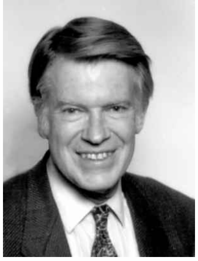
JOURNAL OF PROPULSION AND POWER
Vol. 19, No. 6, November–December 2003

Solid Rocket Enabling Technologies and Milestones in the United States

Leonard H. Caveny
Fort Washington, Maryland 20744
Robert L. Geisler
Tehachapi, California 93561
Russell A. Ellis
Saratoga, California 95070
and
Thomas L. Moore
Chemical Propulsion Information Agency, Columbia, Maryland 21044



Leonard H. Caveny retired from the Ballistic Missile Defense Organization (BMDO) in 1997 where he served as Director, Science and Technology Directorate. He received Mechanical Engineering B.S. and M.S. degrees from Georgia Tech and Ph.D. from Univ. of Alabama. He served in the US Navy 1956–1959 as Engineering Officer of a Destroyer. His solid rocket motor experience includes Thiokol's Huntsville Division (1960s), Guggenheim Laboratories of Princeton University (1970s), Air Force Office of Scientific Research (AFOSR) in the (1980–1984), and Strategic Defense Initiative Organization and BMDO (1984–1997). He chairs the National Research Council (NRC) Panel to evaluate proposals on Advanced Propulsion Research for AFOSR. He serves on the NRC Committee for the Review of NASA's Pioneering Revolutionary Technology Program. His present consulting includes solid rocket systems, energetic materials, and ignition. He authored over 50 refereed articles and received 11 U.S. patents. He is a Fellow of AIAA and recipient of the AIAA Wyld Propulsion Medal.

Robert L. Geisler received a B.S. in Chemical Engineering from the University of Cincinnati in 1958. He worked in the solid rocket program at the Air Force Rocket Propulsion Laboratory (AFRPL) for 32 years through 1990. He was intimately involved in the ARPA Principia project after Sputnik and helped to establish and conduct the AFRPL in-house and contractual programs on solid propellants; hazards; surveillance, aging and mechanical behavior; plumes; combustion; nozzles; and performance prediction and measurement. He was a key figure in providing technology base and support programs for Minuteman, Peacekeeper and the Titan solid booster programs. He has experience in failure investigation work on major solid rocket systems; detonation hazards; aluminum combustion and related phenomena. He rose through the ranks from project engineer to director of the Vehicle Systems division where he directed the efforts on satellite technology; systems analysis; the National Hover Test Facility, Kinetic Kill Vehicles and Electric Propulsion. Now in his 45th year in solid rocketry he has worked on most aspects of solid rocket propulsion and serves as a private consultant for a number of organizations. He serves on the AIAA Solid Rockets History subcommittee. He is an AIAA Associate Fellow.

Russell A. Ellis received a B.A. from Columbia College, Columbia University in 1958, a B.S. in Mechanical Engineering from the School of Engineering, Columbia University in 1962, and a Master's Degree in Engineering Administration from the University of Utah in 1971. He served in the US Navy 1958–1961 as Engineering Officer of a Destroyer. In 1962 he began what is now a 41-yr career in the solid rocket industry. His first nine years were with Thiokol/Wasatch and the next 32 at Chemical Systems Division, Pratt and Whitney, San Jose, CA. He retired in 2003 and now is a Consultant to the industry. He is well known for his work in advanced nozzles and materials, particularly application of carbon–carbon ITEs and exit cones to nozzles. He authored the NASA nozzle design monograph and has presented and published over 50 technical papers associated with solid rockets. He serves on the AIAA Solid Rockets Technical Committee as a member of the Education subcommittee. He is an AIAA Fellow.

Thomas L. Moore received a B.S. in Mechanical Engineering from West Virginia University in 1983 and an M.S. in Technical Management from The Johns Hopkins University in 2001. He spent the first ten years of his career at Hercules' Allegany Ballistics Laboratory (ABL) in Rocket Center, West Virginia, where he held various assignments in tactical missile propulsion and launch eject gas generator development, production, and R&D programs. In 1993, Moore joined the Chemical Propulsion Information Agency (CPIA), a U.S. Department of Defense Information Analysis Center operated by The Johns Hopkins University, where he supervises CPIA's technical services to the propulsion industry, and edits and maintains several national solid propulsion reference manuals and databases. He is currently the Deputy Director of CPIA. In 2001, he successfully nominated Allegany Ballistics Laboratory for recognition as a Historic Aerospace Site by the AIAA. Moore has authored several solid rocket history papers and wrote the annual Solid Rockets highlights for *Aerospace America* magazine from 2000 through 2003. He is an AIAA Senior Member and member of the Solid Rockets Technical Committee (SRTC).

Received 7 August 2003; revision received 8 September 2003; accepted for publication 9 September 2003.

The accomplishments of the U.S. solid rocket community are chronicled via discussion of ten enabling technologies and the people and organizations that produced them. This approach demonstrates the vibrant and advancing nature of solid rocket technology; to call it a history implies a recollection of something finished. The paper addresses key events and technology in a substantive manner by defining the major concepts (e.g., Pyrogen igniter, large case-bonded grains, composite cases, Flexseal TVC, extendible exit cone), new materials (e.g., carbon–carbon, Kevlar®) and the advances in tools (e.g., hazard tests, thermochemistry tables, and standard performance prediction packages) that were central to technological advancement. The paper chronicles how these keys enabled incredible advancements ranging from the 260-in. space booster to miniature multi-axis divert propulsion systems. Space limitations prevent discussion of many interesting concepts tested but not fielded. In view of the companion paper by Alain Davenas, "The Development of Modern Solid Propellants" in this issue, this paper focuses on hardware advancements.

Introduction

BY 1945, the unguided powder rockets described by Morey[1] were routine. In this paper, the people and solid rocket motor (SRM) technology that enabled modern missiles by 1960, and entire new families of missile and space applications since 1960, are chronicled. Ten major enabling technology areas, components, or events, having major impacts on the direction of modern solid rocket propulsion and motor designs, are identified. These *enablers*—all matured since the 1960s—are categorized in the Table. This paper limits focus to hardware advancements, because the companion paper by Alain Davenas[2] focuses on the development of modern solid propellants," an equal contributor to the advances in solid propellant rocketry.

After the landmark JATO program at GALCIT and Aerojet[3] in the late 1940s, the impetus for producing new solid rocket systems was driven primarily by the cold war. The United States needed improved JATO units to get fully-fueled and fully-loaded B-47s into the air. During this time (1950–1960), solid rockets played a major role in the U.S. air defense system. The Korean War in the early to mid 1950s provided requirements to upgrade all classes of the World War II solid-propelled weaponry. Systems used in Korea were essentially WW-II technology, e.g., the Zuni extruded double-base grains. Following the Korean War, this led to the rapid development of the Falcon, Sparrow, and Sidewinder air-to-air missiles; the latter was introduced in 1956 and versions are still being upgraded. The famous and innovative NOTS developed the first passive homing air-to-air missile.[4] [Note: For consistency, the names of DoD organizations at the time of the event or their zenith will be used independent of the period, e.g., NOTS, AFRPL, and MICOM. Unusual terms used more than one section are defined in the Glossary.]

Table Ten enabling technologies that matured since 1960

1) Propellant grain technology
Grain and motor design
Solid propellant structural integrity
2) Case technology
3) High performance component technology
Components
IHPRPT program
4) Large motor technology
Large segmented and monolithic boosters
The big booster early years
Big boosters following the Space Race
Big booster effort at AFRPL
The 260-in. motor
5) Interceptors
Nike
Sprint and HiBEX
Patriot
DACS
6) Thermochemical modeling and simulation development
JANAF thermochemical tables
Shifting specific impulse calculations
Solid performance program (SPP)
Combustion
7) High area ratio nozzle technology
8) Air-launched missile technology
Sidewinder
Sparrow
AAMRAM
Falcon
SRAM
9) Mastery of hazards
SOPHY
DDT, IM, and ESD
10) Small tactical motor technology

The Space Race started with the advent of the Soviet launch of the world's first satellite, Sputnik, on 4 October 1957. This gave impetus for the Department of Defense (DoD) to produce strategic systems such as the silo-based Minuteman ICBM and the submarine-based Polaris Fleet Ballistic Missile (FBM), and for the 1958 establishment and massive funding of NASA to produce large boosters. These missiles and their successors inspired the massive funding for solid rocket propulsion for the next four decades. Solid rocket development programs took on greater importance in terms of national priority and resources in the 1960s, after the vulnerability of the U-2 spy plane signaled the need for space surveillance systems. The solid rocket industry was called upon to rapidly develop boosters weighing over ten times that of the Minuteman missile to lift new generations of surveillance satellites. From this program evolved the workhorse Titan III 120-in. (3.05-m) diam segmented solid booster, which provided the U.S. eyes in space for over four decades and paved the way for the civilian space program, i.e., NASA's Space Shuttle SRM boosters.

Along the way, the necessary empirical and analytical predictive tools had to be developed to enable the rapid growth in motor size and performance. As large as the leap from tactical to strategic solid rocket motors was, it was completely overshadowed by the further leap to the even larger segmented boosters. These factors placed emphasis on the development of modeling and simulation technologies, as well as the ability to validate and verify these tools with carefully-designed and instrumented tests. The solid propulsion community faced a task akin the Manhattan Project in developing highly-sophisticated devices before the advent of the modern computer and digital electronics. During the first decade of the Space Race, the transition was made from mechanical calculators and slide rules to mainframe computers. In the 1970s, pocket calculators and mini computers (strange punched-tape devices) took part of the computational load before desktop computers entered the scene in the mid 1980s. With the aid of digital computational and data acquisition tools, the science of solid rocket propulsion predictive capability matured and became an important part of the story. The largest technology barrier presented by the scaling up of solid rockets was to provide an adequate thermal protection system at minimum mass. The thermal protection system had to survive particle-laden gases approaching 3600 K for 60 s in ICBMs and 120 s in large space boosters. This was a hard-won battle. Early designs were done on a cut-and-try basis; this became impractical. There were other difficult problems such as the structural and ballistic analysis of office-building-sized composite structures designed with very low margins of safety to be light enough to fly efficiently. Conquering these issues required teams of talented people working many years.

Given the above challenges plus the myriad of issues on safety, reliability, service life, plume physics, ignition, combustion theory, manufacturing quirks, and integration, it is little wonder that the rocket scientist gets and deserves great public recognition for the mastery of complex technical issues.

An important historical observation is most of the tactical and commercial solid propulsion systems would not have been developed without the national security investment in ballistic missile and military space booster systems. The realities of national priorities today raise the issues of our ability to capture and nurture the hard-won Cold War solid rocket propulsion knowledge and to sustain it in future generations. This is a volatile national treasure and the investment on the scale of the last half century will likely never be repeated.

Before 1945: Two World Wars

The history and personal stories of solid rocketry before 1945 are the subjects of many books and papers.[3–6] Indeed, the lives and contributions of such people as GALCIT's[3] Theodore von Kármán, John W. Parsons, Frank Malina, and Thiokol's[7] Joseph C. Patrick and Harold W. Ritchey can be found in multiple volumes and papers. This paper focuses on the period after 1945 and acknowledges others whose important technical contributions (often in the early part of their careers) are not as well noted.

The late Loren Morey[1] of Hercules wrote an excellent history of this era. He notes that despite his fame as the father of U.S. liquid rocketry, Robert H. Goddard actually did some of the pioneering work on these early solid rockets at the outset of World War I. As armament work languished in the U.S. between the wars, Army Lt. Leslie Alfred Skinner of the Army Aberdeen Proving Ground and Clarence Nichols Hickman, a Goddard coworker and original leader of Section H of the NDRC, kept the fledgling solid rocket program alive. The budgets rarely exceeded $10,000 per year in those decades. When World War II arrived, this nation's embryonic solid rocket program was quickly put to the task of developing and fielding a host of rocket-propelled munitions.

1945–1960: Proving Ground for Modern Era

Two points in time are selected to assess the solid rocket technology, 1960 and 2003. Our 1960 snapshot comments on some of the key people and significant advancements made during 1945–1960 that formed the foundation of solid rocket community. The 2003 snapshot discusses advancements since 1960. The major advancements in fielded propulsion systems are tied to the Ten Enabling Technologies in the Table.

By 1960, each of the services and NASA had major full-feature SRM (solid rocket motor) facilities and expert staffs. Prominent among the research and development centers were: the Army Propulsion Laboratory at Redstone Arsenal, Alabama and Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland; Naval Ordnance Test Station,[4,8] China Lake, California; Naval Ordnance Station, Indian Head, Maryland, the Air Force Rocket Propulsion Laboratory at Edwards AFB, California (established in 1959); and the NASA Centers at Pasadena, California (JPL), Cleveland, Ohio, and Langley, Virginia.

