fired just above the canopy of a heavy rain forest. The US Army was primarily interested in tree damage that might impede the movement of troops and vehicles and in the attenuation of the blast wave overpressure and dynamic pressure within the forest area. The test was conducted at the Iron Range Test Site, North Queensland, Australia.
- Operation Distant Plain. During 1966 and 1967, the Technical Cooperation Panel sponsored a series of shock and blast experiments at Suffield and at a site near Medicine Hat, Alberta, Canada. Two events (3 and 5) in the series at the Suffield station provided an opportunity to compare airblast produced in the summer with that produced in a winter environment (frozen ground) by equivalent 20-ton TNT charges. These two shots were a follow-on to a series of three 20-ton shots fired at the Nevada Test Site in 1963. The data provided by those shots indicated the need for more overpressure measurements as close to the charge as possible. These two events of Operation Distant Plain were intended to duplicate the charge configuration, position and weight of the Flat Top explosions in the alluvium of the Suffield Experimental Station and to provide data on cratering, ground, shock, and air blast. The results showed differences in air blast phenomena in the pressure region greater than 200 pounds per square inch; the differences were manifested by a lower pressure under winter conditions than under the summer conditions.

  Event 4 of this series occurred at a site in the Dominion Forest Reserve near Hinton; the site was selected because it was a nearly ideal location for conducting an experiment in a managed coniferous forest, similar to that found in Northern Europe. The charge for this experiment was 50 tons of TNT block built on the surface in the form of a hemisphere. The objectives of the BRL effort here were to measure air blast parameters on the surface in a cleared sector and in a forested sector, on the surface and above the surface. The results showed significant differences in air blast parameters measured over the cleared and the forested sector.

Because it was extremely expensive to use TNT explosive to simulate explosions from nuclear weapons, attempts were made to substitute other volatile materials. During Operation Distant Plain, a 125 ft. diameter hemispherical Mylar balloon filled with an oxygen-propane mixture was the explosive source. The resulting yield was equivalent to 20 tons of high explosive.

Sponsored by DASA, the Naval Ordnance Laboratory investigated the use of ammonium nitrate soaked with fuel oil (AN/FO), cost approximately twelve cents per pound. Ballistic Research Laboratories measurements made for two 20-ton shots and one 100-ton shot showed that at pressures of 30–200 psi, the AN/FO had an effective weight of about 0.8 that of TNT. The AN/FO combination was used in the DASA-sponsored event DICE THROW held at Giant Patriot Site, White Sands Missile Range.

In Project ESSEX (Effects of Sub Surface Explosions) 10-ton charges of gelled nitromethane were used as the explosive source. This series of experiments was designed to gather information needed for effective deployment of atomic demolition munitions and earth penetrating warheads. The Laboratories successfully measured air blast parameters in the crater and near-crater regions for four subsurface detonations.

Air Blast Focusing. Although BRL research into the effects of meteorological conditions on blast waves was a relatively minor effort, it gave results of great practical significance. Blast waves, of course are generated whenever explosives are detonated or artillery weapons are fired. Under certain meterological conditions in the lower atmosphere, such as temperature inversions, blast waves can be focused, thereby increasing the intensity of the air shock in specific regions. Such focused blasts can cause annoyance to residents living near proving grounds and prompt complaints, and, at times, claims for damages.

BRL prepared a handbook describing a technique for evaluating meteorological conditions that could cause blast focusing. In addition to providing a method for predicting blast focusing, the technique can also be used to assist in determining the validity of claims for damage resulting when explosions occur accidentally or when explosive tests might be held without consideration of meteorological conditions. The handbook was expected to be useful to range control officers, demolition teams, safety personnel, claims officers, and public relations officers, as well as to personnel engaged in experimental work. To ensure rapid, widespread application of the prediction technique, BRL engineers conducted short courses to train personnel from all services involved in outdoor explosions or artillery weapon firings.

HYPERVELOCITY IMPACT (HYPERBALLISTICS)

As noted briefly in the introduction to this chapter, modern trends in both military and nonmilitary scientific development made imperative the extension of fundamental knowledge concerning terminal ballistic effects to much higher velocities than had been studied previously. To contribute to the store of fundamental information in high velocity terminal ballistics, the Laboratories instituted a program of experimental and theoretical research. The initial purpose of the program was to determine the fundamental laws governing crater formations under hypervelocity impact conditions.

The first problem to be solved was the development of experimental techniques for investigation in a new velocity realm (in conventional ballistics of the late 1950's, 5000 ft/sec, about 1.5 kilometers per second).

However, the range of velocities attainable in the laboratory still fell far short of the maximum values of interest. That deficiency was overcome by an appropriate choices of target materials. Because the term "hypervelocity" is relative, referring to impact velocities greater than the velocity of sound in the target material, truly hypervelocity conditions could be reached by using lead targets (in which the velocity of sound is 1.2 km/sec) rather than steel or aluminum targets (in which the velocity of sound is 5.0 km/sec).

Qualitative results from the first series of experiments showed that at low velocities (0.6 km/sec to less than 2.0 km/sec) the striking pellet penetrated essentially intact, cavitation caused a hole diameter at the crater entrance considerably larger than the pellet, but with a diameter at the bottom essentially equal to that of the pellet. For velocities above 2.0 km/sec, the hole became hemispherical in shape and remained so for even higher velocities.

The results of pellets striking at oblique conditions was interesting; at a lower striking velocity (2.32 km/sec), impact at 30° produced a nearly hemispherical crater. Impact at 60° produced a very shallow and asymmetric profile. If the velocity was increased to 3.22 km/sec, a symmetrical hemispherical crater was formed, even at 60° obliquity. Thus, it was evident that if the impact velocity is sufficiently high, a symmetrical crater will be formed even at very large angles of obliquity. This result was of particular significance in 1958 to astrophysicists interested in the formation of craters on the moon.

One of the arguments against the theory that moon craters were formed by meteor impact was based on the observation that all of the craters are symmetrical, even though it is not logical to assume that all of the meteorites struck the moon at normal incidence. The results of the hypervelocity experiment showed that the symmetry of the craters does not imply that the impact necessarily took place at normal incidence. Thus the theory of meteorite formation of the moon craters could be considerably strengthened.

From these early experiments, a concept of the mechanism of hypervelocity crater formation was developed; the process is far different from that of penetration by armor-piercing projectiles. Under hypervelocity conditions, the projectile deforms and "disappears" very rapidly, its kinetic energy being transferred to the target material in the form of a compression wave. The compression wave causes further displacement of the target material (cavitation), enlarging the crater, until its energy has been expended in work done to overcome the target material's resistance to deformation.

A theory based on the concept was developed; it readily explained all the qualitative features of the experimental observations but left undetermined the precise manner in which the target absorbs the energy imparted.

As more data were accumulated, it was concluded that the crater volume was proportional to the kinetic energy of the impacting body, for a number of metals, over a range of striking velocities varying from the sound velocity in the target material to a maximum of 5.5 km/sec. Data obtained with microparticles traveling at velocities of 10 to 12 km/sec indicated that the same relationship existed, even to that high a velocity. These experimental results were in essential disagreement with the best theoretical treatment of the problem available in 1959, which was based upon the assumption of hydrodynamic flow throughout the process. Continuing studies confirmed in 1960 that the phenomenon could not be explained adequately by purely hydrodynamic means; there were a number of clear indications that the plastic properties of the target material are of primary importance in determining crater volume.

By 1961 the hyperballistic studies carried out had produced a physical model of the phenomenon resulting from hypervelocity impact in homogeneous isotropic materials. In that year the model, which had been almost universally accepted by the scientific community, was extended to anisotropic, inhomogeneous materials. From this model, several inferences could be drawn that were of significance for practical application in the problem of damaging an incoming intercontinental ballistic missile.

First, plates with thicknesses many times that of a projectile can be perforated under hypervelocity conditions; however no significant portion of the impacting projectile will be found behind a target thicker than the dimensions of the pellet. Thus, behind even moderately thick plates, the only damage to be expected would be that produced by target spall fragments created by the stress wave. Second, these fragments will be fairly large and will be spread over a considerable area, but will be traveling at relatively low velocities and will have limited damaging capacity. In view of the tremendous pressures developed under hypervelocity conditions, this behavior would be true for any conceivable projectile material and even low density, very soft target materials.

Research in this general area continued at BRL through 1976. However, emphasis changed periodically; much of the work was subsequently sponsored under the Army Materiel Command program for Anti Ballistic Missile Materials Hardening. See below.

FRAGMENTATION

Not long after the end of World War II, the Laboratories had initiated a major program for research to cover all aspects of fragmentation; the objective was to increase the effectiveness of fragmentation weapons. The program was to continue without interruption through the years covered by both volumes of this BRL history.

By the end of 1956, a great deal had been learned about the physical properties of fragments. Pre-formed and controlled fragments had been developed for use in projectiles and missiles, and work was under way to find metals with more desirable fragmentation characteristics than the forged steel then being used in fragmenting munitions. The appearance of ductile cast irons on the American market at that time had also made it possible to conduct exploratory experiments with high explosive shells made of the new ductile and malleable cast irons, which were also known as nodular irons.

It should be no surprise that the long-term goal in fragmentation research was a computer program which would describe the fragmentation of an artillery shell, wherein input data were furnished by sub-programs that could describe initiation and detonation of the explosive, stress wave propagation and deformation in the shell casing, the initiation and propagation of cracks, flight characteristics of the fragments, and lethal effects against personnel or materiel targets. The development of these subprograms demanded more thorough understanding of the detonation process in explosives, the role of metal substructure subjected to intense stress pulses, the analysis and classification of defect structures leading to fracture, and so forth. Note that much of information obtained from such fundamental research could find applications in penetration and armor tasks.

The success of the program was evident by the 1960's when BRL-developed technology could provide self-forming, self-forging, and blast-focusing fragmentation warheads. When coupled with advances in fuzing, guidance and control technologies, these warheads found use in concepts for Copperhead, SADARM, and STAFF. Yet to be applied were concepts for 155-mm shell that in one instance could deploy 120 one-quarter pound fragments at a velocity of nearly 6000 ft/sec. Moreover, the flight direction of the fragments relative to the projectile would be uniform from round to round. Another concept for the 155-mm shell would focus and project more of the available fragments down and forward toward the target area than the currently available conventional air-burst shell can.

Materials Research. In early 1956, representatives from the Office of the Chief of Ordnance, the Ballistic Research Laboratories, and Watertown Arsenal met at Picatinny Arsenal with representatives from the Chamberlain Corporation and the American Radiator and Standard Sanitary Corporation, both manufacturers of military shell, to establish a program for develping improved 105-mm high explosive shells. The program embraced the design, development, testing and evaluation of shell to yield fragments capable of giving a thirty percent increase in lethality, compared to the current shells. It was known that the conventional 105-mm shell gave fragments excessively large—hence an inefficient use of both explosive and the metal casing. Also known at that time, through the results of BRL research in lethality, was that small fragments at very high velocities were extremely effective against human targets.

The results of work by BRL and Watertown Arsenal had shown that the metallurgical properties did exert considerable effect on fragmentation parameters and that the most promising prospects were inherent in metal casings made of ductile cast iron. In an alternate approach BRL had shown that projectiles made of cold-worked steel tended to produce finer, more nearly optimum size fragments than the standard forged steel shell. However, the cold-worked shell still gave fragments that were too large.

Under the cooperative program, experimental 105-mm shells of the same size and shape as the standard M1 shell were designed and made of two types of ductile cast iron, pearlitic malleable and nodular graphitic. It was expected that the fragments from the ductile iron shell would be of better aerodynamic shape, more numerous and closer to optimum mass. The expectations were confirmed by tests; the improved performance was verified by lethality studies against personnel targets for selected low, medium and high shell angles of fire. Depending upon the posture of the target, the experimental shell showed gains in lethal area varying from 36 to 67 percent to 103 to 150 percent.

In the continuing effort to select suitable material for controlled fragmenting munitions, the Laboratories, in the mid-60's, investigated the metallurgy of steel powders. The high production rate and competitive production costs of sintered and heat-treated shell made from powders appeared promising. Other approaches, e.g., liquid metal casting, metal casting, mechanical working of cast metal, unusual and expensive heat treatments necessary to improve the fragmentation behavior of a wrought material, and composite casting of hard penetrators in a ductile matrix, presented expensive problem areas which could not be resolved easily. The results of BRL tests using steel powder cylinders showed that the powder metallurgy of steel provided a promising way to produce the desired controlled fragments. Although there were some disadvantages such as low density and low ductility, the causes of the disadvantages were known and were being resolved.

These empirical investigations into metals for use in controlled fragmentation were paralleled by theoretical research. Consequently, by 1970 the capability existed to evaluate the fragmentation behavior of cylindrical castings made from an iron-graphite powder mixture. The fragment mass distribution was shown to be related to metallurigical variables of the casting. The mechanical properties (yield strength, elastic modulus, elongation to fracture, and ultimate tensile strength) of the alloy had been measured and correlated with its apparent density. Observations of the hardness and microstructures of powder metal castings fabricated from sponge-iron powder and electrolytic iron-graphite powder mixtures before and after led to a model accounting for the role of porosity in the break-up process. The end result was a general development technique for optimizing fragment mass distribution from a naturally fragmenting casting.

Explosives and Fragmentation. The capability to model the characteristics of fragmentation was inhibited by the complexity of the explosive-metal system, hence, the long time reliance on empiricism to provide the answers to narrow, very specific problems. Certain aspects of the explosive-metal system could be treated adequately by simple analytical formulations to describe fragment velocities and fracture characteristics and in more refined detail by infinite finite-difference codes such as HEMP and HELP, which are described below in the section on penetration.

To provide additional insight into the coupling of explosive and metal parameters, late in 1973, BRL undertook a rather comprehensive analysis of the effect of the explosive type upon the casing material. To broaden the scope of the applicability of the results, parameters such as casing material and thickness were varied as well as the type of explosive. Five different high explosives were used as fill in two types of steel casings, mild steel and a more frangible steel (HF-1).

The test results showed that the fragment mass and number distribution were sensitive to the explosive fill, with the average fragment mass decreasing as explosive energy or pressure increased. Moreover, the sensitivity to explosive fill became less as the casing thickness decreased, and the more frangible alloys were less sensitive to the type of explosive fill. The data also showed that for a given shape and casing material, the fragment kinetic energy increased linearly with explosive energy. Furthermore fragment kinetic energy correlated better with explosive energy than with pressure, thereby illustrating that energy is a better figure of merit for fragment speeds than pressure. Another outcome, important for modelling purposes, was that equilibrium thermodynamic calculations using the TIGER Code, could be used to estimate the relative fragment kinetic energy delivered to a steel casing upon fragmentation.

PENETRATION: KINETIC ENERGY AND SHAPED CHARGE PROJECTILES

Shortly after World War II had ended, BRL developed a penetration theory to clarify and simplify the problem in determining the probability and extent of armor penetration by kinetic energy rounds, then generally known as armor piercing (AP) rounds. Force equations were used as the starting point and the assumption was made that a constant force resisted the projectile throughout its penetration of armor. Working from that basis, researchers could develop formulas for determining ballistic limit, residual velocity, and critical angles of attack. Remarkably, results from these relatively simple predictive formulas agreed closely with predictions based on empirical formulas derived from test data.

Nevertheless, as late as 1957 the situation was far from satisfactory. There really was no theory of armor penetration that could predict with acceptable accuracy the penetration performance of kinetic energy projectiles against armor. Until a general, reliable theory could be made available, it appeared necessary to determine the projectile performance by test firings or to make predictions based mainly on the results of past test firings.

Test firings, in quantities adequate to determine penetration characteristics over various conditions were, and are, expensive. Also, they could occur only after projectile and gun hardware were available. Thus, considerable system development was necessary before projectiles could be test fired. Substantial savings in time and money could be realized through the availability of a reliable, comprehensive predictive scheme that would permit estimates of the penetration performance over a wide range of conditions covering significant variations in projectile type, striking velocity and obliquity and caliber, as well as variation in armor material and thickness. the development of such a scheme became a major objective in BRL kinetic energy research for the next twenty years.

Concerning shaped charges, an intensive research program to obtain information needed to understand the formation and performance of effective shaped charges had been initiated in 1946 by Army and Navy agencies and government contractors, industrial and academic. BRL participated actively in this work, with even greater emphasis during the 1950's.

The program provided the basic data needed to identify and evaluate the factors determining shaped charge performance. The relationship between the angle and diameter of the cone was well established as was the way in which standoff affected the penetration capabilities of a shaped charge projectile or rocket. It was determined that a shaped charge jet contained a relatively small group of discrete hypervelocity fragments and that the total number of these fragments depended on the size of the explosvie charge, the angle of the cone, the thickness and material of the liner and many other factors. Work was continued to refine this information.

BRL investigations in that work included evaluating the different metals of which shaped charge cones could be made and categorizing metals according to which had the most desirable characteristics. Metallurigical investigations were made to determine what general properties of metals (hardness, melting, point, ductility, and tensile strength) had an appreciable effect on the penetration capabilities of shaped charges.

Around the middle 1950's, the BRL phase of the shaped charge program was given a new emphasis. More and more attention was directed to investigating the possibility of controlling the spin of shaped charge projectiles, increasing the damage potential of shaped charge weapons, devising effective defense against shaped charge weapons, and systematically disseminating information about shaped charge research and development work so that all agencies participating in the program could keep fully abreast of the progress being made. The last item was aided considerably through international conferences on shaped charges, inaugurated by BRL in 1960.

At the time at which the second volume of BRL's history begins, the Army was considering shaped charge warheads for a wide variety of applications. The requirements varied enormously and the design characteristics of the most efficient shaped charges to accomplish the various purposes consequently differed over an equally broad range. It was clear of course that there could never be sufficient experimental observations to demonstrate all the effects of variations of design characteristics in all of their possible permutations. Thus, similar to the requirements for the design of kinetic energy penetrators, the design of shaped charge warheads required development of an analytical procedure, so that the most efficient design for a given purpose could be developed without resorting to time-consuming, expensive trial and error development.

The various aspects of shaped charge theory had been combined in a code for machine calculations. The machine code could provide a detailed description of all characteristics of the jet and its effect on a target, given the specifications for the geometry of the warhead and properties of the materials used, and the properties of the target. However, certain essential parameters such as manufacturing imperfections and the effects of confinement on the partitioning of detonation energy, could not be considered by the code. Much remained to be done to refine shape charge performance modeling and to improve its accuracy.

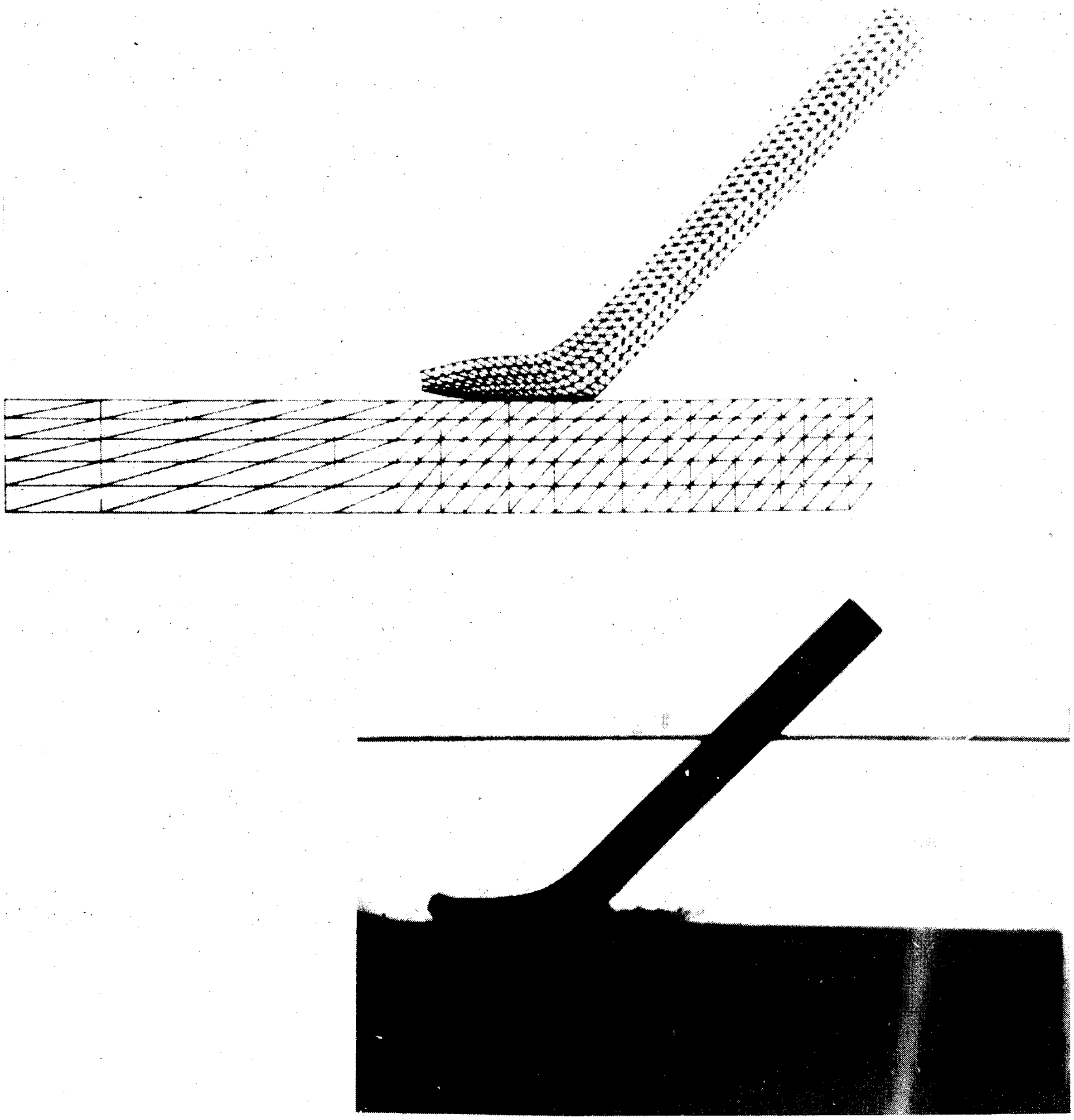
Kinetic Energy Penetrators. As implied above, penetration mechanics has always been a difficult subject for analysis, and frequently, progress has followed most rapidly from an experimental rather than a theoretical approach. To illustrate these alternate approaches, the following discussion attempts to trace the development of kinetic energy penetration technology by considering the results of empirical analyses, the development of long-rod penetrators, and the underlying physical research.

Empirical Analysis. In 1957 personnel at the Laboratories collated data then available at Aberdeen Proving Ground concerning perforation of steel armors by kinetic energy (KE) penetrators. The data were used to construct a series of curves which could be used to predict, with reasonable accuracy, the perforation achievable by conventional KE projectiles, namely armor piercing, armor piercing capped, and high velocity armor piercing types. Performance was measured against rolled and cast homogeneous armor at obliquities ranging from 0° to 70°. It was not expected that the curves would be very accurate for predicting performance of projectiles which were shaped very differently from those used in the test firings, or if there were marked changes in the quality of projectile or armor.

The measure of penetration performance was the "ballistic limit" a concept which had been used for many years. The concept had evolved over a number of years; in the past it had been assumed that for a particular projectile-armor combination there existed a velocity (the ballistic limit) which, if exceeded by the projectile, would result in perforation. If the velocity was not exceeded, the projectile would not perforate. The concept had been modified in the late 1950's to consider that there exists for each velocity a probability of perforation associated with a given projectile armor combination. Usually the probability was considered to rise smoothly from 0.00 to 1.00 as velocity increases. For example, the lowest velocity at which the associated probability of obtaining a perforation is 0.50 is called the V_{50} limit. Similarly, the lowest velocity at which the estimated chance of obtaining a perforation is nine-tenths would be called the V_{90} ballistic limit.

In 1963, studies of penetration processes of long rods against finite targets showed that the concept of the V_{50} ballistic limit was not useful for the design of kinetic energy penetrators. The relationship between the striking velocity (V_S) and the residual Velocity (V_R) behind the target showed a steep rise after the intial penetration velocity (V_L) was obtained. Data showed that there is about a 40 percent reduction in V_{50} in going from a length-to-diameter (L/d) ratio of 5 to an L/d of 40. The same experiment which yielded this information provided penetration data for tungsten carbide rod penetrators, length-to-diameter ratios of 25, tested against single and spaced tripartite targets. Tripartite targets are arrangements of rolled homogeneous armor which provide a standard armor array for penetration tests by researchers from the United States, the United Kingdom, and Federal Republic of Germany.

The primary parameter used to define the performance of a given projectile-armor configuration was later defined to be the ballistic limit velocity. (V_L). There came to be general qualitative agreement that V_L is the relative striking velocity that serves as the dividing line between defeat of a given target by a specific penetrator and defeat of the penetrator by the armor. The ballistic limit velocity thus is defined as the lowest striking velocity required for a complete penetration of a target by a penetrator; that is, the



Kinetic energy penetrator, predicted performance compared to actual performance.

penetrator exits the rear face of the target. In 1971 additional data on the penetration by steel and high density rod penetration was collected and analyzed to permit predictions of the limit velocity required to defeat rolled homogeneous armor at various obliquities. The data came from experiments conducted by other agencies and from contemporary experiments at the Laboratories.

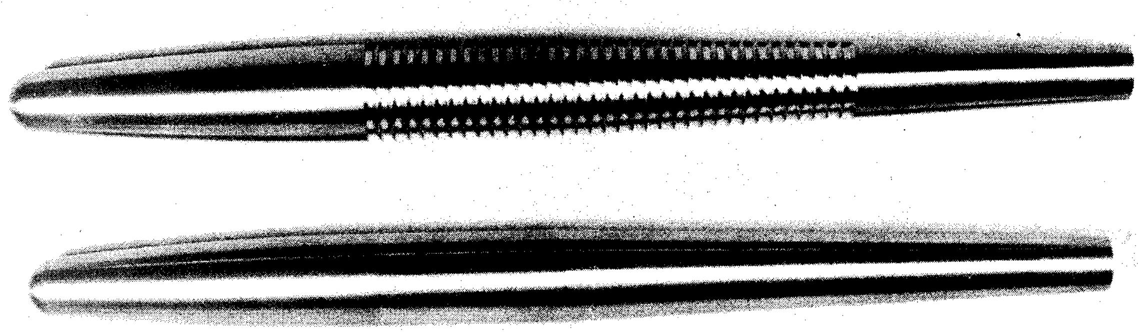
Long Rod Penetrators. The improvements and anticipated improvements in gun technology apparent in the 1960's and early 1970's promised a potential for higher projectile velocities. This potential could be exploited to use K.E. penetrators against hard targets not previously vulnerable. Penetrators with high length-to-diameter ratios appeared to be the strongest candidates to fill this role since the density and strength of the penetrator material and the small diameter combined to provide high sectional density.

The Laboratories' tests using specimen rod penetrators showed that, for the impact velocities experienced, the denser the rod, the greater the penetrating power into monolithic armor. Careful control of alloying and processing of the rod material, all other factors remaining constant, produced substantial gains in performance. When alloying and processing were carefully controlled, depleted uranium, because of its superior dynamic material properties, was found to be better overall than tungsten as a rod material.

At an early stage in the development of the XM-1 Tank, BRL formed a study group to compare foreign and domestic tank gun/ammunition systems. The objective was to recommend the "best or good enough" gun for the tank. Researchers compared the effectiveness of kinetic energy rounds against monolithic armor and two types of non-monolithic armor. Rounds examined included the 105- and 120-mm projectiles from the Federal Republic of Germany, the 110-mm from the United Kingdom, and the 105-mm from the United States. The conclusion of the study group was that, given good fire control, the United States 105-mm M68 tank gun/ammunition system was best or good enough for the XM-1 system.

The results of this investigation encouraged the Laboratories to develop a prototype kinetic energy projectile designated the Silver Bullet for a tri-national competition. Prototype development was undertaken as a possible alternative and stimulus to development of a K.E. round, the XM735, by Picatinny Arsenal.

Although the Silver Bullet concept developed



Silver Bullet Penetrators. Lower penetrator without sabot grip was used to determine possible effects of the sabot grip.

by BRL represented a more advanced penetrator, the XM735 was chosen to be the U.S. entry in the competition because it was a more nearly fully-developed round of ammunition. However, the results of the penetrator work done for Silver Bullet helped, through the free exchange of information, in the final design of the XM735 and contributed to the success of that round.

For the tri-national competition held in 1976, the last of three such competitions, BRL supplied a "growth-potential" 105-mm round, the SB-60-24. That round later served as the prototype for the M833 and XM829 105-mm anti-tank rounds of the 1980's.

It's worthy of note that much of the design concept for the Silver Bullet resulted from an analytical study using HELP, a two-dimensional, multi-material, Eulerian finite difference code for solving material flow problems in the hydrodynamic and elastic-plastic regimes. The code's particular application in this instance was an evaluation of long rod penetrator nose designs of various materials and geometric configurations.

Research in Mechanics of Penetration. The need for accurate three-dimensional constitutive relations for metals hampered development of codes needed to address problems in penetration mechanics, armor design, and high-rate structural loading in general. In research to develop these constitutive relations, the Laboratories acquired data on a known dynamic, combined stress configuration, under wave propagation conditions. Previous combined stress tests had ignored wave propagation effects and were limited by the inertia of testing machines. A typical barrier to such research had been the design of an apparatus that would provide simultaneous torsional and compressive waves under constant velocity impact conditions. BRL scientists were able to design and test suitable apparatus. The data generated were sufficient to predict the governing stress-deformation relationships.

In another investigation it was realized that as the length to diameter ratio increases, the possibility arises that strong axial forces could give rise to unstable, transverse motions. If the axial load is imposed for a long enough time, the transverse displacements may become sufficiently large so that the rod may buckle. Since severe transverse bending could be expected to degrade the penetration process, particularly in the case of multiple impacts, BRL developed a predictive code which could estimate the conditions necessary to produce transverse instability in long rod penetrators.

Shaped Charges. Since the end of World War II, shaped charge warheads and their components had been an important and productive subject for research at the Laboratories. As a consequence, by 1956 the Laboratories had a cadre of young theoreticians and experimentalists whose competence was recognized nationally and internationally. Their research was aided considerably by excellent laboratory facilities, in particular flash x-ray facilities which could reveal the details of shaped charge penetration into metal, and high-speed cameras used to record the details of explosive-material coupling in transparent materials. Not to be overlooked, of course, was the availability of the BRL computers which, again, allowed theoreticians to analyze and predict the effects of varying the parameters controlling shape charge performance.

The Laboratories' competence and productivity were enhanced under the direction of Dr. R. J. Eichelberger, (later to become Director of BRL) who joined the staff of the Terminal Ballistics Laboratory in 1956. Although only in his mid-thirties at the time, Dr. Eichelberger had been a pioneer in shaped charge research and even then was an internationally respected scientist. He was not a stranger to BRL since as a contractor representative, at the Carnegie Institute, he had worked closely with BRL for many years.

Around the same time, in approaching the design of shaped charges, the US policy changed somewhat from previous years. The criteria for evaluation of warheads, in order of importance, became effectiveness, efficiency, mass producibility, and cost.

Effectiveness was defined as the probability of achieving a "kill" with a single shot. Kill probability was weighted far more heavily than depth of penetration, and in some cases, depth of penetration was deliberately sacrificed in favor of an increase in lethal effects.

Efficiency meant minimum weight for a given effect. It was particularly important in warhead design because attempts to increase efficiency by reducing weight closely correlate with increases in variability of performance.

The mass producibility of shaped charge warheads, with few exceptions, was a major consideration; it influenced the choice of components for a warhead; and in many cases prohibited the use of design features which were in theory and in laboratory practice, able to provide considerable increases in either overall performance or efficiency of design.

The last criterion, low cost, had the lowest priority (although it was not ignored) because usually the cost of the missiles and shells was generally so much greater than the cost of the warhead itself. Thus, it was not likely that variations in the cost of the warhead components would materially affect the total cost of the weapon.

These criteria governed the course of shaped charge research at BRL. Since effectiveness was the highest priority, research concentrated on the factors which contributed to kill by shaped charges. Briefly these included the residual jet (the slender, generally fastest moving part of a shaped charge after collapse), the spall (metal fragments) from the inner side of the armor, "bonus effects" (such as heat, pressure, and light, particularly in aluminum armors), and supplementary (follow-through) devices. Of the four factors, the first two were the subject of continuing research; the "bonus effects" were measured but not considered to be particularly important; and the last, subject to little research since there was no demand in the United States for shaped charge weapons with supplementary devices.

The Development of Shaped Charge Theory. As noted above, by 1960 the various aspects of shaped charge theory had been combined into computer codes useful for prediction of warhead performance. These machine codes (copies of which had been transferred to Picatinny Arsenal for use in weapon design) conveniently and quickly gave the detailed description of all characteristics of the jet and its effects on a target. To be sure, there were some restrictions on the use of the codes; the calculations represented performance predictions for theoretically "perfect" shaped charges and the influences of manufacturing imperfections had to be deduced from experience. Moreover, since the effects of heavy confinement upon the partitioning of energy of detonation were not considered, precise calculations could be made only for uncased or lightly cased warheads. While the effects of confinement were well understood from experiment and the theoretical means for considering those effects were available, the necessary refinements to the codes had not been made.

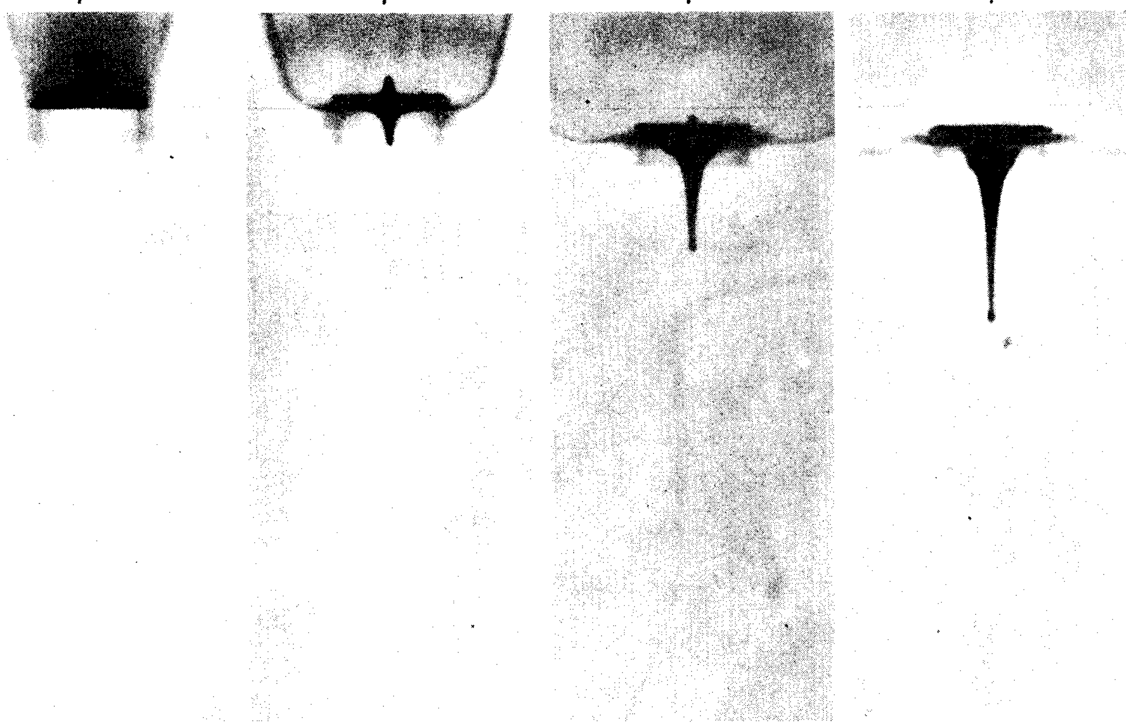
Nevertheless the computational scheme could be used to compare the effectiveness of various shaped charged designs and to arrive at a decision as to the best design for a given purpose. Most importantly, the codes permitted consideration of the effect of any arbitrary change in shaped charge design.

To provide a frame of reference for the following discussions, the computational scheme is described briefly. The machine codes consisted of a number of essentially different theories combined to describe the performance of a shaped charge. The various aspects of the problem which had to be taken into account separately were:

- the interaction between the detonating high explosive and the shaped charge liner—leading to a description of liner collapse,
- the formation of the jet by the collapsing liner—leading to the detailed characteristics of the jet,
- the jet in flight—the initial ductile extension of the jet and its eventual breakup,
- the penetration by the jet—including a description of the hole profile as well as the depth of penetration, and
- the description of the spall produced behind the target face.

With varying degrees of emphasis, these aspects were all to be subjects for research into methods for refining predictive computer techniques.

The first significant modification to the theory occurred in 1962 when BRL scientists presumed



Collapse sequence of a shallow cone shaped charge

that the hydrodynamic equation used to predict penetration by continuous (non-particulated) jets could be extended to consider jets which break up into axial particles before the end of penetration. They presumed the equation held for each individual particle after jet breakup and that the contributions of each particle to penetration could be summed and added to the penetration value attributed to the continuous portion of the jet. The summation ended at a "minimum" jet particle velocity, known as the jet cut-off velocity, obtained experimentally for a given jet and target material. The cut-off velocity was defined to be the velocity of the last particle contributing to penetration. Experiments using radioactive tracers with unconfined 105-mm shaped charges confirmed that the resulting numerical values for penetration agreed with predicted values given by the modified theory.

Subsequently, other BRL workers discovered that the jet cut-off velocity was a function of the standoff distance between the charge and the target, as well as a function of the jet and target material. These functions led to equations which could be used to predict the total depth of penetration by a well-aligned jet into a target as a function of stand off distances.

About five years later, in 1968, BRL found that an increase in the hardness of a steel target resulted in an increase in the jet cut-off velocity, hence a reduction in effective jet length and consequent target penetration. This was an important finding because previous comparisons of penetration depth by a shaped charge into, for example, two different target materials considered only the densities of the targets involved. This "density law" was modified to take into account an additional variable, the hardness of the target. An increase in target strength or hardness decreased the target hole profile, thus limiting the length of jet effective in penetration. This finding led to the conclusion that an effective lightweight material for protection against shaped charges should have low density, high hardness, and resistance to shattering as impact occurs.

Experimental evidence showed that high strength aluminum, when used for protection against shaped charge warheads, was much more efficient on a weight basis than high strength steel. Radiographic analysis of jet penetration showed that the phenomenology of sequential penetration by discrete jet elements differed markedly from that of penetration by a continuous jet. An important conclusion from this work was that the phenomena of penetration by a particulate jet precluded use of the simple expedient, constant "cut-off velocity" previously used to determine total penetration.

The cutoff phenomena continued to be of interest and in 1969 the cutoff in shaped charge penetration was shown to be dependent on the charge to target standoff distance; the theoretical-empirical relationships were confirmed as was the validity of application of the cutoff velocity concept for the termination of shaped charge penetration to targets of various hardness and density. While the investigation into jet cutoff velocity and the effects of target hardness and so forth were being investigated, BRL continued to examine the nature of the jet, in particular, the causes of jet breakup. Rotational degradation of shaped charges had long been known qualitatively and BRL scientists had been investigating causes and cures for this condition since the 1950s. Experimental evidence in 1968 showed that a shaped charge jet had an earlier breakup time when the round had a rotational velocity; thus it was concluded that a substantial portion of the penetration degradation of a rotating shaped charge could be attributed to the shorter breakup time. The in-house efforts by BRL were aided by contract work supported by the Laboratories. The results of one such contract with the Dyna-East Corporation in 1975, was a one-dimensional theory combining a set of formulas that could be used to predict the longitudinal strain in the jet and the radius of the jet. It was considered evident that the breakup is, at least in part related to the stretching and thinning-out of the jet.