By 1960, the companies were tooling up for the production and testing of large boosters. This required large ingredient preparation areas, mixers, curing pits, and test stands on large real estate. For example, Fig. 1 illustrates a large 100-gallon (400-L) mixer of the time, which would soon be superseded by remotely-operated mixers 10 times larger. Three major solid rocket production companies were in full operation at multiple sites:

1) Aerojet-General Corporation,[9,10] Azusa and Sacramento, California

2) Hercules Powder Company,[11,12] Magna, Utah and Rocket Center, West Virginia near Cumberland, Maryland

3) Thiokol Chemical Corporation,[7] Elkton, Maryland, Huntsville, Alabama, Longhorn at Marshall, Texas, and Promontory, Utah.

The other prominent and emerging companies in 1960:

1) Atlantic Research Corporation (ARC),[13,14] Alexandria and Gainesville, Virginia

2) United Technology Center, UTC (later Chemical Systems Division (CSD) of United Technologies Corporation), Sunnyvale and San Jose, California

3) Grand Central Rocket Company,[15] Redlands, California (later Lockheed Propulsion Company)

Fig. 1 Mixing propellant was a hands-on operation in 1957. Crew is discharging a 100-gallon Baker-Perkins mixer at Thiokol Elkton. The propellant is polysulfide and ammonium perchlorate.

4) Rocketdyne Solid Rocket Division, McGregor, Texas (initially operated by Phillips Petroleum)

5) Rohm and Haas Company's Research Laboratories (R&H), Redstone Arsenal, Alabama[16]

As stated, recent histories have been written for most. Also, the aspects of solid rocket development singled out by a professional historian are instructive.[17]

Genesis of Multistage Propulsion

Until the mid 1950s, the solid rocket industry was primarily considered the source of propulsion for tactical systems and a mix of sounding rockets. While this was challenging enough, applications requiring intercontinental ranges and heavy lift rapidly emerged. These requirements demanded total impulse two orders of magnitude beyond what had been demonstrated, plus highly efficient multi-stage strategies. The most prominent visionaries who recognized the inevitability of orbiting platforms and intercontinental weapons were, however, assuming liquid propulsion.

But not all assumed liquid propulsion. As early as 1954 Colonel Edward N. Hall of the USAF Western Development Division,[18] and in 1956 Rear Admiral William F. Raborn, Jr., of the Navy's Special Projects Office, had the vision of simple, quick-response solid-rocket-powered strategic missiles. By 1958, the push was on to make all of the land- and sea-based strategic missiles solid-rocket powered.[11] The propulsion challenges in designing and developing these early Polaris and Minuteman missiles demanded vastly improved mass fraction, burning time, thrust vectoring, motor size, thrust termination, and performance. It was also necessary to *facilitize*, staff, and educate a new industry as rapidly as possible. The unveiling of the three-stage, 69-ft (21-m) tall, 68,000-lbm (30,800-kg) Minuteman missile[19] at the Air Force Association Convention in San Francisco, California in September 1960 defined the industry that was emerging. Each of the three stage contractors developed a technological character reflected by the three stages they developed for this landmark missile. Thiokol became the master of making large first stage boosters, ultimately manifesting themselves in the Shuttle SRM boosters. Hercules deftly designed and built motors of the highest technology for third stages incorporating the highest energy nitrate-ester propellants, the highest mass fraction composite motor cases, and intricate and highly-configured grain designs with thrust termination ports such as in the Minuteman third stage. Aerojet-General became a second stage motor organization with a well-balanced blend of the capabilities of the other two. Their innovative Minuteman second stage design embodied a dual propellant grain and a titanium case. This trend of Hercules producing the highest performing motors and Thiokol the highly reliable large boosters persisted to the 1980s through several generations of missiles, including Peacekeeper, Trident, and Small ICBM. Loren Morey, then head of the Hercules long range plans office, was often heard to remind the troops "Hercules makes $400 suits while the rest of the industry makes $99 suits." They clearly made the higher performing product in those days and it was a couple of decades before the competitors caught up with them in nitroglycerin-based propellants and low-margin composite case designs.

By 1960, the need for large strategic systems enabled the solid propellant industry to project itself into the commercial applications of today. The launch of commercial payloads in the U.S. relies on a wide array of booster and upper stage solid rocket motors. The perennial assertions since the 1960s that solids for heavy lift would be replaced by liquids has not happened. Both the intrinsic characteristics of solid rockets and the steady advancements of the hardware and propellant technology have maintained solid rocket competitiveness, i.e., the ten enablers of the Table and the propellants in the companion paper.[2]

1960: Space Race is underway

Technical Environment

Rocketry was fun in the 1960s. The propulsion industry had a mandate to close the *Missile Gap;* soon, strategic bombers would no longer be a sufficient deterrent. If you were not of that time, you missed the era of frequent large motor tests; none were routine and none went unanalyzed. Learning and recovery from failures was rapid. Indeed, the DoD and NASA fee system *incentivized* building and testing large numbers of motors. (Some will state that the verb *incentivize* is the first aerospace noun-into-verb corruption of the English language; it came before *prioritize*.) This was not a good time for a hand-wringing analyst; program managers preferred to test rather than wait for *one more calculation*.

The solid rocket community as it existed in 1960 is an excellent point of reference. Sputnik pulled the trigger starting the Space Race, but only after introspective delays by Congress and DoD caused post-Sputnik layoffs in the solid rocket companies. Once the money started to flow, new facilities were erected rapidly and staffs increased several fold. By 1960, the solid rocket companies had already shifted into high gear. The several technologically-strong organizations with their roots in the 1940s (Hercules Powder Company, Thiokol Chemical Corporation, Aerojet-General Corp., Jet Propulsion Laboratory, Naval Ordnance Test Station at China Lake, among others) had seasoned technical teams led by competent and exacting engineers and chemists. In this era, digital computers and instruments were just beginning to open new predictive capability. However the majority of the detailed calculations of ballistics, structural analysis, statistical correlations, laboratory measurements, etc. involved slide rules and the noisy, *one on every desk* mechanical calculators. These were supplemented by charts and tables that summarized parametric maps of computer results, e.g., the Dailey and Wood[20] sets of curves for compressible flow over a range of specific heat ratios. Emphasis was placed on collecting and correlating test data, e.g., nozzle erosion by material and propellant type over a range of pressures. Multitudes of such correlations were used in the semi-empirical approaches to selecting critical dimensions and materials for use in increasingly-severe rocket motor environments. Proprietary versions of these correlations were the coins of the realm. Only the derated variants were shared in public forums. As propellants became more energetic, flame temperatures increased and the challenges of thermal management increased. As motor mass fraction and chamber pressure were increased in pursuit of more total impulse, the challenges of containing and channeling the internal flow were daunting. The designers were constantly forced to accommodate regimes using uncharacterized advanced materials and fabrication techniques. The engineers and chemists were never far from the rocket motor hardware; successful ones acquired a keen sense for physical reality.

Even as the pace in the early 1960s accelerated, new engineers were awed by the legacy of the 1950s. The twelve volumes of *High Speed Aerodynamics and Jet Propulsion* (aka *The Princeton Series*), edited by Martin Summerfield, Joseph V. Charyk, and Coleman duP. Donaldson, are a gold mine of practical knowledge on fluid flow, combustion, heat transfer, rocketry,[21] etc. Much of it stemmed from WW-II research or from the researchers trained during that period. For example, the very insightful and practical information and guidelines in the Huggett, Bartley, and Mills[22] paperback are chapters from Ref. 21. By 1956, George P. Sutton's excellent book[23] treating the basic elements of propulsion was in its second edition; in 2000, the seventh edition was published, making it one of the all time top sellers for its publisher. In 1957, Stanford S. (Sol) Penner's book[24] provided a sound theoretical point of departure for theoretical treatments of reacting flows, propellant combustion, performance prediction, plume phenomena, etc. Penner's book was the first-principles complement to several of the chapters in Sutton's book. In 1960, the Barrère and Vandenkerckhove 828-page volume[25] was a reminder that the U.S. did not have a lock on any aspect of solid rocket expertise.

In the 1950s, a turning point in the professional standing of rocket propulsion was the editors of *Jet Propulsion* transitioning it into the respected, refereed Journal of the American Rocket Society (i.e., ARS Journal). In 1963, the rocket propulsion community further enhanced its professional standing by leading the merger of the ARS and the Institute of Aeronautical Sciences, thereby creating the broadly-based AIAA under the leadership of Executive Secretary James J. Harford. Theodore von Kármán continued to influence the community by sustaining an environment for scholarship and technical exchanges among the U.S. and its allies. For example, AGARD (NATO's aerospace R&D framework) and the Princeton Series are his initiatives.

A memorable comment stated "All that most internal ballisticians need to know about compressible flow is in the first eight chapters of Shapiro."[26] Indeed, Ascher H. Shapiro's Table 8.2-Influence Coefficients was sufficiently inclusive for most internal flows. However, manual calculation of pressures, velocities, erosive burning rates, etc. along complex configurations was tedious. By the early 1960, computers were starting to relieve this tedium. For example, one of the authors (LHC), simply integrated (along the motor axis) the partial derivatives of Shapiro's Table 8.1 using elementary numerical techniques (on an IBM 650) to achieve a flexible internal ballistics design tool still serving well after forty years.

In 1960, keeping up with and assessing the solid rocket literature was already a problem. A fraction of it was idealistic, rather than useful, for quantitative prediction and analysis. Publications that obfuscated non-intuitive or complex processes were plentiful. The art of going from first-principle formulations to working tools for aerospace exactness had to evolve rapidly. By 1960, the inventory of accredited tools was rapidly increasing. This was a time of learning how to make analysis useful for prediction and correlation. A few of these tools are cited to define the era, while giving a few people and organizations attribution for their important contributions.

Organization Leaders from Leaner Times

In 1960, the solid rocket companies were led by talented and dedicated technologists: chief engineers, department heads, and chief scientists. As evidence of the sophistication of the solid rocket research and development community, the first volume of the American Rocket Society (ARS) Progress in Astronautics and Rocketry[27] was on solid rocketry; it summarized the results of high quality, pragmatic research. In 1960, urgency dictated our pace, not the present-day concerns over cost, process, and environment. The chief engineer of Thiokol's Huntsville division, Richard H. Wall, is representative of his contemporaries. In the 1950s, despite lean budgets, working on the boundary of safety, and competition among the pioneering companies, nothing was left to chance. Dick Wall was exacting and anyone working for him aspired to be as exacting. Those who made the mistake of jumping to a conclusion were rejoined by Wall, "Are you telling me something or are you asking a question." Finding the cause of flight failures before the modern era of many channels of high-speed data required real detective work and a keen sense of solid rocket physical processes. Again, using a Dick Wall anecdote to illustrate a point: a sustainer in-flight failure produced 12 pieces of hard but sparse evidence. After working long hours over a weekend, several of the team defined a plausible failure mode consistent with 11 of those 12 clues. They were ready to declare success and go home. Dick Wall firmly and swiftly rejected it. In another 12 h, his re-examinations yielded a failure scenario fitting all 12 clues and conclusively pinpointing the failure mode. The rapid advances that occurred in the 1960s are sometimes attributed to the more-than-ample budgets. The remarkable advances chronicled in this paper came from the leadership of first-rate technologists plus the enthusiasm of those who came after Sputnik.

The intellectual leaders of the early 1960s included people attracted by the challenges of rocketry. Many of the research leaders and scientists were trained in the 1930s and 1940s and matured in the 1940s and 1950s. Many had the strength of their own convictions and vigorously (and sometimes colorfully) defended their positions. The technical exchanges among Leon Green, Martin Summerfield, Edward W. Price, and Norman Ryan still ring in the ears of the younger engineers privileged to benefit from their exchanges. These were exchanges on interpretation of physical principles with goals of achieving even more performance and reliability. They did not suffer those who offered flawed or idealized physics; they disdained those not aware of the work of others. Many of the leaders in 1960 set high, but obtainable standards and goals. Most did not waste their own energies considering 'blue sky' conceptual propellants and motor designs.

Military Leaders Achieve Prominence

During the close the Missile Gap crisis following Sputnik, each of the military services had well-seasoned leaders who became identified with large solid rocket systems. All of these Flag Officers had perspective that transcended technology. In the late 1950s, both the Army and the Air Force long range missile programs had to overcome the strong biases of their liquid rocket heritages. The Submarine Navy had less to overcome; the storability of solids was compelling.