The result of the new model was a formula for strain as a function of the original position of the jet material on the liner. The importance of the strain formula for the jet was that the stretching of the jet was related analytically to the parameters which govern the collapse of the liner and the formation of the jet. Similarly, a formula was obtained to express the jet radius as a function of the axial position at the liner. Calculations using the formula showed reasonable agreement with experimental measurements.

During the same period, BRL researchers were estimating the strength of the copper material in a jet from a typical shaped charge to determine if the deformation of a stretching continuous jet is sensitive to the strength characteristics of the material. The results of the calculations indicated that the strength of the jet material plays a major role in controlling the dynamic "necking" process which occurs before breakup of a stretching jet.

The investigators took a series of sequential flash x-rays of jets from shaped charges which were initially spinning about their axis. The data indicated that below a certain rotation rate, no effects caused by rotation were observable. However, above that rotation rate, radial fragmentation of the jet was clearly evident. The breakup was caused by high centrifugal forces acting on the spinning jet material. Since no radial breakup occurred below a certain initial rotation rate, the conclusion was that the jet material has sufficient strength to balance the centrifugal force. The experiments gave quantitative data for estimation of jet flow strength. These estimated values proved to be consistent with predicted values given by the calculations.

Since shaped charge jets are often required to penetrate one or more thicknesses of material before reaching the main target body, it was important that BRL develop a reliable theory for the residual penetration achievable by ideal shaped charges. Each perforation consumes jet material from the higher velocity region (or forward portion) of the jet so that the residual jet left available for the main target body will have a lower tip velocity than the initial jet. The material to be perforated could be, for example, skirting plates separated from each other and the target by air spaces. The residual penetration is affected greatly by the first standoff distance to the initial skirting plate, the air space between plates and the main target, as well as the more obvious factors of skirting plate thickness and density. BRL experimental work in 1966 showed that less of the rear portion of a jet is effective in penetration as the standoff distance is increased. For mathematical development of the experimental observations, the residual penetration capability of an ideal jet at any standoff was derived. Approximations of this residual jet theory applied to shaped charge jets whose experimental penetration standoff curves were known, provided predictions which agreed more closely with experimental results than did predictions based on the Fireman-Pugh Theory which had been used for the preceding twenty years.

However, it was pointed out, that even for precision manufactured shaped charges the actual performance would be less than that of ideal shape charges at high standoffs due to the effects of air on the jet particles during flight (jet particle retardation, wavering, tumbling, ablation, and so forth). The residual jet theory was refined by BRL again in 1972; however, the results are not yet available to the public.

When a shaped charge design is established, it becomes necessary to have some reasonable estimate of effectiveness against armored targets before the development has progressed very far. Up until about 1959, it was generally necessary to fire prototypes of the warhead against a replica of the intended target, record and assess the damage inflicted and from observations estimate the probability of the actual target being rendered inoperative.

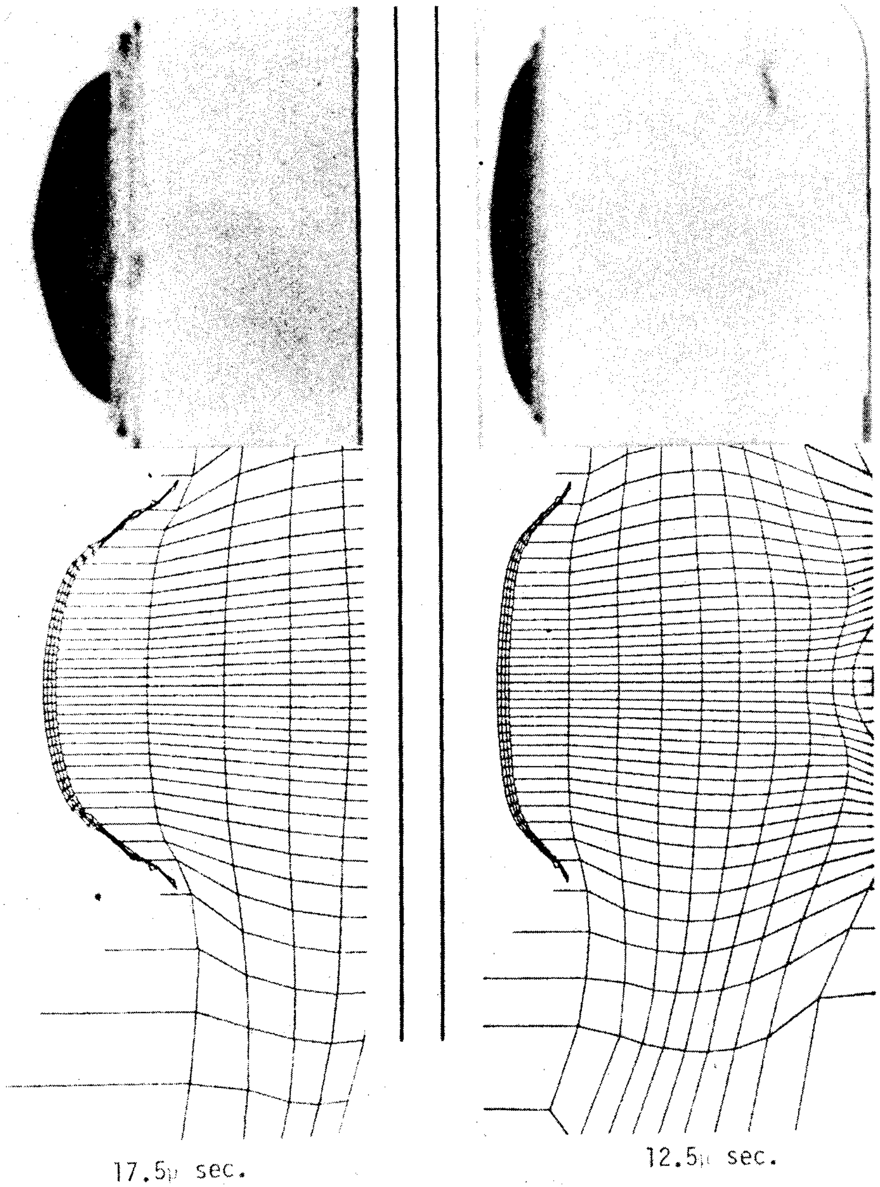
It had been recognized for some time that the particles spalled from the inner surface of a target were largely responsible for the damage inflicted by a perforating jet, and that the amount and nature of the spall depended upon the characteristics of the jet. Thus, if the degree of damage inflicted could be correlated with warhead design features, penetration parameters of a shaped charge round, and target spall, the evaluation of effectiveness could be done without field tests against proposed targets. The result would be economical expedition of development programs. BRL work had shown the relations between mass, velocity and spatial distribution of the spall, and the parameters of the jet. Analysis showed that the number of useful spall fragments produced was directly proportional to the rate of transfer of energy from the jet to the target near the exit point. This was a substantial step towards the goal of eliminating experimental evaluation to a substantial degree by substituting fundamental data for vulnerability tests against a target. (The goal would be reached in the 1970's with the development of point-burst vulnerability models such as SHUTE and AVVAM.)

The elementary results of 1959 were later refined in 1965; equations were then derived to predict the number of spall fragments that would be produced by a shaped charge jet that perforated a target of any thickness at any standoff distance.

By the beginning of the 1970's the Laboratories had available a two-dimensional advanced Eulerian, hydrodynamic code for predicting shaped charge performance. Known as the Ballistic Research Laboratories Shaped Charge (BRLSC) code, the program was extremely useful in providing insight into the material flow associated with liner collapse and jet formation. The BRLSC solutions also could aid designers in their efforts to optimize jet characteristics.

As this era in BRL history was drawing to a close, BRL was attempting to apply the HEMP code to the simulation of shaped charge warhead performance. The HEMP computer code, a finite-difference technique, was developed by the Lawrence Livermore Laboratory to solve problems involving two-dimensional, unsteady motion.

For shaped charges with relatively wide angles, the code can accommodate the liner deformation, reasonably well in the initial stages of formation. These calculations can provide the velocity of the jet tip, but the deformation cannot be followed far enough in time to provide a complete description of the jet. For conventional shaped charges, the calculations cannot directly predict the jet formation; however, with slight modifications in the jet formation region, a collapse velocity distribution can be calculated. The standard jet formation equations can then be used to convert these collapse velocities to jet properties. Good agreement exists between experimental data and calculated collapse velocities. However, because



Performance versus computer prediction

of the sensitivity of the jet velocity distribution to the collapse velocity distribution, the predicted jet velocity distribution is not accurate. Therefore, this prediction technique was not considered successful; a complete solution was believed to be achievable with the use of an Eulerian code.

Spin Compensation. Rotation seriously degrades the penetration capability of a shaped charge carried in a spin stabilized projectile. The degradation is a consequence of the conservation of momentum in the metal liner during the process of liner collapse and jet formation. Resulting centrifugal forces tend to spread the jet and dissipate its energy over a larger area, thus reducing the depth of penetration. As noted above, around the mid-50's, BRL began to emphasize research into techniques to compensate for spin.

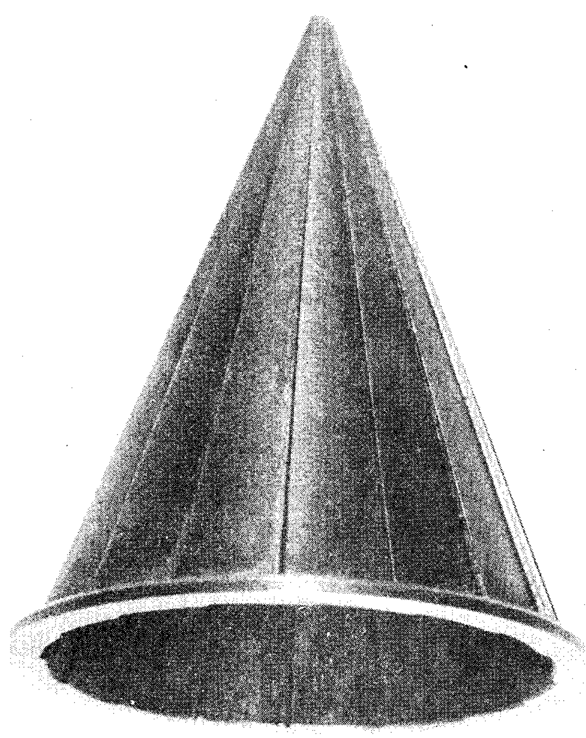
The discovery through experiments by the Firestone Tire and Rubber Company of "built-in" metallurgical spin compensation in shear-formed copper liners led to the use of rotary extruded liners. The extrusion process resulted in spin compensation which minimized the effects of rotation, but was effective only at low spin-rates. Later experiments at Firestone indicated that the optimum spin compensation frequency (the rotational frequency for which the best penetration performance of the round is obtained) depended upon manufacturing parameters. Firestone reported that the distortion angle measuring metal displacement depended on the conditions of liner manufacture and that the optimum spin-rate varied linearly with that angle.

Thus in 1958, in a joint effort with Picatinny Arsenal, the Laboratories carried out experiments with rotary extruded shaped charge liners to determine the effect of precisely controlled manufacturing parameters on the "built-in" metallurgical compensation effect, and to determine the highest compensation frequency that could be attained with the rotary extrusion technique. Results of the experiments indicated that liners manufactured by the rotary extrusion process could be compensated for rotation effects up to frequencies of 45 rps. It was concluded that the possibility of attaining higher optimum spin-rates by the extrusion process was not promising and that other techniques should be considered.

It was known that spin compensation could be achieved by diverting a very small portion of the explosive charge to produce a tangential component in the vector representing the velocity with which each element of the metal liner approaches the axis of symmetry. If the average value of this component of the collapse velocity could be made equal to the tangential velocity due to the initial round rotation, the liner would collapse as though it had no initial rotation and produce a well-formed coherent jet.

The "fluted" liner appeared to offer promise for practical application of the tangential velocity concept. A fluted liner is made by forming asymmetric serrations in an ordinary metal liner. Many design parameters enter into the applications of fluted liners; while the effects of variations in the parameters could be predicted qualitatively from theory, BRL (and others) found exhaustive experimental data necessary to provide the essential quantitative correlations. By 1957 BRL had derived satisfactory spin compensation liners for 57-mm and 75-mm rounds spinning at the service rates of 210 rps and 180 rps, respectively.

These early "orthodox" fluted liners were manufactured in a process using mated metal dies in which the flute depth increased linearly from the cone apex to the base. While the linear flute technique did not completely compensate for any one specific optimum rotational frequency, it was used to design shaped charges ranging from 20-mm (800 rps spin rate) and 40-mm (60 rps) to the 152-mm (105 rps) shell then



Fluted shaped charge liner

contemplated for use in the main battle tank armament system.

In experiments designed to provide higher compensation frequencies and to reduce the dispersion in optimum spin rate produced by orthodox liners, BRL researchers pointed out that those goals could be achieved by means of non-linear flutes. The non-linearity referred to the relationship between the flute depth and liner radius. The experiments also provided the quantitative data needed for the design of non-linear flutes and the machine needed to cut the flutes. The results of these experiments which had been conducted in 1959 and 1960 were confirmed by similar but more precise experiments in 1963. Also at this time, BRL scientists reviewed the history of spiral fluted conical liners which had been proposed to spin compensate shaped charges. Early use of spiral liners (first reported by the Explosives Research Laboratory, Bruceton, Pa. in 1945) had been unpromising so little work had been done on them for nearly twenty years. It was concluded that properly designed spiral liners could add to the compensating tendencies of special manufactured liners and that a sine-wave spiraled liner also showed promise.

Explosives Research. To describe the interaction between the detonating high explosive and the shaped charge liner, BRL had developed a unique phenomenological treatment. The treatment started with a mathematical description of the rarefaction produced within the detonating explosive, as a function of the boundary conditions of the charge, and used one-dimensional theory of characteristics and the experimentally-known properties of the high explosive. The approach gave a complete and detailed description of the collapse of the shaped charge liner and was incorporated into the shaped charge computer code.

At the end of the 1950's, the effects of explosive composition, in particular the free energy evolved during detonation, had been well-understood for some time. Since jet energy is proportional to the energy of detonation, or to detonation pressure, total hole volume produced by a shaped charge could be correlated with detonation pressure or energy. That meant that the lethal effectiveness of a particular design would increase if a higher energy explosive is used. So far as the depth of penetration was concerned, there was no such simple relation discernible. However, it was known that whether or not penetration increased, the hole volume would; so, there was always a benefit to be gained by using a higher energy explosive.

Nevertheless, confirmations of predicted performance, refinements and subsequent modifications to the computer codes made it necessary to carry out additional experiments in research on explosives for shaped charges.

The collapse-velocity function for a shaped charge liner was one of the specifications needed as input to the computer code. Until 1962, the only collapse function known was for one charge, the 105-mm Composition B, unconfined test charge used at the Laboratories. The liner collapse-velocity curve of a Composition B charge was modified to permit calculations of penetration and hole profile for charges having the same configuration but loaded with Octol and TNT explosives. The computed values agreed favorably with experimental observations made subsequently. The success of these calculations opened the way for many interesting and useful calculations relative to shaped charges.

In an attempt to improve the quality of the explosives used in shaped charges and thereby decrease the variability in their performance, the Laboratories investigated the possibility of using pressed powdered explosives. Plastic-bonded, powdered explosive (PBX) appeared to offer two advantages; it contains more than 90 percent of the higher energy HMX or RDX explosives, and it is extremely homogeneous. Moreover the homogeneity is not disturbed in the pressing or forming process. Cast explosives usually used to fill shaped charge rounds settle and become less homogeneous when melted, agitated and later cast into a mold as part of the charge manufacturing procedure.

The results of the work demonstrated that despite apparent advantages, PBX pressed cavity charges were not acceptable. In forming the cavity of a shaped charge liner, precise alignment of the central axis of the cavity with the axis of symmetry of the charge must be maintained. The pressed cavity charges did not hold tolerances as well as the cast charges and there were air gaps at the core apex as well as difficulties in inserting the liner into the explosive.

Around 1969–1970, influenced to a large degree by the demands of the Vietnam conflict, a somewhat more ambitious program was undertaken to determine the influences of explosive fill on shaped charge warhead performance. Ten different explosive fills were evaluated on the basis of fundamental jet properties and penetration performance. To minimize variations caused by hardware or explosive loading, only high quality metal components and explosives meeting rigid loading specifications were used. Multiple flash-radiographs of the jet free flight and the penetration process were used to evaluate the performance. Also, the BRL Analytic Shaped Charge (BASC) Code was used extensively to interpret the data.

Two conclusions followed: warhead performance improved with increasing explosive energy, and jet elongation increased with explosive energy. The second conclusion implied that the greater the explosive energy, the larger the proportion of the liner that ultimately becomes penetrating jet. The effects produced by the more energetic explosives combined to form longer, more massive, and higher energy jets. There were also indications that jet ductility increased. It was also concluded that increasing confinement could provide the same effect as a more energetic fill. Thus confinement or added explosive energy could be used to increase the kinetic energy of the jet.

All of these conclusions were supported and confirmed in an analytical study performed by a BRL contractor, Systems Science, and Software, in 1975. They used numerical techniques to analyze performance of six shaped charge configurations. The results were obtained using an improved version of the BASC code. (Based on the HELP, Hydrodynamic Elastic Plastic Code).

Although by 1976 shaped charge theory and analytic prediction codes were in excellent shape, there were a few unknowns remaining. Shaped charges had always shown large round-to-round variations in penetration performance and frequently had shown large lot-to-lot variations as well. These variations have been attributed to asymmetries in the explosive loading, the metal parts, or the initiation point. The situation with Octol was particularly interesting since it was often claimed that the long standoff performance of Octol-filled shaped charges, despite the higher energy available, fell below that of TNT-filled warheads. Since voids (empty spaces) in the explosive could be the possible source for both types of variations in Octol-loaded rounds, BRL analyzed the performance of void-free shaped charges. Curiously, the average long standoff performance of the void-free Octol-filled round improved remarkably (and as expected, exceeded that of TNT-filled rounds), but the round-to-round variation in performance increased. This behavior would be the subject of future investigations.

Materials Research. Essentially, there are five properties governing the performance of shaped charge liners: ductility, density, compressibility, purity and metallurgical structure and pyrophoricity.

Of those properties, ductility was the most important; in the shaped charge jet, most materials elongate much more than they do in the standard tensile strength tests designed to measure ductility. However, ductility greater than that obtainable from copper could not be exploited because of the unusually long standoff distance needed. This seemed to rule out the use of materials such as eutectic alloys, at least temporarily.

High density was a desirable characteristic so far as penetration was concerned; however, high density materials usually have a low sound velocity so that they were usable only in a few configurations to ensure jet formation.

There was little or no interest at BRL after 1960 in further research into the remaining properties.

The high ductility characteristics of lead-tin eutectic alloy were being examined for possible use in US Army warheads by BRL in 1970. To produce a high density alloy with superior ductility for warhead applications, in 1972 BRL proposed to press, then sinter samples of various mixtures of lead, tin, and tungsten powder and lead-tin eutectic alloy. Subsequent thermomechanical processing would generate high ductility in the lead-tin phases of the alloy system which would act as a ductile matrix for the dense tungsten particles. A theoretical analysis of the distribution of tungsten particle size and particle spacing relative to the surface tension of the continuous portion of the jet was conducted to ensure that, under shock loading, the high density particles would not develop dynamic segregation and become uninvolved in the ballistic process. (Some success had been obtained at BRL using lead-antimony alloys. However, the performance of the alloys was erratic and consistently high penetration was not achieved.)

Results obtained from examining the microstructure and mechanical properties of the lead-tin alloy led to a postulate that, for an alloy to be "superductile" at high strain rates, a finely dispersed structure of micron-sized particles, randomly oriented was needed. A great deal of data supporting this postulate was obtained from x-ray orientation studies, ultrasonic and metallographic analysis, and cinemicrographic examination of the alloy during deformation tests.

BRL treated several different materials thermomechanically to put each into the required microstructural condition. Shaped charge liners were formed out of the materials and some liners from each material were fired to analyse penetration performance. Concurrently, laboratory tests were carried out to define the microstructure of the alloys. The results of the firing tests and the laboratory analyses showed that the materials which had the postulated microstructure required to give high ductility at the high strain rate gave excellent penetration. Alloys without the required microstructure performed poorly.

In a slightly different approach to improving the penetration performation, BRL performed experiments to evaluate the feasibility of using copper as the basic liner and electroplating a high density metal on the inner surface. Since the inner layer of the charge liner is the part that normally forms the jet during collapse, the substitution of a high density metal for the inner layer should generate a high density jet—providing that the normal collapse process was not disturbed or destroyed by the bi-metallic liner.

Standard copper liners with a thin layer of gold on the inner surface gave an increase in total penetration of about 50 percent over that expected from copper alone. The results agreed with the theoretical prediction and the experimental results showed that gold exhibited superductility under the ultra-high strain rates typical of the collapse and jet formation processes.

Exploitation reports from the US Foreign Science and Technology Center in 1971 showed that tin-plated copper liners were found in USSR rocket-assisted HEAT grenades. These warheads in the RPG-7 were used in large quantities in Vietnam. The conical copper liners were tin-plated on both the inner and outer surfaces. The question naturally arose as to what advantages the tin-plated copper liners might possess. The obvious answer was that tin-plating prevented corrosion of the liner; such corrosion could come from manual handling, interaction with the atmosphere, or interaction with the constitutents of the explosive filler.

BRL performed a test series with tin-platted cones prepared by hot-dipping and electroplating processes. However, the test results showed that except for possible improved corrosion resistance, tin-plated cones offered no improvement in performance.

EXPLOSIVES RESEARCH

There were two main purposes justifying the Ballistics Research Laboratories research in the chemical and physical fundamentals of initiation and detonation. The first of these was to clearly define those mechanisms for use in analytical hydrodynamic codes describing the explosive/metal coupling in shaped charges and fragmenting munitions. The second was to apply the resulting knowledge of the chemistry and physics of the phenomena to new explosives or to the improvement in the performance of current explosives. While the former mainly served BRL in-house interests, the latter was part of an inter-agency program, "Explosives Research and Detonation Physics," between BRL and the Picatinny Arsenal (after the formation of the Army Material Command, the US Army Munitions Command and the lead laboratory for Explosives Research).

A summary, in 1959, of the work done over the past several years on the initiation of high explosives by pressure waves transmitted across air gaps or metal barriers had led to a model of the phenomenon. While the details of behavior of shock waves responsible for "low-order" detonation which preceded "high-order" detonation were known to vary with the composition and geometry of the explosives, the qualitative features of the theory appeared to be valid.

The following year, an accumulation of quantitative observations of low-order detonation provided a complete picture of the velocity distribution at a low-order reaction front. The shape of the reaction front changed continually, becoming more drastically curved as it proceeded down the charge, until the low-order detonation underwent the transition to high-order detonation or degraded into a non-reacting shock. This understanding of the velocity of the propagation of the reaction zone, necessary for rigid description of the hydrodynamic processes, was complemented by the development of a technique that could measure directly the transport velocity of the ionized particles behind the detonation wave. Results obtained by the technique agreed closely with the theoretical calculations of particle velocity predicted by the classical hydrodynamic theory of detonation.

These velocity measurements of the chemically-supported shock wave as it built to steady-state detonation were supported in 1963 when a technique for measuring the pressure at the shock front was developed. Measurements of that additional hydrodynamic variable, together with the conservation laws for mass and momentum permitted a complete description of the propagation wave in an explosive, in particular for Composition B.

Inadequacies in the various predictive models for detonation behavior continued to exist, however, and demanded that a more thorough understanding of the detonation process be obtained. Consequently, during 1964–1965 a new program on explosives was initiated. The objective was to provide thermodynamic and chemical kinetics data which could be combined with the existing hydrodynamic codes describing detonation.

By the early 1970's, BRL researchers (and others) using shock tubes to study the detonation processes in gases had shown that, in contradiction to the existing detonation models, detonation is a multi-dimensional, non-steady process with inherent oscillatory instability. The researchers then undertook to extend the findings of the gas phase research to the region of military interest, i.e., to the condensed phase of cast and pressed solid explosives such as TNT, Composition B and others.

The results of the extension were remarkably significant. The researchers found that, despite the extremely different physical conditions that exist in the detonation of solid military explosives, nearly all of the gas phase phenomenology could be extended to solids. Strong experimental evidence supported the theoretical conclusion that detonation proceeded via inherent oscillatory instability which generated transverse shocks.

While much of this work considered macroscopic processes explainable in terms of continuum mechanics, BRL was also busy in constructing microscopic models which would predict events in the observable regime. One example was the research into ignition energy transfer in crystals. An understanding of the mechanisms whereby lattice vibrational energy is transferred into the internal freedoms of molecules of organic explosives could explain how chemical reactions could be initiated. Coupling that knowledge to the other steps leading to detonation (and combustion in propellants) would provide designers with the capability to predict the intrinsic sensitivity of the materials. It would also provide information on the essential physical and chemical properties needed by the organic compounds useful as explosives (or propellants). BRL was successful in developing a theoretical model, supported by experiments, to predict the energy transfer processes in organic crystals.

Aside from the need to understand the process by which shock waves initiated reaction and build-up to detonation in high explosives for fundamental purposes, there was the need to know the parameters controlling the vulnerability of ammunition to hostile fire. It was known for a given explosive composition, that physically heterogeneous forms would undergo a more rapid transition to detonation than homogeneous forms. They would also sustain detonation in smaller diameter charges. This suggested to BRL scientists that, at the same pressure level, the heterogeneous form had a higher energy release rate, believed to be a function of the internal surface area associated with discontinuities within the charge. To test this hypothesis, BRL physicists attempted to relate the energy release rate to the shock wave acceleration in pressed TNT charges of known density and specific interval surface area. As of 1976, the results of experiments were inconclusive.

ARMOR

The Ballistic Research Laboratories have had a long history of research into effective countermeasures against shaped charge and kinetic energy rounds that an enemy could use against US armored tanks and other vehicles. As mentioned above, this interest included research into active, reactive, and passive armors. In the 1960's and 1970's, the Laboratories became even more heavily and directly involved in research and development of armor. Efforts in the 1960's were directed towards applications to the post-1965 main battle tank, the MBT 70 and its follow-on the XM803. During the 1970's, most of BRL's armor research was directed toward the design and development of the armor for the M1 Abrams Tank; the development of this armor was a matter of considerable significance to contemporary main battle tank development.

While the exact composition of the M1 armor is not available for public disclosure, suffice it to say that the armor gives a unprecedented amount of protection against antitank rounds; both kinetic energy and shaped charge types. It is considered to be invulnerable to all USSR shaped charges.

Active Armors. Active armor, in general, refers to a protective system capable of detecting an incoming projectile, then defeating it by means of an explosive. One of the most sophisticated of these systems, code-named Dash-Dot was developed primarily by the Harry Diamond Laboratory in the early 1950's. The system used a sensing device to acquire and track the incoming projectile; a computer to accept the ballistic information and to predict the expected impact region; and an appropriately-located linear shaped charge timed to detonate so that its fragments would intercept the projectile and destroy it. One of the major problems involved in the use of explosives in an active armor is the proper timing and triggering of the detonation. Active armor, such as the Dash-Dot system attempted to solve that problem through advanced electronics. Since prospective users were not enthusiastic about the concept and because of engineering difficulties, the idea was abandoned in the later 1950's. However, the apparent promise of the concept prompted sporadic research at BRL throughout the 1960's and 1970's.

The next investigation of active armor occurred in 1970 when BRL made an analysis of the accuracy required to predict the position of an incoming projectile. It was concluded that of several sensor systems considered, a 35 GHz pulsed radar system was the only one that could meet the requirements. This work was followed in 1973 by a proposal to use the radar detection scheme and a shaped charge array on the armor to cause asymmetric initiation of the explosive in the incoming HEAT round. The shaped charge array would be aimed electro-mechanically after impact but before the formation of the jet from the collapsed metal liner in the incoming round.

Reactive Armors. The term refers to an armor array which uses reactive material, such as high explosives, to defeat a penetrator or shaped charge warhead. The reactive material is usually detonated by shock waves generated by the impact of the munition on the armor. In mid-1956, BRL reported test results from two experimental composite armor arrangements: glass armor (discussed more fully under Passive Armor, below) and glass-explosive armor attacked by representative kinetic energy projectiles. These particular armors had been selected for testing because they had been found previously to possess some merit in defeating the chemical energy HEAT and HEP projectiles. Neither armor had been designed specifically to protect against kinetic energy projectiles and little was known as to what to expect. The criterion selected, rather primitive by today's standards, was the "Army Ballistic Limit;" perforation was considered to be achieved when light could be seen through the armor plate. The glass armor plate consisted of a three-inch thick glass block positioned between a one-inch thick rolled homogeneous armor (RHA) face plate and a two-inch thick RHA base plate. The glass was separated from each plate by one-quarter inch thick felt. The glass-explosive armor array was similar except for a dome cast into the glass block. A pentolite charge was inserted into the cavity.

Rounds fired against the target were 90-mm AP, 90-mm High Velocity AP and caliber .50 AP. The standard for comparison was round performance against four-inch thick rolled homogeneous armor. The results of the test led to the conclusion that the arrays did not show any marked advantage over solid steel of equivalent weight.

The search for an effective armor against shaped charge warheads led in 1957 to "spacive" armor, a combination of spaced armor and explosive armor. In this BRL concept, cast homogeneous armor plates had closely spaced cavities which contained embedded explosive covered by mild steel plates. The armor showed considerably greater resistance per unit of weight than any armor found previously. Spacive armor was considered an expedient, useful as an armor-applique should events dictate additional HEAT protection before more suitable approaches could be developed.

In 1976, the last year which this history covers, a concept for a "reactive" armor was proposed. The system differed from the "active" system because an elaborate sensing system was not required, and also, there was no attempt to destroy the oncoming projectile before it struck the armor. Reliance was to be upon a "tipping" concept which would be effective for both shaped charges and kinetic energy rounds. It would be particularly effective against long-rod penetrators which could be seriously affected by high yaw at impact.

Passive Armor. It has been known for many years that laminated armor arrangements with one or more air spaces between layers sometimes showed greater resistance to penetration than did a solid armor of equivalent weight. However, since the opposite effect sometimes obtained and the fundamentals causing variations in performance were not understood, such armor arrangements were little used. Some tests had shown that spaced armors could defeat HEP projectiles and cause degraded performance by tungsten carbide kinetic energy projectiles. In 1958, controversy existed as to whether spaced armor was effective against shaped charge rounds. Conclusions derived from the results of one series of tests indicated that spaced armors were of litttle value and, possibly, were not as good as conventional armor. Other researchers however reached the opposite conclusions. Consequently, BRL designed tests to determine the effects of a simple spaced armor design on statically-fired shaped charge rounds by systemically varying some of the geometric parameters. The conclusions were that there was a finite reduction in penetration attributable to the spaced configuration, independent of the amount of space or thickness of the faceplate; there was a strong variation in penetration, dependent on the air space and the standoff distance of the shaped charge; and, there was also a weak variation, with the thickness of the armor tending to reduce the effects caused by the spaced armor array.

Vulnerability analyses, made in the latter part of the 1950's, of armored vehicles to tactical nuclear weapons showed that the personnel hazard, for which the effective range of the weapon is greatest, is the nuclear radiation produced by the detonation. Field tests had shown that current tank armor did not give optimum radiation shielding per unit weight. However, the data were inadequate as a basis for design of better shields. Therefore, through an interagency agreement in 1960 the Oak Ridge National Laboratory (ORNL) assisted the Ballistic Research Laboratories in determining the factors to be considered in the design of shields for tanks, as well as their relative importance, and developing optimum shields with simple geometric configuration.

Experimental results were obtained for neutron-associated accumulated radiation dose behind laminated slab shields composed of armor steel and various sheilding materials such as polyethylene, lead, depleted uranium and Boral. An analysis of these results, with theoretical studies of the gamma-ray attenuation of the shields, permitted development of an optimization procedure. The procedure allowed prediction of the laminated shield having least weight which would reduce the free-field dosage to a specified level behind the shield. Among the conclusions derived from this ORNL and BRL effort were: as much of the armor steel should be placed on the inside of the shield as ballistics considerations allowed, and approximately one foot of polyethylene was sufficient to reduce the fast neutron dose to negligible proportions compared to the gamma-ray dose.

The same year, the Ordnance Tank and Automotive Command asked the Laboratories to evaluate the protection provided by a special radiological armor against the 105-mm shaped charge round. The armor consisted of one-inch steel armor face plate, twelve inches of polyethylene shield, and four-inch thick steel armor back plate. The angle of attack by the round was sixty degrees. Initially, the protection offered by the armor array was calculated by using the residual penetration theory of Pugh and Fireman; later, the calculations were checked by experiment. The results showed that with a 105-mm shaped charge of a quality comparable to the laboratory charges, the armor would provide protection more than 99 percent of the time. However, if high quality charges were used, they would defeat the armor.

In addition to looking for armors that would prevent penetration by shaped charges, BRL researchers were interested in finding techniques that would suppress the spall fragments that were produced as a result of penetration. Any substantial reduction in the number of effective spall fragments, as well as in the cone angle of fragment dispersion, should reduce the level of damage within the vehicle crew area. The results of preliminary tests at BRL had shown that one-inch thick molded polyethylene in firm contact with the rear surface of armor would reduce the number of fragments. Subsequently in 1961, a more comprehensive test was carried out to evaluate the protection offered by the polyethylene technique.

The results led to the conclusion that one-inch thick polyethylene behind armor plate attacked by a shaped charge reduced the number of effective spall fragments appreciatively; however, the relative effectiveness of the layer decreased with increasing hole diameter. On the other hand, increasing the thickness of the polyethylene provided protection over a greater range of profile hole diameters. The protective mechanism was identified as one wherein the polyethylene absorbed spall particle energy rather than inhibiting spall formation.

Although further vulnerability analysis showed that there was apparently small benefit to be gained in terms of reduced probability of kill, a fragment controlling liner in a tank might be of considerable advantage in protecting personnel, particularly in lightly-armored personnel carriers. Since the proposed future heavy tank being considered for development in the mid-60's was expected to have three inches of polyethylene for radiological protection, the spall controlling capability of the polyethylene could be considered a bonus.

Glass had been shown to be very effective in degrading the penetration performance of a shaped charge jet. A material reaction phenomenon, known as the "Rebound Theory", attributed to glass was first postulated by R. V. Heine-Geldern. To explain the mechanism of the stopping power of glass against the jet, the theory proposes that the glass material, after suffering an initial deformation, rebounds elastically in a radial direction against the incoming jet. Thereby, the jet is disrupted, portions of the jet are destroyed and individual portions remaining are forced out of alignment. The disturbance to the jet caused by the steel-glass-steel arrangement has been observed conclusively in flash radiography at BRL (Post-1976 research at BRL has altered the theory substantially.)

The Laboratories' interest in ceramic armor appliques for defense against shaped charges was rekindled in 1967 to counteract the 57-mm and 75-mm HEAT rounds being used against US materiel in Vietnam. Exploratory diagnostic tests at BRL suggested that boron carbide armor (then being used in lightweight armors) had a potential to defeat shaped charges. The studies showed that boron carbide behaved like glass under similar test conditions.

The US Army Materials Research Agency (AMRA) supplied boron carbide blocks to the Laboratories for further expermients to verify the effectiveness of the material against shaped charges. The results of the BRL investigations showed that boron carbide ceramic used in a composite armor provided great resistance to penetration by shaped charges. It was found that the boron carbide material had the stopping power equivalent to a material having a density of 15.2 grams per cubic centimeter (six times its actual density of 2.5 gm/cc). The use of boron carbide composite armor to provide a given amount of protection would reduce the overall weight of the armor required to 59 percent of that of an equivalent all-steel armor.

Some five years later BRL investigated the effect of density variations in solid (low compressibility) targets on shaped charge penetration. The materials included copper, aluminum and its alloys, magnesium, steel, boron carbide and plastics. Shapes included rods, cones, plates, and random fragments embedded in low or high density matrices. Only one approach used rods smaller than the jet diameter (about 0.3 of the jet diameter) closely spaced so that the jet encountered a rod, regardless of the entry point.

Except for the case of rolled homogeneous armor, even as late as 1975, very little data existed on the performance of large kinetic energy penetrations against multi-armor plate. This situation was understandable in light of the large amount of resources that had gone into research into the effects of shaped charges. However, it was still necessary to provide protection against kinetic energy rounds without severe weight penalties. There was some evidence that multiple plate armors containing materials lighter than steel could provide adequate protection against kinetic energy rounds.

Thus, BRL carried some tests to provide data on the effectiveness of aluminum armor in stopping a high density (tungsten alloy) projectile and to justify or improve existing aluminum penetration equations. The penetrator from a round originally designed for the MBT70's 152-mm gun was chosen to be a representative projectile. In these tests, the projectile first passed through a rolled homogeneous armor before striking the aluminum armor. Analysis of results showed insufficient evidence to warrant modifying the constants of the penetration equations. It was found also that multiple target was capable of breaking the round; however, the manner of damage was not predictable. The overall conclusion was that considerable more information was required.

In a somewhat different aspect of armor research, BRL made a comparative analysis of the effectiveness of foreign and domestic armors against shaped charge attack. Aside from the intrinsic value of such an evaluation to the armor specialist, the information would be useful to vulnerability analysts. Component conditional kill probabilities (the probability of achieving a kill, given a hit) for particular set of terminal effects parameters are needed to compute the vulnerability of any given target. Much of the data used by the analyst comes from experiments. In the case of foreign armors, the armor must be obtained by cutting various sections of armor from captured vehicles, which obviously are difficult to obtain and expensive to transport. Should it be possible to substitute domestic armors with similar mechanical and metallurgical properties for foreign armors in tests, the problems of availability and cost would be solved.

To determine whether significant differences existed between foreign armor and comparable domestic armor, BRL subjected both types to tests with shaped charges. The results of the tests, using exit hole diameter and spall ring diameter as criteria, showed that no substantial differences existed in the response of foreign and domestic armor to shaped charge attack.

Research into Fracture and Spallation. As early as 1959 in this period of BRL's history there was considerable research devoted to identifying and quantifying the response of armor materials to shock loading. In that year, for example, investigations of the effects of intense stress pulses upon the structural properties of metals had clarified many of the conflicting conclusions reported in scientific literature and brought to light previously unreported phenomena. Among the most interesting results were those obtained from studies of very intense stress pulses (extending into the megabar range) upon iron alloys. It was found that wholly reversible polymorphic transformations occurred when the stress intensity was between the threshold value and several hundred kilobars. At higher intensities, irreversible transformations occurred. It was also observed that interstitial atoms in alloys tended to be carried along by the stress wave, resulting in rather extensive inhomogeneties in the material.

Observations of impulsively loaded single-crystal metal specimens demonstrated that, even at very high stress levels (several hundred kilobars) a purely hydrodynamic description was not valid to describe the deformation of an isotropic material. Deformation occurred preferentially along, the same crystallographic planes that predominate in static loading. This conclusion was confirmed about a year later, even for the case of very short stress waves. Concurrent studies were made of the relation between the plastic deformation and the fracture produced by intense stress waves and the time interval between the occurrence of the two phenomena. Photomicrographs of explosively loaded copper single-crystals with a fracture showed that deformation systems on either side of the fracture surface were completely different in orientation, implying that deformation took place after the fracture rather than before. The conclusion was that the major deformation occurred as a result of reflected tension waves rather than during the initial compression wave. However, similar observations on iron single-crystals showed that the deformation bands were continuous across fracture surfaces, leading to the conclusion that in iron the major plastic deformation occurs during the initial compression wave. The following year, experiments with single-crystal and polycrystalline copper specimens, explosively loaded, showed that material does not fracture instantaneously, but there are finite times associated with the formation and propagation of cracks. The fractures leading to spallation were caused by tensile stress waves produced when a compressive stress was reflected from a free surface.

Since it has been determined that the time to failure of a material should depend upon the stress time profiles of compressive waves within the material, behavior such as phase transitions, stress relaxation, strain hardening, and unloading effects all became subjects for investigation and consideration in precise, quantitative predictions of tensile failure. The first step by BRL scientists was the study of phase transitions in ferrous alloy armors. This began in the early 1970's.

In the meantime, however, experiments to determine the magnitude of the effects of armor microstructure on penetration had been carried out. Shaped charges had been fired into steel, steel armor, and white cast iron. The results proved that target microstructure was a significant variable in the penetration process; differences attributed to microstructure could be distinguished after only 50 microseconds of penetration. Moreover, these differences had a cumulative effect during penetration such that total penetration differed markedly, as much as 25 percent. Strain mechanism and crack initiation were different for the various micro-constituents and were accordingly presumed to be different for each metal target. The fracture symmetry and strain produced in the steel was a function of the direction in which armor plate passed through steel mill rollers during production.

With respect to the last conclusion, it was found that degraded performance shown by some rolled homogeneous armor plate (RHA-2) was due to the presence of slag inclusions. These inclusions had been redistributed during the rolling process, developing planes of weakness in the plate. Consequently, it was no longer considered that hardness specification would be adequate to ensure good or even consistent performance of armor plate. Armor specialists at BRL recommended that inspection and quality control techniques for armor be expanded to include metallurgical sectioning and ultrasonic imaging to determine the presence of macro- and microstructural imperfections (and thus prevent acceptance of imperfect RHA).

Continuing studies of shock-loaded metal crystals indicated that vacancies are produced during passage of a compressive wave and that these vacancies coalesce into pores under the subsequent action of the reflected tensile wave. Such pores become the primary nucleation sites for spall fractures.

It had been shown that the microstructure of a metal can be manipulated in a rational systematic manner to control the level of damage induced by a shock wave. The control was achieved by first postulating the mechanism by which damage is induced (in this case, porosity damage modeled as resulting from coalescence during shock wave intersection) and then determining a microstructure (controlled precipitates) to compete for the vacancies and thus suppress damage. This work by BRL opened the door to a new concept for tailoring material response to ballistic-loading.

By the end of 1976, the Laboratories were well on the way to characterizing rolled homogeneous armor in terms of a set of material parameters that allowed the analysis of fracture following impulsive loading. These endeavors were being supported by in-house and contractor efforts and involved computer modeling, verification of model assumptions, and measurement of the material parameters as a function of the initial metallurgical state. The qualitative phenomenology of failure processes had been identified and some analytical models had been formulated in terms of the identifiable material parameters. The failure/fracture processes identifiable included the nucleation and growth of incipient cracks, fragmentation by coalescence, and separation by plastic shear deformation. Some nucleation and growth and fragmentation parameters had been measured. Experiments were continuing to characterize the behavior of aluminum samples undergoing spallation fracture as a result of biaxial strain loading.

However, there was still a scarcity of shock wave data for armor steels. In the absence of such data, BRL and other researchers commonly had applied data for shock waves in iron to codes to predict the response of steels to explosive and impact loading. Consequently, the Laboratories undertook research to establish shock wave data for rolled homogeneous armor.

NUCLEAR RADIATION AND EFFECTS

Broadly speaking, and excluding here the work on nuclear blast simulation which has been covered earlier, BRL efforts were concentrated in four main areas, Defense Against Nuclear Weapons, Nuclear Effects Simulations, Anti-Ballistic Missiles Materials Hardening Technology and Nuclear Effects Assessment and Mitigation. All of these are explained in some detail below; again unfortunately because of national security restrictions, many of BRL's activities and accomplishments in this area cannot now be detailed adequately.

The approach emphasized the development of codes describing the integrated, i.e., synergistic effects of nuclear weapons. The initial step in such an approach was to define the nuclear environmental conditions; once those had been defined, BRL researchers could investigate the loading or force functions leading to damage. Mechanical loading included blast combined with thermal radiation and x-rays (in some specific case, bomb debris); and radiative loading included neutrons, gamma and x-rays. An important aspect of the programs was the analysis of the sensitivity of the models (computer codes) in terms of the precision of the input effects parameters.

The Laboratories' capabilities in nuclear effects research were enhanced substantially as a result of the abolishment of the Aberdeen Research and Development Command and the subsequent transfer of the Nuclear Defense Laboratory to BRL. A brief historical background of the Nuclear Defense Laboratory (NDL) is noted here.

NDL traced its origins to a group of specialists from the Army Chemical Warfare Laboratories Protective Division at Edgewood Arsenal, Maryland. The first task of the group, assembled in 1948, was to evaluate protection offered by Chemical Corps equipment against radioactive particles. Specific projects included tests to determine the efficiency of filter materials in removing radioactive aerosols from the atmosphere and the effectiveness of gas mask canisters in absorbing radioactive vapors.

NDL participated actively in all US Atomic

Weapons Tests, beginning in 1951 with Operation Greenhouse at the Pacific Proving Ground in the Marshall Islands. Early projects involved sampling and analysis of fallout, contamination and decontamination studies, gamma and neutron radiation shielding studies, evaluation of protective shelters, measurements of neutron flux and thermal radiation, and so forth.

In addition to nuclear weapon test participation, NDL carried out an extensive laboratory program. Instruments such as fallout collectors, aerial survey devices, neutron and gamma detectors, and thermal radiation devices were developed and evaluated.

From 1948 to 1960, NDL had been known as the Radiological Division of the Chemical Warfare Laboratories. In 1960, NDL was establised as the US Army Chemical Corps Nuclear Defense Laboratory, a class II activity under the Army's Chief Chemical Officer. In 1962 it was renamed the US Army Nuclear Defense Laboratory and placed directly under the Army Materiel Command. And as noted previously, NDL became part of the Aberdeen Research and Development Command in 1968. At that time Dr. Donald Eccleshall was the acting Director of the Laboratory.

Under its various names, the Laboratory had made significant accomplishments in radiation transport codes, protection criteria, dosimetry, fallout prediction codes, decontamination procedures, radiation shielding data, waste disposal equipment, vulnerability data, data compilations, and test instrumentation.

Defense Against Nuclear Weapons. Here the Ballistic Research Laboratories directed efforts towards developing the technology for radiation shielding and response calculations; providing the fundamental information necessary to calculate neutron and gamma transport and energy disposition, to design or improve nuclear instrumentation and to determine nuclear vulnerability of Army systems; and investigating nuclear phenomena related to advanced concepts and future nuclear applications.

Shielding and Response, Neutron and Gamma Ray Transport. To support research in the large number of shielding problems of major importance in weapon effects and weapon systems studies, in 1957 the Laboratories undertook a comparative study of methods for calculating gamma and neutron attenuation in ordnance equipment. The object was to establish a relationship between accuracy of effort and accuracy of computational methods and results. Theoretical work resulted in simplification of the Monte Carlo method used for calculations of neutron transport. (The Monte Carlo method is a statistical trial and error calculating technique used where there is a great number of variables and successive repeated calculations are required to establish probabilities.)

The approach followed was to use sampling techniques, designed to reduce the number of particle time-and-space histories that must be calculated to achieve a given accuracy. When applied to a problem with a known analytic solution, the simplified method gave results that compared favorably with the standard Monte Carlo method.

Once in hand, the simplifed Monte Carlo method was applied to the construction of computer codes to predict neutron and gamma transport in various materials, or combinations of materials. Within two years, BRL had available a slab code which could consider up to eight regions with as many as four elements per region. The code included elastic scattering and incorporated differential cross sections. The code also accounted for neutron interactions giving rise to gamma rays; thus it provided suitable source distributions for transport of the neutron induced gamma rays.

Concurrent with the development of the slab codes, BRL was conducting slab shielding and other experiments with which the computed results could be compared. These experiments investigated the transmission of monoenergetic neutrons through slabs of iron, polyethylene, and laminated slabs of iron and polyethylene, and an M48 tank.

These shielding codes gave complete information on the collision processes within the slabs and the energy and angular distribution of the neutrons emerging from the slabs. However, the codes, up until 1963, considered only the transmitted primary radiation. The characteristics of radiation shielding properties of materials also requires data on the transmitted dose due to secondary radiation; in many cases the transmitted dose due to secondary radiation is comparable to that of the primary.

Again, using the Monte Carlo method BRL constructed a computer program which provided transmission and reflection values for both primary and secondary gamma radiation. The code named GRATIS (for Gamma Ray Transmission Induced Spectrum) could calculate transmission and reflections in stratifed dimensions. The code could handle monoenergetic neutrons or a discrete spectrum of neutron energies. The improved computer capacity provided by BRLESC computer permitted a large number of Monte Carlo iterations to be traced, thereby reducing the inherent statistical fluctuations in the results from Monte Carlo calculation.

GRATIS was applied to calculate secondary transmission data for various plane stratified slabs, concrete, and samples of Nevada Test Site soil.

The Monte Carlo method and technique using discrete ordinates were appled by BRL in 1972 to calculate gamma ray transport in air above fallout fields containing radioactive sodium, cobalt, and cesium. Gamma ray fluxes, differentiated in energy and time were calculated for several altitudes above the various fallout fields.

The calculations were made to assess the feasibility of a high altitude airborne radiac (radiation detector) system being considered by the US Navy. Considerable effort was being expended to develop a sensitive system that could be installed in a high performance aircraft to gather gamma ray data under realistic high altitude conditions (i.e., 600 knots, 5000 feet). The design of such a sensitive radiation detection system depended upon accurate knowledge of the gamma ray flux existing at various altitudes above the ground level.

The Laboratories provided spatial, energy, and angular distributions of gamma rays from a monoenergetic, isotropic, plane source. Four separate monoenergetic sources were considered and the calculations were made for fluxes at altitudes varying from three feet to ten thousand feet. The method developed for this rather specific application could, however, be applied to more general applications in evaluating structure shielding effectiveness and determining characteristics of combat vehicle radiaiton shielding.

Fallout. Since detonation of the first nuclear device in 1945, the prediction of fallout deposition has been a military requirement. For low air- and surface-bursts and subsurface-bursts, lethal fallout areas can extend to ranges greater than those for any other nuclear effect. The residual radiation hazard must be considered by planners in the offensive and defensive use of nuclear weapons. Protection against this hazard becomes paramount for troop safety once the immediate effects of a nuclear explosion have subsided.

Many models for predicting fallout deposition were postulated by various defense organizations during the period 1945 to 1965. These models ranged from simplified manual calculations to relatively complex computer codes. However, it became obvious that there was little agreement between the results from various models, and in some cases, results were unrealistic.

The Defense Nuclear Agency (DNA), then the Defense Atomic Support Agency, in 1965 sponsored a research effort to collate all known fallout data. These data, combined with certain principles of chemistry, physics and engineering, were used to construct a sophisticated computer code for fallout prediction. The code was the result of joint efforts of Army and Navy Laboratories and contractors; the Nuclear Defense Laboratory directed the overall effort. The code was completed in 1968; it is called DELFIC, an acronym for Defense Land Fallout Interpretive Code.

Since 1968, DELFIC has been maintained and improved by the Ballistic Research Laboratories. By 1975, the code was in its fifth generation of major improvements. There are six modules in the computational sequence: initial conditions, cloud rise, cloud rise-transport interface, transport, output, and multiple burst. All possible events in the history of fallout particles, from detonation to deposition, can be calculated directly with minimum use of algorithms and scaling factors.

This sophisticated code requires correspondingly detailed input information. Besides total yield, fission yield and height of burst; input is needed on winds, atmospheric conditions, ground zero soil characteristics, and one of twelve types of fission. There are eighteen categories of output information available as maps or tables.

Shortly after the development of the DELFIC, the Nuclear Defense Laboratory constructed a DELFIC-based code for specific Army requirements. In this code, called PROFET (for Prediction of Fallout at Early Times), the rigorous calculations in DELFIC were replaced by appropriate algorithms and input requirements were minimized. The output is in the form of numerical or symbolic maps of exposure, exposure rates, Army operational exposure zones, or maneuver exposure. PROFET was followed by an extremely simplified DELFIC-based code prepared by Stanford Research Institute, under a contract to DNA. Called SEER (Simplified Estimation of Exposure to Radiation), the code provided maps of exposure, exposure rate, and particle time of arrival.

Because they are all single cloud models, the DELFIC, PROFET, and SEER codes cannot handle fallout problems involving subsurface detonations. Subsurface detonations, such as those from earth penetration warheads, can produce a base surge cloud as well as the main cloud. The first suitable two-cloud model was prepared by Lawrence Livermore Laboratory under contract to the Energy Researh and Development Administration, formerly the AEC. Known as KDFOC, the code requires extensive manual preparation of input. The manual computations were programmed by BRL; an alternate BRL cloud model was incorporated and an output option giving maps of operational exposure zones was added to the KDFOC to produce the Army code AUGER.

The Ballistic Research Laboratories is the custodian for DELFIC, PROFET, SEER, KDFOC, and AUGER. The Laboratories run all the codes for Department of Defense agencies and their contractors and for the Arms Control and Disarmament Agency of the State Department.

As 1976 drew to an end, the Laboratories were continuing to compare the results from all of the codes, using common data and wind information.

At NDL and later, after 1968, at BRL, code generation was supported by research into the phenomenology of fallout formation and the characterization of the radiochemical and physical properties of the fallout particles.

Research into the mechanisms of fallout particle formation emphasized understanding the attachment (eg. through nucleation or condensation) of gaseous fission products to various solid substrates. The results were significant for interpreting the radioactive distribution observed in fallout particles and in making general predictions regarding condensation behavior on oxide and metal substances. In a slightly different aspect of this research, BRL derived a simple geometric model that accounted for the effect of depth of burial on the fallout from atomic demolition weapons and demonstrated the consistency of the model with the limited empirical data.

Research into the radiochemical and physical characteristics of the fallout materials included the use of electron probe microanalysis to determine the elemental distributions within fallout particles produced by several US nuclear detonations. Samples were obtained from shots occurring at the Nevada Test Site and the Pacific Proving Ground in the Marshall Islands.

Nuclear Debris. In June 1958, a BRL analysis of the effects of a nuclear detonation in the exosphere (i.e., outside the sensible atmosphere) for the first time disclosed the importance of the trapping of the weapon's debris in the earth's magnetic field; this trapping suggested a potential lethal mechanism that could be used to defend against enemy re-entry vehicles. Thus a quantitive analysis of the potential lethality was made and the results reported to the Advanced Research Projects Agency (ARPA) in September 1958.

Within several years, BRL physicists had developed a two-dimentional hydrodynamic code to describe the motion of the debris from high altitude nuclear detonations with various initial conditions, such as the mass of the bomb, its yield, and burst height. Production runs gave results showing debris position and other related data as functions of time after detonation.

The BRL hydrodynamic code (identified in 1965 as the BRL 2D Hydro Code) was then used for a theoretical description of the debris motion and resulting air shocks of four nuclear detonations occurring during the US nuclear test operation FISHBOWL. The availability of experimental data from the four high altitude shots (Tight Rope, Blue Gill, King Fish, and Check Mate) permitted direct comparison with the code output. Consequently a limited scaling law was derived giving debris motion as a function of a weapon yield. These first calculations considered the motion of the debris for only very early times. Somewhat later times were considered in subsequent computations. Again direct comparisons between the computed results and the FISHBOWL data was possible. The two main parameters compared were the horizontal debris expansion and the rise of the center of the volume occupied by the debris, both as functions of time.

For very low yield "cold" nuclear weapons, where x-ray and thermal radiation yields are very small, weapon debris is the dominant kill mechanism. In the mid-70's, the Ballistic Missile Defense Advanced Technology Center (BMDATC) was investigating the effectiveness of these low yield weapons against threat re-entry vehicles. For those investigations the Laboratories calculated the characteristics of the early time debris and the debris impulse; such data were essential to lethality analyses needed by BMDATC.

Nuclear Effects Simulations. These activities encompassed operations at BRL involving the various radiation simulation facilities, and at sites other than those of the Laboratories. These simulators provided neutron and other particle sources for cross section measurements; radiation effects research and nuclear model studies; and intense neutron fluences for radiation damage tests, calibrating field test and other instruments. Many of the results from experiments using these facilities found use in radiological shielding work, as will be seen.

Operations BREN and HENRE. The design of radiologically protected vehicles and structures depended on accurate, experimentally correlated shielding data. In 1962 members of the Laboratories had participated in a series of experiments (Operation BREN) conducted at the Nevada test site. The objective of the experiments was to obtain shielding data useful for the design of radiological shields effective against a point isotropic fission source. These experiments, under the control of the Atomic Energy Commission, used a tall steel tower and the Oak Ridge National Laboratories Health Physics Reactor mounted on a hoisting mechanism. The reactor could be operated at heights up to 1500 feet above the ground.

For several years afterwards, there still remained a need for experimental neutron data from an isotropic monoenergetic point neutron source. Mathematical radiation transport models had been constructed by BRL to predict the effectiveness of radiological shields against the neutron spectrum then currently of interest; these predictions had not been validated by experiment. It was of fundamental as well as of practical interest to determine experimentally the transmitted and incident dose and spectra for several shield enclosures. The data needed were for neutron and gamma photons from a 14 MeV isotropic source as a function of source height and radial distance.

To meet the need for the data, several experiments, designated Operation HENRE, were initiated and designed as a joint effort between the Atomic Energy Commission and the Defense Atomic Support Agency. The programs used a custom-made one-stage accelerator with a 14 MeV monoenergetic neutron output. The accelerator, mounted on the BREN tower, could be stationed at preselected positions 20 to 1500 feet above ground level.

Operation HENRE provided data on incident (free-field) and transmitted spectra and dose for neutron and gamma photons for several "idealized" geometric enclosure shields. The data, obtained as a function of source height and distance from the HENRE source, were used to verify the BRL shielding computations.

Fallout Simulation. BRL research into the effects of fallout began in 1968 and were essentially a continuation of the ongoing work at the former Nuclear Defense Laboratory. During the period from 1968 through 1976, the Fallout Simulation Facility at Edgewood Arsenal was used to analyze the fallout shielding characteristics of Army vehicles and to confirm prediction techniques for determining exposure rates in buildings located in fallout radiation areas. In both instances the fallout radiation field was simulated by a cobalt-60 source. (See also the section on Instrumentation and Facilities below.)

In the event of a tactical nuclear attack when fallout may be spread over a large area, a field commander must be able to assess the possible effects on surviving personnel. The residual radiation hazard created by the fallout could seriously impair offensive and defensive capabilities. To assess this hazard for personnel operating combat vehicles, protection factors provided by the vehicles structure must be known.

Although some experimental measurements had been made during nuclear weapon field tests, the information was not always reliable or consistent. Calculations of the protection or shielding factors are extremely difficult because of the complex configuration of the vehicles involved. Therefore, BRL used controlled experiments to determine the protection factor against residual gamma radiation for standard Army tracked vehicles. These vehicles included Tanks, Cargo Carriers, Self Propelled Guns and Howitzers, Reconnaissance Vehicles and so forth. Mannequins simulated crew members and passengers. The protection factor, defined as the ratio of the free field exposure rate to the exposure rate at a shielded radiation detector, was determined for each personnel position. These efforts also involved tests to determine the best position within the vehicles for a radiac which could survey the residual gamma radiation field.

So far as the second major effort by BRL in residual radiation measurements is concerned, many investigators had been engaged for some time in experimental efforts to check the validity of calculational methods designed to predict the protection afforded by structures in a fallout area. The procedure, known as the Engineering Method, was developed by the Defense Civil Preparedness Agency (formerly the Office of Civil Defense). It is used extensively by architects and engineers to predict radiation shielding effectiveness of existing and proposed buildings.

The results of validation experiments in most instances had indicated good agreement with calculations. One of the exceptions, however, involved the specific geometrical configuration in which the radiation detector is placed in a basement and exposed to radiation that has first been scattered in the above ground wall and then has penetrated an overhead barrier to reach the detector. This is commonly referred to as "in-and-down" scattered radiation.

It became very important to assess accurately this particular phase of the residual radiation problem since it is very likely that most fallout shelter areas will be located in basements in private homes or public buildings. In a continuing comprehensive experimental program, BRL researchers measured the "in-and-down" scattered radiation using a basement over which a variety of above ground configurations could be constructed. The measurements were particularly significant because they were made in what is considered a "clean" experimental configuration. That is, the structure was made almost entirely of reinforced concrete. It was thus possible to study the effects on the various radiation parameters without having to make corrections for perturbations caused by heavy steel reinforcing members.

Fundamental Research. The Laboratories' accelerator and reactor operations supported specific research in nuclear radiation to provide a base for nuclear technology requirements of the Army. The prime requirement was and remains determination of the effects of nuclear weapons on defensive and offensive systems. Some of the specific research subjects investigated during the 1968–1976 period included:

- Small-Angle Neutron Scattering, which provided the precise differential cross section data needed to calculate radiation transport and to determine radiation effects in materials.
- Neutron Cross Section Measurements, which

measured inelastic scattering cross sections and large-angle elastic cross sections for elements important to defense applications.

- Dependence of Damage on Neutron Energy, which assessed neutron damage in silicon diodes as a function of neutron energy.
- Neutron Producing Reactions, which provided precise data on neutron-producing reactions used as accelerator neutron sources needed to study neutron cross sections measurements and radiation effects.
- Angular Distribution of Radiation, which exploited a new technique, stroboscopic perturbed angular correlation, to study fast transient annealing of radiation damage in solids.
- Energy Loss and Ranges of Heavy Ions in Solids, which developed a new, relatively general method to measure energy loss and ranges of heavy ions in matter.

X-Ray Energy Deposition Simulation. To minimize costly underground nuclear tests on missile structures it was important to have the capability for simulating the loading induced in military weapon systems by the deposition of nuclear radiation. A procedure widely used to simulate blow-off impulse loading of shell structures (e.g., re-entry vehicles or interceptor missiles) is to apply layers or strips of sheet explosive to the outside of the structure. The layers or sheets are usually separated from this surface by a thin attenuator layer of soft material to prevent spallation from the inner surface. Since the sheet explosive cannot be detonated simultaneously over its entire surface, but produces a plane or curved detonation front sweeping over the structure, it was questioned whether the procedure would produce the same structural response as the simultaneously applied x-ray loading which it is intended to simulate.

To clarify this matter, BRL calculated the response of fixed-end cylinders to a particular distribution of impulse intensity for three cases: a load pulse initiated simultaneously on the entire frontal half of a cylinder, a plane detonation front sweeping longitudinally, and a plane detonation front sweeping circumferentially. The calculations were performed by using the REPSIL code developed by BRL. The code employs a finite difference approach to treat the large deflection, elastoplastic response of thin shells. The response predictions were made at lethality levels; i.e., at impulse intensities sufficient to produce deflections of the order of the radius of the cylinder. The results provided reliable information useful to designers of experiments simulating the effects of x-ray loading on shell structures.

Hardened Anti-Ballistic Missiles (ABM) Materials Technology. The Army Materiel Command program for the development of hardened ABM materials was initiated and formulated to address the problems foreseen in ABM concepts for 1980 and beyond. On a shorter time scale, during the period covered by this history, the BRL program responded to requirements generated by the Advanced Ballistic Missile Defense Agency. The result of extensive joint efforts between BRL and the Army Materials and Mechanics Research Center, the broad comprehensive program in materials technology addressed the nuclear free-field environment, damage mechanisms, materials description and evaluation, and materials development. Within those three areas some of the more specific subjects included the provision of bare nuclear device and nuclear weapon output data, determination of accuracy requirements for the input data used in nuclear effects prediction codes, theoretical and experimental investigations of the loading and response of ABM materials, and the development of new materials that could meet the environmental and performance requirements of area and terminal interceptors.

Sourcebook for Free-Field Nuclear Environment Data. The preparation of the several volumes comprising the sourcebook was undertaken under the auspices of the Ballistic Research Laboratories in an effort to provide accurate, detailed, current data describing the free-field environment produced by a nuclear weapon. The emphasis was placed on providing data that would meet the needs of people involved in ABM materials-hardening research. The data provided are defined as the set of parameter values which describe completely the environment created by an above-ground detonation of a nuclear device in the absence of any other man-made objects.

The sourcebook was published in six chapters, each a separate volume. In order, starting with Volume I, the chapters contained an introduction and general description of the phenomenology of a nuclear explosion, compilations of nuclear warhead output and the effects of weaponization, neutron and gamma ray data, x-ray data, blast data and thermal and dust data.

Based on their background, experience, and interest, different groups (including some with members from the Army Munitions Command) wrote various chapters. For this effort no new calculations were performed and the sources included both open and classified literature and personal communications.

Critical Parameters in X-ray Interactions with ABM/RV Materials. One objective of the material response program at the Laboratories was to develop computational models for calculations associated with the Anti-Ballistic Missile materials hardening program. Meeting the objective required determining the sensitivity of material response calculations to uncertainties in input data, incomplete physical modeling, and approximations in the geometric description of the target.

By 1976, the effects of these various parameters on material response predictions used in vulnerability and lethality studies involving US ABM's and foreign Re-entry Vehicles (RV's) had been thoroughly investigated. A comprehensive set of calculations had been performed involving x-ray transport in both the atmosphere and in targets; energy deposition in target materials including ablators, substructures, and components; and the hydrodynamic material response of linearized structures to energy deposition.

The calculations showed the importance of the fluorescence process in x-ray energy deposition calculations for relevant material/free-field combinations, and the sensitivity of angular dependence in the x-ray free-field to x-ray deposition in a simulated ABM/RV. It was also found that the ability to predict and to understand the response of materials to rapid energy deposition depended strongly on the form of the equation of state for the material. The equation of state had to be able to treat accurately each of the thermodynamic states through which the material passed both during and after the rapid energy deposition.

Nuclear Assessment and Mitigation. Atmospheric tests of nuclear weapons had shown that radar propagation will be affected severely in a nuclear environment. The consequences of reduced radar effectiveness coupled with the vital role played by radar in ballistic missile defense systems were responsible for great urgency to be placed on the resolution of the radar problem. Considerable resources had been devoted to the investigation of the problem and to the development of ways to improve radar capabilities.

Some approaches had relied heavily on the ability to predict, *a priori,* the quantitative state of the disturbed atmosphere and its effects on radar propagation. That was done through the use of rather extensive nuclear weapons/atmospheric phenomenology computer codes. As a consequence, within the limits of accuracy of the codes used, it was possible to predict the detrimental effects radar systems would suffer. Accordingly, efforts had been under way for some time to improve the accuracy of the codes.

An alternative, proposed by BRL in the early-70's was to minimize the dependence of radar systems responses on such prediction. This approach, "mitigation technique" applied to any combination of BMD resources that could be developed and used to reduce the severity of the problems caused by the degradation in radar propagation. Thus, the objective of this BRL program was to identify promising mitigation techniques that could be used in then current BMD planning and provide some guidelines for future BMD concepts.

Under this objective, the Laboratories obtained significant results from research into the effects of non-equilibrium phenomena on radar obscuration volumes, blast effects on the blackout contour, and shock induced atmospheric re-ionization. The fundamental question in the last area was whether the passage of the shock wave might temporarily reverse the tendency of the atmosphere to restore itself to relative neutrality. The possible re-ionization effects were found likely to be significant in some region about the point of detonation; BRL researchers were able to quantify the degree to which radar performance might be compromised by incorporating nonuniform shock temperatures and densities into deionization codes. This was done for a variety of burst yields and altitudes. Phenomenology maps were developed showing the conditions (i.e. weapon type and detonation altitude) under which each of the re-ionization effects became significant. The maps enabled rapid quantitative assessments of the effects to be made for a given set of conditions.

LASER EFFECTS

Research into the effects of laser beams began with the 1960's at the Ballistic Research Laboratories. At that time the research was centered on studying the physical effects which occur when intense optical beams interact with material surfaces. The beam, target material, and environmental properties that affect the interaction processes were all subjects for research. The Laboratories interest in laser research continued for the next fifteen years, by which time many of the laser phenomena had been well described and modeled and BRL had begun to investigate and develop lasers generating x-ray and other high frequency beams. At that time, too, continuing interest in the potential military applications of lasers and technological improvements in lasers had resulted in the availability of higher powered lasers for additional research.

Experiments and Theory. The ruby laser used in the early BRL experiments generated a beam of coherent radiation at a wave-length of 6943Å. The laser was used in a long-pulse mode, which gave an output energy of up to 400 joules over a time of approximately three milliseconds; or in a q-switched or short pulse mode, which had an output of almost one joule in a time of about fifty nanoseconds.

The general phenomena occurring in beam/target material-surface interaction were known qualitatively by 1965. At very low incident beam power, gas desorption and thermionic emission occur, followed by emission of neutral particles, ions, many atomic-sized chunks of material, and small fragments as the incident power levels are raised. Part of the incident laser beam is reflected by the surface, the fraction so reflected depends upon both the surface condition and the solid state properties of the material.

At higher incident beam powers, the vaporized target material becomes a plasma composed of electrons, ions and neutral particles, the first two in approximately equal numbers. The plasma is formed during the early part of the laser pulse and becomes hotter during the duration of the pulse; the plasma lies between the target surface and the incoming laser beam. In close to the target surface there are some microscopic particles and there may be some macroscopic chunks, the latter moving slowly away from the target. At the high incident power densities, the plasma absorbs most of the incident laser beam and at sufficiently high incident powers, the plasma formed will absorb the entire laser beam after the plasma has been formed and heated during the early part of the pulse. The only energy reaching the target after this has happened is energy re-radiated by the hot plasma.

Succeeding analytic and theoretical work had as its objective quantitative description of these various phenomena. By 1971 BRL researchers had summarized the results of theory and experiment to provide estimates of the characteristics of laser weapons capable of producing military damage. The damaging effects were categorized according to mechanical, thermal, and electronic. Each category was further subdivided so that the laser intensity level, irradiation time, and the irradiated area needed to produce damage were estimated. The estimates considered restrictions introduced by atmospheric effects, target-induced effects on the beam, tracking and pointing errors, and areas of uncertainty such as laser technology development.

Two separate models were developed which treat the interaction of high-intensity pulsed laser beams with metallic targets in an atmospheric environment. These were the RIPPLE (RIP-Pulsed Laser Effects) code developed by Systems, Science, and Software for BRL, and the LASXPT code developed in-house. Both codes provided completely unified treatment by coupling the response of the air and the target.

The LASPXT code was developed especially for studies involving non-equilibrium interactions between the laser beam and atmospheric plasmas. The code predicts atomic ion and electron densities as well as temperature and density profiles in the plasma.

Comparison of the calculations made using the LASPXT code showed good agreement with results from an analysis of experiments on the initiation of laser supported combustion waves. These experiments were carried out using the NASA-Ames high power laser facility (approximately 35 kilowatts, continuous wave, 10.6 micrometer wavelength laser). The analysis provided a good understanding of laser supported combustion wave formation and propagation and good correlation with the underlying physical processes.

Narrow X-ray and Other High Frequency Photon Beams. Technological developments occurring over the decade of the 1960's drew attention to the possible military applications of gamma ray and x-ray lasers. BRL investigations into the gamma ray laser concept in 1974 led to the conclusion that several specific approaches were not feasible, but that laser-induced fusion offered intriguing possibilities for a very intense neutron pump source to provide excited states in atoms:

At the same time, the Laboratories began to investigate narrow high-frequency photon beams such as would be produced by an x-ray laser; the initial emphasis was on atmospheric propagation and target effects. The results would be used to specify the desired characteristics of such a device. Continuing research would then relate these characteristics to technology capabilities—current and projected—and evaluate the usefulness of such beams relative to other techniques and systems.

A computer simulation was developed for x-ray propagation; the code accurately predicted the beam-matter interaction, and with subsequent improvement was able to handle hydrodynamic motion. The improvement completed the task of modeling nonlinear propagation characteristics which lead to extended ranges for x-ray laser beams. Pulse characteristics conducive to maximum range could also be determined. It was concluded that the pulse characteristics could be achieved at physically reasonable power levels, that the direct energy deposition of these penetrating pulses should have significant effects on explosives and electronic circuits, and other secondary effects were possibly effective damage mechanisms.

Concurrently, BRL began to investigate a concept for a pulsed soft x-ray laser device using ion-atom collisional pumping. The proposed method exploited the large probabilities for producing inner shell vacancies in ion-atom collisions. It appeared likely that this mechanism could lead to an excited-state population sufficiently dense for amplification by stimulated emission of radiation to occur. The discovery of a new mechanism for producing x-rays in ion-atom collisions indicated that the concept could be extended to provide harder x-rays. However, difficulty was encountered in establishing a stable ion source of sufficient brightness.

COMBUSTION EFFECTS

A broad program at the Laboratories on the ignition properties of a wide range of ignition sources of military interest ended in 1957. A general conclusion from the program was that neither a temperature nor an energy criterion was adequate for the wide range of ignition sources of interest in fire damage studies. The experiments conducted in the program further indicated that although temperature may constitute a sufficient condition for ignition, it is not a necessary condition. They also implied that critical experiments could be conducted to test that concept by producing free radicals of the appropriate type and releasing them in combustible materials.

The vulnerability of US materiel to fuel fires evident in the Vietnam conflict caused a resurgence of interest into research in the ignition and combustion of fuels. As is usual when the military aspects of a particular effect are considered, there were two viewpoints: how to decrease the vulnerability of US materiel to the effect and how to improve weapons effectiveness against foreign materiel.

A common source of initiation of sustained fires in combat materiel is the flash of the flammable vapors. To devise methods for preventing (or on the other hand promoting) the transition from flash flame to sustained consuming fire, knowledge of the controlling factors is essential.

BRL developed a simplified one-dimensional model of the transition of premixed flames to diffusion flames in a liquid-gas system. Numerical solution of fuel, oxygen, and energy conservation equations generated temperature and species concentration profiles for all times after the initiating flash. Typical system parameters considered in the model were fuel volatility, residual oxygen concentration, vertical gas velocity, liquid surface temperature, initial gas temperature, and fuel heat of combustion. Iterative studies varying the parameters gave a number of critical conditions for fuel pool ignition. This essentially exploratory model provided a first, semi-quantitative description of the transition from flash to fuel fire. Experimental data acquired by BRL showed general agreement with the calculated ignition delays.

In another approach, a method was developed for modeling the ignition of fuel-oxidizer systems with emphasis on the role of chemistry in a combined chain-thermal theory. Ignition limits as functions of temperature, pressure and composition as well as ignition delay times and specie evaluation curves were calculated for three systems: hydrogen-oxygen, methane-oxygen, and carbon monoxide-water-oxygen.

Calculations on the role of additives in breaking reaction chains in the ignition process led to the discovery of a halon additive which promised to reduce the vulnerability of diesel fuel while permitting the fuel to perform satisfactorily in an engine. (See Fire Safe Fuels on page 184.)

Researchers also investigated flame spreading over fuels for cases where the bulk temperature was above the flash point or below the flash point. Flame spreading velocities were measured experimentally for decane and nine fuels. The measured flame velocities correlated with the difference between the flash point of the fuel and the initial test temperature. It was found in general that flames spread more rapidly over the low flash point fuels than over high flash point fuels at a given temperature.

An empirical, linear relationship was derived for flame spreading velocities at fuel temperatures below the flash point in terms of a variable equal to the fuel flash point minus the fuel temperature (for values of the variable ranging from 3° to 75°C).

RESEARCH INSTRUMENTS AND FACILITIES

Many of the major facilities required for research in terminal ballistics were already available for use in 1957. Major laboratory facilities included reinforced chambers for experiments involving initiation and detonation of explosives, fragmentation and shaped charge penetration; shock tubes; and high altitude simulation chambers. Field facilities on Spesutie Island included barricaded positions for conducting live investigations into blast, fragmentation, or penetration effects; and other hazardous experiments.

However, as research needs dictated, new facilities such as particle accelerators, the Army Pulse Reactor Facility, and the Dual Shock Tube Facility were added. And as changing research requirements dictated, certain facilities were phased out or transferred to other jurisdictions. For in terminal ballistics research, as well as throughout the Laboratories, the philosophy prevailed that research be need-oriented rather than facility-oriented.

Photoelastic Technique for Determining Dynamic Deformation. For measuring the transient response of impacted targets, BRL workers developed a photoelastic technique that determined dynamic deformations on the surface of metal bodies. A sheet of birefringent plastic was bonded to the metal part so that the middle plane of the plastic was perpendicular to the target surface. During transient deformation of the body, the sheet was photographed by a conventional polariscope with a spark light source. The fringe pattern observed was used to evaluate the strains at the metal-plastic bond. A detailed experimental and theoretical investigation of the method was carried out with photoelastic sheets attached to slender rods of steel and aluminum subjected to explosively-induced strain pulses. The dynamic strain distribution in the rods, determined by analysis of the fringe photographs, agreed well with control data provided by conventional electric resistance-wire strain gages. Examination of interaction effects between the rods and the birefringent sheets indicated that such interactions could either be neglected, or in some cases, accounted for properly.

Dynamic X-Ray Diffraction From Shaped Charge Jets. The Laboratories developed a technique and apparatus to produce and "image" the x-ray diffraction patterns in collapsing (stretching) shaped charge jets. There were several reasons for the development of this capability. Critical experiments were needed to test the validity of the theory describing the thermodynamic state of the jets. New alloy liners were being developed for which insufficient experimental data or theoretical background were available on which to base estimates of the thermodynamic state. Also, some data had implied that these alloys might exist in a fluid state after passing through the collapse stagnation point. Since lack of shear strength might critically influence reactions against targets, verification of the state of various jets is critical to the interpretation of jet/target interactions.

The technique consisted of pulsing an x-ray source at the proper time so that a collimated beam of unfiltered radiation impinged on the jet. The transmitted diffraction pattern (produced by the characteristic radiation) was amplified through conversion to an optical signal via a fluorescent screen and then use of the optical signal to stimulate photoemission. A multi-stage electrostatic amplifier then accelerated the electrons which were converted back to an optical signal of higher intensity via a phosphorescent screen. The image on the phosphorescent screen was then photographed.

A system was developed later to use Laue back reflection phenomena in diagnostics. This enabled imaging of diffraction patterns from higher opacity materials where the Laue transmission technique was not feasible. This system could be applied to other basic research areas as well; for example, phase changes and lattice dynamics under general shock loading.

X-Ray Photography. X-ray photography for observing the jets produced by lined shaped charge jets became an important research tool to explain jet behavior. The obscuring cloud of smoke and flame which inhibits ordinary photography, does not affect flash radiographs which produce clear, sharp outlines of the jet material with exposure times on the order of 0.1 microseconds.

The flash radiographic system in operation at the Laboratories since February 1952, with subsequent improvements, continued to be used at BRL.

The flash radiographic technique was extended in 1972 and 1973, respectively, to methods for obtaining behind-the-target data, and studies of the fragmentation characteristics of shell.

Behind-the-target data are needed to evaluate penetrator/armor performance, assess damage behind the target, and to determine round lethality. Previous methods for obtaining the data had required high speed cameras, an illuminated panel with a superimposed grid pattern, and a recovery medium such as multiple layers of Celotex. Setting up the experiment, recovering the fragments, and reading the camera film were time-consuming and costly. Fragment recovery was essential to correlating fragment weight, velocity and patial distribution.