On 25 September 1945, the Bureau of Ordnance (BuOrd) Chief formally notified NDRC of the Navy's definite need for the ABL facilities that had been operated by George Washington University for wartime weapons research. The War Department subsequently transferred ownership of the property to the Navy, and the Hercules Powder Company of Wilmington, Delaware accepted a BuOrd contract to operate ABL. The deal for Hercules to continue operations at ABL was brokered by none other than Commander (later Vice Admiral) Levering Smith, Head of the BuOrd Rocket Propellant Research and Development Division, and wartime colleague of Ralph E. Gibson and Alexander Kossiakoff. Both Gibson and Kossiakoff were prewar academics who founded ABL and went on to become directors of JHU/APL. Little did Smith know that his role in preserving ABL would be of substantial benefit to the Polaris fleet ballistic missile program that he would lead ten years later. Smith, as a commander at NOTS, participated in developing a 50-ft (15.2-m) solid-propellant missile called Big Stoop, signaling the Navy's Polaris aspirations. Smith became a legend in the FBM program and for his management maxims, (e.g., "Deployment takes precedent over improved technology."), interface control, and goal discipline. He is a prime example of how the Navy kept talented officers in one important career path (solid rocketry) for major parts of their careers. He started in the lab at NOTS and followed the solid rocket career path to ultimately become the Chief of SSPO, one of the most demanding technical jobs in the Navy.

In 1959, the Air Force relocated rocket propulsion research and development personnel (including author RLG) of the Power Plant Laboratory at Dayton, Ohio to the Luehman Ridge region of Edwards AFB. Thus, the Air Force Rocket Propulsion Laboratory (AFRPL) was founded. During this same year, Colonel Samuel Phillips was assigned to the Air Force Ballistic Missile Division as Director of the Minuteman Intercontinental Ballistic Missile Program. Upon assuming that position, he learned that the Minuteman (MM) schedule had been accelerated by a year. Phillips was trained as an electrical engineer and was a decorated WW-II fighter pilot. He honed his large program skills on an incredible series of successful revolutionary systems, including the B-52 bomber in the early 1950s and the Falcon and BOMARC missile programs. In 1959, the first tethered, vertical-launch tests of the Minuteman rocket were conducted at AFRPL by Boeing from underground test silos. The previously-estimated sixteen launches needed to complete the test program were reduced to eight by skillful planning and engineering. Shortly after these extremely successful and efficient tests, the MM rocket completed its development and entered the Air Force's strategic arsenal. MM was introduced in 1962 with less fanfare than the submarine-launched Polaris in 1960; MM joined the company of the already-proven liquid oxygen/hydrocarbon-fueled Atlas. (General Bernard Schriever led a team that fielded the Atlas, the first successful U.S. intercontinental ballistic missile, in 1958.) General Phillips went on to fame as Director of the Apollo Manned Lunar Program.

In November 1955, Major General John B. Medaris became the first commander of the newly created Army Ballistic Missile Agency (ABMA) at Redstone Arsenal, Alabama. Medaris, trained as a mechanical engineer, took on a wide range of challenges including development and production of the liquid-fueled Jupiter-C intermediate-range ballistic missile and the weaponization of the Redstone ballistic missile. On the very day Sputnik was launched, the new Secretary of Defense Neil H. McElroy was visiting the ABMA; Medaris briefed that the Army could launch a U.S. satellite using the Jupiter-C launch vehicle in a few months if told to go ahead. Under his energetic leadership, coupled with the von Braun team, the Army began its several pioneering accomplishments in the space arena.

The Jupiter C (renamed Juno I by JPL for the satellite launch configuration) consisted of a modified Redstone liquid rocket topped by three solid-propellant upper stages composed of fifteen 6-in. (152-mm) diam Scale Sergeant motors manufactured by JPL.[28] (The JPL Scale Sergeant motors were from a former sounding rocket program and were not related to the larger, 31-in. (787-mm) diam, tactical Sergeant missile motor later developed by Thiokol Huntsville). The Scale Sergeant used 22 kg of ammonium perchlorate/Thiokol LP-33 polysulfide propellant. The second stage was composed of an outer ring of eleven Scale Sergeants; the third stage was a cluster of three Scale Sergeants grouped within that ring. The fourth stage was a single Scale Sergeant containing a more energetic propellant formulation and was permanently attached to the Explorer I satellite. The spin stabilization induced radial loads of 180 g, requiring the first-ever spinning static-test fixture to validate performance and motor integrity. Indeed, on 31 January 1958 solid rocket upper stages inserted the very first U.S. satellite into orbit! However, the inefficient clustering of small rockets delivering less that 210 s of Isp made clear the opportunity to progress via new enabling technologies. From this major success, the SRM community gained momentum for the missile race and soon-to-be-fielded improved upper stages.

On 16 January 1958, DoD announced the new solid propellant missile Pershing as the Redstone replacement. The Martin Company of Orlando, Florida was awarded a letter contract on 28 March 1958 for research, development, and initial production of the Pershing. By March 1958, Medaris became responsible for all Army Ordnance programs in the rocket, guided and ballistic missile, and space fields. In January 1958, the National Security Council assigned the highest national priority to the Nike-Zeus Antimissile Missile development program. In the Medaris environment, both Pershing and Nike-Zeus flourished. The first Pershing launch was conducted on 25 February 1960; the Pershing was first deployed in August 1963. Medaris retired from the Army on 31 January 1960. His dedicated efforts in engineering related to guided missile development, as well as his work to create public understanding of Space Age challenges and promises, marked him as one of the nation's leading authorities on the evolving U.S. space program.

Technology Leaders

In 1960, several hundred people deserved the title technology leader. In the paragraphs and anecdotes that follow, only a fraction are singled out. Those receiving recognition tend to be those with open literature publication and long involvement in the professional societies. Other technology leaders are mostly known only by their coworkers because of the nature of their work or its classification. Indeed, many excellent papers in the JANNAF proceedings are caught up in the declassification backlogs and cannot be referenced.

Probably the most useful rocket motor design empirical relation is Donald R. Bartz's[29] 1957 predictor of nozzle convective heating. In 2003, his correlation is still a reference for comparison. Bartz, of JPL, started with a familiar Nusselt number relation for turbulent convection in pipes, incorporated simple relationships to approximate transport properties and correlated them with heat flux data measured in liquid rockets.

In the 1950s, Aerojet had a number of perennial contributors to the research literature. Leon Green, Jr.,[30] (later at Aeronutronic) published a series of technical papers and notes that addressed the issues confounding interior ballisticians. The practical guidelines he provided, including such observations as the coupling between motor internal geometry and small variations in burning rate, were immediately useful. Green's relatively uncomplicated experimental rocket motors were instrumented to provide correlatable data. Richard D. Geckler, W. Hoyt Anderson, Richard F. Chaiken, and coworkers tackled a wide range of practical problems, e.g., Refs. 31, 32, and 33.

By 1955, Richard P. King and Joseph E. Pelham, Thiokol Huntsville, demonstrated the important concept of using a small rocket motor to ignite a much larger rocket motor. By 1958, the term Pyrogen[34] was coined. The Pyrogen designs anticipated the need to ignite motors in space and to uniformly ignite large length-to-diameter motors.

In the early 1950s, Edward W. Price, NOTS, began publishing a series of papers addressing internal flow with mass addition (i.e., the flow channel wall is burning propellant) and combustion instability. He attempted to integrate burning rate relationships and to address design considerations. Reference 35 is representative of this work. These useful papers defined the mechanisms of pressure drops and losses and attempted to prescribe design procedures. To some extent, the complications pointed out in the Price papers were an impetus for the development of numerical solutions capable of accommodating the more general boundaries and burning rate laws. The 1960 digital computers (e.g., IBM 650) could handle the more general formulations and led to new internal ballistic design tools.

Barnet R. Adelman and David Altman led United Technology Center (later CSD) to success with large segmented solid rocket booster development for the Titan III system. Adelman, while Director of Vehicle Engineering for the Ramo-Wooldridge Corporation in the mid 1950s, was a leading proponent for solid-propellant-powered ballistic missiles. His persistent advocacy was central to Minuteman being powered by solid propellant. David Altman's propulsion career spans from JPL in 1945 to attracting national attention for hybrid propulsion in 2003 as Consulting Professor, Stanford University.

The pioneering work of Samuel Zeman and Arlin Graves[36] on exploding bridgewires (EBWs) and associated components such as through-bulkhead initiators were key steps in the development of safe and robust ignition systems. Implementation of the EBW technology to ignite a pyrotechnic sequence enabled igniter designers to more confidently avoid accidental ignition due to extraneous electromagnetic excitations, e.g., radar. Typically, EBW initiators apply 1–2 J at up to 3000 V to explode a small-diameter (0.025-mm) gold or platinum wire with a length of 1.5–2.5 mm. The resulting thermal energy suddenly ignites an insensitive pyrotechnic, which, in turn, ignites the primer propellant in the igniter sequence. One of the big advantages of a through-bulkhead initiator (TBI) is that it is a non-electric device and therefore, is not subject to the potential hazards associated with typical electroexplosive devices. A TBI consists of a metal body with a high strength bulkhead in the center and explosive charges on both sides of the bulkhead. A small charge of a secondary explosive serves as the donor and the output side has a similar charge to serve as the receptor (plus some heat-producing pyrotechnic material). Initiation is achieved by coupling a confined detonating cord, such as mild-detonating fuse (MDF), to the TBI. The MDF is initiated by a detonator contained in an out-of-line safe-and-arm device.

Ellis M. Landsbaum spent his early years (1955–1961) as a flow and combustion specialist[37] at JPL. He joined the newly-formed Aerospace Corp in 1961. Landsbaum soon became the corporate memory for the myriad of Air Force solid rocket motors ranging from the original Titan-III to the most modern EELVs and the large family of apogee kick motors. He continues in his sixth decade of correlating and explaining rocket motor phenomena and solving key issues relating to the Air Force booster programs.[38,39]

All through the 1940s, various forms of instability (e.g., acoustic modes producing 1–6 MPa (145 to 870 psi) overpressure) plagued solid rockets. Overcoming these problems often required the art (the practice often did not qualify as a science) of performance-robbing mechanical solutions such as resonance rods, drilled holes along the grain, and cast-in baffles. Intuitive and ineffective fixes were plentiful, but understanding of the driving process was lacking. Frank T. McClure,[40] Robert W. Hart and their co-workers at John Hopkins University Applied Physics Laboratory (APL) were among the first to address acoustic instability by applying the essential physics. APL assumed a national leadership role[41] with respect to national coordination. The 1960 working group was a good representation of the 1950 to 1960 aerothermodynamics leadership. Their 1960 conclusions were sound. A reader is struck by the 1960 statement advising relatively simple models be developed primarily to indicate the direction a rocket motor "parameter should be varied in order to enhance stability" (Ref. 41, page 34). They warned, "in view of the complexity and variety of the phenomena . . . realistic theoretical analysis is out of the question." Their last section advocates the common sense approach of quantitative experiments closely coupled with theory. This is in stark contrast to the post-2000 trend to ever more complex numerical simulations and fewer rocket experiments. Some will look no further to explain the rapid advances made between 1950 and 1970.

In a conversation between Martin Summerfield and Frank McClure before a 1970 meeting at APL, McClure asked Summerfield what research caught his attention. Summerfield responded by including non-steady burning and combustion instability in his list. McClure then questioned Summerfield in an effort to learn after all those years (i.e., 10) *what was left to do*. Finally McClure closed off the discussion with the words, "I can not imagine that working on those refinements is satisfying." This was one of the few times that Summerfield was observed (by LHC) to be bested in collegial chat. McClure told Summerfield something he knew very well, i.e., too much refinement takes researchers beyond the deterministic part of the problem. Indeed, many of the chief engineers in 1960 were masters of achieving the right mix of first-principle theory, empiricism, and physical insight to succeed on the frontiers of rocketry.

CPIA and JANNAF

Any overview of U.S. rocketry must acknowledge CPIA and JANNAF. The Chemical Propulsion Information Agency (CPIA), established in 1962, evolved from the earlier Solid Propellant

Information Agency (SPIA). Industry technical exchange activities were first chartered under the Interagency Chemical Rocket Propulsion Group (ICRPG) in 1962 and became the current Joint Army-Navy-NASA-Air Force (JANNAF) Interagency Propulsion Committee in 1970. CPIA, operated by The Johns Hopkins University, is the administrative arm of JANNAF. The reporting, archiving, standardization, and coordinating functions of these coupled organizations contribute directly to U.S. successes and, indirectly, to worldwide technology. The collegial JANNAF process is the key to industry cooperation on common technical issues, and its working groups and workshops sustain essential perennial working relationships. U.S. specialists can get in sync with system developments at the JANNAF Propulsion Meetings held in nice places; the consensus most memorable is Incline Village, Nevada in 1978.

The Companies

The tangible strengths of the U.S. solid rocket community are in the hundreds of aerospace companies, i.e., the prime contractors, propulsion companies, propellant ingredient manufacturers, case fabricators, specialty houses, and support contractors, to name a few. The competition among them, and the pursuit of excellence to meet the national need, molded a community of technologists, either fierce competitors or good partners, depending on the teaming. In this paper, a few of those involved are mentioned. As discussed, the heritage and personalities of several of the propulsion companies are relatively well documented and known, e.g., Aerojet and Thiokol. By anecdote and example, a few lesser-known insights are offered.