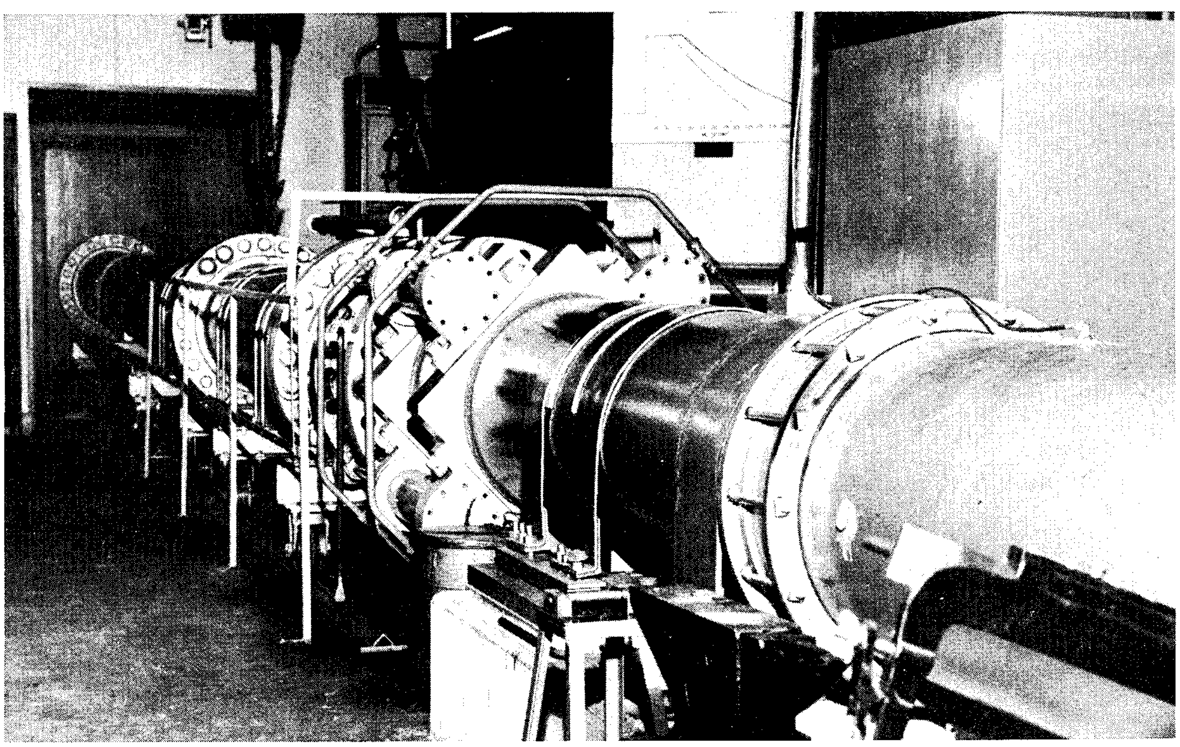
The new, multi-flash radiographic method permitted measurements of the fragments in flight. Four x-ray tubes, arranged in orthogonal pairs, provided radiographs of the projectile in free flight before target impact. A similar set of four x-ray tubes located behind the target provided orthogonal radiographs to provide the data needed to determine residual parameters.

The fragment images were read on a film reader which stored the image coordinates on computer cards. The film coordinates provided input to a computer code which calculated the velocity, weight and spatial distribution of fragments and in the case of a kinetic energy penetrator, the residual rod. The computer program could reduce large amounts of data in a very short time.

A stereo-sequential flash x-ray radiographic technique also was developed to study the fragmentation characteristics of warheads. Providing dual observations of fragments in space and time, this system permitted accurate computations of fragment motion. The system provided data on the speed, direction, and original position on the shell of a fragment resulting from warhead detonation.

Shock Tube Facilities. There were two air shock tube facilities in constant use at BRL during this period. The older of these facilities, mentioned briefly in Volume I, is the BRL 24-inch diameter shock tube, employed for general research into shock wave phenomena and calibration of gages used to measure blast parameters in shock waves produced by high explosive and nuclear detonation. The newer shock tube, initially known as the Nike-X Shock Tube and later as the BRL Dual Shock Tube Facility, was built for the specific purpose of determining the effects of large magnitude air shock waves upon large engine-generator sets. As time passed however, the capabilities of the Dual Shock Tube Facilities were exploited for other purposes.

The BRL 24-inch Shock Tube. The history of this shock tube dates back to 1949 when plans were being made to construct a shock tube at BRL to calibrate blast gages and to study shock interaction problems. The shock tube was completed in 1950, and at that time, was capable of providing blast waves 60 milliseconds in duration. This long duration capability made it an attractive instrument for the study of blast wave effects from large explosions. Its large diameter made it suitable for studying blast wave behavior on and within models of structures mounted within the tube. It became immediately apparent that the shock tube could meet nuclear blast effects simulations requirements of the Atomic Energy Commission and the Department of Defense. A comprehensive research program was initiated which resulted in marked advances in the state-of-the-



BRL 24-inch shock tube

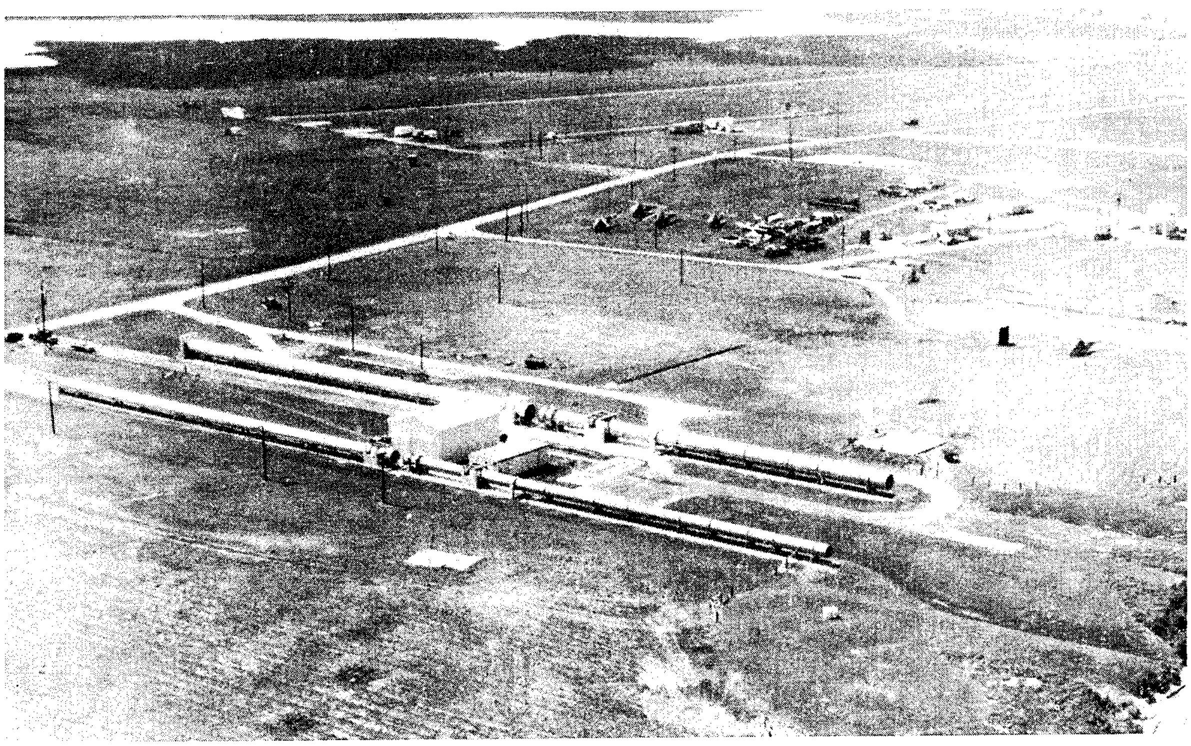
art in measuring and predicting blast-structure interaction. These research efforts also produced design improvements and modifications to the basic 24-inch shock tube. Additional shock tubes were designed and brought into operation to enhance the capabilities of the facility and to cope with more stringent and specific research requirements.

A significant portion of the 24-inch shock tube work supported the research needs of the Office of Civil Defense and other agencies interested in protective shelters. Such work included investigations of the shock waves in ventilation ducts and access passageways, the manner in which the shock waves filled shelter rooms, and the response of objects within the rooms. The results of these experiments, conducted on small scale models, were often used to predict the response of full scale structures exposed to blast from nuclear weapons and large conventional explosions such as those occurring in the Canadian series.

Dual Shock Tube Facility. The engine-generator sets tested in the Dual Shock Tube Facility were typical of those to be used in an anti-ballistic missile system. Because such systems would have to operate even possibly within a nuclear blast environment, it was necessary to know the effect on power output during transient air shock loading of the engine's air intake and exhaust systems.

Since the Office of the Chief of Engineers, Army, was responsible for the design and construction of electrical power systems they had initiated plans for the facility. Shock tubes had been chosen for evaluating engine performance because of shortcomings of two other alternatives: underground nuclear tests, which were too expensive; and high-explosive tests which did not have sufficiently long shock wave durations.

In testing, an engine was placed between the two parallel shock tubes. Ducting from the smaller shock tube, five and one-half feet in diameter, was connected to the engine inlet. Ducting from



Dual Shock Tube Facility

the larger, eight feet in diameter, shock tube was connected to the engine exhaust outlet.

The operating rate for two-tube operation was one shot every two days for weak shocks and one shot every three days for strong shocks.

Explosives Modeling Facility. To provide high quality explosive charges needed for research in the shape and quantity needed, without delay, the Laboratories maintained an explosives modeling complex. The complex was located in a remote area on Spesutie Island, about three miles from the main BRL building compound. Press loading, cast loading, charge analysis, charge machining, and temporary storage operations each took place in a separate building. Three typical Army ammunition storage magazines were used for long-term storage of explosive materials.

Charges could be examined for chemical composition, drop-height sensitivity, heat of explosion, and density. Internal flaws could be detected by x-ray analysis.

The facility was able to provide changes of the necessary quality to keep pace with tasks that required 5000 to 7000 charges of numerous shapes and sizes annually.

3-MeV Van de Graaf Positive Ion Accelerator. This accelerator, installed at BRL during 1958–1959 was used to produce monoenergetic beams of neutrons ranging in energy from 0.025 MeV to 19.6 MeV. The beams were used to analyze the spectral dependence of neutron transport through slabs of composites formed of iron and borated polyethylene. These analyses were performed as part of the Army's Radiological Armor Program.

Once calibrated, the Van de Graaf accelerator was unsurpassed as an accurate source of neutron and gamma rays, which could be used to determine the response characteristics of nuclear radiation detectors over a wide range of energies. It was used extensively to calibrate various detectors.

As noted briefly above, the Van de Graaf accelerators could not provide sufficient neutrons to simulate adequately the radiation effects produced by nuclear weapons. The requirements for such simulation would be met by the Army Pulse Radiation Facility which was entering the initial planning stages in 1959.

However, before the Van de Graaf accelerator operation was phased out in 1967, it had been used to complete experimental and theoretical determinations of monoenergetic neutrons through iron, polyethylene, and laminated slabs. The calculated angular and energy distributions of transmitted and reflected neutrons were analyzed and correlated with theory. The transport of neutrons into various shielded compartments contained within a box made from armor plate had been analyzed and compared with theory.

Tandem Van de Graaf and Cockcroft Walton Accelerators. The Ralph J. Truex Tandem Van de Graaf Facility, located at the Nuclear Defense Laboratory, Edgewood Arsenal, Maryland was dedicated in September 1968. The facility was named in honor of the late Col. Ralph J. Truex, who had been active in Department of Defense nuclear research and development programs until his retirement in 1962. An important research tool for the Nuclear Defense Laboratory, the Accelerator came under operational control of the Aberdeen Research and Development Center (ARDC) late in 1968 when the Laboratory was transferred to ARDC. The Tandem Van de Graaf became a BRL facility when ARDC was abolished in 1972 and the Nuclear Defense Laboratory (later known as the Nuclear Effects Laboratory and subsequently the Radiation Laboratory) became one of the Ballistic Research Laboratories.

The accelerator facility, costing more than $4 million at the time of its construction, was the only research tool of its kind in the US Department of Defense. There were, however, seven other similar accelerators at various locations in the US.

The 15-MeV tandem Van de Graaf accelerator provided beams of precise, variable, and spatially well defined charged particles with energies up to 16 MeV protons and deuterons and to higher energies, tens of MeV, for heavy ions. The facility operated in a pulse mode and, for example, provided nanosecond bursts of protons or deuterons which could be used to create energetic neutrons for neutron time-of-flight spectroscopy.

At the time the Nuclear Effects Laboratory became part of BRL, the tandem accelerator was being used full-time for programs in nuclear physics such as cross section measurements, nuclear structure and reactions, nuclear state lifetime measurements, and nuclear reactions in light nuclei.

The tandem accelerator was closed in 1974 and transferred to the University of Pennsylvania. The decision to close the accelerator came about as the result of two factors: one was the decision by the Deputy Director for Research and Engineering, DOD, that the basic nuclear physics work performed at the Radiation Laboratory more properly fell within the purview of the Atomic Energy Commission and the general scientific community; the other was the decision that it was no longer feasible for BRL to continue compiling extensive small angle neutron cross section information for elastic and inelastic scattering for possible future use. Much cross section data existed in both the military and civilian scientific communities, and it had become more effective to contract for or otherwise obtain cross section information for specific needs.

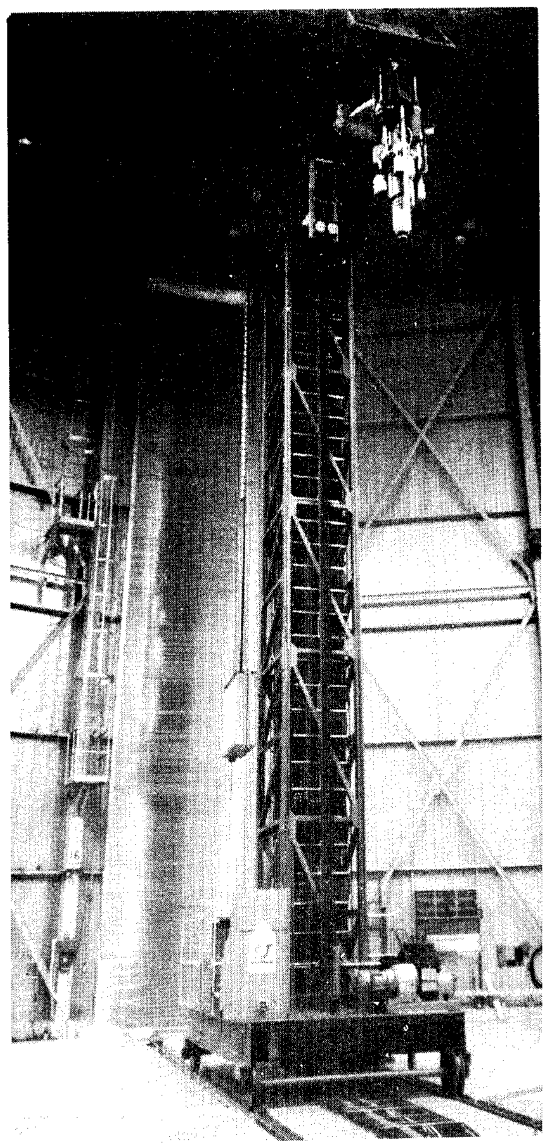
The National Academy of Sciences had determined that the University of Pennsylvania was potentially the most effective and qualified user of the accelerator.

The 750 keV Cockcroft Walton positive ion accelerator was acquired by the Nuclear Defense Laboratory in 1960. It was used primarily as a 14MeV neutron source and for limited cross section measurements. It was equipped with a neutron time-of-flight capability and an on-line data acquisition and processing capability. It was closed around the same time the tandem accelerator ceased operations.

The Army Pulse Reactor Facility (APRF). The Army Pulse Radiation Facility was designed to meet the Army's need for a facility (located within the Eastern Seaboard) capable of providing large fast neutron and gamma radiation within microseconds. The fast pulse radiation capability is necessary for determining transient responses of material in nuclear environments.

The reactor itself is an advanced version of the Health Physics Research Reactor at Oak Ridge National Laboratory, which had been operating since 1962. The Oak Ridge National Laboratory played a key role in the design and testing of the APRF reactor.

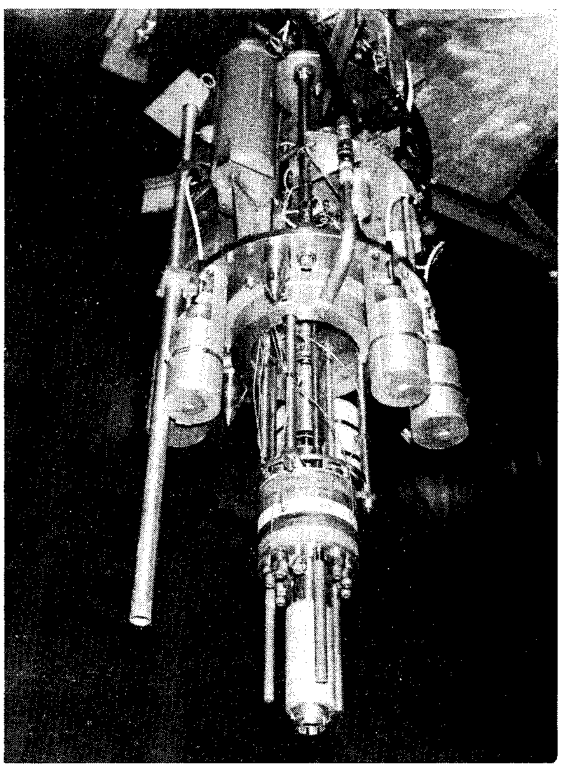
The design of the APRF was a direct outgrowth of projected user requirements. Thus the reactor can be used for high dose irradiation of small objects, as a point source for radiation detector studies and irradiation of bulk objects. The first



Army Pulse Reactor on Transporter

requirement led to the incorporation of a "glory hole" running through the center of the core, providing a fast neutron fluence of about 9×10^{14} neutrons per square centimeter per pulse. The second two requirements resulted in the design of a large volume, low radiation backscatter Reactor Building. The reactor can be moved about within the building and to an outdoor test site by mechanical device known as the reactor transporter. On the transporter the reactor height can be varied up to 44 feet above the ground or floor.

The neutron fluence, which reached its full width in about half the maximum pulse time of 40 microseconds, simulates the nuclear radiation created by the burst of a 500 kiloton TNT-equivalent fission device at a distance of 1000 meters in a vacuum. Radiation absorption and scattering in air enable the reactor to simulate the radiation from a much higher yield device.



Close-up of Army Pulse Reactor

Because of its location, the APRF economically and efficiently served the heavy concentration of Army agencies and contractors located along the Eastern Seaboard.

On January 12, 1976, the Army Pulse Reactor Facility was transferred from BRL's Vulnerability Laboratory to the Test and Evaluation Command, Aberdeen Proving Ground. The transfer, directed by DARCOM, was based on the results of a Department of the Army Reactor Study carried out by the Harry Diamond Laboratory and on the comments provided by BRL, the Test and Evaluation Command and the DARCOM Safety Office. An important factor in the decision was the evolution of the Reactor Facility to an organization primarily providing testing services.

Radiation Fallout Simulation Facility. This facility, located at a remote area at Edgewood Arsenal, is used for shielding research. The area includes 60 acres of land of which 24 acres are cleared. The surface of the test facility is graded, rolled, and treated with a herbicide to prevent plant growth. A point-source circulation system, in which cobalt-60 and cesium-70 sources with strengths up to 3000 curies can be used, simulates a uniformly distributed fallout radiation field.

The point sources, pellets encased in non-magnetic steel capsules, are propelled at a constant velocity by water pressure through nylon tubing. The nylon tubing can be arranged in patterns to provide the desired exposure intensity. The source spends the same length of time in any unit area. Since integrating dosimeters, which measure accumulated exposure, are used as detectors, the net effect is as if the area covered by the tubing is evenly contaminated by the source for the given exposure time.

A smaller test area is equipped with a similar circulating system for experiments on a smaller scale.

vulnerability analysis and vulnerability reduction

The BRL history in vulnerability analyses extends back to 1945 when the Office of the Chief of Ordnance directed that work start to determine the optimum caliber for aircraft weapons. Much of the work was funded by the US Army Air Corps. In 1946, the work was supplemented with a project to determine optimum characteristics for anti-aircraft and aircraft weapons. The next step, in 1947, was a program designed specifically to determine the vulnerability of combat aircraft and guided missiles to ordnance weapons: the findings were applied to the design of aircraft and missiles to reduce their vulnerability and also to the design of aircraft and anti-aircraft weapons, to increase their destructive power.

Within the next few years the weapons effectiveness field was expanded at BRL to evaluate weapons and weapon systems of all types and to determine the vulnerability of armored vehicles and ground targets. Efforts in vulnerability analysis expanded during the Korean Conflict, of course, primarily for *ad hoc* work.

While playing a small but important role at BRL, the value of vulnerability analysis and vulnerability reduction was not universally recognized or accepted by materiel developers. The creation of AMC and its subordinate materiel commands in 1962, tended to diffuse the sharp focus provided by the Office of the Chief of Ordnance on ordnance materiel development; however, it provided an opportunity for the applications of vulnerability technology to wider fields where impact could be made during the design stage.

Realizing this and the necessity for a greatly expanded effort in vulnerability work, the Director of BRL established a Vulnerability Working Group temporarily while he sought authorization for funds and personnel for a full-scale Vulnerability Laboratory. The Laboratory was subsequently established; Alvan J. Hoffman was the first Chief of the Laboratory.

Before long, the Vulnerability Laboratory had a comprehensive program considering the vulnerability of foreign and domestic targets. Studies of foreign targets led to the exploitation of damage mechanisms for more effective use or better design of US munitions; studies of the vulnerability of domestic targets led to methods of reducing the vulnerability and increasing the survivability of US materiel and personnel. Stressing vulnerability reduction as an elementary principle in materiel design, the Laboratory Chief and his staff continually reviewed and exchanged vulnerability information with the commodity commands, project manager offices, central laboratories, and industry. In July 1971, BRL became the Army's Lead Laboratory for Vulnerability/Vulnerability Reduction. This meant that BRL was responsible for formulating, coordinating, promoting, and managing the vulnerability program throughout the Army. As the Lead Laboratory for Vulnerability, BRL was influential in the Quad-Services (Army, Navy, Air Force, and Marines) Joint Technical Coor-

Mr. Alvan J. Hoffman, Chief, Vulnerability Laboratory, received his BS (Mechanical Engineering) from the University of Pittsburgh and his MS (Mechanical Engineering) from the University of Delaware. Mr. Hoffman joined the BRL staff in the early 1950's.

dinating Group for Munitions Effectiveness. The Vulnerability Laboratory had an important role in evaluating munitions effectiveness and preparing munitions effectiveness manuals.

This summary of BRL's work in vulnerability also covers the accomplishments made while vulnerability work feel within the purview of the Weapon Systems Laboratory which was discontinued in 1968.

The beginning of this period in BRL's history saw the Laboratories deeply involved in analyzing a broad spectrum of targets that included nearly all types of Army materiel in the field, being developed—and in some cases still in the conceptual design state. Looked at in another way, they were classified as Surface Targets, Aerial Targets, and Personnel Targets. These analyses were accompanied by research in analytical procedures that could provide mathematical models having uniform treatment of various damage mechanisms and linking the different elements in vulnerability analysis. These efforts included techniques for describing classes of targets, scaling techniques that could treat variations in target size and structure, and techniques that could consider synergistic effects.

An equally broad range of foreign materiel and threats was considered, in the latter case, from small caliber rifle fire to large nuclear explosions.

During the early phases of the Vietnam conflict, BRL representatives, as part of the Advanced Research Project Agency (ARPA) team on-site in Vietnam, estimated the vulnerability of the aircraft to small arms fire and suggested protective measures to improve the survivability of many of the aircraft being used there. Later reviews of reports on hits from ground fire showed how BRL-suggested armor had protected crew members, thus validating BRL vulnerability estimates. While this work was of immediate value, the more significant effect was an the consequent increase in the effort being placed on vulnerability analysis and passive defense techniques for Army helicopters—an effort that would lead in later years to more damage-resistant aircraft and to better evaluations of Army aircraft requirements. For the duration of the Vietnam conflict and thereafter, BRL was to be heavily involved in the aircraft survivability problem.

Through the late 60's and early 70's vulnerability work was largely *ad hoc* in nature because of Southeast Asia oriented activities and *post mortem* evaluations of systems for which needed vulnerability and survivability data had never been obtained in the development stages. However, bit by bit more fundamental work was being done that offered freedom from *ad hoc* testing programs and promise of attainment of comprehensive analytic techniques.

Much work was done to identify targets of importance, to classify them and to assign a priority, and to determine the type and severity of the threat posed against them.

The largest effort went into ground target vulnerability because the targets were so many and so varied. Of particular interest in these efforts were the extensive evaluations of anti-armor weapons and vulnerability analyses of armored vehicles attacked by those weapons, which were becoming increasingly effective. Field firing tests and laboratory experiments provided empirical data for quantifying damaging effects of kinetic energy penetrators and shaped charge rounds. Quantification of damaging effects, coupled with concurrent development of damage assessment techniques, led ultimately to recommendtions for optimum materials and optimum calibers for penetrating ammunition. Results from these efforts also provided the basis for improving the survivability of armored vehicles and their components. Also of special interest and value were the analyses of trucks subjected to blast and penetration effects. The results of these analyses were extremely valuable because for the first time they provided truck interdiction kill criteria. The information was used subsequently throughout the Department of Defense.

Wound ballistics had received major emphasis for a number of years, but the effort had been mainly empirical. Beginning in 1960, the program was designed to exploit the techniques of computer simulation and analysis so as to reduce dependence upon direct experimental observations. For example, mathematical models of the significant organs of the body were used with a theoretical or quasi-theoretical treatment of the penetration process.

A "computer man," an anatomical model in which cross-sectional slices of a human body are coded according to type of tissue, location, damage susceptibility, and ability to retard penetrating missiles was constructed. This made possible assessments for wound tract analysis for horizontal trajectories in a few hours where before several months had been needed to make manual projections and assessments.

METHODOLOGY

The Ballistic Research Laboratories had made remarkable progress in vulnerability studies during the first decade following World War II; nevertheless, in 1957 vulnerability was still a relatively immature discipline. Vulnerability data were missing for many complex targets, and, for that matter, for many simple ones. There was still strong reliance upon the results of *ad hoc* tests for data for analyses, and it was difficult, if at all possible, to apply the results of the tests to vulnerability predictions of targets in the same class, but differing in size and shape. The primarily manual preparation of three-dimensional target descriptions of major weapons and systems was slow and laborious, a factor that affected the time of response to requests for information and the detail to which target descriptions were prepared.

The situation was to change over the next twenty years as the Laboratories emphasized a comprehensive approach to the acquisition of vulnerability data and the development of computerized analytical and modeling techniques that could be applied to broader, general classes of materiel targets. *Ad hoc* testing was minimized except for that necessary to support US efforts in Southeast Asia or to conduct post mortems on US systems for which vulnerability and vulnerability reduction factors had not been considered during the materiel design and development stage.

Consequently, by 1976 BRL was able to exploit the high speed and massive data handling capabilities of computers in response to urgent demands for vulnerability estimates and to provide the information with a much firmer confidence in its reliability. This came about not only through improvement in methodology itself, but also through the deliberate introduction of uncertainty and sensitivity analyses throughout the vulnerability program. Apart from providing the level of confidence for vulnerability studies, the uncertainty and sensitivity analyses indicated the degree of detail, and hence, time and expense needed for a study. A discussion of some of the improvements in the analytical approach follow, essentially chronologically.

Development of Ground Cover Functions. One of the most important measures used to evaluate the terminal effectiveness of weapons against ground targets is lethal area. In order to calculate lethal area, the analyst needs to know the expected number of lethal fragments striking a given target located at some point in the ground plane. To determine that, the analyst needs three inputs: a function relating to the fragmentation characteristics of the shell, a function relating to the casualty-producing power of the shell fragments, and lastly, a function describing the average presented area of a target, considering its location with respect to the shell burst. This last function, known as the ground cover function was the subject of a series of investigations which had as its objective the development of standard ground cover functions for men targets in various configurations. Using terrain information developed by contractors for BRL the analysts developed cover functions for standing troops. The values were stated as functions of the height of shell burst and distance from ground zero. The ground cover function was extended later to consider the case of soldiers in typical infantry defensive positions. The US Infantry School and the US Artillery School provided information on typical defensive positions and photographs of troops occupying them. The degree of cover afforded to ground troops under attack by air burst weapons was used to determine the average presented areas for burst elevations varying from 0° to 90°.

Relating Blast to Damage. About the time the Vulnerability Laboratory was estalished, there was an urgent need for a method to predict, with an acceptable level of confidence, the damage levels that would be experienced by structures exposed to transient loads caused by blast. The then current analytical techniques were only partially successful in predicting elastic response and most vulnerability problems were concerned with gross structural damage, including permanent deformation. The usual approach to these response problems had been to conduct expensive and time consuming blast trials with targets of specific interest or with targets quite similar in configuration and strength.

Over the years, the Laboratories, and other agencies, had amassed considerable experimental data on the mechanical response of simple structural models as well as realistic complex structures to external blast loading. The investigations with simple structures were part of a continuing effort to develop laws for predicting damage to more complex targets; the data acquired on the actual complete targets were used to make vulnerability estimates based upon empirical results. It appeared that perhaps enough data had been gathered to permit a comprehensive understanding of dynamical structural response, as contrasted to the day-to-day empirical effort to determine the vulnerability of specific targets. A reinterpretation of the experimental data already collected did indeed lead to a useful generalization for the relationship between explosive weight and distance in predicting an arbitrary level of response in a target. The relationship facilitated vulnerability studies and reduced the number of experimental blast trials needed to establish lethal distances. The relationship was independent of the damage category or response level, as well as the type of explosive.

Target Descriptions. Development of the Combinatorial Geometry Computer program by Mathematical Applications Group, Inc., Elmsford, New York, under contract to BRL, provided the laboratories with the essential tool needed to describe geometrically complex structures or vehicles. The computer description represents the structure in terms of sums, differences, and intersections of twelve simple geometric solids, such as spheres, cones, parallelepipeds and so forth. The combinations of sums, differences, and intersections are governed by the mathematical rules of set theory. A complete Com-Geom description of a target consists of three elements: a solid table, a region table, and a region identification table. The parameters of the solid, one of the twelve geometric shapes, give its location, size and orientation within a coordinate system established for a target. A region is the space occupied by a single solid or a combination of solids. In the region identification table, each region is assigned an identification code number which identifies each specific region as either a component of the target or as an air space. The region identification table also accommodates descriptive data giving the type and percentage of material making up each region. Thus, the Com-Geom program provides a complete three-dimensional target description which serves as the input code for BRL computerized evaluations of vulnerability. The Com-Geom program was later improved, again through contract with Mathematical Applications Group, Inc; to include other geometric solids, a pre-processing scheme to simplify operations, and an extension of the Com-Geom technique to model trees and bushes. The ultimate goal was to integrate the tree and bush model with models of terrain features, camouflage nets, and descriptions of vehicles. The extension of the Com-Geom program to model vegetation and terrain was part of the AMC Target Signature Program. (See Target Acquistion, Guidance and Control.)

Geometric Information for Targets (GIFT) Computer Code. The development of the FORTRAN computer program GIFT by BRL vulnerability experts in the first half of the 1970's represents a break-through in vulnerability analysis techniques. With only the target description defining the three-dimensional shape and spatial location of the components of a target, the GIFT code can provide: an illustration of the components of the target from any view, simulated engineering drawings of the target, components, the projected area of the components from any view, the centroids of area and perimeter of the target from any view, and other similar physical parameters.

When, in addition to the basic target description data, the densities of the components are provided, the GIFT code can compute the moments of inertia of the target from any view, the center of gravity of the target, and the weight of components of the target. These analytical results of the GIFT code have been verified through empirical measurements.

For vulnerability analysis codes such as the Armored Vehicle Vulnerability Analysis Model One (AVVAM-1), GIFT can simulate the paths of fragments and projectiles and provide data on the thickness and the angle of incidence of the components of the target encountered along the projectile or fragmentation paths. These data are subsequently the input information for the vulnerability analysis code which determines the damage that a given projectile or fragmenting munition could do to the target.

For target signature codes, the GIFT code can simulate the path, for example of a coded beam of laser energy, and compute the angular and spatial values of the components of the target which are needed as input to a target signature code. The target signature analyst can then simulate a laser semi-active terminal homing situation and determine the intensity versus time data for each laser pulse for each quadrant of a four-quadrant laser detector.

With Com-Geom and GIFT, the laboratories were well-positioned to provide faster, more reliable methods of analysis with reduced dependence on costly, time consuming test firings.

AVVAM-1. The Armored Vehicle Vulnerability Analysis Model-1 was developed at BRL to assess analytically the vulnerability of armored vehicles. It could also be used to analyze the performance of anti-armor weapons, as well as to assess the vulnerability of other structures. AVVAM was an outgrowth of an existing BRL digital program based on relations between the characteristics of certain weapons and vehicle damage, as observed from the results of antitank tests.

AVVAM-1 was based on analytical evaluations of the damage inflicted on individual critical components and the aggregate effect of these damaged components on compartment and overall vehicle vulnerability. The AVVAM-1 calculational procedure could also evaluate the potential protection afforded critical component by intervening components. During 1975–1976, AVVAM-1 was supplanted by the Vulnerability Analysis Surface Targets (VAST) Model which could accommodate a later internal-point-burst analysis model, SHUTE.

The SHUTE Internal Point Burst Vulnerability Model. The SHUTE Model, in 1976, represented the latest in a series of "parallel ray" internal-point-burst vulnerability models. Unlike its predecessors, SHUTE explicitly evaluates the effects of armor spall and penetrator fragments, collectively considered spall, as well as the effects of the main penetrator body. SHUTE is possible because of the development of high-speed, large-memory computers.

An important assumption in the SHUTE program is that damage from spall can be approximated over a larger cell size, i.e., a bounded area considered by the computer program, than damage from the penetrator can be. That unique assumption means significant cost reductions in vulnerability analyses without significant loss in accuracy. Time for computation of spall effects can be very long (expensive), while time for computation of main penetrator effects is relatively short (cheap) SHUTE provides precision where it is most necessary and least expensive.

In an analysis, spall damage is calculated for each large grid cell then stored in a matrix. As each smaller cell is considered by the computer, the spall matrix is searched for any spall damage whose cell of origin contains the small main-penetrator cell. Thus, the attack summary data which relates the attacking projectile to the damage sustained by each critical component of the target, includes main penetrator hits and spall-induced damage.

Correlation of the data to the effect on a combat situation is through a subroutine that gives final vulnerability values for various tactical kills. Final output includes tactical kill ratios, vehicle vulnerable areas, component vulnerable areas, centroids of vulnerable areas, graphs giving cumulative probability of kill, and "picture plots" showing cell probability of kill.

Computation of Vulnerable Area and Repair Time (COVART) The development of COVART provided a method for determining the single-round vulnerable areas of various targets and for predicting the time required to repair the damage done to a target. With a geometric description of the target as an input and appropriately simulated penetrator trajectories through the target, the computer program can determine the vulnerable area and repair effort for various fragments or projectiles impacting on the target skin, with selected masses and velocities. The repair time can be expressed as the minimum elapsed time, in hours, to repair the damage—given an unlimited supply of technical personnel, equipment and replacement parts, or simply as repair effort in total man-hours required to repair the damage.

The Vehicle Code System (VCS). Through a contract with the Oak Ridge National Laboratory, BRL developed an analytical technique for evaluating the protection provided to the crew of a ground combat vehicle against the initial radiation from a nuclear detonation. The technique, known as the Vehicle Code System (VCS), is a modular type radiation transport code that calculates the transport of radiation from the point of detonation, through the air, to the vicinity of the vehicle. Radiation transport through the vehicle is then calculated using a Monte Carlo code. The use of the Monte Carlo code reduces computer time required to calculate radiation transport through the combat vehicle, the more complex portion of the transport calculation. The combinational geometry program GIFT describes the combat vehicle. Coupling codes fold the results of the transport calculations together, giving the free field and in-vehicle neutron and gamma-ray dose, from which the protection factor can be calculated.

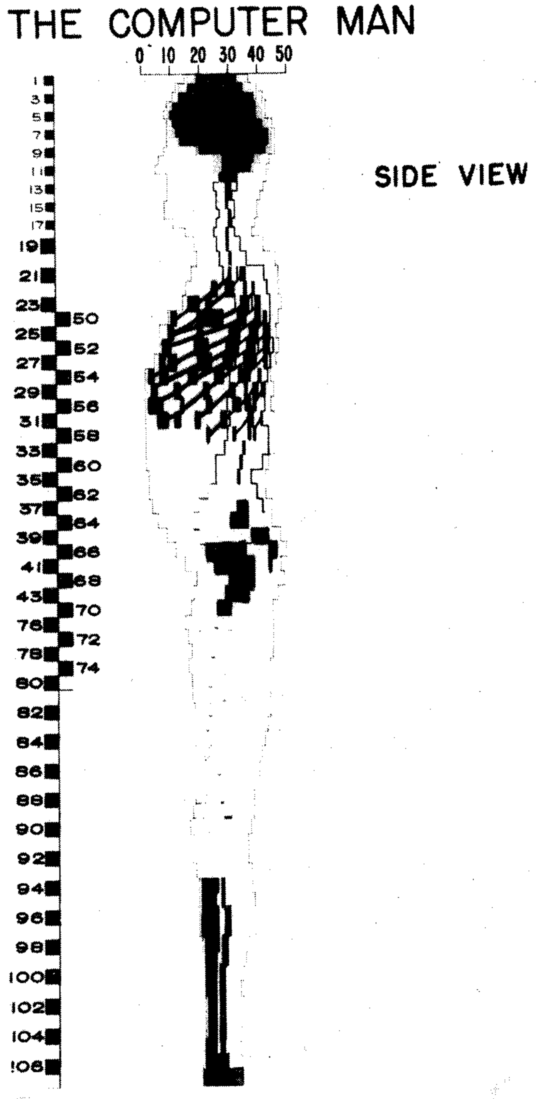
Since simplicity of application was BRL's main goal in constructing the VCS, the VCS became an efficient and trustworthy tool available for use by vulnerability analysts lacking the expertness of the usual, rather small band of radiation transport experts.

WOUND BALLISTICS

For many years research in wound ballistics at the Ballistic Research Laboratories relied upon the results of direct experimental observations. The approach, carried out through a cooperative effort with the Biophysics Division, Chemical Warfare Laboratory Edgewood Arsenal, Maryland, was to conduct experiments in which fragments, bullets, and flechettes were fired into animals to establish physiological damage and to determine depths of penetration of the missiles into various tissues. (Later, gelatine blocks were used to simulate animal tissue.) Next, on the basis of detailed anatomical drawings, the surface to the human body was divided conceptually into small areas on which the consequences of similar impacts were considered. Medical assessors examined each wound tract and decided what the effect of the wound would be on the ability of a soldier to carry out prescribed duties at different times after being wounded. These assessments were averaged for hundreds of wound tracts to give an estimate of the wounding potential of a random hit on a soldier for a given missile striking at a given velocity. Although these efforts were to continue they became of lesser importance to BRL and they were phased out shortly after 1976.

In a broader approach to the problems of wound ballistics, BRL in 1962 began to use mathematical models of the significant organs of the body with theoretical treatment of the penetration process. These models and the augmented memory capacity of the BRLESC permitted computer simulation and analyses, thereby reducing significantly the reliance upon empirical efforts. Details on these models and for other activities in wound ballistics research are provided below.