The birth of the chemical propulsion business at Hercules was a monumental step for the company and the solid rocket community. In March of 1958, Hercules was at a crossroads with a declining commercial explosive business and the prospect of rapid growth in the rocket propulsion area. Their experience with manufacturing solid rockets was as an operator of DoD facilities. At that juncture, they reorganized to become an independent producer for military and civilian space programs. Their explosives department established a new Chemical Propulsion Division with Lyman Bonner of the Allegany Ballistics Laboratory (ABL) as director of development. Under his visionary direction and zeal, this operation took off with management's guidance to "think big."[11] The brilliant Bonner was an expert in rocket propellant design and development, interior ballistics, spectroscopy, and molecular structure. At Hercules, he was technical director of ABL from 1945 to 1955, and director of development in the explosives and chemical propulsion department from 1955 to 1965. During World War II, he received the Navy's highest civilian honor, the Distinguished Public Service Award, for developing new propellants for rockets and guided missiles. With this auspicious start, Hercules became one of the major manufacturers of ballistic missiles for all of the services.

A key technological challenge for Hercules was to develop effective designs and processes to manufacture propellant grains for larger and faster rockets. The existing extrusion process limited grains to the available press size. A new process based on the NDRC Division 8 research of John F. Kincaid and Henry M. Shuey at the Bureau of Mines' Bruceton Research Laboratory near Pittsburgh provided the opportunity to answer the challenge. The new cast double-base propellant manufacturing process consisted of treating nitrocellulose granules (casting powder) with a solvent (principally nitroglycerin), a plasticizer, and a stabilizer, then heating and curing the resulting mixture to form a homogeneous mass that could then be cast into molds and cured to make large diameter grains of so-called NC/NG propellant. Whereas the largest extruded grain to that date at ABL was 6 in. (150 mm) in diameter, the first cast double-base grain had a diameter of 16 in. (400 mm). Cast double-base grain configurations, and the size thereof, seemingly had no practical upper bounds. Intricate geometrical grain configurations permitted a high degree of ballistic tailoring.[42] Both men went on to become pillars of the industry in the fields of propellants and hazards. Kincaid became an Undersecretary of Commerce in the Kennedy administration and Shuey was part of the senior management of the Rohm and Haas Research Laboratories, Redstone Arsenal, and a national leader on ballistics, performance, hazards, and safety. Both men were principal consultants to the Navy SSPO and had a major impact on the FBM program.

In 1949, Arch C. Scurlock and Arthur Sloan started Atlantic Research Corporation (ARC) in downtown Washington to work on a three-month propulsion research contract from the Navy, as part of Project Squid. The ARC corporate and technical achievement histories were recently documented.[13,14] Their mid 1950s quarterly reports include the very thorough research on increasing the burning rates of end-burning motors by including axial wires, e.g., silver. In 1963, some of patents on this technology were issued pursuant to previously-submitted applications placed under secrecy orders.[43] The wired end-burners stemming from this era are still operational. Among the most notable accomplishment in ARC's first decade was the Charles B. Henderson and Keith E. Rumbel breakthrough of jumping from 5% aluminum (then considered an upper limit) loading to 15–20%. They formulated denser, more energetic propellants that efficiently burned aluminum. Their work anticipated the insightful T^* concept as described by Walter E. Baumgartner of Lockheed Propulsion Company,[44] i.e, *Does the formulation without Al produce a flame temperature (T^*) sufficient to ignite the Al?*

Chemical Systems Division (CSD) of United Technologies Corporation (now Pratt and Whitney Space Propulsion San Jose) was formed by Barnet R. Adelman, Herbert Lawrence, and David Altman in 1958 as United Research Corporation of Menlo Park. In 1959, the company became part of United Aircraft Corporation and was renamed United Technology Center. In this same year, retired Lt. Gen. Donald Putt joined the company. The specific goal of the company was the development of large segmented solid rockets. CSD became known initially for its success in development and production of the segmented 120-in. (3.05-m) boosters for the Titan III-C and IV-A launch vehicles. In subsequent years, CSD is considered a leading innovator in the SRM industry with such novel devices as the Techroll® fluid bearing and hot ball-and-socket thrust vector control (TVC), bolt-extrusion thrust termination, and the supersonic splitline flexseal nozzle. CSD is known for numerous firsts in the SRM industry including the first production use of carbon–carbon ITEs and EECs, the first use of Kevlar® for cases, development of the first redundant drive electromechanical actuator, and the first electromechanical liquid injection valves.

Not all the major rocket companies survived to the 1980s. In 1954 the Grand Central Rocket Company[15] occupied a site near Redlands, California. It was founded and led by Charles E. Bartley, who gained his solid rocket experience during his GALCIT involvements.[22] One of their first big contracts was from the Martin Company for the third stage of the Vanguard rocket, 18-in. (0.46-m) in diameter with 1066 kg of composite propellant. On 17 March 1958, the Vanguard inserted a U.S. satellite into orbit using a solid propellant final stage. By 1961, the company was renamed Lockheed Propulsion Company after purchase by Lockheed. They had several successful programs and several near successes as they competed for the large booster contracts. Employment peaked at 1,600, but after a series of difficult projects, e.g., SRAM, the company was disbanded in 1976 and much of its equipment sold to South Korea.

During its short tenure, the Rohm and Haas Research Laboratories, Redstone Arsenal, Alabama had perhaps the strongest per capita technical team in the industry. It was the home base of Henry M. Shuey, the renowned advisor to DoD. R&H operated a modern Army-owned facility from 1949 to 1971.[16] Its peak employment was 300. Its initial charter involved propulsion for small tactical systems, e.g., shoulder-fired weapons such as the Light Assault Weapon (LAW). However, the talented R&H staffs were quickly assigned some of the more challenging aspects of programs such as Nike-Zeus, Hawk, Pershing, and Sprint. Segments of their analytical capability were among the best in the industry, and much of it was made available to the industry via their quarterly reports. They succeeded admirably in their assumed role of consultant to industry. One of the authors (LHC) benefited greatly by his many visits to R&H to learn the techniques referred to in the *quarterlies* written by Stanley E. Anderson, William H. Groetzinger, William C. Stone, Charles E. Thies, et al. R&H had one of the strongest advanced energetic-materials synthesis groups. They quickly became masters of devices[45] and micro-motors[46] for evaluation using small amounts (∼10 g) of novel propellants of uncertain stability. The 1970 dispersal of the R&H expert staff was a boost for many aerospace organizations.

Academic Institutions

The Navy's Project SQUID, initiated in 1946, was DoD's first broadly-based science program for jet propulsion. Even though only a fraction related to solid rockets, it stimulated interest and sustained many university propulsion researchers though the 1950s. By the mid 1960s several universities had first-rate solid rocket experimental research capabilities, e.g., those at Caltech-JPL, the Maurice J. Zucrow-led Jet Propulsion Center at Purdue University, the Martin Summerfield-led Solid Propellant Group at Princeton University, and the Norman W. Ryan-led Combustion Laboratory at the University of Utah. The DoD basic research agencies (ARO, ONR, AFOSR, and ARPA) and NASA supported dozens of solid-rocket-related research programs in universities. The larger programs included several professors and senior staff, technicians, and five to ten graduate students. Propellants were made and motors or laboratory devices loaded and tested. From those programs came professionals such as John R. Osborn, J. Michael Murphy, Ronald L. Derr, Herman Krier and R. H. W. Waesche, who by graduation were prepared, by their national participation, to be part of the community and to quickly take a leadership roles in practical programs. During the 1970s other academic institutions established solid rocket laboratories, for example, Kenneth K. Kuo at Pennsylvania State University; Ben T. Zinn, Warren C. Strahle, and Edward W. Price at the Georgia Institute of Technology; and Roy E. Reichenbach and David W. Netzer at the Naval Postgraduate School. Many innovative and practical laboratory techniques and improvements stemmed from the academic institutions.[47]

DoD Laboratories

The propulsion laboratories of the three Services are the glue that holds the U.S. SRM community together. Their requirements and efforts have guided the industry for decades in many technical areas. Their in-house research programs often used unique facilities to accomplish research and development of broad interest. Many of these topics are covered in this and the Davenas paper.[2] In recent years, all of the DoD propulsion laboratories followed the industry trend of reduced resources, while striving to maintain capability to design, qualify, and build new and advanced tactical, space, and strategic solid rocket systems. The most prominent SRM center for each service is singled out while recognizing other DoD laboratories also made many significant contributions.

Army Propulsion Laboratory (MICOM)

The Army Redstone Arsenal in northern Alabama together with related local organizations became the birthplace of much of the Army solid rocket program. The Army MICOM (Missile Command) along with Rohm and Haas and Thiokol's Huntsville division formed the powerful and productive Huntsville triumvirate in U.S. solid rocketry. [Note: Important segments of the 1950s Redstone Arsenal solid rocket history are in Ernest S. Sutton's privately printed "How a Tiny Laboratory in Kansas City Grew into a Giant Corporation: A History of Thiokol and Rockets, 1926–1996," January, 1997. Reference 7 summarizes parts of it.]

The facility was born because of escalating global tensions in the 1940s. Congress approved funds in April 1941 for the Army to construct another facility to supplement production at Edgewood Arsenal, the Chemical Warfare Service's only chemical manufacturing plant. The selected site became known as Huntsville Arsenal. The first Commanding Officer of Huntsville Arsenal, Colonel Rollo C. Ditto, broke ground for the construction of the 160-acre facility on 4 August 1941. Recognizing the economy of locating an ordnance assembly plant close to Huntsville Arsenal, the Chief of Ordnance built a facility adjacent to the Chemical Warfare Service's installation. Initially known as Redstone Ordnance Plant, the plant was redesignated Redstone Arsenal on 26 February 1943. The principal products in the early days were ordnance items including smoke and tear gas grenades, thermites, bombs, and mortars.

Army Colonel Carroll D. Hudson (a Stanford University-trained mechanical engineer) was the first Commanding Officer of the Redstone Ordnance Plant. He served 25 September 1941 to 1 October 1943. Between 30 November 1948 and 7 May 1952, Colonel Hudson again served as Commanding Officer of what was then renamed the Redstone Arsenal.

On 28 October 1949 the Secretary of the Army transferred the Ordnance Research and Development Division Sub-office (Rocket) at Fort Bliss, Texas to Redstone Arsenal. Among those transferred were Wernher von Braun and his team of German scientists and technicians, who came to the United States under Operation Paperclip during 1945 and 1946. With the arrival of the Fort Bliss group, Redstone Arsenal officially entered the missile era. The period dating from January 1950 to August 1962 was a time of outstanding success for the Army's rocket and missile programs. It was also the period during which the Army made its most notable contributions to the nation's space effort. Leaders of the solid rocket program in this era included Marvin Hall and Niles White. The latter was a versatile solid rocket expert who also managed and directed the highly-productive Rohm and Haas and Thiokol Huntsville Army contracts. This relationship started in April 1949 when the Elkton Division of the Thiokol Corporation, located at Elkton, Maryland, signed an Army contract to research and develop rocket propellants. This activity moved to Redstone Arsenal, where it began operation in June 1949. On 3 March 1951 the Redstone Arsenal Commanding Officer broke ground for the $1.5 million Josiah C. Gorgas Laboratory for Rohm and Haas, the arsenal's solid propellant research contractor.

General McMorrow became the first Commanding General of MICOM on 5 June 1962. He served in that capacity until his death on 24 August 1963. Later that year, the new research and development facility was dedicated to his memory, the Francis J. McMorrow Missile Laboratory. In the early 1960s MICOM was part of the major ARPA Project Principia to advance energetic materials and managed several of the major programs.

Development of the Pershing, an intermediate range ballistic missile using two solid rocket stages, started on 16 January 1958. The Army led the way in solid rocket missile and aircraft interceptor technologies in the 1960s. In this regard, the MICOM program focused on high-burning-rate propellant technology for the Nike, Sprint and Spartan programs. This effort waned in the 1970s with the exception of the air defenses systems, which evolved into the Hawk and Patriot missiles. MICOM has been a leader in exhaust-plume-visibility technology; they developed the first smoke tunnel to scientifically study this problem. Billy J. Walker of MICOM has also been a leader in plume-radiation code developments such as the SIRRM code. The MICOM has also been a leader in the important field of solid-rocket-related Insensitive Munitions as mentioned elsewhere in this article. The MICOM technology supported the development of a host of other well known solid rockets including the Chaparral, Corporal, DART, Dragon, Entac, Hellfire, Honest John, Javelin, Lacrosse, Little John, Multiple Launch Rocket System (MLRS), Patriot, Redeye, Sergeant, Stinger, and Tube-launched Optically-tracked Wire-guided (TOW).