Wound Tract Analysis by High Speed Computer: The Computer Man. A method for machine computation of the probability of a small missile incapacitating a man was proposed at BRL in 1961. The method presumed that a man could be represented by a number of small rectangular boxes, as small as might be desired for analysis. Each box would be assigned a specific tissue property, and each tissue would be given a particular vulnerability formula and a particular retardation function. The formulas and functions would vary for different kinds of projectiles. The method would provide the probability of incapacitation for a standing man struck by a small projectile with a specified speed and a random

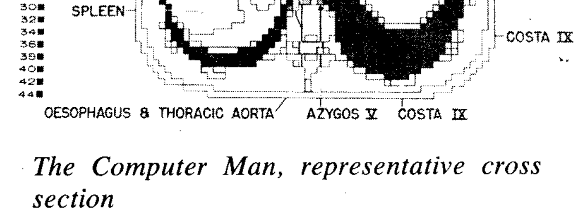


The Computer Man, side view

angle of approach. It was pointed out that the procedure was suitable only for modern high-speed computers with sufficiently large high speed memories and auxiliary storage capacity. BRL did not then possess such a computer; however, the scheme had been proposed in view of the capacities of BRLESC which was being built at the time. However, some cross-sections of the human anatomy were coded for the ORDVAC to explore the feasibility of the scheme. The results of the feasibility study as well as those from preliminary analyses using the BRLESC suggested only small differences between the computer results and results obtained previously by manual techniques.

Within a few years, wound ballistics experts had constructed a "Computer Man" that served as the basic target description to be used with the digital computer for wound tract analysis. Each of the cross sections of the human anatomy described in "A Cross Section Anatomy" written by A. C. Ecyleshymer and D. M. Schoemaker in 1911 were coded for computer anlayses. (The same cross sections had been used at BRL and Edgewood Arsenal for manual evaluations.) Each horizontal slice of the human anatomy was divided into rectangular parallelopipeds and each elemental volume was assigned pertinent information such as type of anatomical component, retardation of the missile velocity during transit, incapacitating effects due to damage and so forth. The "Computer Man" description plus the computer code replaced the manual tracing techniques that had been used for detailed examination of thousands of hypothetical wound tracts. Wound tract analysis by high speed computer reduced the time required for a typical incapacitation study of a single missile at three speeds from several months to less than one hour—an important factor in the length of time for an overall vulnerability analysis.

The development of the combinatorial geom-



The Computer Man, representative cross section etry technique for generating target descriptions of vehicles and structures led naturally to a similar approach for describing human occupants, crew members or passengers for example, in an Army vehicle. The result was ADAM (An Analytic Description of an Articulated Man) designed to represent crew members in Army vehicles described by Com-Geom. ADAM furnished prototype descriptions of soldiers in standing and sitting positions. Since ADAM had the same mass and dimensions of the Computer Man, within the Com-Geom approximation errors, the probabilities of incapacitation developed for the Computer Man were applicable to ADAM.

Wound Data and Munitions Effectiveness Team (WDMET), Vietnam. Until the Vietnam conflict, efforts to collect battle-field data on wound ballistics were limited in breadth and depth. In August 1966, the Vice Chief of Staff of the US Army announced a requirement for the gathering of data useful for evaluating the effectiveness of antipersonnel munitions deployed in Veitnam. The work was to include a comprehensive study of wounds and the behavior of the casualties after they had been wounded. The WDMET was organized to fulfill the mission enunciated by the Vice Chief of Staff, and a data collection format was compiled to meet the data requirements of various government agencies. A team of 43 men with various military specialties was given training in ballistics, wound ballistics, and data collection procedures in the spring of 1967 at Edgewood Arsenal; by late July, the team was operating in Vietnam. Another group of ten men was assigned to Edgewood Arsenal where they received, processed and analyzed the data from the Vietnam teams. Working with this group, members of the Wound Ballistics Group at BRL designed a complete system for storage, retrieval, and analysis of the WDMET data for the BRLESC. Col. Thomas R. Ostrom, later to be Deputy Director/Commander, BRL, was the Commanding Officer, WDMET, 1968–1969.

The analysis provided a simple enumeration of the frequency of occurrence of the various factors, correlations between pairs of factors, and a three-way correlation of factors. Examples of the factors covered by frequency analysis included, for example, the number of hits on body armor and helmets, the actual versus the expected number of hits, and so forth. Two-way correlations included, for example, location of wounds and whether or not some physical activity was accomplished. The most complex correlation, three-way, for example, included the injury type (killed in action, died of wounds, wounded in action, etc.), the type of weapon causing the casualty, and the distance between the soldier and the injury-causing agent (weapon or detonation).

In June 1969, WDMET was succeeded by Battle Damage Assessment Reporting Teams (BDART's). These teams, four in number, were fielded in Vietnam by the Army as part of a larger Tri-Services program. The teams were deactivated in 1970.

Body Armor and Helmets. Ever since World War II the Army has been interested in devleoping various types of light weight armor materials to be worn by combat troops for protection against fragmenting munitions. The most common of these materials have been various types of nylons and plastic films.

Vests and breeches made of nylon and doron materials were developed, tested and used by troops in the field during the Korean conflict. Dr. Floyd A. Odell, then chief of the Biophysics Laboratory at Edgewood Arsenal, was an early researcher in wound trauma and body armor. He is credited for the introduction of body armor in Korea. Dr. Odell became Associate Director of the Ballistic Research Laboratories in 1968.

The performance of these protective garments in Korea was encouraging enough to warrant further research and development. Other materials were developed subsequently, and in 1961, BRL evaluated the protection provided by standard nylon and doron vests compared to that provided by three newer materials. The results of the evaluations were presented in graphs showing the percentage of the reduction in lethal area and the percentage of protection efficiency of armor achieved as a result of armoring portions of the body. The presumed threat was flechettes. It was concluded that doron armor on the thorax and abdomen would reduce lethal area and achieve protection efficiency approaching that which would be achieved by a perfect armor.

About five years later BRL evaluated the then standard US Army and US Marine Corps armor vests and some titanium composites on the basis of their capability to reduce the number of casualties ordinarily expected from a hand grenade and fragmenting munitions. The latter included US 105-mm and 155-mm rounds and a USSR 122-mm round. The US rounds included the 105-mm Beehive round. The analysis considered the distribution of fragment impact obliquities and the consequent distribution of fragment residual velocities. The results of the analysis are still classified (1983).

An estimate of the residual velocity of a projectile or fragment after perforation of armor is essential for an analysis of the effectiveness of a body armor. It is important to know the ballistic conditions under which the armor is defeated, and given that a soldier becomes a casualty, to be able to predict the residual velocity behind the armor. Knowing this velocity, allows quantitative evaluation of the degree of injury.

Empirical data provided by the Body Armor Branch at Edgewood Arsenal were used in the late 1960's to construct mathematical models for use in determining the expected residual velocities of cubes that perforated specific armor materials, as a function of the cubes' size, impact velocity, and striking angle. The task of selecting an appropriate model to characterize the behavior of fragments against various armor configurations, given to BRL, was part of the activities of a Joint Interservice Body Armor Committee. The committee had as its primary mission the selection of an armor vest that would satisfy the operational requirements of the major branches of the military service. The BRL model was adopted by the committee as an analytical aid for evaluating candidate body armors.

The problem with empirical equations developed to estimate the ballistic limit (velocity at which fifty percent of the fragments of a given weight and velocity will penetrate the armor, while the remaining fifty percent will not) and residual velocities was the inability of analysts to apply them to material thicknesses other than those tested. In 1971, BRL modeled the physics of the penetration process, based on the concept of classical inelastic collision between two masses. The new model was a substantial improvement and was to find application in the Army Materiel Command's Five-Year Personnel Armor System Technical Plan which began in 1971. The AMC plan was developed by representatives from BRL, AMSAA, Natick Laboratories, the Human Engineering Laboratories, the Biophysics Laboratory at Edgewood Arsenal, and the Army Materials and Mechanics Research Center.

Algorithms for the Sizing of Helmets. A major effort in the AMC Five Year Technical Program alluded to above was directed towards producing a protective helmet of improved shape with better stability and retention characteristics, probably better fitting, and with greater area coverage. In support of those objectives, BRL and the Biophysics Laboratory developed a mathematical descriptor of the upper human head which takes into account the variation in the head shape and size and can be used to size prototype helmets.

Several algorithms were supplied to meet the characteristics of the desired helmet. Each algorithm partitioned anthropometric data on the heads of U.S. Army personnel in blocks of similar size and shape and then assigned a "size vector" to each block. The Human Engineering Laboratories also cooperated in this research.

Casualty Criteria for Incapacitating Soldiers. The key to wound ballistics analysis and the subsequent application to vulnerability studies are the criteria which relate the physical characteristics of a fragment, bullet, or flechette to the effect on a soldier. Up until 1956, the mathematical function describing casualty criteria had not considered incapacitation as a function of the soldier's duties, or, for the most part as a function of time after wounding. The chief difference between the new criteria introduced then and the most widely-accepted criteria used until that time was that for the new scheme, the probabilities of incapacitation approached unity for very small fragments at relatively high velocities, and for larger fragments at moderate velocities. This was opposed to the older criteria which gave a maximum probability of incapacitation of 0.36—a value based upon early analyses in which a soldier was considered to be incapacitated only if fatally or severally wounded.

Continuing efforts to establish firm casualty criteria were marked in 1962 by development of a mathematical function providing the conditional probability that a random hit with a steel fragment or flechette would incapacitate a helmeted soldier wearing a winter uniform. By January 1965, techniques were at hand that could provide conditional kill probabilities for fragments, stable flechettes and tumbling flechettes for single random hits against a soldier.

The underlying premise in the wound ballistics program (that US offensive weapons should be designed to incapacitate rather than kill, for several reasons), had been the driving force to establish a lower limit for lethality, that is, the threshold of lethality. In 1974, BRL proposed a concept for modeling lethality due to projectile-inflicted wounds, as a hyperbolic combination of projectile momentum and kinetic energy. The concept was verified by the application of data gathered from thoracic wounds. The sources of data were the experimental results from tests on animals, a BRL collection of information on gunshot wounds in patients admitted to the Cook County Hospital, Chicago, Illinois, and the reports gathered by the Wound Data Munitions Effects Team during the Vietnamese Conflict.

AERIAL TARGETS

The Laboratories' program here included generation of data to evaluate the performance of the Army's non-nuclear air defense systems. The fundamental data needed were estimates of the vulnerability of foreign bombers, fighters, helicopters and missile targets to US air defense missiles, gun anti-aircraft systems, and small arms fire. The results were applied to essentially all of the missile and predicted-fire gun systems developed or undergoing development in the period 1957 to 1976 (and later as described in the following chapter). Since, for various reasons, all potential foreign aerial targets could not be analyzed, priority was given to vulnerability analysis of those targets considered to pose the greatest threats—according to estimates of foreign materiel capabilities. As much as possible, the BRL analyses examined component vulnerabilities so that results could be applied to other aircraft or missiles having similar components.

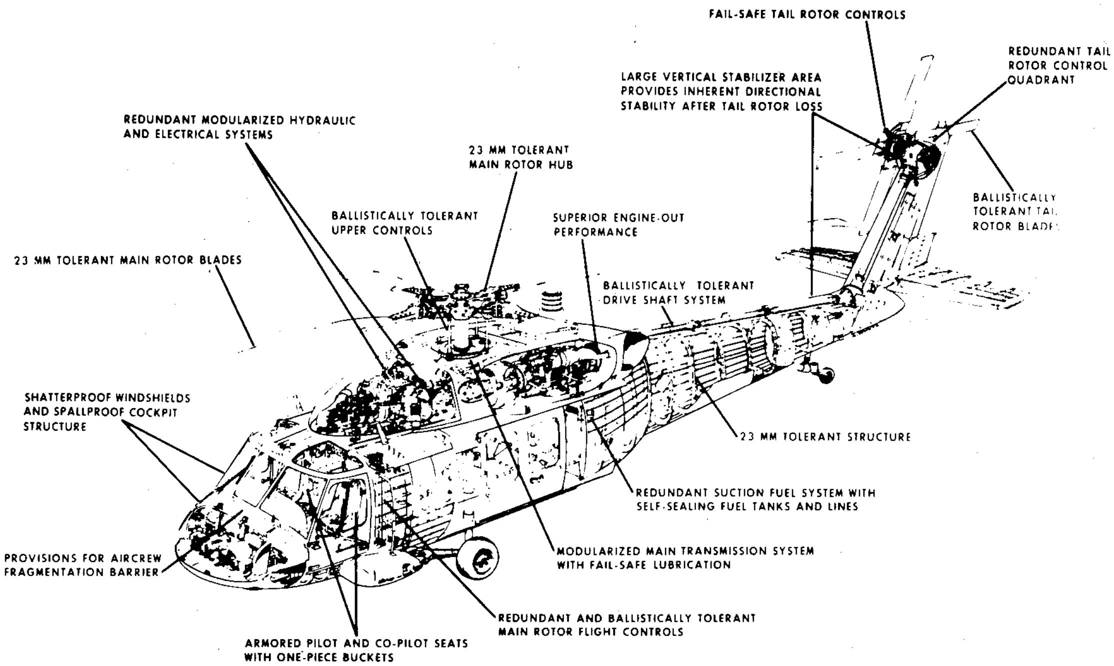
As US involvement in the Vietnam Conflict deepened, the emphasis switched from vulnerability evaluation of foreign enemy targets to the evaluation of US aerial materiel and the determination of ways to reduce US aircraft vulnerability. While much of the work was *ad hoc*, looking for quick-fixes for existing systems, BRL also began to become more involved in analyzing the vulnerability of conceptual aircraft for the Army. The latter involvement meant that BRL had to provide estimates on larger numbers of proposed designs, first from a rather cursory quick look, followed later by a specific analysis of designs which had showed the most promise. With the advent of new, more sophisticated aerial systems, BRL continually reviewed, revised, or if required, developed new "kill" criteria for assessing the vulnerability of the systems.

The development of the Army's Utility Tactical Transport Aircraft System (UTTAS) and the Advanced Attack Helicopter (AAH) can serve as a example of the value of the laboratories contributions to aircraft vulnerability reduction.

The development program for the UTTAS represents the first major Army vehicle procurement that incorporated requirements for non-nuclear vulnerability reduction. Incorporation of those requirements was the direct result of BRL initiative.

As the result of the integration of twenty or more vulnerability reduction features into the design of the system, it was expected that the UTTAS would be about ninety percent less vulnerable to 20-mm ammunition than the UH-1B helicopter, the work-horse of the Vietnamese campaign. The survivability features are the direct results of BRL vulnerability analyses.

BRL played a similar, even more successful role in the development program for the AAH. Survivability specifications achieved third place in the priority of characteristics desired for the aircraft. Moreover, it was through BRL research that the potential threat of the 23-mm HEI round was recognized; thirty to seventy percent of the AAH vulnerability to that round evolved from



BRL contributions to reduction in the vulnerability of US helicopters

the main rotor blades. The helicopter industry was challenged to address that problem.

The ultimate results of the BRL aircraft vulnerability reduction program are aircraft superior in survivability and a level of competition that inspires helicopter builders to develop and expose innovative helicopter survivability technology.

Some representative efforts contributing to aircraft vulnerability analyses and reduction techniques follow.

Blast Vulnerability. As a result of numerous tests using bare charges of explosives against aircraft at Aberdeen Proving Ground during 1947 through 1955, a great mass of experimental data had been acquired describing aircraft response at sea level. While these data had been useful for vulnerability analyses, the BRL analysts realized that a method was needed to scale blast effects on aircraft at sea level to effects occurring on aircraft at altitudes. The scaling approach was used because it was impractical to determine experimentally the efficiency of external blast warheads against aircraft at altitude. The B-29 aircraft was selected as a representative target because of the large amount of experimental data available; the weights of explosives used in the experiments ranged as low as twenty pounds to as high as three thousand pounds. The next step was to construct comprehensive vulnerability curves of the B-29 at sea level and to relate the experimentally-determined lethal distances with determinable values of two important blast parameters—peak pressure and positive impulse. Threshold damage curves were obtained by drawing curves through combinations of peak pressure and impulse associated with the sea-level distances; it was then presumed that those curves would be invariant with altitude.

The curves were then modified to consider the reduced values of peak pressure and impulse at altitudes of 30,000 feet and 60,000 feet and thus to provide the ratios of altitude vulnerable areas to sea-level vulnerable areas.

This interest in the vulnerability of aircraft to blast was to continue at BRL. However, the thrusts of the experiment often changed. For example, the introduction of increasingly high performance aircraft brought about considerable changes in structural design to provide the additional strength needed to sustain inherent high loading stresses. As a result, there was considerable variation in the vulnerability of these advanced structures to explosive blast. There were two methods that could be used to predict blast vulnerability curves for each new aircraft: prediction of blast vulnerability by theoretical means after a detailed analyses of the aircraft structure, or assessment of damage following actual detonation of explosives about the aircraft under controlled conditions. Used for many years the theoretical approach had been time consuming, but more importantly, often in considerable error. While BRL continued to rely on empirical means to update vulnerability estimates, improving skill and confidence in prediction techniques enabled the analysts to construct blast vulnerability curves for new or proposed aircraft.

Air support operations in Vietnam focused BRL attention on the vulnerability of parked aircraft from small explosive charges and infantry ammunition. Troops operating in remote areas, under conditions of limited or guerrilla warfare depended greatly upon air support for tactical and logistical operations. Survival and combat capability of ground troops would be much more difficult without air support. The aircraft often operated from undeveloped strips, in or near the combat area, and were the object of continual enemy action, on the ground as well as in flight. BRL analyzed the effects of blast on a typical jet fighter and bomber, general utility single rotor helicopter, tandem rotor helicopter and medium transport. The criterion used for a successful attack was the inability of the aircraft to be flown successfully before major repairs had to be made.

Some ten years later, in 1975, BRL analyzed the blast response of helicopters parked in revetments similar to those that had been used to protect helicopters in Vietnam. The primary objective was to determine the effect of blast on a typical helicopter (UH-1B) and to compare the effect with that experienced by a helicopter not protected by a revetment. A secondary objective was to measure pressure loading on both helicopters in an attempt to correlate local pressure with structural response. The underlying reasons for the experiment were the lack of test data on the blast vulnerability of targets protected by revetments and a corresponding lack of an analytical technique describing the blast environment within a revetment containing a target. It was found that the revetment would protect the helicopter (and other light drag-sensitive targets) from translation and subsequent damage. However, the revetments did not protect overpressure-sensitive targets from damage; as a matter of fact, for some cases, the shock reflections within the revetment increased overpressure loading significantly—causing the protected aircraft to be damaged more severely than the unprotected. At any rate, it was found that the revetment could withstand considerably higher overpressures than the helicopters they were designed to protect.

Although the major effort at BRL for aircraft vulnerability addressed conventional warfare, competence was also maintained to analyze the vulnerability of aircraft to nuclear effects. While the methodology used at BRL was believed to be adequate for reasonable predictions of aircraft damage due to nuclear blast, it had not been validated by experiment. Event Dial Pack, a 500-ton conventional explosive detonation simulating nuclear blast, provided an opportunity to validate the methodology.

BRL's initial objective was to determine the structural and component response of fixed and rotary wing aircraft parked at various blast intensity levels, and to compare the results with predictions based upon the current methodology.

Initially, two obsolete US aircraft were to be made available for the experiment; however, later on four currently operational US aircraft and one obsolete Canadian jet fighter aircraft became available for testing. Because of this rare opportunity to experiment with current aircraft, it became as equally important to obtain damage data as it was to evaluate the prediction methodology. The results showed that the current methodology for predicting gross structural damage to aircraft provided acceptable estimates. Moreover, the results showed that the need for additional testing of this sort was questionable, unless there were radical changes in future aircraft designs, construction, or materials.

Damage to helicopter in field revetment

Analysis of Combat Damage to Aircraft in Vietnam. Throughout the United States' involvement in the Vietnam Conflict, BRL continually analyzed combat damage to US aircraft and the casualties suffered by personnel aboard aircraft. These efforts were supported by an Army Materiel Command program for the Reduction of Vulnerability of Army Aircraft.

The basis for the analyses was the Ground Fire Damage Report (GFDR) which was required each time a military aircraft was hit by ground fire in Vietnam. Copies of the GFDR's were forwarded to BRL on a regular schedule. Information in the GFDR's was supplemented by data from the US Army Board for Aviation Accident Research at Fort Rucker, Alabama, the Casualty Branch of the Adjutant's Generals Office, and the Army Concept Team in Vietnam (ACTIV) Liaison Office. Supporting operations data, number of sorties and flying hours by month, were acquired from charts and tables prepared by the Aviation Data Collection Center of the US Army Support Command (Vietnam).

Thus BRL had available for statistical and vulnerability analysis, data on the number of sorties flown, sorties hit, circumstances of hit, components hit, crashes, forced landings, mission aborts and casualties. This made possible the correlation of hit frequency with the type of weapon, aircraft range, altitude and speed, direction of hit and other factors.

Combat casualties reported for combat personnel aboard aircraft included those injured in crashes caused by ground-fire hits on the aircraft as well as those wounded directly by projectiles, fragments, and debris impact. These casualties were defined by type, severity, anatomical location, crew station and so forth.

Access to detailed actual combat data provided an invaluable means for checking the conclusions of empirical tests, correctness of analytical methods, accuracy of necessary assumptions, and the usefulness of the general techniques developed by BRL to estimate the vulnerability of currently operational aircraft as well as designs for future aircraft. In addition, the data provided means for evaluating the effectiveness of protection equipment added to aircraft and an objective basis for methods proposed to further reduce aircraft vulnerability.

Systems Vulnerability Analyses. Before enumerating some of the aircraft systems which BRL analyzed and describing some of the vulnerability reduction techniques applied to improve aircraft survivability, it seems appropriate to review some basic concepts in vulnerability methodology. First, to determine the vulnerability of aircraft, the term "kill" must be defined. By 1960, several categories of kill had been defined, primarily by BRL, used for a number of years, and accepted by vulnerability and weapon systems analysts. For fixed-wing aircraft, these categories included "K," "A," "B," and "C." The "K" kill refers to a type of kill in which the aircraft goes out of controlled flight immediately as a result of the damage. The "A" kill occurs when the aircraft fails to continue controlled flight five minutes after the damage occurs. A "B" kill means the aircraft will fail to return to its base, and a "C" kill means that the aircraft will not complete its mission. The "C" kill does not imply that the aircraft will be lost.

There were three categories of kill for helicopters: "attrition," "forced landing," and "mission." The attrition kill is defined as that damage to the helicopter which will cause it to crash and become a complete loss. The forced landing kill is just as it implies; i.e. the pilot lands, powered or unpowered because he received some indication of damage. The mission kill for a helicopter is defined the same as "C" above.

To continue, the vulnerability of an aircraft is usually expressed in terms of vulnerable areas, where the total vulnerable area of an aircraft can be calculated as the sum of the vulnerable areas of the components. The vulnerable area of a component, or of an aircraft, is defined as the product of the presented area of the component, or the aircraft, and the probability that a hit on the area means a kill. The probability of kill for the components is determined empirically through tests or by analysis of combat damage. Experimental data are obtained from firing various caliber projectiles or fragments against the components. Then the total single shot kill probability (ssk_p) for a weapon firing against an aircraft is derived by dividing the total aircraft vulnerable area by $2\pi S^2$, where S is the standard deviation in the firing error of the weapon.

Finally, in considering a kill on an aircraft from one or more hits, the analyst must describe how the kill occurs. For example, if one hit defeats a component in an aircraft, such as the engine, the result can be a kill—for a single engine aircraft. The analyst calls the engine a singly vulnerable component. If multiple hits are necessary for an aircraft kill, such as in a two-engine aircraft where each engine must be defeated, then the analysts calls these components multiply vulnerable.

Except for the "kill" categories, these definitions and procedures apply to vulnerability of all types of targets subjected to penetrating mechanisms. The analyst starts with the target description, defines the threat and the kill criteria, and ultimately derives the measure of vulnerability—in terms of vulnerable area and single shot kill probability.

Now, to return to a discussion of BRL activities in aircraft vulnerability analysis and vulnerability reduction.

Aircraft Systems. Throughout the period of this history, vulnerability analysts emphasized the threat to aircraft posed by ground fire, in particular, 7.62-mm (caliber .30), 12.7-mm (caliber .50), 14.5-mm (caliber .60), 23-mm armor piercing incendiary (API) and high explosive projectiles. However, this emphasis did not preclude analysis of fixed-wing vulnerability aircraft to the threats posed by surface-to-air missiles, similar to those of the US Redeye. Some of the US materiel considered in that effort were single-engine aircraft, twin-engine aircraft, and versions of variable-wing sweep aircraft.

A partial list of the helicopters analyzed during the 1960's through the first half of the 1970's included fielded systems such as the UH series, in all its versions, the AH series used to escort and protect troop-carrying helicopters flying in formation; the OH series used for observation and reconnaissance missions; and the CH series of utility helicopters used to transport troops, cargo, and weapons in the combat area. Proposed systems, as noted above, such as the UTTAS, AAH, and ASH (Advanced Scout Helicopter) were also analyzed.

Supporting these overall vulnerability analyses were the results from many tests designed to provide the single shot kill probability of individual components or systems. For most tests actual components were used; in some instances, recourse was had to mock-ups closely resembling actual components. Results were obtained, to name but a few, for rockets and TOW missiles stored in pods mounted on helicopters, ammunition stored in gunship magazines, fuel systems, pressurized hydraulic lines (particularly with respect to incendiary ammunition), turbojet and turboshaft engines, and power train systems.

While priority was given to the analyses of US systems, as time and resources permitted BRL also analyzed the vulnerability of USSR aircraft such as the Bison, Bear, Badger, Backfin, Blinder, Farmer, Fishbed, Flashlight, Cub, and Hound.

Missile Systems. The analysis of missile vulnerability is quite complex, because it involves many factors. First, there is the actual physical state or condition—storage, transport cycle, launch configuration, flight, or re-entry (for strategic missiles). Second, there are the various kill mechanisms—fragments (including small arms fire), blast, thermal radiation, and nuclear radiation (neutrons, x-rays, and so forth). These damaging mechanisms may act singly or jointly to cause different types and varying degrees of damage. A complete vulnerability analysis would demand first a description of the system's condition, and then, inclusion of the influence of all these damage mechanisms. However, here we can only discuss limited vulnerability analyses considering for the most part only the effects of fragments and blast. The descriptions and results of analyses considering other damage mechanisms are, in the main, still classified.

In May 1957, the Armed Forces Special Weapons Project, soon to become the Defense Atomic Support Agency (DASA) sponsored an atomic weapons vulnerability program. (As early as the fall of 1949, BRL had investigated the vulnerability of these weapons for DASA.) For this program, DASA provided BRL with obsolete weapons or components thereof for firing tests to determine the vulnerability of those special weapons to fragment, projectile, and airblast impact. BRL derived kill probabilities for single or multiple fragment (projectile) impacts as a function of random direction of attack. The vulnerability was estimated in terms of vulnerable areas which would provide a weapon "dud", assuming several fuzing options.

About the same time, BRL, fired single fragments at solid propellant rocket motors varying in size from two inches to nearly twelve inches in diameter. The results showed that the fragment impact necessary to destroy a rocket engine was a function of the case thickness and material.

These initial efforts are typical of the vulnerability analyses that BRL continued to provide. As was the case for aircraft analyses, these evaluations of US missiles were paralleled by analyses of the vulnerability of USSR systems such as the FROG series, and the SS (surface-to-surface) series of tactical missiles.

In analyzing the vulnerability of missiles to blast, BRL followed a dual approach involving the use of scaled thin-walled shells exposed to various weights of high explosive, and full-scale experiments involving actual missile systems and supporting equipment exposed to blasts from very large amounts at high explosives.

From the start it was presumed that blast could defeat missiles by crushing the missile skin or deforming the bulkheads and frames, causing misalignment on the launcher, overturning the launcher, and damaging the internal components as a result of severe accelerations.

Enough data were obtained from blast exposure of thin-walled unstiffened cylindrical shells to establish a method for predicting the permanent deformation of such cylinders. The method correlated the free air overpressure and blast impulse with the cylinder response. The amounts of high explosive used ranged from one pound to fifteen tons.

Full-scale experiments were carried out at Yuma Proving Ground, Arizona and at the Ca-

Damage to Titan Missile exposed to air blast

nadian Defence Research Establishment, Suffield (DRES), Alberta, Canada. At Yuma Proving Ground, several types of parked missiles, including a Jupiter missile were exposed to blasts from charges ranging from 500 pounds to 30,000 pounds.

At DRES, BRL participated in nuclear weapons effects tests in which high explosive charges were used to simulate the blast from a nuclear weapon. In the first of these tests, Operation Snowball, nine missiles were exposed to the blast from the detonation of 500 tons of explosive. The missiles, located at predetermined predicted levels of overpressure and impulse, included three Hawks, three Jupiters, two Nike-Hercules, and one Sergeant. The results were as expected, and the data were used to generate iso-damage plots as functions of charge weight, distance, overpressure, and impulse for various categories of damage.

In July 1970, BRL participated in another 500 ton TNT blast trial (Event Dial Pack) to determine the effects of blast on the internal and external components of a representative tactical missile system. The targets in the experiment were two Lance missile systems, one representing the launch condition, the other a transport condition, i.e., parked on its self-propelled launcher in the lowered, fastened position. Specific objectives for the test were correlation of component response with the gross structural damage to determine overall vulnerability, determination of how well the Lance missile system met the materiel requirements for nuclear blast hardening, and to validate methodology for determining missile vulnerability as a function of gross damage.

The susceptibility of the Lance system to blast was evaluated and changes in design were recommended to enhance its blast survivability.

By 1970, BRL had completed susceptibility/vulnerability studies of the Sergeant, Lance, and Hawk systems, considering the full range of missile conditions from stockpile to launch.

Vulnerability Reduction. The underlying emphasis in BRL's work in vulnerability reduction, regardless of the class of materiel, was the need to consider vulnerability reduction as an integral part of concept formulation along with the other engineering and development aspects of materiel acquisition. Otherwise, vulnerability reduction fixes, tacked on as retrofits or add-on kits in the field or at the factory, almost always penalized some other functional aspect of the system. They tended to be expensive, both in dollars and their impact on the overall ability of the system to perform its mission. The BRL vulnerability analysts repeatedly stated that it was better, cheaper and more efficient if vulnerability reduction and survivability could be incorporated into the design of a system from its very inception. Ultimately, the message was to get through; by the end of this period (1976), standard survivability/vulnerability reduction requirements were becoming part of the specifications packages for new systems to be acquired.

Despite the foregoing, many significant improvements were made to rotary aircraft as a result of add-ons and retrofits. A few examples should suffice to illustrate such improvements.

During 1962, the apparent vulnerability of helicopters used in combat areas of Vietnam posed an urgent need for lightweight armor. Traditional armoring materials offered very limited practical protection even for weights up to 20 and 30 pounds per square foot. In responding to this need, BRL contributed to the development by a contractor of a laminated ceramic and fiberglass armor that could stop a caliber .30 projectile under any impact conditions with the armor weighing only 8.5 pounds per square foot. In the process, two limited protection systems, weighing in the range of 6 to 15 pounds per square foot were developed and applied to protect helicopter crews and small boat crews in Vietnam.

The immediate need was met by the application of two phenomena observed and refined in a BRL firing range, "the tipping plate concept", and "the holed plate concept". In the tipping plate concept, a very light plate is used to induce severe yaw, thereby causing the bullet to present maximum area to the primary armor which can consequently be of less thickness and weight. To be effective, the phenomenon requires striking obliquity on the tipping plate of 15° (from the normal) and a distance of about 18 inches between the tipping and the stopping plate. Those two limitations were overcome, with some weight penalty, by the holed plate concept. That system consisted of a perforated one-quarter inch thick steel plate (to strip, break up or slow down a bullet) backed with doron to stop the bullet. The BRL representatives on the team sent to Vietman by ARPA, helped in demonstrating and applying the two concepts to combat helicopters. This introduction of lightweight armor crew seats was credited, some ten years later, with saving more than 500 lives.

Other improvements proposed by BRL and retrofitted on helicopters included an oil bypass system for the Cobra which usually provided enough operating time after damage had been incurred for the pilot to return to his flight base, and crash resistant fuel tanks which retained fuel instead of rupturing during a crash. These tanks virtually eliminated post-crash fires. Since crash fires had been the main cause of fatalities aboard helicopters, the Army expected to save many lives through this single measure; the tanks were also incorporated in newly built aircraft.

Since the fuel system in an aircraft could be a major survivability problem in aircraft combat, BRL continually reviewed the design of fuel systems in proposed aircraft. Changes in fuel system components could alter significantly the influence of the fuel system on survivability. A good illustration of this was provided when BRL was asked by Boeing Company to review the design of a modified Chinook helicopter. As proposed, the new design would have entailed an increase in vulnerability. The problem was resolved when BRL suggested substitution of aluminum fuel tank mounts for the original magnesium mounts.

Other suggestions for reducing the vulnerability of aircraft included redundant circuits for critical avionics equipment; the use of solid lubricant components in bearing and gear box systems which could continue to operate for a significant time after the loss of normal oil lubrication (the goal was to provide thirty minutes of extra life for transmission bearings following the loss of oil); and the use of inert hydraulic fluids.

Through published guides, participation in seminars and source selection evaluation boards, and direct contacts with Army agencies and industrial contractors, BRL continually emphasized the virtues of early consideration of means for improving aircraft survivability. In so doing, the laboratories did not dictate configurations, components, or materials; rather, the approach was to expose the major considerations for aircraft vulnerability and the many "pitfalls" in design details, and to stimulate and encourage consideration of "built-in" protection throughout the design of military aircraft.

SURFACE TARGETS

From the 1957 analysis of the vulnerability of land mines carried "piggy-back" on trucks to the analyses of vulnerability of sophisticated and complex command, control, and communication systems in 1976, BRL examined the vulnerability of a broad variety of surface materiel. Such materiel included armored combat vehicles, support vehicles, firepower systems, night vision systems, ammunition, and radar systems. Threats included air blast, fragmentation and other penetration mechanisms, incendiaries, fire, and nuclear phenomena. In addition to analysis of US equipment, BRL also analyzed the vulnerability of foreign equipment, in some cases through evaluation of actual equipment, in other cases through constructed target descriptions.

For the most part many of the techniques developed for aerial systems analysis were applied to the analysis of surface targets (and vice versa). The chief modification was in the categorization of "kills". For armored vehicles these were an:

- "M" kill or Mobility Kill in which a vehicle was damaged to the extent that it would not execute controlled movement.
- "F" kill or Firepower Kill in which the main armament was damaged beyond use, or if a missile system, the missile could not be launched successfully.
- "K" kill in which the target was damaged to the point where it is economically unrepairable (catastrophic kill), or
- "P" kill or Personnel kill in which at least thirty percent of the passengers were incapacitated.

The vulnerability of the targets was usually expressed in terms of the single shot kill probability.

A significant milestone was reached in October 1970 when Dr. R. B. Dillaway, then the Deputy for Laboratories, AMC, directed BRL to sponsor seminars on vulnerability reduction of military equipment. As the lead laboratory for vulnerability and vulnerability reduction research, BRL was given the task to organize and host the first such seminar. The theme for the first meeting was Vulnerability Reduction of Surface Materiel. Attendance at the meeting was limited to DOD personnel whose efforts were directly related to the life cycle of equipment in the design or development stage.

Maj. Gen. John R. Guthrie, then Deputy Commanding General for Materiel Acquisition, set the urgent tone for the seminar in a keynote address which underlined the importance that the Army Materiel command attached to the subject of vulnerability reduction of Army Materiel and the need for injecting vulnerability reduction considerations into weapons systems design throughout the life cycle from inception to disposition. To a marked degree, this recognition of the value of vulnerability analysis was the result of analyses performed by BRL and the unceasing stress that the Laboratories placed on vulnerability analysis as a fundamental process in the materiel acquisition cycle.

Systems Vulnerability Analyses. A great deal of effort was expended in these two decades on the analyses of foreign systems, primarily USSR materiel, but an almost equal amount of effort was applied to the analyses of US surface systems. In the discussions of representative efforts which follow, the U.S. materiel will be discussed first; where appropriate, analyses of USSR equipment follows.

Armor Systems. Early efforts had as their goal the acquisition and compilation in a useful format of the results from tests of kinetic energy (KE) and High Explosive Anti-Tank (HEAT) rounds fired against U.S. Army tanks, the T26E4 and the M47. This compilation provided the initial "data base" for the use of tank vulnerability analysts. However, results from cooperative research conducted by the United States, the United Kingdom, and Canada gave a much broader and more useful basis for tank vulnerability and armament lethality assessments. At the Third Tripartite Conference on Tank Armament held in the United Kingdom during 1958, representatives from those countries established a working group on antitank trials and evaluation. Meeting for the first time at BRL in May 1959, the working group reviewed available trial results, decided where additional experimental evidence was required, and planned a test program. During summer and fall 1959, the working group conducted an extensive series of antitank tests at the Canadian Armament Research and Development Establishment (CARDE). The objective was to provide data upon which to base the design of a warhead for an armored fighting vehicle Guided Missile Weapon System (for US and British versions). The CARDE Trials, as they came to be known, met the objective, and of great significance, provided data giving vulnerability specialists their first opportunity to examine the effects caused by varying a broad spectrum of warhead parameters in a carefully controlled experiment.

Several years later, 1962, BRL investigated the possible advantages to be gained from suppressing armor spall fragments after a HEAT round perforates the tank crew compartment. Considered were the kill probability given a perforation, the overall tank kill probability given a hit, and the number of casualties per crew compartment perforation. While the detailed results from the investigation are still classified, it can be noted that the reduction in overall tank kill probability is modest even for 100 percent spall supression, but substantial reductions in casualties per crew compartment penetration can be achieved under certain conditions.

In September 1965, the Project Manager for Combat Vehicles awarded a contract to Cornell Aeronautical Laboratories to make a parametric design/cost effectiveness study to support the Mechanized Infantry Vehicle-1970 Program, the MICV-70 program. While acting as a technical supervisor of the contract, BRL also prepared all the lethality/vulnerability data needed for the study. The magnitude of the task can be judged by noting that vulnerability estimates were provided for fifty conceptual configurations of the vehicles and five existing vehicles to threats posed by eleven gun-projectile combinations. Possibly even more remarkable, this was the first full-scale attempt for a complete analysis of a MICV-type vehicle.

Fires and explosions which frequently follow a munitions attack against an armored vehicle can have devastating effects on the vehicle as well as on its crew. Such effects and their causes are, of course, extremely interesting to vulnerability analysts; so, in 1974 BRL analysts studied the frequency and causes of damaging effects for the M48 series tanks which were lost in combat in Vietnam. In addition to enumerating and calculating the percentage of combat losses which were accompanied by secondary fires or explosions, the researchers categorized them according to the type of attack and identified which combustibles in the tank were primarily responsible for the fire and/or explosion. Casualty rates were also correlated with the type of attack and the incidence of fire. The work concentrated on the diesel-powered M48A3 because it was the principal tank used in Vietnam, but also considered the gasoline-powered M48A2E which was used for a short time in Vietnam.