Air Force Rocket Propulsion Laboratory (AFRPL)

The Move to the Desert: From its formation in 1947 until Sputnik in 1957, the Air Force had a single Propulsion Laboratory located at Wright–Patterson AFB, Dayton, Ohio, which was principally devoted to air-breathing propulsion. The rocket group was part of a small branch with the forward-looking name: The Non-Rotating Engine Branch, which encompassed all AF solid, liquid, and ramjet propulsion R&D. The early solid propellant work was limited to JATOs, jet engine starter cartridges and air-launched rockets such as the Falcon Guided Air Rocket (GAR) series. There was also work on a rocket-assisted-take-off motor for the BOMARC, Mace, and Matador pilotless bombers, which were essentially early turbojet-powered surface-to-surface cruise missiles. The solid rocket in-house program at WPAFB was limited to occasional tests of JATO sized rockets with 100 lbm (45 kg) or less of propellant. Meanwhile, in 1958, the Minuteman development efforts at the Western Development Division under General Shriever were blossoming. A decree was issued by Maj. Gen. J. W. Sessums, Commander, Headquarters Air Research and Development Command (to whom all of the AF laboratories reported) to move the Dayton rocket group to a remote 65-square-mile area at the Edwards AFB Air Force Flight Center in the Mojave Desert of California.

The reason for the relocation was clear and succinct as stated in a letter[48] dated 10 April 1959 from Lt. Gen. Roscoe C. Wilson, Headquarters USAF, to Maj. Gen. Sessums. The letter cited the need for a strong Air Force capability in rocket propulsion with the primary objective of retaining the maximum degree of Air Force influence and participation in the one-million-lbf ($\sim$4,500 kN) thrust engine development, together with cooperation on all the ARPA and NASA propulsion programs. Related justification[49] cited the remoteness of the site and its proximity to the western contractors and Air Force Project Offices engaged in missile development. A follow-up directive from Colonel McKee, Headquarters, Air Research and Development Command (ARDC) set an operational date of no later than 1 September 1959. The plan required a technical organization capable of guiding the Air Force rocket propulsion applied research program, together with development of the captive-test capability to evaluate rocket engines, associated components, and complete ballistic missile systems. The manpower allocation was a total of 250 military and civilian personnel. The Dayton rocket group represented the nucleus of the existing USAF capability in rocket engine applied research, so every effort was made to transfer them intact.

Colonel Harold Norton was commanding officer of the existing rocket test contingent at Edwards AFB, which had been growing since 1952.[50] Of the 127 people transferred from Dayton, Colonel Harold Robbins was the ranking officer and Donald M. Ross the leading civilian. The new Rocket R&D Group at Edwards AFB immediately functioned as a laboratory and desired the prestige of the title "Air Force Rocket Propulsion Laboratory (AFRPL)" reporting directly to the ARDC, as did other AF laboratories. Col. Robbins and Don Ross had their staff artist design a logo and letterhead for AFRPL stationery, and they purchased two reams of it. Secretaries were told to use the new stationery for all correspondence, except Col. Norton's letters to Washington. Within a few weeks, the rocket propulsion community became aware the AFRPL existed at Edwards AFB. With continued use of the new stationery, the AFRPL name became familiar in Washington offices, and newspaper articles used the AFRPL title. Shortly thereafter, official orders emanated from Headquarters, ARDC assigning the AFRPL to the Research and Technology Division of that Command, effective 1 December 1962. A celebration at AFRPL followed with Col. Robbins as Master of Ceremonies.

The AFRPL produced a continuous stream of talented military and civilian scientists, engineers, and leaders. Charles R. Cooke headed the solid rocket division for many years and his young principal branch chiefs included Robert L. Geisler, Lee G. Meyer, and Clark W. Hawk. The military included Colonel Jerry N. Mason who managed the Peacekeeper development for the Air Force and Lt. Francisco Q. Roberto and Lt. Robert C. Corley. Later, as civilians at the laboratory, Roberto and Corley gained national recognition as energetic materials synthesis and solid propellant formulation experts.

Unique among Government rocket labs, AFRPL covers every type of rocket propulsion, i.e., solid, liquid, hybrid, electric, and nuclear. This full-spectrum lab covers strategic, space, and tactical rocket applications as well as the multiple-application technologies including combustion, plumes, mechanical behavior, aging, and non-destructive testing. AFRPL brokered and managed innovations in all these areas for several decades. The lab has historically sought a 50/50 mix of officers and civilians, resulting in a balance of continuity between the more permanent civilians and the transient but more aggressive, mission-oriented military. The deliberate flux of people though AFRPL trained several thousand government and industry leaders.

AFRPL became noted for the development and use of a number of critical test devices now well known throughout the world. These include the Ballistic Analysis and Test System (BATES) series of solid rocket performance test motors, precision static test stands, and the CHAR and HIPPO nozzle materials test motors. These motors were designed to be analyzable to the greatest degree possible and have reasonable fidelity in the test conditions compared to operational motors. Also notable are the 1-42 altitude test facility and the 1-36D high hazards explosive test area, the latter sited for 1 million lbm (454,000 kg) of TNT. The lab also pioneered many propellant formulation and ingredient evaluation efforts in its 1-30 Propellant Evaluation Facility. The more spectacular large solid rocket test stands have gained notoriety with test support activities for Minuteman, Titan III, Titan IV, SRMU, and Peacekeeper. From the early days of the Space Defense Initiative Organization (SDIO), AFRPL built and operated the National Hover Test Facility where Lightweight ExoAtmospheric Projectile (LEAP).type vehicles have been demonstrated.

AFRPL became an early leader in plume technology; thermochemistry; performance prediction; mechanical behavior, aging, and surveillance; combustion; explosive hazards; propellant formulation and ingredient synthesis; high temperature nozzle and insulation materials; extendible exit cones; composite cases; and TVC. In recent years, AFRPL is a major player in the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) solid rocket and materials programs described later.

China Lake Propulsion Laboratories (NOTS)

About 80 miles due north of the AFRPL in the Mojave Desert of California is China Lake, the home of one of the oldest and most productive government propulsion laboratories. It is presently called the Naval Air Systems Command Weapons Division (NASCWD). It was also known, in recent times, as the Naval Air Warfare Center (NAWC) Weapons Division, but to all who know her she will always be NOTS (Naval Ordnance Test Station). There was no large-scale military rocket program in the U.S. until 1941 when Charles C. Lauritsen of the California Institute of Technology (Caltech) prodded the Navy to action,[8] and the main rocket effort of the U.S. in WW-II began. In 1943, adequate facilities were needed for test and evaluation of rockets being developed for the Navy by Caltech. At the same time, the Navy also needed a new proving ground for all aviation ordnance. The Caltech work initially built on the British rocket work in which (extrudable, nitrocellulose-based) ballistite propellant was used to make cartridge-loaded grains. The book[51] by R. N. Wimpress and B. H. Sage, written in 1945 and published in 1950, states they treated only "dry-processed double-base propellants." However, the 208-page book treats every physical process inside rocket motors and provides general design guidelines, without references because they were confidential. Their failure to cite any other workers is unfortunate since attribution for their accomplishments has been lost. The rocket work was done at Eaton Canyon[52] in the San Gabriel foothills near Pasadena, California. Flight tests were conducted at Goldstone Lake near Barstow, California, on what is now Fort Irwin. Both facilities were inadequate to handle the expanded effort.

NOTS was established in response to those needs in November 1943. The NOTS mission was defined in a letter by the Secretary of the Navy dated 8 November 1943: ". . . a station having for its primary function the research, development, and testing of weapons, and having additional function of furnishing primary training in the use of such weapons."

The Propulsion Systems Division of the NAWC and the associated supporting organizations represent the Navy's principal center of excellence for research and development for missile propulsion—both solid propellant and air-breathing systems. The organization has evolved over the last 59 years to continue meeting the changing propulsion expertise needs of the U.S. armed forces.

Construction of the China Lake Pilot Plant commenced in May 1944, and began operation on 18 November 1944. By 1958, nearly ten million rounds of extruded solid rocket motors using NOTS technology were produced. After the war ended, cognizance for operation of the plant was transferred to NOTS. The original site was changed to a more remote one and the size of the plant was doubled to nearly 100 buildings. Although safety was the major factor in this decision, it was not the only goal. The Navy, through Caltech, had taken the lead it the development of solid propellant technology in this country, and it desired to maintain this leadership after the war.

At the close of the war, the role of the China Lake Pilot Plant changed from production to research and development. In the mid 1950s, the Salt Wells Pilot Plant, built and operated by the Atomic Energy Commission, was transferred to NOTS to form the China Lake Propulsion Laboratories (CLPL). A significant credit to the China Lake propulsion program has been the achievements of the Michelsen Research Laboratory.

Several people were very important in shaping the character and philosophy of the Navy's research and development programs that led to the 1943 establishment of the Station.[4] Captain (later Rear Admiral) William S. (Deak) Parsons, who as Experimental Officer of the Naval Proving Ground, developed a philosophy of military–civilian teamwork in weapons research and development that was to have a profound effect on the NOTS. Charles C. Lauritsen, head of the Caltech wartime rocket program was a driving force behind the establishment of NOTS.

Numerous wartime rocket projects were accomplished at NOTS. During the period, 1944–1948,[4,6] the Navy fielded an outstanding military-civilian team at NOTS including L. T. E. Thompson, first Technical Director of NOTS and principal author of the NOTS management philosophy; Captain (later Rear Admiral) Sherman E. Burroughs, Jr., first Commanding Officer of NOTS and exemplary member of the Station's military-civilian team; and Commander (later Vice Admiral) John T. (Chick) Hayward, the Station's first Experimental Officer.

Places and projects that help characterize NOTS during the period are Michelson Laboratory, the Station's primary research facility (and symbolic heart of the R&D program at China Lake); the 5-in. (127-mm) High-Velocity Aircraft Rocket, Holy Moses, famous product of the Caltech–Navy team (used extensively in combat in WW-II); and a Bumblebee surface-to-air missile test vehicle. The latter was part of a program that characterized the emergence of guided missiles and the importance of NOTS' extensive ranges to the Navy's overall effort. At center is the 11.75-in. (0.3-m) aircraft rocket, Tiny Tim, the Navy's first really big rocket, a bunker-buster that saw limited service near the end of WW-II.

A broadening scope of work and life at the NOTS took place during the years 1948–1958.[4] China Lake leaders reflect the combination of technical, military, and social elements that made NOTS unique. These individuals include William B. McLean, the genius behind the development of Sidewinder, Technical Director of the Station 1954–1967, and one of those most responsible for the "China Lake Way." Another leader was Captain (later Vice Admiral) Levering Smith, who, as Head of the Rockets and Explosives Department and as Associate Technical Director at NOTS helped solidify the military–civilian team. As Technical Director of the Polaris Missile Program, Captain Smith established China Lake as a major player in Polaris. He also sponsored both the Skytop propulsion and San Clemente Island underwater-launch test facilities.

NOTS provided conceptual studies as well as major Test and Evaluation programs for some of the major projects during the 1950s. Among these were the 6.5-in. (165-mm) antitank aircraft rocket, *Ram*, developed and delivered in a month to meet urgent needs in Korea; and Holy Moses, a WW-II product of the Caltech–NOTS team that remained a mainstay of the Fleet for two decades. At center is the original Sidewinder—the heat-homing rocket—which quickly epitomized the China Lake philosophy of weapons research and development. The Terrier–Tartar–Talos family of shipboard missiles (stemming from the Bumblebee test vehicle) was symbolic of the programs that helped establish the unparalleled guided-missile ranges managed by NOTS.

China Lake has a full-spectrum capability for support of research and development, test and evaluation, and in-service support of propulsion systems. Included are research facilities for synthesis of new energetic materials, characterization of propellant formulations, and the study of combustion instability. Composite design and fabrication facilities are available for design and winding of composite motor cases. A special real-time radiography system enables monitoring internal ballistics during motor firing. Multi-axis test stands are used to resolve side forces for TVC-equipped motors. Full environmental, safety, and insensitive munitions testing can be conducted in the test area. Indeed, the NAWC work on insensitive materials (IM) and innovation is World renown.

The role of China Lake changed over the decades from a production plant to a research and development center. As the industrial propulsion infrastructure developed in the U.S., the role of China Lake shifted toward developing technologies for propulsion and providing the Navy a technical agent for direction of contractor development and production. The value of the laboratory and its partnerships with industry is illustrated by the large number of successful transitions to fielded systems.

After 1960: New Generation of Technologists

The propulsion companies had the resources and motivation to invest in modern, well-equipped laboratories. The Space Race and the modern facilities attracted a new generation of well-trained and highly-motivated engineers and scientists. The following paragraphs touch on how they extended the knowledge and techniques they inherited.