The principal source of data was the information collected under the "Combat Operations Loss and Expenditure Data-Vietnam," (COLED-V) program initiated by the Army Vice Chief of Staff in a letter to the Combat Development Command, April 1966. The main purpose of the COLED-V program was to establish a basis for estimating equipment losses and ammunition expenditures in counter-insurgency conflicts. Data collection and processing began officially on 1 July, 1967, after a three-months trial. The information collected through COLED-V was supplemented by data acquired, in 1969, under the Army's Battle Damage Assessment Reporting Program (BDARP), which was part of a large US Tri-Services effort. For the Army's part of this effort, four specially trained teams lived with troops in four areas of Vietnam and collected data on vehicles damaged in combat. This collection method differed from the COLED-V system where military personnel themselves reported damage as each case occurred. The BDARP reports gave information on hit locations and damage caused by effects from fire, explosions, and blast. Usually, an attempt was made to assess the repair status for each vehicle. Casualty information, statements from interviews with military personnel, photographs and medical records accompanied BDARP reports. Thus, the BDARP reports were more detailed than COLED-V reports. In July 1970, the Army decided that sufficient information was available to meet its requirements so data collection was terminated.

The results of BRL's work showed that fire and explosion effects usually accompanied combat losses of M48 tanks in Vietnam, because most fires spread eventually to the ammunition, if they did not start there. It was clear from the data that mines were the dominant cause of loss, but they caused fire and explosion less than ten percent of the time. Shaped charges and other methods of attack accounted for only about twenty percent of the losses, but were accompanied by fire and explosion at least fifty percent of the time. For shaped charge attack, ammunition seemed to be primarily responsible for fire/explosion two-thirds of the time and fuel responsible for only one-third of the time. In cases of mine attack the roles were reversed, with fuel responsible two-thirds of the time and ammunition responsible about one-third of the time. Casualty rates were clearly higher for shaped charge attack.

The application of the Armored Vehicle Vulnerability Analysis Model (AVVAM), see above, to an analytical study of the USSR T55 Tank in 1974, illustrates the ever-increasing capability of the Laboratories to make detailed, complex vulnerability analyses. The analysis quantified the lethality of a spectrum of shaped charge effects in frontal attack on the T55 medium tank. The results illustrated the behind-armor effects characteristics and their combinations that would be most lethal in achieving a firepower kill, given a hit on the tank. AVVAM accounted not only for damage inflicted on components in the direct line of fire, (shotline) but also for the damage inflicted by armor spall or munition sprays on components located away from the munition shot line.

The essentially constant evolution of USSR armored vehicles called for continued vulnerability analysis by BRL, often hampered by a lack of specific data. Thus considerable effort was expended in constructing estimated target descriptions and extrapolating improvements in Soviet systems. Nevertheless, BRL did carry out many vulnerability analyses on Soviet equipment. Included in such analyses were the Joseph Stalin III, the T-54, T-55, and T-62 medium tanks; the BTR-60 PB armored personnel carrier, the PT-76 amphibious tank, and the BMP-76 amphibious armored infantry combat vehicle. In several instances, under the FEVA program, prompt and residual radiation shielding characteristics were obtained.

Other Vehicles. The use of gasoline or diesel powered cargo vehicles for logistical support of military operations is of prime necessity in the distribution of materiel or personnel to specific points of operations. Thus, information concerning the vulnerability of such vehicles is of particular interest to the services. Analyses of trucks and their components considered threats from blast, fragments and fire. To answer a question from AMSAA as to whether radial tires would be more resistant to perforation than bias-ply tires, BRL conducted firing tests against both types of tires. The results showed no differences in protection, provided that the thickness of the two types of tires is the same at all points. More generally, the results of the experiments were used to derive an empirical equation describing the residual velocity of a fragment after it perforates various thicknesses of truck tires.

A comprehensive vehicle vulnerability program was initiated in the fall of 1963 between BRL and the Naval Weapons Center, China Lake, California. The program was designed to determine the vulnerability of several generic foreign truck targets to a broad range of penetrating damage mechanisms.

Generic truck targets were designated by BRL on the basis of evaluation and classification of Sino-Soviet bloc vehicles into general types. The Falcon R & D Company, under contract to the Naval Weapons Center, developed the technical target descriptions and programmed mathematical descriptions for use with computers.

The USSR Zil-157 Truck was the first to be studied. The Zil-157 is the principal medium truck of the USSR Army. Other Soviet trucks analyzed included the KrAz-214, the principal heavy duty truck; and the Zil-130G, a long wheel base cargo vehicle. Initially, the estimated vulnerability data were based on analyses of US trucks; however, as intelligence data became available, more accurate target descriptions were developed for those Soviet vehicles.

Weapon Systems. For many years vulnerability analyses of US artillery systems had been incorporated in weapon systems analyses performed by BRL. For the most part, too, only the artillery crew had been considered vulnerable at an artillery position. The materiel and its ammunition had been excluded from the analyses because no approximate vulnerability data had been available. However, with the formation of the Vulnerability Laboratory in 1968, more emphasis was placed on the analyses of US artillery systems *per se*. The development of the Com-Geom and GIFT codes for constructing target description proved to be invaluable in the rapid preparation of reliable vulnerability analyses of artillery weapons. For example, in 1975, BRL completed a vulnerability analyses for a firepower kill of four US towed artillery weapons. The four pieces included two 105-mm and two 155-mm guns. The threat was posed by a single, compact, steel fragment. The analysis showed a clear ranking of the vulnerable areas of the weapons.

The increasing emphasis on the vulnerability of artillery weapons was paralleled by a similar increasing emphasis in the vulnerability of ammunition. Until 1970, efforts to derive a satisfactory measure of the vulnerability of high explosive munitions to steel fragment attack had been hampered by a lack of experimental data. To remedy this deficiency, BRL carried out a number of tests in which steel fragments were fired against US 90-mm, 105-mm, 175-mm HE (composition B) artillery projectiles, 81-mm shells containing TNT, and various sub-munitions. (Similar tests were also carried out against some foreign ammunition; the limited data from these tests did not provide a sound basis for rigorous statistical analysis). The results from the US ammunition tests were used to determine the contributions of fragment mass and striking velocity required to initiate explosive reactions with an associated probability.

Soviet systems for which vulnerability estimates were made included the truck-mounted 17 round, 140-mm rocket launcher, the 57-mm S60 anti-aircraft gun, and the 152-mm D20 gun/howitzer. In 1975 the Laboratories assisted the Vulnerability Analysis Team at the U.S. Armament Command, Rock Island, Illinois, in generating vulnerability data on a 122-mm D-30 gun howitzer.

Radar Systems. The capability of modern military aircraft to penetrate target areas at sonic speed and over a wide range of altitudes essentially excludes all methods for detecting aircraft other than radar. The consequent importance of radar installations as elements of a defense system led to consideration of radar vulnerability. BRL efforts in this field began in 1960 when the Naval Ordnance Laboratory asked BRL to test the vulnerability of early warning antenna assemblies to air blast. Such efforts continued intermittently until 1974; during that year some fifty parabolic antennas were damaged through a variety of techniques. Spherical charges of pentolite provided blast overpressures and small high explosive bomblets provided fragments for damaging the reflectors. Other reflectors were damaged by crushing or removing sections. The results showed that the antenna performance was relatively insensitive to loss in surface area until about twenty-five percent of the surface area had been removed, but was very sensitive to surface deformation caused by blast overpressure.

Nuclear Weapons. Under a program that began in 1949, BRL continued to conduct test firings of fragments against nuclear warheads. The work was done for the Defense Atomic Support Agency (in 1956, the Armed Forces Special Weapons Project) under its Atomic Weapons Vulnerability Program. The components of nuclear warheads were analyzed to determine the effects on a warhead's operation if each component was damaged individually or in combination with other components. The Laboratories provided estimates of vulnerable areas resulting in a "dud" weapon assuming a random direction of attack, and probability of a weapon kill for several fragment weights. The program was completed in 1966.

Vulnerability Reduction. The spectrum of activities to reduce the vulnerability of surface targets was quite broad. During the years of the Vietnam conflict it embraced many *ad hoc* tasks, hastily accomplished to answer urgent requests from the combat zone for practical techniques to reduce the vulnerability of many classes of materiel. Typical of such requests was one from the Army Concept Team in Vietnam for a method to reduce the vulnerability of the M113 Armored Personnel Carrier to 57-mm and 75-mm recoilless rifle shaped charge rounds. While the detailed results of this particular task cannot be made public, the objective was met by the use of a bar-armor applique. However, despite the interruptions of planned activities, over this twenty year period, a continuing program was pursued to reduce the vulnerability of ammunition and fuels, all classes of materiel; to harden targets against blast, fragments, and shaped charges; and to decrease the vulnerability of armored vehicles to damage from internal stores.

Vulnerability Reduction in Stacked Ammunition. In the logistic process the Army accumulates large quantities of ammunition at various distribution points. While individual rounds of ammunition are inherently hazardous, when ammunition is stored in large quantities, fire or detonation greatly magnifies the hazard. Other than changes in the design of ammunition or changes in storage procedure, modifications of packaging to reduce combustibility are the primary means available for reducing losses.

The Ballistic Research Laboratories and Frankford Arsenal had engaged in a joint effort to evaluate the effectiveness of fire-retardant treatments in reducing the vulnerability of stacked 81-mm Mortar, 90-mm TP-T, and 105-mm H.E. Semi-Fixed ammunition. Tests were conducted wherein stacks of ammunition packaged in standard and modified packing material were subject to small arms fire and fragment impact. The tests showed that fire-retardant paint and chemical impregnation of the wooden ammunition boxes, can retard the rate at which fire propagates through a stack. Both treatments eventually fail if the stack is subjected to high-temperature over a long period of time.

Fire Safe Fuels. The usual approach to minimize damage ensuing from fuel fires is to use fire extinguishing equipment as soon as possible after a fire has started. In the case of solid combustible materials some progress has been made in preventing fires from even starting by the introduction of chemical fire retardants into the bulk of the material—making it more difficult to ignite. For liquid fuels, attempts have been made to reduce their fire hazard by altering their physical properties through gelling or emulsification. The addition of chemical fire inhibitors to liquid fuels to prevent fires seemed to have been avoided until the 1970's, when BRL researchers initiated work to find an inhibitor or combination of inhibitors which would render liquid fuels nonflammable at normal atmospheric pressure, but still permit them to perform satisfactorily in high-compression engines.

The work concentrated on the inhibition of diesel fuel, partly because the current trend was toward a universal fuel resembling diesel for all Army vehicles and aircraft. However, other fuels considered included gasoline and the jet fuels JP-4, JP-5, and JP-8. Also considered were hydraulic fluids, engine oils, and transformer oils.

Using halongenated hydrocarbons as chemical inhibitors for liquid fuels, BRL developed a method for reducing their fire hazard to zero under storage conditions without reducing their usefulness as fuels under engine operting conditions. Further development of the method was undertaken by the Army Mobility and Equipment Research Development Command Information about this BRL technology was sent also to the National Bureau of Standards, the University of Southern California, and the Illinois Institute of Technology.

An interesting incidental result from the research was the discovery that when Halon 1301, bromotrifluoromethane, was added to the intake airstream of a diesel engine, the engine RPM increased. This information was passed to the Naval Ship Engineering Laboratory, Philadelphia, Pa.

Reduction in the Structural Vulnerability of the XM198 Howitzer. A BRL vulnerability analysis of the XM198 towed 155-mm howitzer being developed in the 1970's showed that the new howitzer would be much more vulnerable to single fragment impact than the M114A1 howitzer then being used by the Army. Upon learning of this increase in vulnerability, the Project Manager for Cannon Artillery Weapon Systems requested that BRL undertake a program to increase the survivability of the XM198. The program was to proceed in three steps in which BRL would: first, demonstrate analytically that it was feasible to improve the survivability of the howitzer; second, propose specific modifications to the XM198 which would implement the vulnerability reduction features suggested through the analysis techniques; and, third, quantify the increase in survivability resulting from the proposed modifications.

Constraints imposed by the late stage in the design of the howitzer dictated that the addition of ballistic protection to the critical components be the technique used in this instance. After using a computer analysis to identify the critical components, BRL analysts evaluated the effectiveness of four different schemes. Through iterative exercise of the computer code a final configuration, incorporating optimum properties and thicknesses of materials for the gun equilibrators and an armor shield was chosen. The reduction in vulnerability achieved was more than twenty percent greater than the initial value believed possible.

Armored Vehicle Ammunition Vulnerability. Ammunition can be the most important single contribution to the vulnerability cross section in some systems for a given threat. BRL had shown that the propellant in large caliber ammunition is significantly more of a vulnerability problem than the high explosive fill of the warhead.

The introduction of combustible cartridge cases for large caliber rounds called for an examination of the effect on the vulnerability of various vehicles. For such analyses, the conventional metal-cased round was used as a reference standard; however, the analyses showed that even with the conventional cases, the rounds contributed significantly to system vulnerability. These results led to the realization that for comparison purposes the conventional round provided a poor standard.

This state of affairs led BRL researchers to seek new avenues for reducing the vulnerability of armored vehicles to internal ammunition stores—for example the use of externally vented ammunition compartments (a technique first proposed by the British) and low vulnerability propellant.

Vented ammunition compartments were being considered for use in the MBT70 about the time that tank development program had been cancelled. The Tank and Automotive Command and the Project Manager for the XM803 Tank (successor to the MBT70) had applied the compartment concept to the follow-on tank. Results from tests with the XM803 gave rise to cautious optimism although more data and evaluation were required before the vented compartment concept could be declared feasible.

In December 1975, BRL conducted tests with live 105-mm rounds stored in simulated tank ammunition compartments. These tests were part of a program to generate information for the design and evaluation of such compartments for the developing XMI Tank. The program was sponsored by the Project Manager's Office for the XMI; in its final form, the XMI or General Abrams Tank would incorporate vented ammunition storage compartments.

In the same year, BRL investigated the possibility of developing a propellant which provided equivalent ballistic performance at much higher thresholds for impact and thermal initiation. To evaluate the concept, BRL researchers selected a propellant that had been developed as a candidate for caseless small arms ammunition and which appeared to have reasonable impact and thermal stability. This propellant designated LOVA-XIA (Low Vulnerability Ammunition) was composed of 75 percent HMX explosive and 25 percent polyurethane as an inert plastic binder. Results of impact and thermal tests showed that propellant vulnerability could be adequately reduced with a propellant formulation such as LOVA-XIA. The next stage in the research would be evaluation of the interior ballistics performance of the propellant. (See Interior Ballistics Chapter.)

In 1976 BRL applied the ammunition compartment concept to the US 155-mm self-propelled Howitzer, M109. As was the case for the battle tank, analyses showed that the vulnerability of the entire system could be reduced drastically if the vulnerability of the propellant charges could be reduced or eliminated. To validate the concept, the TERA Group of the New Mexico Institute of Mining and Technology constructed and tested a series of vented ammunition compartments. The last test in the series involved a full-scale compartment, large enough to hold eleven propellant charges, bolted to the side of the interior of a Self-Propelled Gun hulk. From the results of the tests, BRL vulnerability experts concluded that a vented ammunition compartment would indeed reduce the vulnerability of the M109 SP Howitzer.

ASSESSMENT OF THE CONTINUOUS WAVE LASER THREAT

The potential of high-powered continuous wave (cw) lasers for use as offensive or defensive weapons introduced a new dimension to vulnerability and vulnerability efforts at BRL. In developing methods for assessing the vulnerability of cw lasers, BRL logically took the existing methodology for conventional weapons and adapted it to lasers. The adaptation was needed because of the marked differences in the characteristics of lasers compared to those of bullets or fragments. The most critical difference is the continuous nature of the laser threat versus the discrete (time) nature of penetrating munitions. Too, the accuracy with which a laser can be trained on a target is very different from the almost random distribution of fragments from a shell. A third difference lies in the size of the impact area, which is small in the case of a bullet or fragment, but could be larger than many vulnerable components in the case of a laser.

Disregarding damage mechanisms that are specifically intensity dependent (such as blow-off impulse loading), BRL analysts were able to account for the differences and construct a laser vulnerability analysis model. The model offered quick implementation, making use of previous target data; fitted a fairly wide range of parameters with one analysis; and was amenable to sensitivity studies and optimum parameter searches.

An early application of the laser vulnerability code was its use in the generation of data for use with a missile vulnerability code. There was some Army interest in using the high energy laser as a defensive weapon against tactical air-to-surface missiles. To evaluate the laser's effectiveness against missile threats, missile vulnerability data were required. BRL analysts constructed such a code and prepared a code user's handbook. The output of the code combines the results of both catastrophic and subtle kill mechanisms and gives the differential probability of hit as a function of miss distance dP_H/dx. The missile vulnerability code required two basic types of input—the probability of kill data provided by the laser vulnerability code and intelligence information about specific targets—to produce an overall probability of kill as a function of laser dwell-time.

During the 1970's BRL completed laser vulnerability analyses on helicopters, various missiles, and other Army materiel. As of this writing, the results remain classified. At the same time these vulnerability analyses were being carried out, the underlying phenomena of high powered laser effects were being investigated by the Terminal Ballistics Laboratory.

SPECIAL PROJECTS

Although vulnerability analysis was a discipline little more than a decade old in 1957, it had proven its value as an analytical tool for weapon systems evaluation, and thus, for informed decision making. The Laboratories' competence in this field was widely recognized, and as a result, Army agencies and others called upon the Laboratories to lead many special projects, such as those which follow.

Foreign Equipment Vulnerability Analysis (FEVA). Project FEVA was established in August 1969 to exploit USSR combat materiel acquired by the US Department of Defense. Acting as the agent for DOD, the Army Materiel Command distributed various types of this materiel among the commodity commands and laboratories, according to their primary missions. This was done following the premise that the experience and basic knowledge necessary to recognize significant improvements and useful design techniques resided with those development commands where the final exploitation would have to be made.

The drawback to that approach was that the prime capability to quantify the sensitivity to targets to various damage mechanisms and for target vulnerability analysis existed at the Ballistic Research Laboratories. Thus, AMC appointed BRL executive agency for the FEVA project and gave the Laboratories responsibility for training Vulnerability Analysis Teams (VAT's) which were to function at each of the commodity commands. While AMC provided some funds to encourage the commands to form the basic teams, FEVA was to be carried out by people then employed. (Unfortunately, this plan was hampered because AMC was undergoing a reduction in force at the time.)

Project FEVA was an outgrowth of Project MEXPO sponsored by the Joint Technical Coordinating Groups for Munitions Effectiveness. One phase of Project MEXPO consisted of vulnerability analysis of Soviet combat materiel. For this phase, in September 1968, almost sixteen months after the Arab-Israeli "Six Days War," a group of US scientists, engineers, and technicians representing the three US Services, and including the US Marine Corps, proceeded to Israel to conduct an on-site evaluation of the vulnerability of Soviet materiel. The vulnerability was analyzed through an extensive examination of combat damage and the results from controlled experimental firings of US ammunition against the Soviet materiel.

Project FEVA provided an unusual opportunity for determining the vulnerability of MEXPO materiel to US weapon systems, preparing target descriptions for US evaluations of foreign materiel, and substantiating analytical predictions.

Wooden Shoe. The office of the Chief of Ordnance requested, in October 1961, that the Laboratories examine applications of conventional anti-materiel ordance to unconventional warfare. Personnel of the OCO believed that a systematic study of the types of targets that might be encountered in unconventional warfare (UW) could aid in coordinating research and development activities associated with UW—activities under the control of OCO. Their opinion was supported by the fact that many of the targets which might be involved in UW were substantially different from those normally considered to be military targets, and so, the method of attack could be radically different.

While in the past considerable attention had been devoted to military targets and effectiveness of various weapons against them, little attention had been focused on the types of target which might be attacked profitably by guerrillas or underground resistance forces using means at their disposal.

BRL's first step was to survey any existing knowledge and other current activities related to unconventional warfare and anti-materiel devices and techniques for their use. A three month effort by BRL resulted in these findings:

- the destruction achieved by guerrillas and underground fighters could produce results greatly out of proportion to the number of men and the amount of materiel committed,
- the current research activities aimed at improving destructive capabilities of guerrillas and underground forces were small and relatively uncoordinated, and
- no one had sufficient knowledge to achieve essential coordination; this was largely because there had never been a systematic study of targets and their vulnerability to destructive devices.

BRL suggested that the Ordnance Corps was well qualified to lead a systematic analysis of target vulnerability and suitability, because of existing facilities, technical competence, and extensive experience in vulnerability analysis. It was pointed out that proper implementation of a vulnerability program would require participation by research and development agencies of the other Army Technical Services and agencies outside the Army.

Subsequently, an effort was undertaken, Project Wooden Shoe, to collect information of UW targets, analyze the targets to identify vulnerable points, test means for destruction against actual targets, recommend research and development needed, and publish sabotage and destruction manuals.

BRL contributions to Wooden Shoe were a

series of analyses categorizing targets which could be found in various geographical areas believed to be susceptible to unconventional warfare. Each analysis was accompanied by a review giving insight into the kind of society formed by the indigeneous population, and its economic, intellectual, governmental and military development. The analysis included tables of target complexes, with priority evaluations for destruction, component vulnerability and other pertinent remarks. This series of analyses was augmented by reports analyzing specific subsets of targets, reporting the results of tests designed to evaluate the practicality of using conventional ordnance items as UW weapons, and describing special UW devices.

Project HAVE NAME. Carbon-graphite fibers are used widely as the main component in composite structual materials. Although weighing very much less, these composites have strengths equal to those of metals. Thus, they are very attractive for use in commercial, industrial, and military products where weight-saving is important. Consequently, they have found many applications; for example, in aircraft frames and aerodynamic surfaces, automobile components, and so forth. Many sorts of carbon-graphite fibers have been manufactured for use in composites, but while useful, these fibers can be an electrical hazard under certain circumstances.

The fibers are electrical conductors; when electrical or electronic equipment is operated in a carbon-graphite fiber-laden environment, airborne fibers may enter the equipment, bridge electrical gaps, and cause the equipment to fail. While the hazard to industrial complexes had been recognized and documented, vulnerability experts at BRL were the first to quantify the threat posed by carbon-graphite fibers to many classes of military equipment. They gave the code designation HAVE NAME to the phenomenon associated with the hazard. Their assessment of the seriousness of the threat was supported by AMSAA, who recommended in 1972 that BRL be appointed the lead agency for a comprehensive program to predict vulnerability of foreign equipment and susceptibility of friendly systems to carbon-graphite fibers.

A project office was established at BRL to do fundamental research into the nature of the phenomenon, to lead vulnerability analyses of all classes of Army materiel, and to coordinate Army efforts with those of the Navy and Air Force. In June 1975, the Department of Defense set up a Tri-Service Joint Technical Coordinating Group for HAVE NAME.

The results of the HAVE NAME Project, which was terminated in the late 1970's, were numerous analyses of all sorts of military materiel, methods for predicting vulnerability and susceptibility of equipment to carbon-graphite fiber threats, and publications of numerous guides and handbooks for the protection of electrical and electronic installations and equipment.

Suppressive Structures. The application of suppressive structures to ammunition production lines in lieu of reinforced concrete walls is based on the concept that vented walls will be exposed to less blast loading than solid walls. Because the four walls in a suppressive structure could be designed to remain intact after an accident, the structure would offer less hazard to surrounding buildings and passersby than the currently-used production buildings which have a blow-out wall and roof. (The original concept for a suppressive shield was proposed by Paul King, a former BRL safety officer, then employed by National Space Technology Laboratories, General Electric Corporation.)

Under the management of Edgewood Arsenal, an AMC program was initiated to demonstrate the feasibility of suppressive shielding for a spectrum of hazardous operations and to ready the concept for use in a Munitions Base Plant Modernization and Expansion Program. Edgewood Arsenal solicited BRL assistance on both of these endeavors. The Laboratories were asked to participate, first as a critic then later as the main testing agency in their "Category 1" feasibility demonstration. Category 1 represented the largest fragment and explosive hazard to be considered; a typical Category 1 operation involved an ammunition melt-pour system processing 2500 pounds of TNT. BRL recommended strongly that a series of scaled tests be performed to screen candidate materials and structural designs and that the scaled tests be followed by one full-scale final test. Edgewood Arsenal agreed and BRL was asked to conduct the scaled tests. BRL conducted one-quarter scale tests in 1975 and full-scale fragmentation tests against segments of four candidate shields in 1976.

Nuclear Reactor Containment. For the Atomic Energy Commission, the Labortories conducted comprehensive experimental and analytical studies of the response of reactor containment shell to simulated reactor "runaway". The possible but remote danger that a nuclear reactor may produce a power "excursion," where energy could be released at a much higher rate than normal, was (and continues to be) of vital interest to the civilian population as well as those directly concerned in industry and government. Although an "excursion" is not a nuclear explosion, should an "excursion" occur, the reactor core could be disrupted and contaminate the surrounding atmosphere and water. Thus, all nuclear reactors constructed near inhabited areas are surrounded by a containment shell designed to contain the most violent power excursion of which the reactor is credibly capable.

Since the existing knowledge was based entirely on theory, the objective of the BRL work was to quantify dynamic and static loading of containment shells under various energy release rates and to determine a theoretical and analytical base for design criteria. The experiments included measurements of air blast resulting from bursting reactor core vessels and measurements of the response of a series of scaled model reactor containment shells to the simulated excursion. The range of energy release rates probable in nuclear power excursions was simulated by using propellants and high explosive which reacted at various rates.

While these studies were in progress, in 1957 the Air Force's Wright Air Development Center, planning a nuclear reactor for research and development work, consulted BRL regarding the adequacy of a proposed design for the containment structure. Based on the results from experiments on a one-quarter scale model of the reactor constructed at BRL, recommendations were made for minor modifications which were expected to make the structure entirely adequate.

This work on reactor containment, sponsored since 1956 by the Reactor Development Divison of the AEC, came to a successful conclusion in 1963. A number of analytical solutions and experimental vertifications of elastic and plastic container shell responses were obtained for a wide variety of conditions. Experiments also yielded a method for increasing the blast resistance of outer containment vessels by lining them with shock absorbing materials. The most significant results were incorporated into a "Handbook of Outer Containment Structures" for use in nuclear reactor design.

The Performance of Handgun Ammunition. A Handbook for the Law Enforcement Assistance Administration (LEAA). In December 1972, the National Institute of Law Enforcement and Criminal Justice of the LEAA approved and funded a project to study the terminal effects of police handgun ammunition. The project had been proposed by the Law Enforcement Standards Laboratory (LESL) of the National Bureau of Standards. Late in 1973, LESL awarded a contract to BRL to conduct the study, report the results, and draft guidelines for the selection of ammunition for law enforcement services handgun ammunition.

The impetus for the program had come from law enforcement agencies throughout the United States who had questioned the effectiveness of their service ammunition. Many who had not already adopted a new caliber weapon and ammunition were considering the possibility of doing so. The trend was toward higher velocity ammunition or to a different, usually larger, caliber weapon. The trend was prompted by law enforcement agencies growing awareness of the ineffectiveness of the traditional police service round, the caliber .38 Special round nose lead bullet. Unfortunately, this ineffectiveness was brought to light often by the wounding or death of a policeman who had hit his target but was unable to incapacitate his opponent.

Although the change might appear to be a simple decision to a patrolman, it is often a complex problem for the agency and the local government, who must consider every effect which any change in ammunition may have on the community. The choice of one round over another, or of one caliber in favor of another, depends upon the answers to technical questions. But, the lack of credible answers to those questions made such decisions complex and speculative. However, bullet selections must be made with due regard to the effectiveness against the criminal—as defined by maximum stopping power (not lethality) and maximum safety to citizens.

To provide state and municipal law enforcement agencies with guidelines for the selection of handguns and ammunition, BRL analyzed three characteristics of the terminal behavior of handgun bullets. These were the relative incapacitation of human targets, ricochet hazards, and material penetration capability. The emphasis was on commercially available ammunition from 9-mm (caliber .355) to caliber .45. The Laboratories conducted extensive investigations of all significantly different handgun bullets in that range of calibers, available to US law enforcement agencies. The experiments were carried out to determine exactly what produces human incapacitation by handgun bullets (relative stopping power); which, if any, of the existing theories on the subject were correct; and, in particular, whether relative stopping power could be determined solely in terms of bullet properties, i.e., mass, velocity, shape, construction, and caliber.

The model for stopping power consequently developed was based on a complete assessment of a confrontation between an officer and an armed criminal. The behavior of the bullet in the target was only one variable in the data used in the model. The vulnerability of humans to incapacitation by bullets, the trajectory of the bullet within the body, the ability of the officer to hit the target, and his point of aim were considered in detail.

The information and conclusions from this BRL work were incorporated in the LEAA Handbook, "Performance of Handgun Ammunition."

Tank Gun Rounds Versus Masonry Structures. The assessment of potential threats to the security of the United States emphasizes the importance of possible Western Europe battle fields. Both NATO and Warsaw Pact forces are built primarily around fast moving mechanized/armor units. However, cities and towns built across many critical avenues of approach create obstacles to the rapid movement of forces in Europe.

A re-evaluation, in the early 1970's, of the importance of masonry targets in those urban areas engendered a new interest in the terminal effectiveness of ammunition against such targets. Reliable predictions on the lethality of munitions against masonry structures could not be made because of the lack of quantified test data upon which to base such estimates. Some data were available for complete structures.

To obtain some of the needed information, BRL, the Armor Center, and the Viper Project Manager's Office jointly planned and conducted an effectiveness test of 105-mm tank ammunition, the LAW, and the tank-mounted LAW systems against masonry targets. AMSAA also supported discussions defining the test objectives.

Target structures which had been built in the 1950's for atmospheric nuclear tests were made available by the Nevada Operations Office of The Energy Research and Development Office. Rounds were fired against five types of walls, including brick, brick and cinder block, and various thicknesses of reinforced concrete.

The results provided immediate useful information to the armor community on the comparative performance of 105-mm high explosive ammunitions and were responsible for changes in training, tactics, and ammunition development. The Viper Project Manager and the Infantry Center also found the results of the LAW and tank-mounted LAW tests useful.

The time was ripe in 1953, to take advantage of advances in the professional field of operations research, computer capacity and speed, and the outstanding competence of BRL scientists and engineers, particularly Dr. Frank Grubbs, in applied statistics and weapons reliability, and Morgan G. Smith in weapon systems evaluation.

The Weapon Systems Laboratory with Dr. Grubbs as its chief, was established then to exploit those three factors for weapon system analysis and evaluation. Operations research techniques were applied to research in methods for evaluating complete weapon systems as well as to evaluation of the methods themselves. The discipline inherent in statistics was applied to the design of experiments to provide data for weapon system analyses and to the surveillance of ammunition, an activity that had broadened to encompass many other subjects.

Early representative research in methods for evaluation included work on ground target distribution, techniques for computing lethal areas for fragmenting devices, combat analyses, optimum dispersion of a salvo of rounds to achieve an engagement kill, and analyses of tank duels.

The establishment of a war games and game theory branch made it possible to apply game theory and the methods of operations analysis to the evaluation of weapon systems. Much of the work beginning in 1956 and lasting for several years thereafter concentrated on reducing military strategies and decisions to a mathematical form that could be programmed for use with the digital computer. The computer program thus developed could be used for numerical treatment of simulated battles where it was possible to analyze the influence of variations in tactics and in the use of certain weapons in a particular engagement.

From 1953 until 1968, vulnerability analysis and vulnerability reduction techniques were subjects carried within the general purview of weapon systems evaluation. Although weapon systems evaluation depended heavily for input information upon the other Laboratories, particularly the Target Applications Branch of the Terminal Ballistics Laboratory, it was the demand for information useful for vulnerability analysis that was most pressing. The need for such information became ever more critical and urgent as American troop involvement and combat activities expanded in Southeast Asia. With the establishment of the Aberdeen Research and Development Center in 1968, BRL retained responsibility for generating vulnerability information, although responsibility for overall materiel evaluations passed to the Army Materiel Systems Analysis Agency (AMSAA), newly formed about a nucleus of people from the former Weapon Systems Laboratory. AMSAA's responsibilities included re-

Mr. Morgan G. Smith, Chief, Weapon Systems Laboratory, 1967 to 1970, received his BS (Mechanical Engineering) from the University of Mexico. Before coming to BRL in 1949, Mr. Smith was a mechanical engineer with the Research and Development Division of New Mexico School of Mines; there he was in charge of aircraft damage trials. He left the Laboratories in 1970 for a position as Division Chief, Army Materiel Systems Analysis Agency.

search on methods for evaluating weapons, weapon systems, and ammunition, as well as war gaming.

The Army's need for vulnerability information was expanding, due in no small part, to the spin-off of AMSAA, so in mid-1968 the Director of BRL established a Vulnerability Working Group within the Terminal Ballistics Laboratory. By mid-1969, this Vulnerability Working Group consisting primarily of people from the Target Applications Branch had been augmented by a group of vulnerability specialists from AMSAA to form a Vulnerability Laboratory in BRL. (To provide continuity in the discussion of vulnerability efforts, this volume devoted a separate chapter to the history of vulnerability and vulnerability reduction at the Laboratories.)

After 1968 weapons systems research took a new tack at BRL. Emphasis was placed on new technical approaches (or combinations of approaches) for solutions of Army problems. This emphasis led to the formation of the Concepts Analysis Laboratory (CAL) during the first half of 1971; the new laboratory replaced the Signature and Propagation Laboratory. The Concepts Analysis Laboratory subsequently became the focal point for the technical system studies at BRL—integrating various scientific and engineering capabilities of BRL to concentrate them on the analysis and synthesis of system concepts. Technical system studies by CAL did not consider logistics, lifetime costs, tactical scenarios, and so forth; those subjects fell within AMSAA's purview.

During its lifetime, 1953 to mid-1968, the Weapon Systems Laboratory completed a remarkably large number of weapon systems evaluations. After the end of the Korean War, the urgency with which results were required was none the less, because the Ordnance Corps and later the Army Materiel Command needed the information as a basis for decisions concerning long lead-time weapon development (and costs and cost impact on other systems). Developing combat engagements in Vietnam made the results even more urgent and critical.

As was the case in Volume I of this history, it would be neither practical nor desirable to attempt to describe in detail all of the weapon systems evaluations at BRL. Accordingly, only the character and scope of the weapon and weapon systems evaluations, with some examples of important results to provide the flavor, will be discussed in following sections. Before proceeding, however, it seems appropriate to discuss, as distinct subjects, the Future Weapon System Agency at BRL and the Joint Technical Coordinating Group for Munitions Effectiveness. The description of weapon systems and concepts analysis work follows this discussion.

THE FUTURE WEAPON SYSTEMS AGENCY

Early in the spring of 1958, there occurred an event which was to have important effects upon

Mr. Harry L. Reed, Chief, Concepts Analysis Division, received his BS degree from the Massachusetts Institute of Technology. Except for an eighteen month stint as the Scientific Advisor to the Director of Development, Office of the Chief of Research and Development, Department of the Army, Mr. Reed has been at BRL since 1950.

Army material and doctrine development. This was the formation of the Future Weapon Systems Agency (FWSA) at BRL. At that time the Ordnance Commodity Command System was organized to provide effective research and development in several classes of material as, for example, tanks through the Ordnance Tank and Automotive Command, guns through the Ordnance Weapon Command, and rockets and guided missiles through the Army Ordnance Missile Command. However, often it was not immediately obvious whether a given requirement could be met best by a tank, a gun, or a guided missile, or by some other means. Some planners believed the assignment of the job to determine how best the requirement could be met to a commodity command could tend to prejudice the answer. It was to help provide an unbiased source of sound technical advice on weapon systems development to the Assistant Chief of Ordnance for Research and Development that the Agency was formed. Of course, BRL was already acting as such a source through the Weapon Systems Laboratory; however, the time scale to be considered by the FWSA was much more distant in the future.

It was particularly fitting that a group at the Ballistic Research Laboratories was chosen to perform this task for the Assistant Chief of Ordnance, because the rich background of BRL in the basic fields of science underlying weapon system design and the pioneer work in weapon systems evaluation at the Laboratories provided the new agency with a broad base of technical support at a level of competence not available elsewhere.

A talented and able staff of BRL scientists and engineers was directed brilliantly by Mr. Charles L. Poor, who until his appointment to direct the Agency had been the Chief of the Exterior Ballistics Laboratory. (Mr. Poor was later to become Deputy Assistant Secretary of the Army for Research and Development.)

Initial efforts of the Agency were directed towards learning the needs of the Army and how they might be satisfied. It became clear that there was a vast potential for the development of sophisticated weapons in the industrial and scientific communities of the nation. By the same token, however, the people who could help most in developing better weapons were not acquainted with Army tactical needs. In general, they had concentrated on the weapons of total (nuclear) war. Since World War II, there had been major work on intercontinental ballistic missiles, on the air defense of the United States, and on submarine systems for strategic attack; the technologists of the country had been little concerned with and had done little work on new or improved Army weaponry.

As conceived by Mr. Poor, the "Prospect Summer Study" was the first step in learning what contributions technology could make to Army weaponry. The study dealt with weaponry for limited war, in the context of the study meaning all wars except those involving nuclear attack on the homelands of the major world powers.

The premise underlying the study group plan was that a group of highly competent scientists and engineers, drawn from universities, industrial groups and the technical services of the Army, could contribute significant new ideas in weapon system planning—provided they were given an adequate understanding of the purely military aspects of limited war.

An outstanding group of people was assembled for the permanent staff of the Prospect Study. Nearly fifty full-time participants brought together most of the technical skills needed for productive consideration of the problems of weapons for limited war.

With the help of background material provided by some fifty visiting speakers competent to speak with authority on subjects ranging from US foreign policy and its military implications through operational engineering and scientific concepts, the group prepared reports on limited war and then current US technology.

The results from Prospect Study fell into two major categories: influence on planning for research and development and changes in specific development programs. The Prospect reports influenced planning at the US Continental Army Command (then), the Department of Defense, and the Technical Services of the Army. Findings from the study were incorporated in the Continental Army Command's Modern Mobile Army Study (MOMAR).

Prospect Study findings affected, directly or indirectly: Transportation Corps work on a floating base concept and the role of VSTOL aircraft in limited war, feasibility studies of closed-loop artillery systems at the Army Ordnance Missile Command, feasibility studies of an RF beacon by Diamond Ordnance Fuze Laboratory, and proposals for development of delayed fuzing for certain warheads.

Not an inconsiderable accomplishment of the Prospect Study was the assemblage of a group of outstanding experts who had an unusual opportunity to view the functioning of the US military establishment—a view freed of the restraints imposed either by military security requirements or limitations through consideration of political or doctrinaire bounds. Thus, available for future use was a staff of unusually well informed consultants.

FWSA took another important step when it accepted responsibility for conducting supporting research for anti-tank/assault weapons. (The ultimate result of this assignment was the development of the tube-launched, optically tracked, wire command link missile, TOW, which was used with devastating effect in the Vietnam Conflict and the Israeli Yom Kippur War).

The research was to supply information to evaluate, demonstrate feasibility, and design homing systems which had tanks as their primary target. The emphasis of the research was on the use of various electromagnetic phenomena for identification or illumination of targets and for the transmission of information. In carrying out the research, FWSA initiated two programs: a survey of the emission and reflection characteristics of tanks in their battlefield environments, and a series of tests to establish the feasibility of guidance and control concepts proposed by industry for assault weapon systems.

By 1960, the FWSA *per se* had evolved to a Special Projects Group under the direction of Dr. Lampson, but it still focused its activities in research to support the Army's Heavy Assault Weapon (HAW) Program. The supporting research program had been a combination of cooperative industrial efforts and BRL in-house research. Industrial efforts had a dual approach, to obtain immediate information about specific systems having a moderate degree of feasibility and, concurrently, to consider systems typical of classes of concepts. Thus, with the more general in-house research at BRL, the program covered the range of systems appearing to be achievable in the near future.