Paul G. Willoughby and Clayton T. Crowe were part of one of the most productive research groups formed at CSD in the early 1960s. Indeed, *WilloughbyandCrowe* became one word. Their pioneering work included two-phase-flow[53] and spin effects in motors containing aluminized composite solid propellants. The other principal contributors were Robert S. Brown, Roger Dunlap, Robert W. Hermsen, and Mitchell Gilbert. They measured the drag coefficient of spherical particles to complete the drag curve for flow regimes experienced in rocket nozzles.[54] Crowe had also studied drag coefficients as part of his Ph.D. thesis.[55] Hermsen completed studies on metals fuels combustion.[56] *WilloughbyandCrowe* analyzed particle growth in rocket nozzles.[57] Crowe, now at Washington State University, continues to research particle-laden flows. Dunlap, Willoughby, and Brown later performed landmark cold-flow experiments and analyses in support of resolving pressure drop and stability issues in large segmented boosters.[58]

As the technical staffs gained strength, empiricisms were augmented by physical understanding. As an example, several in the industry began to recognize that nozzle erosion (mechanical abrasion) was a misnomer. Rather, the regression of graphite nozzle throats was from chemical attack, controlled by the kinetics of the specific combustion products (i.e., H_2O, CO_2, CO, and OH) reacting with the graphite. The work of Allan J. McDonald,[59] Lawrence J. Delaney,[60] and Robert L. Geisler provided design tools still being used.

Probably more papers have been written on erosive burning that any other solid rocket design consideration. High-speed flow over a burning surface continues to intrigue aerothermochemists of all persuasions. However, most of the treatments either could not easily be used by designers or were specific to a narrow data set. Charles Saderholm[61] took much of the mystery out of predicting erosive-burning relationships of new propellants by introducing an intuitively-pleasing formulism based on thresholds of Mach number and burning rate. Saderholm's work benefited from unpublished threshold Mach number correlations of R&H data by Stanley E. Anderson. In 1973, using Saderholm's relationships and introducing size scaling based on Titan seven-segment data, J. S. Baker argued that the Space Shuttle SRM would not experience erosive burning, in spite of high internal Mach numbers. Baker took the mystery out of scaling geometry. This was a bold prediction that reduced the development cost. In a paper after the first two static tests, DM-1 and DM-2 in 1978, Baker[62] describes the factors that influenced thrust versus time. In his 2003 paper,[39] Ellis Landsbaum notes that after 40 years the Saderholm correlations, scaled correctly, are still the most useful for predicting erosive burning.

The ability to predict thrust imbalance between pairs of large strap-on solid rocket boosters (i.e., zero stage) affects the mass that has to be devoted to correcting the effect on the net thrust vector.

From the early development phases of the Shuttle SRM through flight validation, Richard H. Sforzini and Winfred A. Foster, Jr.[63] worked closely with Ben W. Shackelford at NASA/MSFC to perfect their Monte Carlo approach for dealing with motor-to-motor variability. They accounted for 41 factors that can contribute to imbalance between the motors, e.g., geometric and propellant property variation, and propellant temperature gradient differences due to solar heating. Their extensive correlation with early Titan data and Shuttle SRM static test data produced flight predictions that were quickly validated by the early Shuttle flights.[64]

Liquid propulsion developed from the V2 to the Saturn V giving man access to the moon; meanwhile solid propulsion went from JATOs to the boosters of the Space Shuttle. Key solid ICBM systems developed during this period include Minuteman, Polaris, and, Poseidon; also key was the intermediate range Pershing. Space motors include the Titan strap-on boosters, the Shuttle SRM, Castor, the Star Motor series, and IUS. Air-launched rockets include the Falcon, Sparrow, Sidewinder, SRAM, and Genie. Army tactical missiles include the TOW, Patriot, Sergeant, Nike series, Sprint, and HiBEX (High-g Boost Experiment). Many important trend-setting demonstration motors included Big-B, Hermes, 100 in. (2.54 m), 156 in. (3.96 m), and 260 in. (6.6 m) boosters.

Two figures illustrate how quickly propulsion systems matured between 1960 and 1980. The Air Force 156-in. (3.96-m) motor is a prime example of rapid pace of the early 1960's programs to flight qualify large boosters. The 1964 photograph in Fig. 2 shows the Thiokol 156-in. motor gimbal nozzle. The cutaway view (Fig. 3) of the Peacekeeper Stage II illustrates sophisticated 1980's technology. These two figures also illustrate the challenges faced by those seeking to greatly improve rocket motor performance within the bounds of safety and cost.

Fig. 2 Thiokol 156 in. (3.96 m) motor, Brig Gen Joseph Bleymaier of USAF Space Systems Division, Colonel Harold Robbins, Major Orval Krone, Rafael Felix of AFRPL, and Edward Dorsey of Thiokol. (Tested 12 December 1964 at Thiokol in Utah.)

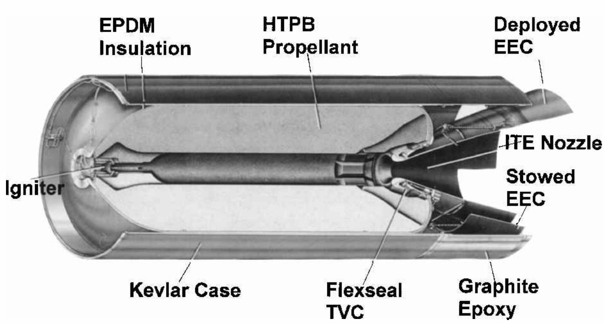


Fig. 3 Peacekeeper Stage II design, showing several key components using 1980's technology, e.g., Flexseal TVC, Extendible Exit Cone (EEC), 3D ITE, submerged nozzle, thick propellant webs, and Kevlar case. Diameter is 93.1 in. (2.36 m). (Aerojet Ref. 10.)

The Ten Enabling Technologies

The ten enabling technologies or technological areas (summarized in the Table) deemed by the authors to have made the most significant impact on the course of the U.S. modern solid rocket program are discussed in the next ten sections, numbered accordingly. In these sections, together with previous references to some of these enablers, the authors attempt to tell the story of the major achievements of the vibrant SRM community. The authors try to tie the outstanding successes of this community to the efforts of organizations, teams, and individuals as well as advancements in materials and analytical capability. (Note: there was no attempt to select the order of importance among the ten. The order is more or less arbitrary.)

1) Propellant Grain Technology

Grain and Motor Design

John S. Billheimer of Aerojet, Sacramento was one of the first ballisticians to automate the process of solid rocket motor design on an early mainframe computer.[65] It was considered a key advancement at the time, and Aerojet had a Hollywood studio prepare a narrated animated film explaining how the program iterated the calculation for small-time increments and for variable grain design cross-sections. This was the beginning of the general application of computers to automated solid rocket motor design.

Stanley C. Browning, chief of the Hercules Bacchus design department through the 1970s, carried this capability to a state of perfection. Under his direction, the group integrated the case, grain, and nozzle design tools into their mainframe computer to a degree not realized by others until the 1990s. He claimed a ten-fold increase in design and analysis capability through this pioneering automation. For example, their analysis computer code for cases[66] also wrote the design report, including all of the technical assumptions and simplifications, and even designed the cams for the case winding machine and produced the drawings ready for submittal to the shop for fabrication. This was a key and very advanced capability for the 1970s and a major factor in his company's burgeoning Trident and Peacekeeper design and development activities.

Solid Propellant Structural Integrity

The early impetus to study structural integrity, aging, and surveillance was the need for a wide operating temperature range for tactical rockets. By the mid 1960s these studies were expanded to support the emerging ballistic missile programs. These were the highest performance motors ever built and there was clearly a need to "build them right the first time" and to provide for orderly replacement of the thousands of missiles and motors to come. The users had to know several years in advance of age-out and failure when to take action for replacement.

Fortunately, such groups as the JANAF Panels and the ICRPG provided the technical base in the 1950s and 1960s for this major undertaking. The Panel on Physical Properties, begun in December 1947, was converted to the ICRPG Working Group on Mechanical Behavior of Solid Propellants in October 1962. This early activity placed structural integrity on a firm engineering and scientific foundation.

A particularly noteworthy contribution to propellant structural integrity was developed at GALCIT by Max L. Williams in 1955. Following successful application of A. J. Durelli's photoelastic technique to study star-shaped propellant grains under internal pressure,[67] D. D. Ordahl of NOTS asked Williams to conduct a national survey of structural integrity work. This survey led Preston Craig of Thiokol to fund the first major structural integrity research effort at Caltech in 1958. Williams, his co-workers and their graduate students (R. A. Schapery, W. G. Knauss, R. J. Arenz, and G. H. Lindsay), made many significant contributions to the area. The completion of this work was one of the most notable early Caltech contributions. The recognition of the time-temperature equivalency (superposition) by Williams, Landel and J. D. Ferry,[68] based on a suggestion by A. V. Tobolsky of Princeton Univ., and the Morland-Lee definition of reduced-time and thermorheologically-simple material behavior,[69] formed the basis for analysis of solid propellant thermomechanical behavior.

Williams' reputation and intense interest legitimatized propellant grain structural integrity as a technical discipline. His tutorial on structural analysis of viscoelastic materials, presented at the AIAA Summer meeting in Los Angeles in May 1964,[70] was followed by publication of the *Solid Rocket Structural Integrity Abstracts* (SRSIA) in 1963–1971. Four feature articles were published by distinguished researchers and engineers in 1965. Landel wrote on the rupture of propellants, Harold Hilton wrote on linear viscoelastic stress analysis, Edward Fitzgerald gave a status of propellant grain structural integrity problems, and S. C. Britton summarized current solid propellant mechanical behavior characterization tests. Other notable subsequent articles include: Norman Fishman on environmental effects, Paul Blatz on the microstructure of composite propellants, Schapery on nonlinear viscoelasticity, Harold Leeming on large SRM structural design (summarizing the methods used by LPC to build and static test several 156-in. motors in the mid 1960s),[71] Jan Achenbach on dynamic response of solid propellants, and J. McKay Anderson's review of the finite element method (FEM) application to grain stress analysis.

The development and use of the FEM occurred almost simultaneously throughout the propulsion community; however, many developments and most developers owe their heritage to the University of California at Berkeley. Eric B. Becker and J. J. Brisbane of R&H produced the first finite element code specifically aimed at solid rocket motor analysis. The nearly incompressible behavior of the solid propellant was accounted for using Hermann's reformulation.[72]

The FEM was rapidly extended to three dimensions for orthotropic and anisotropic materials. Because computational power was limited, finite element codes were developed for asymmetric loading of axisymmetric geometries, in which the loading was approximated by a few terms of a Fourier series expansion.[73] Codes for dynamic loadings and viscoelastic materials were also becoming available by the end of the decade[74,75]

By the mid 1960s attention turned to investigation of solid propellant aging behavior, failure and fracture, and development of nonlinear constitutive relations and FEM codes for analyzing solid propellant mechanical behavior. The concept of a Structural Test Vehicle was coined in an Air Force-sponsored LPC program and instrumentation was developed for measuring the stress and strain states in a SRM. By comparison of the measured-to-predicted data, the inability to predict the transient thermomechanical response of solid propellant using linear thermoviscoelasticity theory was conclusively demonstrated.

By the end of the 1960s, all propulsion companies were actively involved in the development of analytical and experimental tools for structural integrity assessment. Faculty and graduate students at Caltech, Purdue Univ., Texas A&M, the Univ. of Washington, the Univ. of Utah, and the Univ. of California at its Berkeley and Davis campuses were extending the state-of-the-art in solid propellant constitutive modeling, failure and fracture, aging and surveillance, and finite element analysis techniques.

In the 1970s, several technology programs focused on refinement of FEM codes, development of stress and strain transducers, development of predictive service life techniques, development of new propellant mechanical property tests, and investigation of solid propellant failure and fracture.

The Texas Grain Analysis Program (TEXGAP) standardized the FEM approach to grain structural analysis throughout the industry after 1973. The development and maintenance of the code continued with significantly improved versions of the 2-D and 3-D codes released in 1978 and 1986.

Although some efforts to develop devices for measuring stress and strain within a propellant grain started in the mid-to-late 1960s, the Structural Test Vehicle programs at LPC were the first concerted efforts to develop the technologies for in situ measurement of stress and strain. Particular attention was given to understanding gage-grain interaction.

The LPC programs of the 1970s led to the development and application of stress transducers to SRMs. Rocketdyne–McGregor developed an embedded stress gage that they called a Duomorph, and successfully instrumented a full-scale first stage motor with propellant stress and strain transducers during thermal cycling, roll, and transportation tests. The industry continued these efforts through the 1980s.

Environmental load and grain response data for air-launched missiles were gathered and analyzed under the Air Force Project DAME (Determination of Aircraft Missile Environments) for the captive flight environment. A heavily instrumented simulation unit was modified to contain 70 kg of inert HTPB propellant. The Air Launch Instrumented Vehicles Evaluation (ALIVE) Program evaluated the effects of air-launched missile environments on the aging characteristics of advanced HTPB. The Long Range Service Life Analysis (LRSLA) program identified critical failure modes and respective failure limits, and then verified those failure modes/failure limits by analysis and overtest.