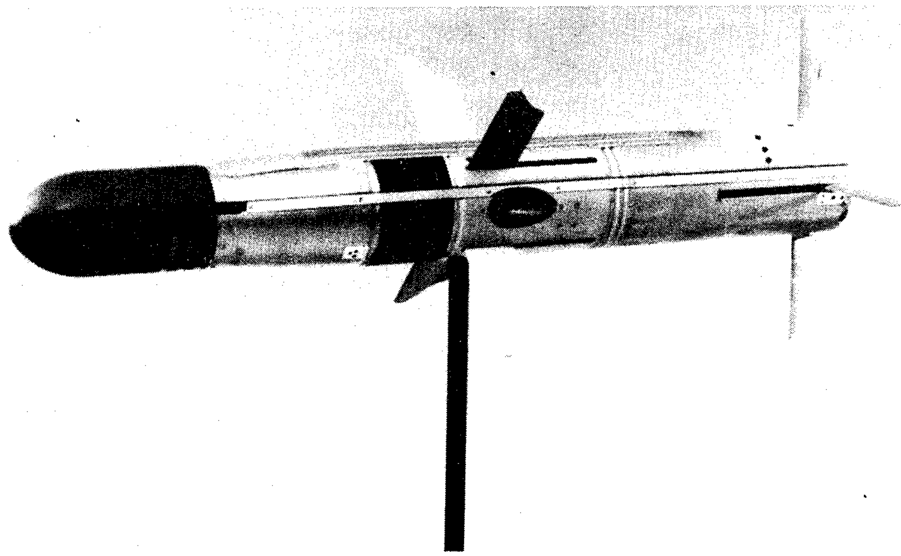
The Laboratories supporting research program in 1960, considered two system concepts: Line-of-Sight, considering automatically tracked missiles and beam riding missiles; and Indirect Systems, considering semi-active systems and passive homing systems.

In 1961, the Weapon Systems Laboratory and the Special Projects Group recommended the TOW infantry anti-tank system for development. The TOW concept was considered by BRL to be currently the most technically feasible anti-tank guided missile. Subsequently, the members of the Special Projects Group acted as technical advisors to thirty-five contractors who prepared proposals for engineering design studies of TOW. Eighteen proposals were received later and evaluated by experts from BRL and other agencies. From these proposals, three contractors were selected to do competitive engineering design studies and to make flight models to be evaluated by a committee of eminent US scientists and engineers. The committee chairman was Professor Maurice Zucrow of Purdue University.

In the meantime, the supporting research program had become largely an in-house program being conducted by personnel in the Ballistic Measurements Laboratory; there the program emphasized research in basic radar and optical phenomena.

The contributions of the Ballistic Research Laboratories to the TOW weapon were recognized in 1974, when, as a joint winner with the Army Missile Command, BRL was awarded the DAEDALIANS Weapons System Award. BRL was commended for its work in the early development and the demonstration of three prototype missiles flown in 1962; those flights proved the feasibility of the TOW concept.

This annual award consists of the Col. Franklin C. Wolfe Memorial Trophy bearing the names of recipients. Usually the trophy is retained by the recipient for one year, but in this particular instance, each winner displayed the trophy for



The Tow missile, sting-mounted for photographic purposes (Photograph courtesy TOW Project Manager's Office)

six months. The Order of Daedalians was established in 1934 by a group of World War I pilots to perpetuate the spirit of patriotism, the love of country, and the high ideals that place service to nation above personal safety or position.

THE JOINT TECHNICAL COORDINATING GROUP FOR MUNITIONS EFFECTIVENESS (JTCG/ME)

Since the inception of the JTCG/ME and up to the present time, BRL has contributed significantly to the success of the efforts undertaken by the Group and to the achievements of its objectives. At the onset of this discussion, it is important to note that the JTCG/ME is concerned with operational effectiveness of weapons, more specifically, the estimation of munition effectiveness in a real world environment which considers the degradation in delivery accuracy as a result of equipment and human factors, environmental effects, the nature and vulnerability of the targets, and so forth.

The JTCG/ME is an outgrowth of the recommendation of the US Air Force Close Air Support Board in 1963 for a joint-service publication containing a comprehensive list of targets and the effectiveness of various types of non-nuclear munitions. The Joint Munitions Effectiveness Manual (JMEM) Working Group was formed with tri-service (including US Marine Corps) representation in 1964 to respond to Joint Chiefs of Staff request for the JMEM. Responsibility for preparation of the manual and coordination of activities was assigned by the Army to AMC, who in turn assigned responsibility to BRL. Dr. Joseph Sperrazza, BRL, became the first chairman of the tri-services working group.

In a letter, February 1965, to General F. A. Benson, Jr., Commanding General of AMC, Dr. Sperrazza suggested that a Joint Technical Coordinating Group be formed under the aegis of the Joint Commanders of the Army Materiel Command, the Navy Materiel Command, and the Air Force Service Command. The purposes of such a Group would be to: resolve deficiencies relative to stockpiled non-nuclear munitions, establish interservice coordination for updating the manual (accounting for new weapons, new data, etc.), and investigate the desirability of expanding the then current effort to include all non-nuclear weapons, e.g., surface-to-surface and surface-to-air. This suggestion from BRL was accepted and the JMEM Working Group was redesignated the JTCG/ME in June 1965.

Also in 1965, the Joint Chiefs of Staff asked the Army to prepare and conduct a program, with full cooperation and coordination with the other services, to gather data on the effects of the environment on both controlled fragmentation munitions (then new) and conventional munitions. Known originally as the Joint Environmental Effects Program (JEEP), the program was later called the Degradation Effects Program (DEP) to avoid confusion with another program with the same acronym. Technical coordination between JTCG/ME and DEP existed informally from the onset; such coordination became formal in June 1966. In February 1968, DEP became an integral part of the JTCG/ME.

The Secretary of Defense requested that JMEM Air-to-Surface (JMEM/AS) methodology be extended to Surface-to-Surface weapons in May 1967. The JCS directed the Army to serve as executive agent for a JMEM for Surface-to-Surface (JMEM/SS) in June 1967. In September 1967, the Joint Commanders approved the plan for a JMEM/SS under the JTCG/ME.

IN February 1969, the Army asked the JTCG/ME to prepare a plan for multi-service evaluation of simple air defense weapons. The JTCG/ME Joint Air Defense Evaluation Program (JADEP) was established for this effort. Publication of the "Air Defense Model Index" in 1970 completed the tasks assigned to JADEP. However, because air defense and attrition are such important military considerations, the JTCG/ME in January 1971 inaugurated a new program, the Joint Aircraft Attrition Program (JAAP) to continue and expand on the JADEP. Around the beginning of 1973, the JTCG/ME instituted the Joint Munitions Effectiveness Manual for Air-to-Air (JMEM/AA). In July 1976, the JTCG/ME abolished the JAAP and the JMEM/AA and consolidated the surface-to-air and air-to-air tasks under the JMEM for Anti-Air).

The extensive JTCG/ME program provides, for the first time, all DOD elements with a uniform basis for weapons employment planning and operational use, determination of munitions requirements, evaluation of new weapon concepts, and stimulation of research and development efforts. Moreover, it marks the successful combination of predictive models, validation experiments and the results of battlefield surveys to give a realistic estimation of the operational effectiveness of munitions. This successful combination owes much to the leadership of BRL personnel who had pivotal roles in managing various tasks and sub-tasks and to the results at BRL research in Weapon Systems Analysis Methodology, Vulnerability Analysis, and Terminal Ballistics Effects. Much of the information from such research described in previous chapters had direct application to JTCG/ME activities and in many cases was generated to meet the needs exposed by the JTCG/ME.

After Dr. Sperrazza left BRL to become Director, Army Materiel Systems Analysis Agency, he continued to be Chairman, JTCG/ME. However, other members of BRL continued to participate in JTCG/ME management activities as chairmen or members of steering committees, working groups, and task groups.

METHODOLOGY

The development of rigorous mathematical models and computer programs suitable for weapon systems evaluation and the subsequent confidence which could be placed in the accuracy therefrom represent a truly remarkable achievement by BRL. Due in large part to the increasing capacity and speed of BRL Computers, and the improving competence of BRL analysts to exploit the new capabilities, weapon systems evaluation became a modern, increasingly sophisticated discipline, While the development in computers permitted the inclusion of more and more variable parameters into a system evaluation, concurrent research in statistics and statistical methods at the Laboratories permitted the higher degree of confidence to be placed in the results. These achievements were aided to a considerable degree when the Weapon Systems Laboratory was reorganized in the mid-50's to devote itself predominantly to systems analysis and evaluation.

Like the techniques used in systems evaluation, the development of analytical and evaluation methods was an iterative process. Assumptions were refined as firm data could be incorporated into models or as experience dictated. Considering the many factors such as threat, vulnerability, survivability, target acquisition, and target allocations, to name but a few, for which input information had to be generated, the construction and exercise of system analysis and evaluation models was a formidable task. The subjects below provide some insight to development of methodology at BRL.

An important aspect of the application of these methods to Army systems problems was the rapidity with which BRL could respond with solutions. BRL analysts worked continually under extremely short suspense times, times often measured in a few days, or in the case of very complex systems, a few weeks. The belief of the investigators in the reliability of the study's conclusions was usually confirmed later when time permitted a more complete and stringent analysis.

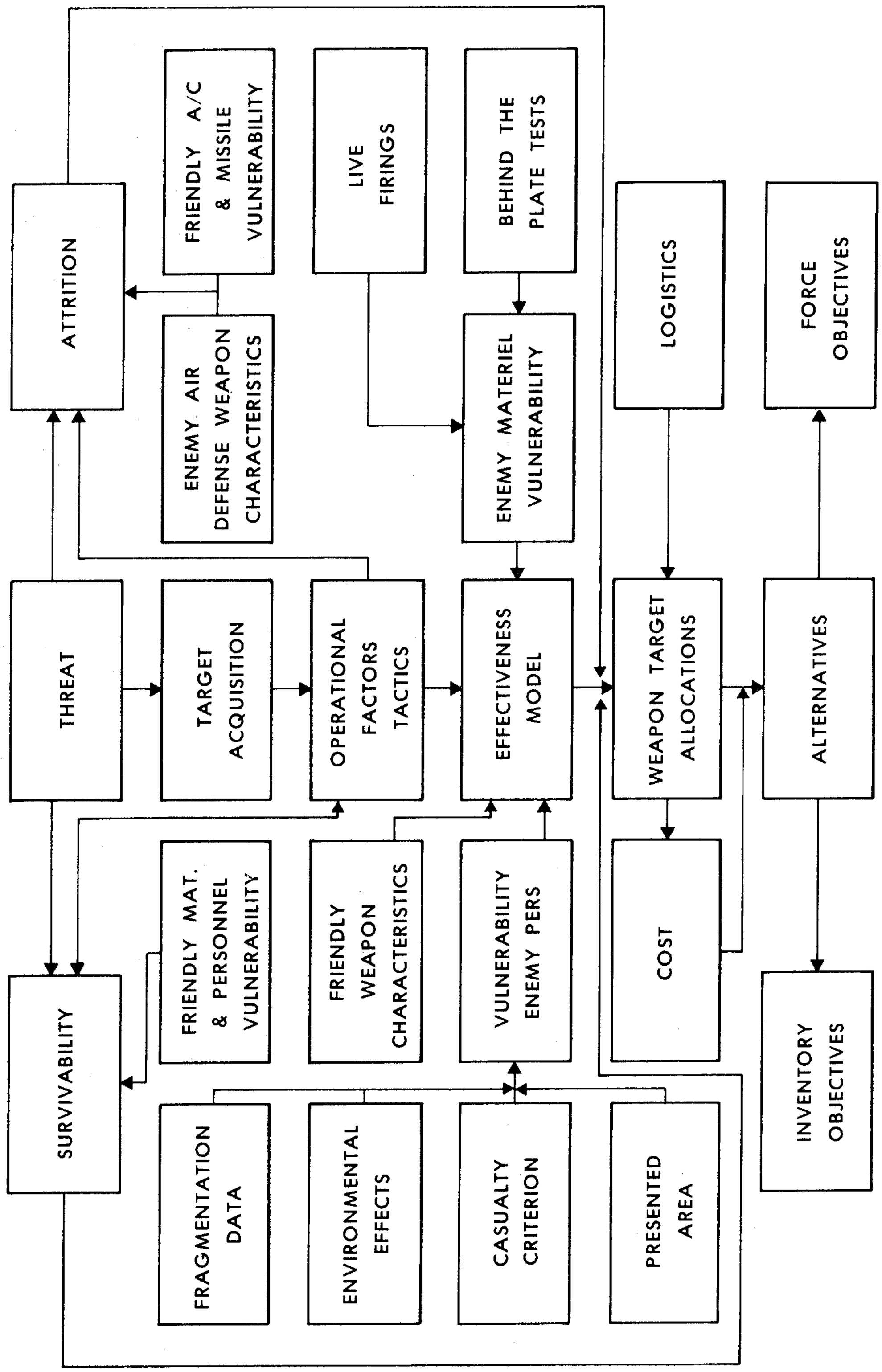
Cost Effectiveness Analyses. The need for a cost effectiveness analysis occurs when there are alternative means for obtaining a desired objective. In evaluating weapon systems, the analysis usually involves certain basic elements: the desired effectiveness against a potential threat (the objective); well-defined weapon families and weapon systems (the alternatives), measures of worth (for cost and effectiveness), and a method for integrating these basic elements, (methodology, the collection of methods used in the analysis and evaluation). Furthermore, to instill confidence, the results must be reported in an objective manner.

By 1966, BRL had established the general procedures for conducting cost-effectiveness analyses and a format for the presentation of results. The basic concepts in the procedure were applicable to analyses of almost any sort of weapon. The methodology used was predicated on the premise that the worth of a new system was based on the total expenditures required to build, field, and maintain the weapons systems in peacetime and the potential wartime effectiveness procured with these resources. Also, its capability should be measured, not by performance as a single weapon, but as a member of a family of weapons. Thus, the cost-effectiveness study aimed at an evaluation of alternate weapon mixes to attack a series of enemy threats. The accompanying illustration is a simplified flow chart for a BRL analysis comparing surface-to-surface artillery and tactical aircraft. Two things should be noted from the illustration; first, each of the governing factors has many subordinate factors which may be varied by the analyst to determine their impact on the outcome of the evalution; second, the analysis can evaluate dissimilar weapon systems performing a similar fire support role.

BRL developed the latter capability in 1964 as a result of a request from the Systems Analysis Division of the Army Chief of Staff for Force Development. The Laboratories selected the Lance missile and the F-4 tactical aircraft as the dissimilar systems to provide a case for developing the methodology. The similar fire support role was that of non-nuclear fire support to ground troops.

This new model introduced consideration of the times of target acquisition and target duration into the analysis. This was a beginning for methodology permitting consideration of the dynamic nature of the battlefield as combat progresses from one phase to another. By the beginning of 1967, BRL analysts had developed a "three dimensional" model which considered the two dimensional presentation of targets and weapons as well as the time-dependent availability of fire units to carry out their missions.

Ammunition Day of Supply. Since one of the factors affecting the worth of a system is the potential wartime effectiveness procured by the expenditure of US resources, it is important to know the summed total of the costs for an Ammunition Day of Supply. As defined in the Dictionary of Army Terms (Army Regulation 310-25, 15 October 1983), the Ammunition Day of Supply is, "the estimated quantity of conventional ammunition required per day to sustain operations in an active theater. It is expressed in terms of rounds per weapon per day for ammunition fired from weapons and in terms of other units of measure for bulk allotment ammunition items." BRL's initial efforts in this area were directed towards developing methodology,



Methodology Diagram: Cost effectiveness analysis for there was no reliable estimating scheme. The approach involved analyses of historical data, target complexes, target vulnerability, accuracy of fire, reliability and effectiveness of weapons, and so forth. Ammunition day-of-supply estimates were made for US tank armament systems and air defense artillery and missile ammunition for hypothetical non-nuclear battle situations in Western Europe. The tank ammunition expenditure was based on a Battelle Memorial Institute comprehensive analysis of tank fire in the European Theater of Operations during WW II.

Submodels for Inclusion in Effectiveness Schemes. As noted above, there were many contributing elements that affected the values assigned to the primary factors in a cost-effectiveness analysis. One for example, had to determine the distribution of targets, the expected coverage of an area by a salvo of rounds, the lethal area for particular weapons, the optimum allocation of weapons against a target, and a tactical scenario, to name a few. For those particular subjects BRL developed:

- Analyses describing the deployment of large scale USSR forces and the distribution of potential targets in a conventional or tactical nuclear engagement. Techniques were developed to subdivide large forces into division, battalion, and platoon sizes. Deployment was described in terms of offense and defense.
- Methods for determining the expected fractional coverage of a circular target with an n-round salvo; values for cover functions which quantify, as a function of height-of-burst and range, the average exposed areas of prone and standing men on an "average" terrain; lethal area estimates for fragmenting shell; and evaluating the effectiveness of a single nuclear weapon against a group of targets.
- A dynamic programming approach to give an optimum solution to the weapons allocation problem for the case involving constraints on the amount of ammunition used. Such constraints might include limited production, size and weight, logistics and so forth; because of the constraints, it might not be possible to totally destroy the target complex or to achieve the level of damage desired (which might be possible were resources unlimited). The problem reduces to minimizing the expected "worth" of surviving targets when resources are limited.
- War games designed for automatic play on digital computers. Two examples are ANSWEG, a non-atomic game and EXTAG, an atomic game. ANSWEG was used to study infantry brigade weapons, with emphasis on daily ammunition expenditures needed to defeat an agressor force having a numerical superiority. EXTAG was used to estimate the optimum numbers of launches of a proposed family of nuclear weapons needed by a US force to defeat a numerically superior agressor force.

ARMORED SYSTEMS

This section deals primarily with cost effectiveness and operations analyses of armor systems. The specifics of research in armor design, armament, and anti-armor projectile/warhead design at BRL have been covered in the chapter on Terminal Ballistics. Likewise, the details on armored vehicle vulnerability and vulnerability reduction—which were and are important factors in armored systems analyses—have been detailed in the chapter on Vulnerability and Vulnerability Reduction.

An important improvement in modeling overall tank effectiveness came about in 1957 with the introduction of a mathematical model describing the manner in which tanks choose cross-terrain routes. Before that time, the role of mobility had been left out of tank effectiveness studies. The question of mobility versus armor was one that was to be of continuous interest to BRL. In later years it became possible to construct an empirical relationship between armor and mobility which showed that tanks with better armor are preferable—for a tank mission limited to advancing a certain distance under fire on a hostile battlefield. By 1976 it was possible to compute the survival probability of a tank during a run on the battlefield. The effects of armor protection, mobility/agility and silhouette could all be calculated. Thus survivability of different combat vehicles could be compared and the effects of mobility and protection could be investigated parametrically. Application of the model to a comparison between the M60 Tank and the XMI Tank (later designated the MI Abrams Tank) clearly showed the advantages of the XMI's reduced silhouette, increased armor protection, propulsion and suspension systems.

The Main Battle Tank (MBT). At the beginning of the 1960's BRL became heavily involved in cost-effectiveness studies of alternatives for the post-1965 US Main Battle Tank. These studies were conducted to support the Combat Development Command and the Army Materiel Command in evaluating several possible MBT programs. At the same time, the Laboratories were involved with efforts of a NATO Technical Subgroup responsible for establishing essential capabilities for the future MBT. The efforts included field experiments and analytical approaches. The field experiments helped determine the probable distribution of the ranges of tank engagements that could be fought in northwest Europe, the ranges of inter-visibility between tanks and target tanks, the effects of atmospheric conditions, optics, type of vehicle, and type of background to the probability of detection, recognition, and identification as a function of range.

The analytical efforts were made to determine the consequences of requiring specified levels of anti-tank capability in future MBT armament systems. In terms of component and systems weight, cost, and development time, these consequences were weighed for fifteen types of weapons at maximum ranges varying from zero to 5000 meters.

From 1963 until 1968 BRL was involved heavily in various aspects of cost effectiveness analyses to support the United States/Federal Republic of Germany Main Battle Tank Program (The MBT70 Program). The program originated in 1963 when the two countries agreed to cooperate and share costs in the development of a new tank to be used by the armed forces of both nations. The objective of the program was to develop a main battle tank that would be tactically superior to any existing tank and at the same time secure substantial reductions in production and logistics costs.

Early in the program, the United States was given the responsibility for a Parametric Design/Cost Effectiveness Study. The primary purpose for such a study was to assist the international working group in selecting an MBT concept for development. Through competitive selection, the Lockheed Missile and Space Corporation, Palo Alto, California, was awarded a contract for the PD/CE Study. The general approach followed by Lockheed was development of a computer model simulating tank combat in a number of representative tactical situations. Each situation involved a defending force and attacking force. Some sixty small unit tactical situations were developed for computer simulation. Each tank candidate concept was run through these sixty combat simulations with various constraining inputs and subgroups in which certain tank characteristics were varied parametrically. For each simulation the success of the friendly force in carrying out its mission was determined, along with such factors as number of tanks killed on each side, the progress of the battle as a function of time, and so forth.

In supporting the PD/CE Study, the Ballistic Research Laboratories:

- played the dominant role in preparing the statement of work for the contract and in selecting the contractor
- provided a Project Officer responsible for technical supervision of Lockheed's work and coordination of the contractor's work with that of various government organizations supporting the overall MBT effort, and
- committed a substantial portion of its resources to support the contractor in several areas in which the contractor had little capability.

With respect to the last item: The US Combat Development Command and the corresponding German organization provided the contractor with tactical scenarios to be used as a basis for the development of the tactical and environmental input needed for the model. BRL helped to develop the sixty small unit actions from the scenarios and to encode the resulting information for the computer. Several BRL employees were assigned temporarily to do that work at Palo Alto.

BRL continued to support the MBT70 program

The Abrams M1 Tank

until it was ended by Congress in 1970. However, in 1968 responsibility for systems analysis had passed to AMSAA; BRL efforts after 1968 emphasized vulnerability analysis and vulnerability reduction, armor design, and anti-tank systems.

The ill-fated MBT70 was succeeded in development by the XM803, designed to cost approximately twenty-five percent less than the proposed MBT70. However, the XM803 program was cancelled in 1971, although there was general agreement in the Army that a new tank was needed. (The need is now being met by the MI Tank (Abrams), type classified in 1980. For the BRL role in its development see Chapters on Terminal Ballistics and Vulnerability and Vulnerability Reduction.)

TANK ARMAMENT AND ANTI-ARMOR SYSTEMS

In 1958 BRL completed an analysis of a tank armament concept based from the outset on the use of a HEAT projectile, rather than on the use of a kinetic energy projectile, as usually had been done in the past. The results showed the feasibility of developing an armament system in which a moderate chamber pressure, lightweight, large caliber, short gun would be used to launch a spin-stabilized, multipurpose shell having a spin-compensating liner for its shaped charge. At the time it was believed that the system would require a fewer number of rounds to defeat existing USSR tanks than would any other tank armament system known to be under development. Growth potential of the system included improved warheads to offset any unforeseen increases in protection that might be provided USSR vehicles, and possibly, use of the gun as a launcher for guided missiles.

The concept was to be realized with the development of the SHILLELAGH missile which could be launched from a 152-mm gun that could also fire conventional HEAT ammunition. Following industry-wide competition, the Aeronautronic Division of Philco-Ford Corporation was given a contract in 1959 for SHILLELAGH research and development. The contract was managed by the Army Missile Command. In the early 1960's, the 152-mm gun/launcher was the main armament of the M551 General Sheridan reconnaissance vehicle. Around the mid-1960's, about 250 vs M60 series tanks were fitted with the SHILLELAGH-HEAT system. These tanks, subsequently designated M60A2's, were considered to be an interim main battle tank until the proposed introduction of the MBT70 in 1975.

In a further extension of the MBT70 tank armament analysis, joint efforts by BRL, the Army Tank and Automotive Center, Picatinny Arsenal, and Watervliet Arsenal led to a concept for a system using SHILLELAGH, a HEAT round, and a kinetic energy projectile. The key point in this system was a launcher that would accept, without modification, the existing missile and HEAT round and fire an effective KE round. Details showing the feasibility of the concept were presented to the Armament Committee of the US/FRG MBT70 Program. As a result, the "SHILLELAGH-KE" system became the leading candidate for the next generation (then) main battle tank.

Throughout this period, BRL was also concentrating on the development of long-rod penetrators for use in kinetic energy rounds under the MBT70 (XM803) programs. A penetrator developed under the programs never reached the field but, its direct descendant, a steel-sheathed tungsten alloy core 105-mm round did. This round represented a quantum jump in capability over previous armor-piercing, fin-stabilized, discarding-sabot (APFSDS) ammunition used with the M68 tank cannon. Credit for further development of the round should be given to Picatinny Arsenal engineers who demonstrated that a APFSDS round could be designed to fly accurately out of a gun tube.

In 1972 BRL suggested that APFSDS ammunition for automatic gun systems as small as 60-mm could be designed to defeat armor used in the USSR T55 tank. The suggestion was based on the results of a BRL analysis funded by the Army Weapons Command. The suggestion provided impetus to the establishment of a technology program, later to be known as Armored Combat Vehicle Technology (ACVT), to develop and demonstrate the anti-tank capability of 60-mm to 90-mm automatic cannons. By the middle of the 1970's, BRL had demonstrated that a 60-mm cannon could defeat the USSR T62 tank, a much less vulnerable tank than the T55. BRL penetrator design efforts in the ACVT program were terminated in 1976.

In the twenty years from 1957 to 1976, BRL was to be intermittently involved in analyses of the delivery accuracy of tank gun fire. The results from Project Stalk, described in the first volume of this history, were reexamined in 1960, confirmed, and extended by including an analysis of the times required for tank crews to fire the first and subsequent main armament rounds. Later research considered the use of thermal shrouds to combat uneven solar heating in gun barrels and the use of non-metallic rotating bands to avoid "velocity creep" introduced as gun tubes warmed from firings.

BRL has been instrumental in developing and advancing all areas of battle tank and other combat vehicle technology. The section which follows describes some BRL activities in anti-armor systems.

Anti-armor Systems. Since 1945, US infantry units have been equipped with recoilless rifles to provide anti-tank and heavy assault firepower. These weapons had been developed to the point where system performance was nominally acceptable out to 1000 yards. Beyond those ranges, however, adequate performance was difficult to achieve. Thus, the United States and other countries turned their thoughts to guided missiles to achieve adequate performance at longer ranges. The French SS-10 missile and the DART system, partially developed by the US, represented developing systems. However, as early as 1958, the United States had recognized significant shortcomings in the SS-10 system. The Army needed new concepts for weapons to replace the 106-mm M40A1 recoilless rifle augmented by the ENTAC missile. The TOW system, discussed at length above, was one answer to the need.

A cost effectiveness evaluation made by the Laboratories in 1963 showed that the costs associated with fielding and maintaining a battalion equipped with TOW weapons were significantly lower than costs associated with the M40A1-ENTAC system, even when TOW initial investment and remaining research, development, testing and evaluation costs were considered. The evaluation was based on analysis of several company-sized war games taken from a tactical situation which pitted a U.S. mechanized infantry division defending against a motorized USSR motorized division.

The Dragon resulted from a Quantitative Development Requirement, Industrial (QDRI) carried out by BRL in 1963. (A part of the Army's formal materiel acquisition process, the QDRI is a formal briefing to which Defense technologists and industry representatives are invited to learn specific weapon requirements, then subsequently, to submit proposals to meet the requirements.) A combination of analysis, simulation, experiments, and flight tests showed the Dragon to be the logical choice to meet user requirements. A later committee chaired by the Army Missile Command later reviewed the findings resulting from the QDRI and consequent evaluations but the recommendations and conclusions of the evaluations were not changed. The M47 Dragon, a medium anti-tank missile was developed as a medium-range complement to the TOW. It was the first and until this date (1983) the only US guided antitank missile that can be carried and fired by one man.

The Viper system resulted from a LAW (Light Antitank Weapon) workshop chaired by BRL in 1967 and the SMAWT (Short Range Man Portable Antitank Weapon Technology) exploratory development program managed by BRL, 1971–73. The Viper, designed to be the successor to the M72 LAW, was conceived as a low-cost one-shot, throwaway weapon.

The Copperhead is a cannon-launched guided projectile which homes on the energy reflected from a laser-designated target. The Copperhead system was an outgrowth of basic technology and systems development work done at BRL during the 1960's. Subsequently, a DARCOM study group, chaired by a BRL representative, postulated system concepts and identified areas where technology was lacking. The most difficult technical hurdle was the hardening of components, in particular guidance and control units to survive the high acceleration launch environment. Here, the experience gained by BRL during the High Altitude Research Programs proved to be valuable. Except for the problem posed by the severe launch environment, the technology was ready; there was a tactical application for a laser-designated artillery round for direct support weapons, e.g., the 155-mm Howitzer. An exploratory development program was formulated. The Army Weapons Command was given the task of carrying out the plan. However, BRL continued to play an active role in the analysis of the aerodynamics of the projectile, in the design and evaluation of the warheads, and in overall system performance analyses. BRL also acted as a consultant to the Naval Weapons Center on their cannon-launched, terminally-guided projectile program. Help was given particularly in warhead design. (The M712 Copperhead projectile was type-classified in 1979.)

With the addition of results from one other important ballistics area, the same basic technology and systems development work at BRL contributed to the development of another anti-tank system, SADARM. The important addition is the self-forging fragment concept, known at BRL in the 1960's as the Ballistic Disk. SADARM (Sense and Destroy Armor) is a submunition ejected from an 8-inch shell. Triggered by a millimeter wave sensor, the parachute-borne submissile fires a spray of self-forging steel fragments against the vulnerable top of a battle tank.

A true "fire-and-forget" system, SADARM owes most of its promise to BRL research in millimeter wave phenomena and armor penetration throughout the 1960's and 1970's, and to concepts analysis work in the early 1970's.

The success of the SADARM concept led, in 1975, to consideration of a similar system which could be used in direct fire from tank guns and infantry antitank weapons. Called STAFF, for Smart Target Activated Fire and Forget, this concept combined millimeter wave sensors and explosively formed fragment penetrators in a spin-stabilized projectile which detonated as it passed over its tank target. As was the case for SADARM, BRL played a major role in the development and testing of the millimeter wave sensors for STAFF. Moreover, BRL designed a computer simulation model which can consider sensor type, sensor performance, delivery error, and terminal ballistics effects as a total system. The simulation model was used to optimize the STAFF design and to evaluate STAFF performance and lethality in many weapon applications and tactical scenarios.

Both SADARM and STAFF are the outgrowth of the Army's Improved Conventional Munitions Program. This program promoted development of technologies relating to terminal guidance of projectiles and target carrying projectiles. The applications of these technologies to the weapon systems of the 1980's and beyond came about in a very large measure as the result of BRL's research in millimeter wave propagation and explosively-formed fragments (self-forged fragments) in the years covered by this volume.

The discussion above has emphasized weapons designed to defeat heavily-armored vehicles; however, BRL was active also in analyzing systems for use against lightly-armored vehicles. As the 1950's drew to a close, the Ordnance Corps became concerned over deficiencies in performance of the caliber .50 machine gun against lightly armored vehicles. The concern arose primarily because of the large numbers of armored personnel carriers and other lightly-armored vehicles in the USSR armed forces. Consequently, in 1961, the Ordnance Corps initiated a program to provide a weapon to replace the caliber .50 machine gun. Designated the Vehicle Rapid Fire Weapon System (VRFWS), the weapon would be used as primary armament of US armored personnel carriers, armored command and reconnaissance vehicles, and other lightly armored vehicles.

The program had two phases; one phase considered a "Successor System" to be developed; the other phase considered an "Interim System" to be selected from several existing weapon candidates, as the best available replacement until the successor system could be provided.

The Chief of Ordnance gave BRL the responsibility for evaluating concepts for the successor role and for coordinating Ordnance Corps efforts to test and evaluate candidates for the interim system role. The basis for evaluation was the system's performance against the USSR BTR-50 armored personnel carrier.

AIR DEFENSE SYSTEMS

For the ten years preceding December 1963, BRL air defense evaluations had concentrated on missile systems; these evaluations had included for example, the Nike-Hercules designed for continental defense and several concepts for strategic defense. However, by December 1963, there was general concern within the Army, a concern shared by BRL, whether there was sufficient forward air defense capability for the Field Army. The concern was not so much for a lack of air defense compared to that of other nations, but for the lack of fully developed air defense systems—considering the amount of effort and dollars that had gone into the development of Army air defense systems. Consequently, BRL systems analysts turned towards effectiveness evaluations of relatively simple and inexpensive gun systems.

The effort in carrying out these evaluations consisted of two parts. One part involved the synthesis of effectiveness indices and the programming of the resulting mathematical model for the computer. The second part involved the analysis of test data to determine the best characteristics of the weapon system to be used for input to the effectiveness index. These studies centered about interim weapons available almost immediately or long-term ultimate weapons incorporating optimum properties.

Since responsibility for complete air defense systems analysis passed to AMSAA in 1968, the discussion below covers analyses conducted by BRL between 1957 and 1968; however, representative technical contributions to various systems are noted for the twenty-year span 1957–1976.

Missile Systems. In the summer of 1957 BRL was asked to "undertake an inhibited study to recommend a complete system that will come closest to meeting the military requirements for Mauler, a proposed successor to Vigilante."(sic) (The Vigilante 37-mm gun system developed by Sperry Corporation in the late 1950's–early 1960's was never fielded.) An interlaboratory task force was formed composed of representatives from Harry Diamond Laboratory, Picatinny Arsenal, and BRL. The report produced by the task force suggested a guided missile system and listed areas in which additional research seemed desirable. The report was sent to the Office Chief of Ordnance, then later to the Army Missile Command (then known as the Army Guided Missile Agency, ARGMA) who used it as a reference in evaluating proposals for feasibility studies submitted by some thirty industrial groups. ARGMA then asked BRL to provide warhead effectiveness estimates to be used by prospective MAULER contractors in making their proposals.

During the time allotted for feasibility studies, BRL carried out extensive work to determine kill probabilities for Mauler against five targets: helicopters, observation aircraft, aerodynamically supported missiles, other aircraft, and short range missiles. Warhead optimization results gave estimates of single shot kill probability as a function of missile standard error of guidance—for blast fragmentation warheads of a given weight but with three different widths of fragment spray. The extensive analyses marked the first time such an optimization had been carried out so early in a system development. BRL continued to support the Missile Command through 1964, providing single shot kill probabilities for various fuze designs and modified warhead parameters.

In August 1958, the Office Chief of Ordnance asked BRL to examine the Redeye concept proposed by the Pomona Division of Convair Pomona, Pomona, California, and to determine where Redeye fitted in the over-all air defense of the field army. The development of the Redeye sytem, a fourteen-pound shoulder-launched antiaircraft weapon, by the Ordnance Corps was unorthodox because the concept had already been under limited development by the contractor before the government funded the program. BRL initiated liaison with the contractor and the project manager; local efforts at BRL were determined primarily by observing the progress of the system and investigating those areas which appeared most likely to cause a change in system effectiveness.

In early 1959, BRL was concerned with estimating the range at which the forward aspect of a jet aircraft would provide sufficient radiation for a homing Redeye missile. Estimation capability was hindered severely by apparent discrepancies in the small amount of pertinent data. At the same time, the BRL researchers determined that there was very little experimental data available on operator detection of aircraft. Consequently, BRL contacted personnel of the Human Engineering Laboratories, also at Aberdeen Proving Ground, and learned that they too were aware of the situation and were planning to conduct some experiments on aircraft detection. BRL supported the experiment which was held at Gila Bend, Arizona in September 1959.

In July 1959, Caywood-Schiller, Associates, under contract with the Ordnance Corps and under the technical supervision of BRL, initiated a series of studies on Redeye. The outcome was a two-dimensional simulation of an interception of a target by the missile. The simulation was used to determine the performance boundaries of the Redeye missile for several target and missile conditions.

The Laboratories, in December 1961, provided the results of the effectiveness analyses, and developed engagement kill probabilities for a single Redeye unit against a jet aircraft—considering target velocities, operator reaction time, initial lead angles, missile performance, and missile supply limits. The Redeye was in production from 1964 to 1972. (It is currently being replaced by Stinger, a similar system having a much improved infrared seeker system.)

In 1961 BRL completed an evaluation of the feasibility of a concept for an anti-missile defense system known as the Strategic Anti-Missile Barrage Objects (Project SAMBO). The evaluation was undertaken on behalf of the Advanced Research Projects Agency as part of a program called Project Defender, a broad class of ballistic missile defense studies. BRL investigated the relationships determining effectiveness, cost and utility of a defensive system based on the use of pellets in space. The evaluation used the most current information available on hypervelocity impact and ballistic missile vulnerability from BRL and other related programs under Project Defender. Besides in-house investigations, BRL supported research at Cornell Aeronautical Laboratories and the Marshall Space Laboratories of NASA on the re-entry characteristics of damaged nose cones. BRL concluded that the SAMBO concept was not feasible. The cost of the pellet shield would be exorbitant; moreover such a system would cause sufficient clutter in outer space as to have serious scientific, political, and military implications.

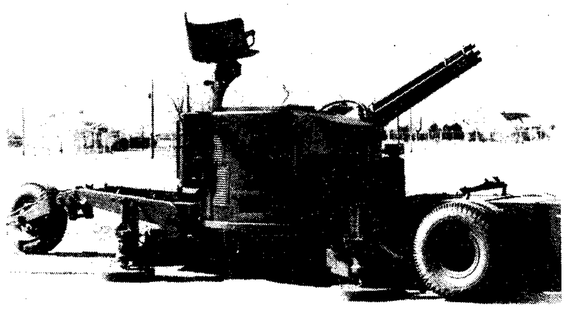
BRL technology contributed to the development and analyses of two missile systems, the Nike-Hercules and the Hawk, fielded respectively in 1958 and 1959. Evaluation of overall inflight performance was made possible through the use of optical measurement techniques developed by BRL; much of the advanced warhead design proposed for MAULER was applied concurrently to Hawk, and weapon systems lethality computer programs were used to determine single shot kill probabilities for both missiles with various warheads against different targets. Typical of these last analyses were investigations of the lethality of the Hawk and MAULER missiles against then current US tactical aircraft, and the Nike-Hercules blast-fragmentation warhead at high altitudes against the USSR's Bison and the USA's QUAIL—the first a heavy jet bomber, the second a pilotless air-to-surface guided missile decoy.

In 1966 BRL provided vulnerability data on aircraft and missiles to the Army Missile Command for use in the SAM-D program. The SAM-D was an advanced weapon system conceived as a replacement for the Hawk and Nike-Hercules systems in the 1970's. It was the successor to two earlier study programs managed by the Missile Command, the Field Army Ballistic Missile Defense System (FABMDS) and the Army Air Defense System for the 1970's. AMSAA provided continuing analyses after 1968.

However, in July 1972, the Chief of Staff for Force Development (ACSFOR) requested that a task group be set up to analyze the technical feasibility of developing advanced non-nuclear warheads for the SAM-D. The warheads should be capable of defeating certain nuclear missile threats. BRL directed the group which included representatives from AMSAA, Harry Diamond Laboratory, BRL and Picatinny Arsenal. The result was the development and exercise of an extensive capability for evaluating non-nuclear warheads and the generation of significant information for use in the design of such warheads. A few years after the analysis had been completed, BRL conducted an investigation for Picatinny Arsenal, responsible for the SAM-D warhead and warhead systems, of the performance of a proposed warhead. Of particular interest here, was the first application of the HEMP code to evaluate warhead performance. HEMP is a time-dependent, two-dimensional Lagrangian finite difference code. Code results showed good agreement when compared to test data for the warhead considered. Later HEMP was used to evaluate modifications to the warhead design. The SAM-D, later designated the Patriot tactical air defense system, is designed to counter large numbers of high speed aircraft and short range missiles at all altitudes. (Scheduled for deployment in late 1984, the Patriot will replace the Nike-Hercules in the high-altitude air defense role.)