The Predictive Techniques for Failure Mechanisms in Solid Rocket Motors program at CSD in the mid 1970s was the most ambitious single program of the decade. This five-year program brought the resources of several University consultants (R. A. Schapery, W. G. Knauss, M. E. Gurton, G. H. Lindsay, W. L. Hufferd, R. R. Parmerter, and P. J. Blatz) to bear on nonlinear constitutive modeling, failure and fracture of solid propellants, instrumented analog motor testing, and similitude characterization testing.

Developments of the 1980s and 1990s were by-and-large simply extensions or improvements of the developments of the 1960s and 1970s. Nonlinear finite element codes were improved and applied more frequently to grain and composite case analyses, stress and strain instrumentation was improved, and development of nonlinear material models for propellant continued. These were applied to high-elongation propellants. Recently, more emphasis is placed on extending the service life of existing motors.

Composite case usage increased starting in the late 1970s. While the finite element analysis codes were capable of analyzing orthotropic materials, only the cylinder behavior was adequately modeled under pressure. Dome behavior, particularly reinforced domes common to the short length-to-diameter space motors, was not reliably predicted. The Automated Generic Case Analysis Program (AGCAP) uses the designed case geometry and constituent material properties (fiber and resin) in a micromechanics model that calculates the effective orthotropic properties of each element in a composite case finite element model. Structural analyses are accomplished using a modified version of the TEXLESP nonlinear elastic finite element code that includes the AGCAP module. An attempt was made to develop an integrated piece of software for the design and analysis of composite solid rocket motor cases. The resulting code, CDAC (Composite Design and Analysis Code), incorporating design modules for particular polar boss geometries, was aimed at preliminary configuration, design, modeling, and analysis of composite cases. The NASA Solid Propulsion Integrity Program (SPIP) improved the reliability of nozzles and propellant grain bondlines.

The dedication and hard work of the analysts noted above, along with that of many others, developed the tools for confident modeling of SRM structural behavior. Designers have these remarkable tools available to ensure the structural integrity of current and future SRMs.

2) Case Technology

The use of filament-wound composite cases for solid rocket motors enabled a reduction in inert mass and a corresponding gain in propellant mass fraction (i.e. ratio of propellant mass to total motor mass) to over 90% for some systems, an impressive value in those days. Today, nearly 95% has been achieved. In the early days, companies including M. W. Kellogg, Goodyear, Brunswick Corporation, and B. F. Goodrich[76] leveraged their traditional manufacturing capabilities and assisted the early solid rocket industry in making filament winding a viable option for rocket motor cases. However, Hercules' purchase of Young Development Laboratories of Rocky Hill, New Jersey in 1958 provided the catalyst for implementation. Richard Young, a veteran test pilot and missile and aircraft designer, was admittedly obsessed with the problem of strength-to-weight ratios for rocket motor cases. As founder of Young Development, he advocated the use of pressure vessels made of fiberglass because they offered a superior strength-to-weight factor compared to conventional steel cases.[11] He subsequently developed the Spiralloy® technique of winding layered glass filaments coated with liquid resin in a cross-hatched helical pattern over a large cylindrical mandrel with rounded ends to produce a continuous, uniform-strength capability throughout the cured pressure vessel. By the late 1950s, cases made by the filament-wound Spiralloy technique and materials proved successful in a series of tests with small rockets designed and developed at ABL.

Not particularly well known in solid rocket historical literature is Hercules ABL's notable development of the X241 upper stage rocket motor. In the mid 1950s, as the U.S. raced to put its first satellite into orbit aboard the Vanguard launch vehicle, ABL was contracted by the Navy to develop a backup for the metal-case Grand Central Rocket Company-manufactured Vanguard third stage rocket motor. The result was the X241, an 18-in. (0.46-m) diam fiberglass composite case motor containing double-base propellant, designed to provide a thrust of 2,720 lbf (12 kN) over a 36-s burning time. On 18 September 1959, the ABL X241 was used to insert into orbit the last of the three Vanguard satellites. The X241 became the first operational upper stage with a composite case, although it was actually used a year earlier as the fourth stage of an unsuccessful, secret NOTS attempt to place an air-launched satellite into orbit.[77,78] By the 1960s, the ABL-designed derivatives, X248 Altair and X254 Antares, and the Hercules Bacchus Works (Utah) BE-3 series of fiberglass composite upper stages and space motors performed successfully in hundreds of civilian and DoD space research missions that required high performance kick stages.

The demand for extended range and payload capability from limited-volume silos and submarines dictated the use of high-mass-fraction upper stages. Armed with Spiralloy technology and early upper stage successes with the X241 and Altair, Hercules set its sights on ballistic missiles by proposing a bold approach for the third stage of the Air Force's first generation Minuteman ICBM—using a filament-wound fiberglass composite motor case loaded with composite modified double-base (CMDB) propellant. The approach succeeded and the first Minuteman missile with Hercules' M57A1 third stage was test launched on 1 February 1961.

Similarly, the Navy Special Projects Office committed to solid propellant rockets for the submarine-based fleet ballistic missile (FBM) program in 1956. Although only peripherally involved in the program at the onset, Hercules was later selected to provide the second stage of the Polaris A2 and A3 missiles because of its expertise in CMDB propellants and lightweight composite cases, as well as its early successes on Minuteman. Developed at ABL, the Polaris A2 motor made its first successful test flight on 10 November 1960.

Thiokol was also using fiberglass composite-case test motors by the mid 1950s, and worked with Young Development Laboratories to develop a filament-wound case for the Matador booster in 1958. With Young's purchase by rival Hercules, Thiokol moved to establish its own R&D organization and manufacturing capability for filament-wound cases in the early 1960s. Thiokol later produced composite cases for the Pershing II stages, Minuteman III third stage, and the Peacekeeper first stage.

In addition, General Dynamics' Lincoln Operations (initially Brunswick, then Lincoln Composites) has long been a major supplier of composite cases to the propulsion industry. Its impressive list of composite case products includes Orbus 21 and Orbus 6, Minuteman III third stage, Patriot Advanced Capability3 (PAC-3), Peacekeeper second stage, Polaris A3 second stage, Sprint stages, and the Trident II D5 third stage.

For the development of the Navy's second generation Poseidon C3 FBM, Hercules and Thiokol established a 50-50 joint venture to develop the two-stage boost propulsion system. This joint venture arrangement continued through the development of Trident I C4 and Trident II D5, until ATK (Alliant Techsystems) purchased Thiokol outright in 2001. By the time the development of the three-stage solid D5 began in the late 1970s, intermediate-modulus graphite fiber became the third generation fiber of choice for composite cases; Kevlar had previously replaced fiberglass and was used for Trident 1 C4 and Pershing II, among others. The Hercules/Thiokol Joint Venture developed the D5 first and second stages, and United Technologies' Chemical Systems Division (CSD-presently Pratt & Whitney Space Propulsion San Jose) developed the third stage, all of which have graphite-epoxy composite cases.

By the 1980s, composites made their way into a number of tactical class demonstration and development programs. The planned AGM-131 Short-Range Attack Missile II (SRAM II) pulse rocket motor developed by Hercules in the late 1980s advanced the U.S. to the brink of qualifying its first graphite composite-case motor for a tactical air-launched application. However, the nuclear-capable SRAM II was canceled by Presidential order in September 1991 as a prelude to the negotiation of the Start II treaty. Nevertheless, SRAM II made substantial contributions to the advancement of the composite motor case state-of-the-art including integral attachments, high-pressure design capability, pulse motor ignition, and elastomeric-thermal-barrier segregation of pulse motor grains.

As conventional solid propellant formulations began to approach their upper limit of performance by the late 1980s, developers turned to high-pressure operation to increase solid rocket motor performance. In 1997, ARC's PAC-3 interceptor became the first qualified and fielded tactical rocket motor to use a graphite-epoxy composite case. The Missile Defense Agency's Theater High Altitude Area Defense (THAAD) missile booster, manufactured by Pratt & Whitney, and the Army's Line-of-Sight Anti-Tank missile motor, manufactured by ATK/ABL are additional examples of tactical systems that use graphite-epoxy composite cases.

Composite cases provide the greatest benefit for large motors, where the resulting gains in mass fraction and performance over metal-case boosters are substantial. Since the initial penetration of the launch vehicle market with ATK's GEM (Graphite Epoxy Motor)-40 monolithic strap-on booster for the McDonnell Douglas (later, Boeing) Delta II in 1990, the growth of graphite-epoxy composite cases in terms of size and use has been rapid. ATK later developed and produced the monolithic GEM-46 and GEM-60 for Delta III and IV, respectively, while Aerojet developed the new Atlas V SRM from 1999 to 2002. ATK also developed and produced the three-segment Solid Rocket Motor Upgrade (SRMU) strap-ons for the Titan IVB launch vehicle. Meanwhile, Thiokol used company funds to develop the commercial Castor® 120 in the early 1990s as a core booster for medium launch vehicles. At 93 in. (2.36 m) in diam and approximately 116,000 lbm (52,600 kg), the Castor 120 is the largest monolithic composite-case booster manufactured in the U.S. In 1996, Thiokol Elkton began the development of an advanced upper stage rocket motor, the 13.4-in. (0.34-m) diam Mk 136 Third Stage Rocket Motor (TSRM)[79] for the Raytheon Standard Missile-3 (SM-3). As shown in Fig. 4 the TSRM has several advanced features including a graphite composite motor case that is filament wound over the cast dual-pulse propellant grain (i.e. case-on-propellant), a graphite composite interstage, a hybrid cold gas/warm gas attitude control system for the coast phases, and flexseal nozzle thrust vector control with electromechanical actuators for attitude control during pulse operation. The TSRM is the first operational tactical class rocket motor to have a movable flexseal nozzle, a feature previously

Fig. 4 ATK Elkton TSRM (Third Stage Rocket Motor) includes a novel two-zone grain for two-burn operation and is the first operational tactical-class rocket motor to have a movable flexseal nozzle. (From Ref. 79.)

limited to large strategic motors and launch boosters. The TSRM completed a series of critical qualification static firings at simulated altitude in 2000, and performed successfully in three landmark Sea-based Missile Defense tests in 2002.

3) High Performance Component Technology

Components

The payoff with high-performance solid rocket motors is greatest with the final stage motor adjacent to the payload. For a motor designed to complete the acceleration of a payload to a given velocity, each kilogram saved in the motor allows an extra kilogram of payload. The payoff is much less with lower stages. For this reason the greater cost attendant to high-performance SRMs is justifiable with motors for the uppermost stage of a rocket, and the development of such motors was therefore focused chiefly on apogee kick motors and the uppermost stage motors of ballistic or interceptor missiles. SRMs have been used in a variety of NASA's space missions. As described in Ref. 80, the designs for these motors are often innovative and the production quantities low.

The major difference between apogee kick motors and ballistic or interceptor missile motors is the latter two require thrust vector control (TVC) whereas apogee kick motors are usually spin stabilized and have no TVC provision. Additionally the early ballistic and interceptor missile upper stages often used thrust termination provisions.

Apogee kick motors for SRMs date back to 1957, but only came into wide use after 1963 following the Syncom 2 satellite achieving the first synchronous orbit using the JPL SR-12-1 apogee kick motor.[81]

As apogee motor development progressed, achievement of higher performance was via a combination of more energetic propellants, higher volumetric loading, and lower inert component mass. The efficient head-end web grain designed by Thomas J. Kirchner went into production in the Thiokol STAR motors in the mid 1970s. This configuration, as implemented by Thiokol Elkton, lowered the mass flow and increased the expansion ratio to provide about 1% performance improvement with no increase in case mass or envelope. Related head-end web configurations were evaluated as part of the Minuteman development at Hercules in the early 1960s, applied in a Thiokol solid gas generator design in the mid 1960s, and used in the Thiokol TX-33 Scout second stage.

Greater mass fraction (propellant mass/total mass) was also achieved by reduction of inert component mass with the use of improved strength-to-weight or improved thermal resistance materials as well as design advancements. The inert components of an apogee SRM are the nozzle, insulated case, and igniter.

Apogee motor nozzle weight reduction was primarily achieved with the use of composite to replace metal. Early designs featured a metallic structure to support thermal barrier materials. As composite technology improved, some nozzle metallic structures were replaced with lighter weight fiberglass-epoxy or fiberglass-phenolic composite structures. The first extensive use of composite structures in a nozzle was in the Pershing I nozzle. More impressive designs followed. The 1967 Thiokol Surveyor main retro motor nozzle[82] (see Fig. 5) illustrates a lightweight nozzle with all structural components except the attach flange made of composites. Even more efficient carbon-fiber-composite structures later supplanted fiberglass.