Gun Systems. In the late 1950's and early 1960's, 90-mm anti-aircraft guns were being placed around large, heavily populated, industrial cities in the Continental U.S. to integrate air defense with Nike-Hercules batteries. Presumably the objective was to provide complete defense against high altitude and low altitude attacks. BRL systems studies provided estimates of the effectiveness of the anti-aircraft guns against postulated targets; kill probabilities were given in terms of the radius of the built-up city plus the damage radius of an enemy bomb.

As may be seen from the preceding section on missiles, there was a strong emphasis on missiles for the air defense role in the field army. For example, in 1960 BRL made comparative evaluations of the anti-missile and anti-aircraft capabilities of systems such as Mauler, Hawk, Nike-Hercules, Redeye, and the Vigilante. Of these only the 37-mm gun Vigilante system was a predicted fire system. Engagement kill probabilities of the different systems were provided for missile and aerodynamically supported targets. The time period was from 1960 to 1970, with particular emphasis on the 1960–1965 period.

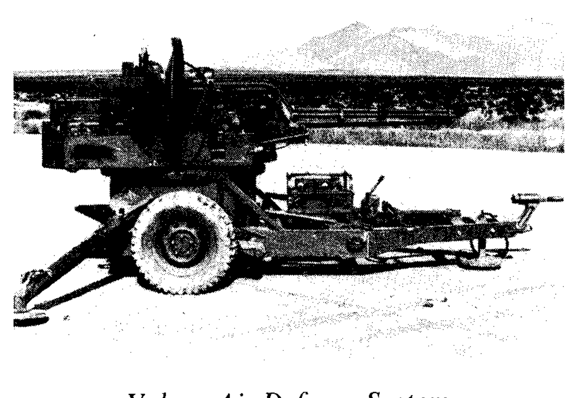


Vigilante Air Defense System

In a similar investigation in 1963, the same four missiles were considered; however, smaller caliber systems were considered, the 7.62-mm and caliber .50 machine guns. The time period considered was 1965–1966.

The emphasis changed abruptly less than a year later as BRL made a comparative evaluation of ten different automatic gun systems. There the emphasis was on lightweight anti-aircraft systems for use by the airborne division. Up to this time the Army had not been interested in lightweight divisional weapons, except for Redeye, because of the high costs of logistics and anti-aircraft crew support. The systems analyzed included two versions of the caliber .50 machine guns, five different 20-mm systems, ranging from a single barrel gun to the M61 Gatling gun with six barrels, a 30-mm system, the 37-mm Vigilante, and the M42 40-mm Duster upgraded by addition of ranging radar and computers (Raduster). The comparison was based on system availability, cost/effectiveness ratio, air transportability, field mobility, and overall performance against targets ranging from low-speed, low-altitude aircraft to high-speed, high-altitude jets. No clear-cut best system emerged from the analysis, but the BRL analysts favored further development and procurement of the Vigilante or, with higher risk, the 30-mm system. (The Army ruled out the Vigilante in 1962.) They also recommended that in the interim the caliber .50 machine gun on the division vehicles be used for air defense against the low-speed, low-altitude aircraft. However, the Army approved the 20-mm M61 Gatling gun for deployment as the Vulcan Air Defense System (VADS) in December 1965. The decision was made largely because the system components were available as off-the-shelf hardware, and there was an urgent need to get some system into the field quickly.

In 1974, the Commanding General, Army Materiel Command, asked the Laboratories to investigate the feasibility of finding a common gun/ammunition solution for the ground-to-air, ground-to-ground, and air-to-ground roles. It was found that the air-to-ground and ground-to-air roles were generally at odds with each other. The air-to-ground role required a round of caliber 30-mm or greater while the ground-to-air systems appeared to increase in effectiveness as the caliber was reduced. Consequently attention became focused on the possibility of a common solution for the ground-to-ground and ground-to-air roles. Again the smallest calibers appeared to give the best solution for the ground-to-air application. In the ground-to-ground role, armor penetration was taken to be the measure of effectiveness. While



Vulcan Air Defense System

the effectiveness increased with caliber, the analysis showed that feasible armor penetration was possible at all calibers between 15- to 60-mm, although the 15-mm round was not an attractive solution. The conclusions were that commonality between the ground-to-ground and ground-to-air roles was feasible and that a round as small as 20-mm might provide the best solution. (The issue of hit probability and the influence thereupon of projectile time of flight was not considered.)

The 25-mm Bushmaster system was under development at the time; part of the impetus for the AMC request for the BRL commonality study was the desire to identify technical approaches for both intermediate and long-term Bushmaster alternatives. Since BRL had found smaller calibers to be more desirable for a common weapon, it was logical to recommend 25-mm as the optimum caliber. However, BRL stipulated that a new round with higher muzzle velocity and lower drag would have to be introduced into the Bushmaster system. The recommendation was not received favorably. The Bushmaster developers were unwilling to accept the schedule delays that a change in ammunition would introduce. The Air Defense community had already decided that a larger caliber weapon was desirable because of increased effectiveness at ranges beyond three kilometers. Consequently, the concept of a common gun for both roles was not pursued further.

A Joint Test for Probability of Hit by Antiaircraft Guns (HITVAL) was established by a charter in February 1972 by the Director of Defense Research and Engineering to the Assistant Secretary of the Army for R&D, the Assistant Secretary of the Air Force for R&D, and the Director of the Weapon Systems Evaluation Group, AMC. The Deputy Director of BRL, Col. Thomas R. Ostrom, was the Test Director for HITVAL.

A rapidly moving target aircraft and the slewing-elevating antiaircraft gun attacking it are very difficult to represent realistically by mathematical models. Moreover, in 1972, there was a lack of input data that could be used to check model validity. The situation was further aggravated when comparisons among the results of different anti-aircraft gun effectiveness models disagree by a factor of two or more. The models disagreed in predicting probabilities of aircraft being hit by projectiles from an antiaircraft gun and in predicting attrition trends. The results of the comparisons and the lack of data for checking the models led to the recommendation for a well-instrumented field test to determine "where the bullets go" when antiaircraft guns fire at maneuvering aircraft.

The HITVAL test was designed to get the data necessary to validate the effectiveness models. Several foreign anti-aircraft systems were tested against a number of US aircraft. A unique feature of the test was the use of frangible ammunition that broke up shortly after if left the gun barrels. This permitted realism to be added to the test as the manned aircraft maneuvered. The test concept required extremely accurate measurement of the target state as a function of time, actual measurement of the gun's elevation and azimuth as a function of time, and computation of a trajectory and miss distance for each round. These calculations were carried out by fitting a mean trajectory to the aiming direction for each round, using ballistic data from preliminary tests. The projectile trajectories were determined by a ballistic program developed and verified by BRL. Despite many test, data, and instrumentation problems, ultimately much useful data was provided by HITVAL.

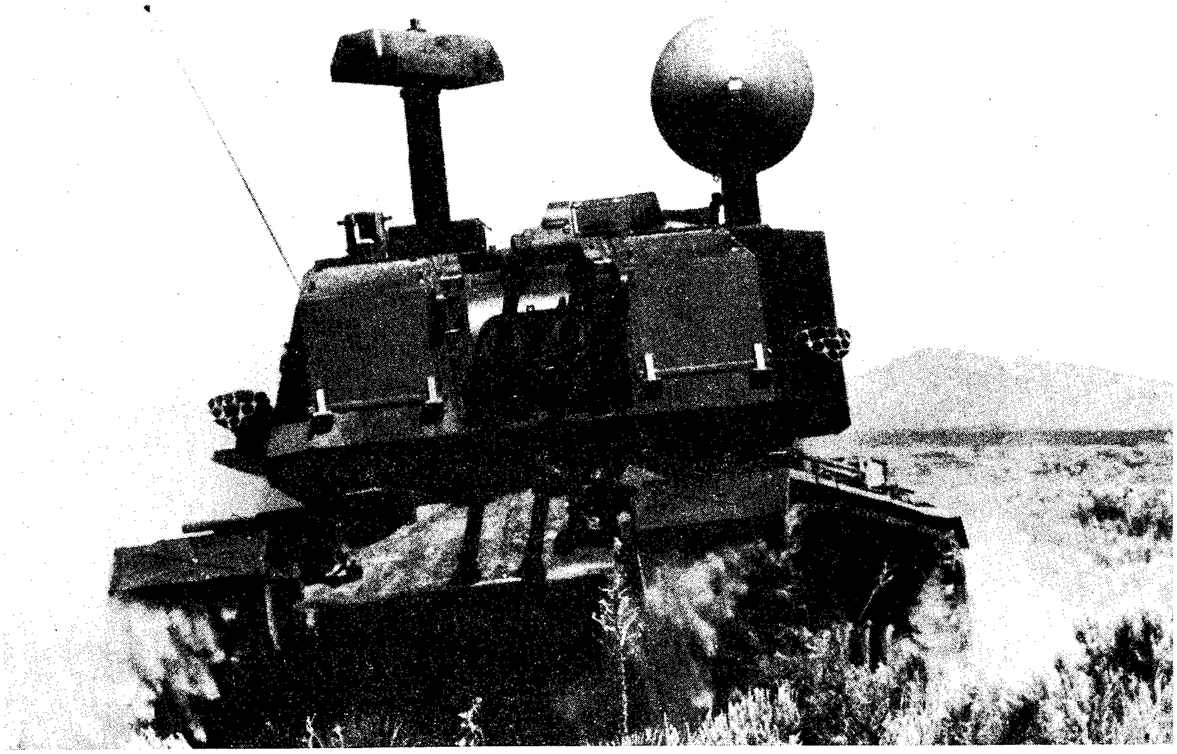
As this period in BRL's history drew to a close in 1976, the Laboratories were becoming increasingly involved in the Army's new development program for the Division Air Defense System (DIVAD). BRL's first involvement came in December 1974, when the Army Armament Command asked BRL to determine the probability of kill against the targets specified in a draft DIVAD Required Operational Capability (ROC) for several 30-, 35-, and 40-mm rounds, including a proximity fuzed round. The proximity round was a unique challenge for the type of analysis. One purpose of the study was to determine whether one of these calibers could be designated as "optimum". However, it was found that the relative effectiveness of the various calibers was highly dependent on target type and trajectory and on the kill criterion. Therefore it was concluded that no optimum caliber could be selected.

BRL continued to play an extremely active role in the development of the DIVAD system. (The DIVAD gun system, now known as the M988 Sergeant York, was cleared for full production in 1982).

Fire Control. Activities within this area at BRL included such subjects as miss distance indicators, fire control computers, detection and tracking systems and prediction algorithms.

BRL sponsored a series of tests to evaluate use of a radar system as a miss distance indicator. The last in this series of tests, conducted at Fort Bliss, Texas, in 1955 and 1956, demonstrated the capability of radar to determine miss distance effectively for 75-mm projectiles out to 3000 yards. Some difficulties were encountered due to radar design. However, it was suggested that a monopulse radar could overcome the drawback inherent in the radars that used a lobing method to determine position. There was no follow-up for about fifteen years until the air defense community initiated a program to develop and procure a miss distance indicating radar system designed specifically to measure the miss distance of gun-launched projectiles. The system, known as the MIDI, uses a modified Nike-Hercules monopulse radar operating in the X-band.

The advantages of using a digital computer for antiaircraft fire control systems were pointed out by BRL in 1957. The inherent primary advantages in using a digital computer, rather than an analog computer, included ready adaptions to complex methods for smoothing and predicting, and the possibility of developing the computer simultaneously with the weapon. The latter advantage also offered a considerable savings in time for systems development. Ease of service provided a third advantage; the digital systems are better adapted than analog systems to "go", "no-go" tests. The fourth and final advantage was higher reliability. It was recommended that digital computers be considered in the development of any new predicted fire system. The first Army air defense gun to use a digital fire control system is the M988 Sergeant York.



Sergeant York M988 Division Air Defense System (DIVADS)

As discussed in the chapter on Target Acquisition, Guidance and Control, BRL became active in research to characterize millimeter wave propagation early in this period. Much of the work was related to design considerations for guidance system operating against ground targets, still an important application. However, aerial targets flying nap-of-the-earth or hovering in a partially masked position are now considered a major threat to be countered by short range air defense systems. Optical trackers will not be a completely satisfactory answer to this threat, because the system must be operable under battlefield conditions, which include adverse weather and dissemination of obscurants. Radar tracking systems suffer from clutter and multi-path signals. Furthermore, survival of the system against anti-radiation missiles requires that the radar system have minimal radiation signatures. The characteristics of millimeter wave radars are ideally suited to overcome the limitations of longer wavelength radars. Their range (limited by atmospheric absorption) is adequate for short-range air defense guns and is advantageous in terms of electronic counter-counter measures. The results of milimeter wave reserch at BRL over the period from 1957 to 1976 (and beyond) should find considerable applications in the future to fire control systems for air defense guns.

During 1975 and 1976 the problem of optimal predictions for evasively maneuvering targets was treated extensively by BRL. The thrust of the work was to provide some bounds on the level of performance that could be expected in an encounter between an intelligent fire control system and an intelligent target. The conclusions of the work imply that even under the most appropriate conditions, predictors have a very limited performance against smart targets; at extended ranges and against random (unforeseeable) target maneuvers, guns have inherently very low performance with the best predictors; to improve gun performance significantly, projectile time-of-flight must be reduced.

SMALL ARMS

During this period BRL analysts studied, in detail, the effectiveness, performance, and design of various small arms. Weapons analyzed included pistols, shotguns, the Special Purpose Infantry Weapon (SPIW), the Squad Automatic Weapon System, and a port-firing weapon for the Mechanized Infantry Combat Vehicle (MICV). The work on the port-firing weapon marks the first instance in which BRL used mathematical models and computer codes to design a complete small arms system.

The pistol study was designed to determine the feasibility of developing a pistol more effective than the caliber .45 pistol. The results showed that it was not possible to provide significantly higher effectiveness under the stringent casualty criterion used for very short range weapons.

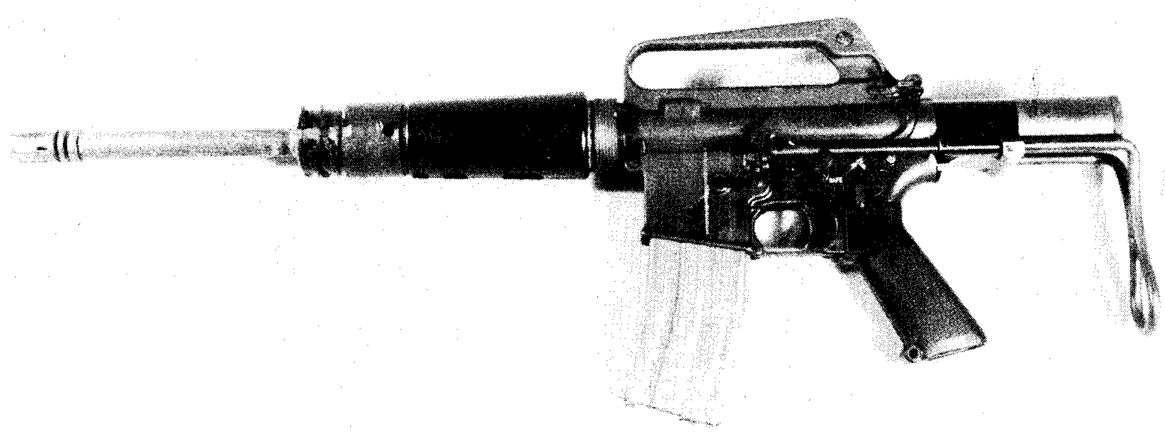
The shotgun analyses considered the ability of the weapons to produce casualties and to clear an area by simply obtaining hits, as desired in overcoming an ambush. The desired effects are not compatible; the greatest number of casualties occur with low round dispersion and greatest area coverage is attained by higher dispersion. However, the analyses showed that a particular shotgun round is a good compromise towards meeting both criteria.

The Special Purpose Individual Weapon (SPIW). By 1957 BRL studies of the infantry rifle had shown that considerable effectiveness should be obtained with a small caliber, high velocity weapon. The apparent advantages were: a flatter trajectory offering increased hit probability, a possible increase in lethality caused by more severe cavitation in high velocity wounds, and considerable savings in the weight of the ammunition and possibly of the weapon. Subsequently, the US Army Springfield Armory designed a caliber .22 rifle which weighed about six and one-half pounds.

The proposal to use flechettes as small arms projectiles prompted BRL, in 1959, to determine the dispersion required to optimize the probability of at least one hit and to maximize the expected number of hits. The scope of this work was expanded the next year; as a participant in an All Purpose Hand Held Weapon Program, BRL reserchers investigated the dispersion associated with automatic fire of small arms. The results showed that, given an optimum dispersion between rounds, a twofold increase in effectiveness could be achieved over that of the then current M14 rifle, in terms of hit probability per trigger pull. Type classified in 1957, the M14 has long since been superseded by the M16 series. The results also applied to automatic small arms fire using multiple projectile (flechette) rounds. It thus became apparent that in view of the lethality of the flechette round and the reduced weight per round associated with them, if a flechette weapon could be developed to yield optimum dispersion, such a rifle would be more effective than current weapons.

All of these results culminated in a concept for SPIW: Multiple projectiles, each of which had a lethality comparable to that of a conventional rifle round, were to be distributed at the target with small dispersion about the aim point. Notably, the concept did not dictate the means by which it was to be achieved. In support of the SPIW program, BRL developed computer models to evaluate the effectiveness of shoulder-fired weapons.

The SPIW concept was validated in a test designed by representatives of BRL, the US Army Human Engineering Laboratories, and the US Army Infantry Board. The test compared the standard M14 and M16 rifles with competing SPIW prototypes provided by contractors, all of whom had chosen to design flechette, sub-projectile rounds. The correlation between the dispersion of a firing burst and predicted hit probabilities was confirmed; terminal ballistics results showed, in most media, that the 7.62 mm ball round and the flechette were about equal in penetrating capability. (Both rounds were considerably better than the caliber .223 round.) The



Port Firing Weapon for Mechanized Infantry Vehicle (MICV) results were the basis for a recommended exploratory development program for a flechette rifle.

In later experiments using US infantrymen, BRL analyzed the most effective mode of fire for the SPIW and the accuracy of SPIW fire compared with that of the M14 and M16A1.

Port Firing Weapon for the Mechanized Infantry Vehicle (MICV). The design and development of a weapon to fire through ports in the Army's MICV (later designated the Bradley Infantry Fighting Vehicle) illustrates again the practical value of BRL's modeling approach. Here BRL coupled an analog model describing the kinematics of a small-arms weapon with a digital model describing the dynamics of the weapon's gas system.

In October 1972, the Army Small Arms System Agency (SASA) asked BRL to use the BRL M16A1 rifle computer models to design a port firing weapon for the MICV. The original concept for such a weapon came from L.R. Ambrosini and R.F. Margarde of SASA.

It was desirable that the weapon have the same operating characteristics as the M16A1 rifle because of that weapon's high reliability; there was also the possibility of cost savings by using M16A1 components in the new weapon. Once the computer models had shown that a weapon was feasible for meeting the specific requirements posed by SASA, BRL, at the request of SASA, designed the necessary components and made a firing prototype. The cost was kept low by using as many of the existing parts of the M16A1 as possible.

The prototype was fired successfully; its operating characteristics closely matched those predicted by the computer model. SASA then asked BRL to make a complete weapon for extensive endurance tests. The weapon, made in the BRL model shops, successfully completed the endurance tests.

Again at SASA's request BRL built six weapons for use in the first phase of a MICV test scheduled for November 1973. The Materials Test Directorate at Aberdeen Proving Ground tested those six weapons. The weapons performed as expected, but the tests showed that a slower rate of fire was desirable to permit the gunner to get on target while expending less ammunition. The computer model was reapplied to achieve a lower firing rate. The result was a weapon that can fire at either 450 or 1000 rounds per minute. (The port firing weapon designated the M231, was type classified in 1980.)

SURFACE-TO-SURFACE SYSTEMS

During World War II the Ballistics Research Laboratories began to evaluate the weapons used by US ground forces against enemy ground forces; the number of evaluations, as well as the nature and complexity of the analyses, increased sharply after the end of the war. Throughout the 1950's there were several analyses devoted to determining the optimum mix of artillery weapons. This was to become a continuing effort as artillery technology evolved. The introduction of rockets and missiles had of course added to the problem of determining the optimum mix for artillery. The new question was, "To what extent might the Army's future requirement for tube artillery be reduced by the availability of free rockets and guided missiles?" Providing the answer to the question became more complicated as BRL considered the case for nuclear tactical weapons and non-nuclear weapons which now included improved conventional munitions and dual-purpose improved conventional munitions.

Systems Comparisons. Unfortunately, the discussion here will be incomplete because many of the conclusions reached in the analyses are still classified for national security reasons; thus, the BRL contributions to specific systems and Army concepts may not be apparent.

In 1957, BRL systems analysts explored the non-nuclear capabilities of various Army artillery systems and concluded that the six-inch cannon should be considered seriously for the role of the future divisional support weapon. The recommendation was contingent on the possibility of developing an adequate self-propelled version meeting both the weight and firing range requirements. The analysis also indicated that the six-inch cannon might be more desirable in the general support role.

The analysis was expanded the same year to consider the role that rockets and missiles might play—considering nuclear ammunition and non-nuclear ammunition, including the improved conventional ammunition. The result was a recommended optimum family of weapons with a proper mix of conventional and nuclear capabilities.

During October 1959, the Weapons Systems Laboratory defined yield, range, and accuracy requirements for nuclear artillery support of the field army (for the 1960–1965 period.) In establishing these requirements the investigators examined two different target distributions—first to show the methodology used, then to show how a change in the target distribution affects requirements. An important attribute of the methodology was the inclusion of compromises in requirements when feasibility studies of a particular system showed that requirements could not be met without incorporating undesirable features into the system.

The next step, now that the requirements for nuclear artillery support had been defined, was to determine which type of weapon system was needed to meet the requirements. BRL considered many types of delivery systems—howitzers, recoilless rifles, rockets and guided missiles. Factored into the study were: accuracy, cost, reliability, complete round weight, ground support equipment, and cost and amount of nuclear material. Tradeoffs made in reaching final recommendations evaluated mobility, reliability, critical material, overkill, and the logistical implications of the various delivery systems. Since weapon systems analysis is a dynamic, iterative process, these findings were revised as improved methods for handling parametric data for specific systems became available. The results were updated subsequently to consider support requirements for the 1965–1970 period. Then, however, specific characteristics of weapon systems were considered rather than which general types. Also, the updated analyses considered the desirability of using the general support weapon for both direct and general support of the army division.

The final step was a complete cost-effectiveness analysis of tactical nuclear weapons. Here BRL examined the desirability of including certain proposed weapons in the Army family of weapons. The effectiveness portion of the study was based on the performance of the various weapons against several target complexes under the application of two sets of target defeat criteria. Ammunition costs included costs of nuclear material, examined from the standpoint of both actual production costs and fair market value in a balanced supply-and-demand economy. The analysis considered the 175-mm gun, the Honest John missile, and the Lance missile (a replacement for the Honest John). The impetus for the study came from the need by higher headquarters for information upon which to base a decision on initiating further development of a nuclear projectile for the 175-mm gun.

In 1963, BRL published the results of cost-effectiveness analyses of non-nuclear fire support systems. The alternative families of fire support systems were examined with a viewpoint to providing a given level of effectiveness at a minimum weight and cost. The alternatives included manned aircraft as well as various artillery systems. The optimum family evolving from the analysis was compared with the firepower projected for 1968 USSR ground forces. The results of the study dramatically emphasized the Army's need for close support aircraft.

System Effectiveness. In addition to the general systems comparisons used to derive recommended optimum families of weapons, BRL provided cost-effectiveness analyses of specific systems, sometimes even specific ammunition types. These analyses also were provided to the Army Materiel Command for use in determining the course of development programs; some representative studies follow.

- 105-mm Sting Ray Ammunition. The primary effort of the analyses was to compare the Sting Ray round with seven competitive 105-mm rounds used against personnel. The Sting Ray was a round loaded with numerous special flechettes.
- Anti-Personnel Effectiveness of the 105-mm Howitzer in a Direct Fire Role. The objective was to compare the effectiveness of three 105-mm rounds used in direct fire up to ranges of two kilometers. Comparison was made in the number of rounds required to achieve a stated percentage of casualties on specific targets. The

rounds compared included the Beehive and two improved conventional munition rounds.

- Effectiveness of Missile Systems Against Nuclear Targets. The Sergeant and Pershing missiles were analyzed to determine their performance against targets appearing in nuclear target complexes.
- Multiple Rocket Artillery System. In 1964 BRL completed a study to: determine the optimum characteristics of a multiple artillery rocket system (MARS); determine whether MARS could provide significant savings in cost and ammunition, if included as an additional member or substituted for an existing member in a family of artillery weapons; and determine the effect of tactical aircraft availability on the preceding. No conclusions could be drawn as to whether MARS could replace adequately one of the existing systems. A subsequent detailed analysis of MARS two years later provided the basis for determining the optimum system characteristics and for measuring the relative efficiency of the family of artillery ammunition with and without MARS. (The Army's MLRS, Multiple Launch Rocket System, entered production in 1980; it uses both anti-personnel and anti-materiel ammunition.)
- Lance Missile System. The assistant Chief of Staff for Force Development asked BRL to establish the number of missiles and warheads that should be procured and stockpiled. Analysts used estimates of the enemy threat in Europe to establish requirements for the number of Lance missiles and warheads needed there for a general non-nuclear war and a general nuclear war. Once the number of missiles and launchers needed for Europe was found, the number was extrapolated to determine world-wide stock required for the complete planned Lance force. A semi-gaming methodology permitted consideration of time factors such as weapon response, target duration, weapon rate-of-fire, and target personnel reaction. The results of the study were received favorably and were largely responsible for the approval of funding for Lance development. The Army ordered full production of the Lance system in 1971.

Extended Range Artillery. During the latter half of 1973, BRL conducted a study on extending the range of artillery projectiles. There were three main questions to be answered. First, does increasing the range of artillery increase its effectiveness? Second, if an increase in effectiveness is found, what causes it (increased survivability because of increased distance from the enemy, increased capability of meauring fires on targets within range, the ability to engage more distant targets, or other factors)? Finally, which of the various methods for increasing the range (super propellants, sub-calibered rounds, rocket-assist and so forth) offers the greatest potential (in terms of effect, time, cost, acceptability by users, et cetera) for hardware development. A major finding by the researchers was the scarcity of methodology available to address problems of this nature; no methodology was found within the US Army community that was adequate to perform such studies in a practical manner. Thus it was decided to develop a new model, the Austere Field Army Concepts Effectiveness (AFACE) model. The model, developed during 1975–1976, represents a quantum improvement in effectiveness modeling with economical use of computer time.

AIR-TO-SURFACE SYSTEMS

As noted previously, many of the analyses carried out by BRL during the period 1957 to 1968 were concerned with vulnerability and vulnerability reduction of aircraft. The results of those efforts, as well as of those occurring during the period 1968–1976 on Vulnerability and Vulnerability Reduction have been described in that chapter.

Also, during the earlier period, Army helicopters and fixed-wing aircraft had been considered as alternatives in weapon systems studies directed towards selecting alternative familites of non-nuclear fire support weapons. The results of the work had shown that high performance manned aircraft could attack effectively some targets at a lower cost than could artillery.

Much of the basic data used in the optimization and feasibility studies of then current and potential weapons for aircraft came from an experiment sponsored by the Ordnance Corps in 1961. BRL was responsible for this experiment conducted at the Combat Development and Experimentation Center at Fort Ord, California. The experiment was divided into two phases. The primary objective of the first phase was to determine quantitatively the susceptibility of typical, stationary, ground targets, to detection and indentification by observers in rotary-wing aircraft flying nap-of-the-earth. The primary objective of the second phase was to quantify the ability of a pilot to fly a preplanned nap-of-the-earth route, identify and acquire with simulated fixed aircraft armament, a specific stationary ground target whose location, with varying degrees of precision, had been made known to the pilot.

The results of these early experiments of 1961, were enhanced by the results of a study by BRL in 1964 to evaluate the aiming and tracking accuracy of UH-1 Helicopter pilots. Test flights were made under controlled conditions under the most favorable weather conditions. Results of statistical analyzes of the data showed that there were no significant differences in aiming and tracking accuracy among pilots.

In a study to determine the most desirable antitank system to be mounted on a UH-1 Helicopter, BRL analysts briefed five aviation officers with Vietnam battle experience on a hypothetical breakthrough by a USSR tank division. The potential targets were delineated generally and in some cases, specifically. Given the background, the five pilots were asked to formulate plans and write operations orders incorporating their concepts on the methods helicopters would use to support an armored cavalry squadron screening the division front.

BRL completed, in 1967, a cost-effectiveness study of helicopter-borne antitank missile guidance concepts. The guidance concepts considered were a beam rider, advanced command-to-line-of-sight, semi-active laser, and optical contrast-correlation homing. The four concepts were compared with the TOW system, where each was pitted against a common target in an identical environment. The cost to kill was the primary measure of effectiveness used in the analysis.

SURVEILLANCE OF AMMUNITION

The combat capabilities of the Army depend greatly upon the reliability, accuracy of fire, and ballistic performance of nuclear weapons, missiles and conventional ammunition systems which are retained in readiness for use by artillery, infantry, tank, and anti-tank forces.

BRL continued to apply rigorous statistical methods to ensure that ammunition would meet all operational requirements, that quality control during ammunition production would provide acceptable ammunition as economically as possible, and that adequate surveillance was maintained on the ammunition after it was stockpiled.

Because evaluations of ammunition status generally depend upon data available only through costly destructive tests and analysis, BRL continued research into evaluation techniques, the statistical design of experiments, and analytical methods which would permit logical inferences and sound conclusions to be drawn.

So far as reliability was concerned, apart from the physical condition, say for example of an aging propellant, more and more attention had to be paid to the reliability of a complex system having many components. Frequently, estimates of the overall reliability for a complex systems were required for which very few tests of the complete system had been made, but for which a considerable number of functioning tests of components had been carried out. The safety and arming systems for nuclear warheads are examples of such components. From the failure rates observed for the components and knowing how the components were combined to form the complete system, BRL surveillance experts could provide an estimate of reliability. The challenge was not to provide the estimate, but to establish the variability in the estimate, ie, to define confidence limits. For this probelm, BRL developed a new method not dependent upon large sample assumptions; it could be used regardless of the amount of test data available for each component or the true failure rate for the component.

Until 1968, BRL continued evaluations of the reliability and ballistic performance of ammunition, development of sampling plans, design of experiments, and the development of ballistic and statistical analyses needed to assess the state of readiness of ammunition stockpiles for combat or training. At that time responsibility for surveillance and reliability work was transferred to the Army Material Systems Analysis Agency. The brief accounts below reveal the nature of surveillance work conducted at BRL from 1957 to 1968.

Studies were made of the reliability and miss distance characteristics of surface-to-air missile systems, Nike-Hercules and Hawk. Theoretical frequency distributions were fitted to large-sample flight data; a portion of the study examined the miss distances as a function of target range, altitude, and velocity. These analyses were particularly pertinent to surveillance evaluations of the reliability and performance characteristics of the surface-to-air missile systems and to detection of any important changes due to aging.

Multiple regression analysis and other statistical techniques were used to examine the effect of age on the ballistic characteristics of surface-to-surface missiles. Large sample data derived from Honest John rockets fired in troop training by United States and NATO field units were used to evaluate accuracy performance of the rocket system. The factors included in the analysis were rocket and launcher type, observed range, nonstandard meteorological effects, computed miss distance under standard environmental conditions and rocket age. Study of the ballistic characteristics as a function of aging, together with accuracy of fire and effects on targets, provided information for appropriate corrective ballistic instructions to field units, reduced the risk of dependence on unreliable or inaccurate missiles in the stockpile and minimized the risk of costly premature replacement.

The development of nuclear artillery and related tactical concepts requiring relatively small but highly mobile combat units required development of new doctrine to exploit the artillery's capability to deliver both conventional and nuclear rounds. In a cooperative effort with the Continental Army Command, the US Army Artillery School at Ft. Sill, Oklahoma, and the Evans Signal Laboratory of the US Signal Corps, BRL analyzed the effects of ballistic and meteorological variables on the accuracy of artillery fire. The results of the work showed that the most important factor in the delivery accuracy was the age of the meteorological data. The use of meteorological data two, four, or six hours old contributed more to inaccuracy in artillery fire than did variations in ballistic properties.

IN MEMORIAM

"The country's foremost expert in the science of ballistics throughout forty years of outstanding service to the US Army; a master in gathering competent people and inspiring them to do creative research. Ballistician, mathematician, and scientist, R. H. Kent achieved well-merited fame for bringing rigorous scientific methods to ballistics."

Dr. Robert Harrington Kent was memorialized in ceremonies held at the Ballistic Research Laboratories on September 24, 1974, with the dedication of a building in his honor. The Exterior Ballistics Laboratory was officially named the R. H. Kent Building. Dr. Kent was chief of the Laboratory from 1945 to 1949.

A bronze plaque memorializing the deceased scientist was unveiled by his niece Mrs. Sidney Grant of South Bristol, Maine. The text of the inscription on the plaque appears above under Dr. Kent's photograph.

Robert Harrington Kent was born in Meriden, Connecticut, on July 1, 1886. He attended Harvard University, obtaining his bachelor of arts degree in 1910, his master of arts degree in 1916. In 1953, his alma mater conferred upon him the honorary degree of doctor of science.

After graduation he became an assistant instructor in physics and a part-time instructor in mathematics. He was an instructor in electrical engineering at the University of Pennsylvania from 1916 to 1917.

In 1917 he entered the US Army and was commissioned a first lieutenant in the Ordnance Corps. He was assigned to the office of the Chief of Ordnance and in 1918 he was ordered to Tours, France, on the staff of the Chief Ordnance Officer, American Expeditionary Forces. He was in charge of ballistic work and was responsible for the preparation of firing tables used with American artillery.

He resigned from the Army and assumed duties as a civilian in July 1919, in the Office of the Chief of Ordnance, Washington, D.C. In 1922 he was transferred to Aberdeen Proving Ground, Maryland, where he worked until his retirement in July 1956.

He worked continuously in interior, exterior, and terminal ballistics at Aberdeen Proving Ground until Col. H. H. Zornig organized the Research Division of the Proof Department at Aberdeen. In 1938 the Research Division became the Ballistic Research Laboratory; Dr. Kent became associate director, a position he held until 1948, when he became associate technical director of the laboratories.

He was a Fellow of the American Association for the Advancement of Science and of the American Physical Society. He was a member of the Institute of Mathematical Statistics, the Institute for Aeronautical Sciences, the National Academy of Sciences, and Phi Beta Kappa.

He was decorated with the Presidential Medal for Merit in 1946, the Potts Medal of the Franklin Institute in 1947, and the Campbell Medal of the American Ordnance Association in 1955.

At the time of his retirement, the R. H. Kent Award was established to be given annually to the person in the Ballistic Research Laboratories for outstanding scientific or engineering achievement.

Dr. Kent died at his home in Havre de Grace, Maryland in February 1961.

"It was primarily the foresight of Col. H. H. Zornig that was responsible for the creation of the Research Division at Aberdeen Proving Ground in 1935 and its evolution into the Ballistic Research Laboratory by 1938. By careful, wise planning, he and his associates organized a broad program of research and an expansion of facilities that prepared the way for the tremendous progress made during World War II and the postwar period. His legacy lives today in the pride we take in the many contributions the Laboratory has made to Army weapon systems and to the civilian sectors of science and engineering, and in the continuing role the Laboratory plays in advancing the sciences of ballistics and defense technology. We are proud too of our staff and of our corporate reputation, international in scope, based upon our contributions, and the quality of our work..."

The quotation, appearing below Colonel Zornig's photograph, is from "Zornig, A Brief Biography" written at the Ballistics Research Laboratories in November 1978. The biography was prepared to reacquaint members of the Laboratories with Colonel Zornig and to affirm the Laboratories' debt to him.

Hermann Heinrich Zornig was born January 19, 1888, on the family farm near Newhall, Iowa. His father Marx Heinrich Zornig was from Grossen Aspe, Schleswig-Holstein, his mother Aniena, from Haupt aus Hemingsted bei Heide, in the same German province.

After attending grade school and high school in Vinton, Iowa, Heinrich Zornig attended Iowa State College at Ames, Iowa. He graduated, class of 1909 with a Bachelor of Science degree in Electrical Engineering. After graduation, he worked at the Testing Department of the General Electric Company until June 1910; following an entrance examination, he was commissioned a Second Lieutenant in the Coast Artillery Corps, US Army, September 30, 1910.

After several training assignments and some short assignments to the Coast Artillery Corps (CAC), in April 1913, he was assigned to CAC units in the then Territory of Hawaii.

While still in Hawaii, Lt. Zornig completed a written examination successfully for entrance into the Ordnance Corps. He was assigned as a student officer to the Ordnance School of Technology, then located at Watertown Arsenal, New York.

After completing his student assignment, 1st Lt. Zornig became a Shop Officer at the Arsenal, successively occupying positions as Superintendent at the various shops. The experience gained there made him knowledgeable in the manufacture of shells for coastal artillery use, casting processes for steel, iron, and some non-ferrous metals, and forging and heat treatment of guns and heavy machinery.

Leaving Watertown as a Major in 1921, Heinrich Zornig attended graduate school at the Massachusetts Institute of Technology; he was awarded a degree of Master of Science by MIT in June 1923.

Major Zornig then went to Picatinny Arsenal in May 1923, becoming Chief of the Technical

Division there in 1925. That assignment was followed by a stint as Assistant Military Attache, Berlin, Germany from 1926 to 1931. While in Berlin, at his own cost, he attended the Technische Hochschule where he studied under Dr. Carl Cranz and Dr. Otto Pappenberg, who were far ahead of most scientists of their time in exterior and interior ballistics.

He returned to the United States in late 1931 to serve as Chief, Ammunition Division of the Technical Staff, Office of the Chief of Ordnance.

In mid-1935, Major Zornig was assigned to the Research Division at Aberdeen Proving Ground, later becoming Chief of the Division—with a promotion to Lieutenant Colonel.

When the Research Division was renamed the Ballistic Research Laboratory in December 1938, Lt. Col. Zornig became its first director. About three-quarters of a year later he was promoted to Colonel.

Besides his many technical and managerial achievements at the Laboratory, Colonel Zornig was recognized for his decisions to choose Dr. Oswald Veblen to be the Chief Scientist at BRL during World War II and to establish a Scientific Advisory Committee of leading American Scientists to assist the Laboratory.

Colonel Zornig served as Director of BRL for about two and one-half years until he was reappointed Chief, Ammunition Division, Industrial Services, Office, Chief of Ordnance.

From January 1942 until September 1944, Colonel Zornig was Director of the Research Laboratory at Watertown Arsenal. He was awarded the Legion of Merit for leadership and vision in directing the activities of the Watertown Arsenal Research Laboratory and for his work in solving major problems which had confronted the Ordnance Department.

He was relieved from his position at Watertown in later 1944 to complete several assignments in scientific intelligence operations in the European Theater of Operations.

In August 1946, Colonel Zornig was placed on the retired list because of a service-connected disability.

He immediately became employed as a Research Engineer in the Research Laboratory of the General Electric Corporation, Schenectady, New York. He retired from that position in 1953.

Colonel Zornig died July 11, 1973, at Bethesda, Maryland, about six months after he had moved from his retirement residence in Coral Gables, Florida.

Colonel Zornig's name has been perpetuated at BRL through the Colonel H. H. Zornig award presented annually to honor a person whose work in support of the BRL mission is outstanding and worthy of special recognition.