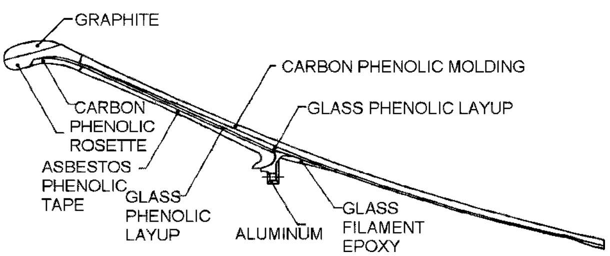


Fig. 5 1967 Thiokol Surveyor main retro-motor nozzle illustrates an early lightweight nozzle with all structural components except the attach flange made of composites. (From Ref. 82.)

Weight reduction of ballistic and interceptor motor nozzles was achieved by the same means as with apogee motor nozzles, but even more significant was development of improved thrust vector control nozzle components. TVC was usually achieved in the early 1950s by use of four nozzles on the motor aft end (rather than a single nozzle), with mechanical deflection devices such as jetavators attached at the exit plane to deflect the exhaust stream by partially blocking the exhaust stream. These devices were inherently heavy (typically of refractory metal), limited in temperature capability, and produced large thrust losses during use. In the late 1950s the canted rotatable nozzle was developed and applied to Polaris.[83,84] This TVC device was simpler, lighter weight, and minimized the loss of thrust during steering. In the early 1960s the ball and socket hinged nozzle with an o-ring seal was developed for Minuteman four-nozzle TVC.[85]

Also during the late 1950s and early 1960s liquid injection TVC (LITVC) was developed and applied to Polaris, Minuteman, and the Titan solid rocket boosters. Unlike the rotatable and hinged movable nozzle TVC methods, LITVC could be applied to a single fixed nozzle. A single nozzle is, of course, more efficient and lower in cost than four nozzles, but requires a longer envelope. A disadvantage of single-nozzle LITVC is the weight, envelope, and cost of the fluid supply system as well as the need for a separate roll control system (needed with all single nozzle systems).

In 1963 the omniaxial elastomeric bearing was invented by John T. Herbert, Frank J. Kovitch, Jr., and Max McCorkle of Lockheed Propulsion Company[86] and named Lockseal® (see Fig. 6).This device, known alternatively as flexseal, flexible seal, flexible joint, and flexible bearing, is one of the key enablers for subsequent SRM

Fig. 6 Solid rocket thrust vector control became more robust via a series of extraordinary inventions. The Lockseal nozzle, shown with John Herbert (one of its inventors), has proven best for most TVC systems since its debut in the 1960s.

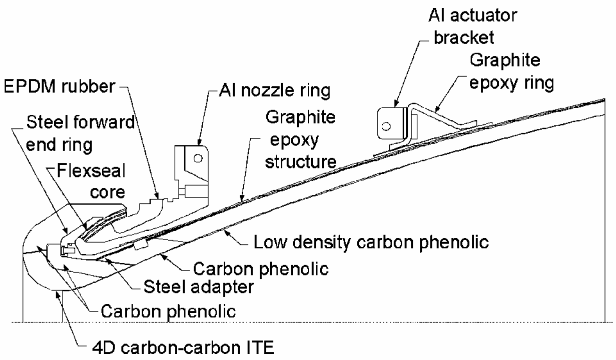


Fig. 7 The flexible seal and composite materials (including the carbon–carbon ITE) allow a very simple and lightweight nozzle design. The flexible seal—here alternate layers of rubber and composite reinforcement—provides a positive gas seal while allowing omniaxial vectoring without sliding friction. Here the flexseal reinforcements extend beyond the rubber layers to provide integral thermal protection, eliminating a separate boot. (Pratt & Whitney Chemical Systems Division, Ref. 87.)

development. This device has been applied in the nozzles of the majority of SRMs developed since including Poseidon, Trident I and II, Peacekeeper, Small ICBM, Space Shuttle Booster, Titan SRMU, and the movable nozzle versions of the GEM SRM series. The flexible seal has an outstanding reliability record with no documented primary failures in the hundreds of flights and test firings in these noted motors.

Figure 7 illustrates the simplicity of the flexible seal nozzle. The fixed and movable parts of the nozzle are connected by the flexible seal element. The element is composed of alternate spherical layers of elastomer and metal or composite reinforcements. The flexible seal provides a positive gas seal while allowing omniaxial vectoring without sliding parts and the frictional torque attendant thereto.

The omniaxial cold ball and socket nozzle, developed in the late 1960s-early 1970s, also continues to be used for movable nozzles such as THAAD and Tomahawk booster because it requires a smaller diameter nozzle envelope than the flexible seal. Its use today is limited to relatively small throat diameter nozzles (less than about 3 in. (76 mm)) because the tight tolerances required for the sliding seal result in weight and cost penalties that make the flexible seal nozzle more attractive with larger diameter throat nozzles.

Another movable nozzle TVC system, developed in the 1970s by CSD, went into production in the large and small IUS motors.[87] This device, the Techroll joint, has the advantage of much lower torque requirements than either the flexible seal or the cold ball and socket. The Techroll joint is a constant volume, fluid-filled bearing using a seal configured with two rolling convolutes that permit omniaxial defection of the movable portion. The fabric-reinforced, elastomeric seal is structurally supported on all surfaces except at the rolling convolutes.[88]

The 3D or 4D (three- or four-directionally-reinforced) carbon–carbon (C-C) ITE, developed in the mid 1970s, was another key enabler for SRM nozzles. Use of these materials in nozzles was explored after their successful development for re-entry vehicle nose tips. Reliable throat designs were originally one of the most challenging SRM technologies. Throat failures in 30–40% of SRM development program test firings were typical prior to the introduction of the 3D and 4D C-C ITEs. Subsequently, throat failures became exceedingly rare.

The first 3D C-C ITE test firings were conducted at CSD in May 1976. During the 1976–1979 period over forty 3D or 4D C-C ITE test firings with small nozzles (2–3 in. (50–75 mm) throat diameter) were conducted by CSD in programs sponsored by the Navy and Air Force or IR&D funds. Success of the 3D and 4D C-C ITEs led to their immediate incorporation in the IUS small and large motor designs, the first production use. AFRPL-sponsored evaluation programs of 7-in. (178-mm) and 15-in. (381-mm) throat diameter ITEs followed. 3D and 4D carbon–carbon ITE evaluation programs took place at other solid propulsion companies in this same period, including efforts at Thiokol Elkton which resulted in application to the STAR series of motors.

Fig. 8 Extended Length Super HIPPO test at AFRPL. This reusable Nozzle/TVC test system was designed to emulate Stage 1 Peacekeeper pressure, throat size, and duration. In the largest configuration, the 2-m diam, ~10-m long motor burned 40,000 kg of propellant at 9.7 MPa (1400 psi) for 58 s to test nozzles with throats almost 0.4 m in diam.

The robustness of 3D and 4D C-C ITEs was best demonstrated in the AF-sponsored Composite Materials Analysis (COMA) program, in which the influence of pressure level, firing duration, and propellant composition on ITE erosion rate was tested. Six identical small nozzles and ITEs, of the design used in the 40 firings referred to above, were test fired with pressure level, firing duration, and propellant composition varied. The original 40 tests were at a pressure level of approximately 1000 psia (6.9 MPa) for a 20-s duration using 90% solids/18% Al propellant. In the two most extreme tests of the COMA program, the same design was fired with the baseline propellant for 61.0 s at an average pressure of 1432 psia (9.9 MPa) and 63.8 s at an average pressure of 1665 psia (11.5 MPa). The AFRPL Super HIPPO motor ((see Fig. 8) was used to achieve these long durations; the HIPPO motor was used for the shorter duration tests. In the latter test, the ITE failed at 61.4 s of the 63.8 s duration (it eroded until there was essentially nothing left); the other survived the test in good condition. Two others were test fired for 17 s at 1590 psia (11.0 MPa) and 16 s at 1960 psia (13.5 MPa) with 90% solids/21% Al propellant. In the latter of these tests, a grain anomaly resulted in a pressure spike shortly after ignition to nearly 6000 psia (41.4 MPa). Despite this, the ITE survived in good condition, as did the ITE in the former test. These extreme tests helped establish the robustness and desirability of the 3D and 4D ITEs.

Nearly every nozzle designed since 1976 has incorporated a 3D or 4D C-C ITE including Peacekeeper, SICBM (Small ICBM), Trident II (D-5), Orbus® 1, Tomahawk Mk-111 booster, THAAD, and the GEM series. Exceptions are the Titan SRMU and the Atlas V strap-ons, which, because of their large throat diameters, could use a more eroding but lower cost carbon-phenolic ablative throat.

As discussed more thoroughly above in Section 2 (i.e., Enabler 2) metallic case inert mass was first reduced with the use of higher-strength steel alloys. Titanium, subsequently used in Thiokol STAR motors, offered both improved strength to weight and higher temperature capability. The latter feature reduced the case insulation thickness requirement. More dramatic structural improvements were achieved with filament-wound cases. Here, development of improved strength-to-weight fibers allowed further weight reduction. Fiberglass was used first. Kevlar replaced it as the fiber of choice in the 1970s, and was, in turn, replaced by graphite fiber in the 1980s. The efficiency of a filament-wound case is measured by the parameter pV/w where p is the burst pressure, V, the internal volume, and w, the mass. Figure 9 illustrates the improvement in case efficiency with material improvements. As indicated in the figure, both Kevlar and graphite fibers were improved after their introduction.

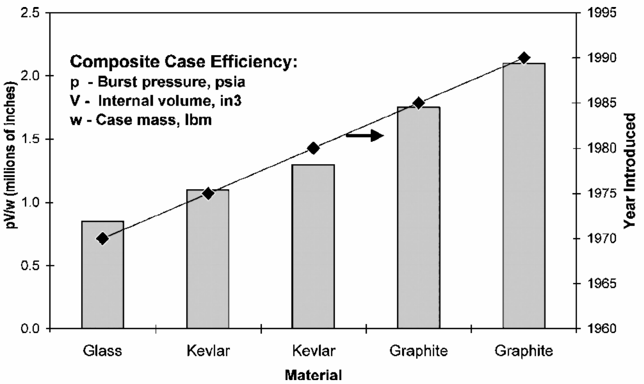


Fig. 9 The efficiency of filament-wound cases continuously improved with the introduction of improved strength-to-weight fibers. Current commercial graphite fibers allow cases with triple the efficiency of the glass fibers first used.

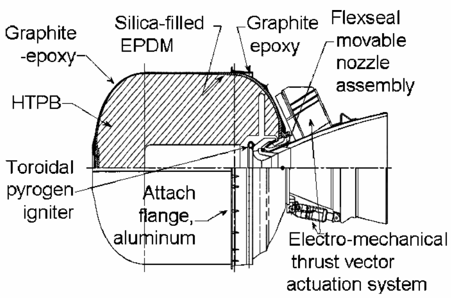


Fig. 10 A high-performance motor is illustrated by the Orbus® 1A. Incorporated are a filament-wound graphite chamber with lightweight insulation, a high-volumetric-loading head-end web grain of high-solids HTPB propellant, a consumable aft-end igniter, a nozzle of nearly all-composite construction with a 4D carbon–carbon ITE, and flexible seal TVC with integral thermal protection and electromechanical actuation. (Pratt & Whitney Chemical Systems Division, Ref. 87.)

A high performance head-end web motor design is illustrated by the Orbus 1A motor (see Fig. 10) . In addition to a composite graphite fiber case, the design features a flexseal movable nozzle; a consumable, toroidal, nozzle-mounted igniter; a 4D carbon–carbon ITE; and electromechanical TVC actuators. Case insulation weight was reduced with the application of one of the improved thermal resistance materials, silica-filled EPDM rubber. The highest mass fraction propulsion system ever flown is believed to be the short carbon–carbon exit cone STAR 48 with a mass fraction of 0.946.

As the igniter is a small portion of motor inert weight, key developments in igniters are more related to reliability and safety than to motor mass fraction improvement. Two key developments are related to transmitting energy through a sealed pressure vessel wall. The first of these was the electro-explosive device. This device with wires molded into a glass insert, a derivative of vacuum tube technology, allowed electric current to pass through a glass insert in the chamber/case wall. The through-bulkhead initiator (TBI) was an improvement in that a shock wave is passed through a metal wall, so pressure vessel integrity is better maintained.

SRM igniters were initially pyrotechnic devices usually triggered by an electric squib. In 1954 Thiokol developed the Pyrogen igniter, which has several advantages over pyrotechnic igniters. The Pyrogen is essentially a small SRM within a larger SRM. A small amount of pyrotechnic material ignited by an electric squib or percussion device (TBI) is used to ignite the Pyrogen. The major advantage of a Pyrogen is it provides a sustained high-temperature flame. Pyrotechnic igniters often provided too short a duration of a high temperature flame for repeatable and reliable ignition, particularly when operating in a vacuum. As the Pyrogen is itself a SRM, its design can be tailored as to the rate and duration of heat release for each need. Safety is improved as large charges of pyrotechnic materials are eliminated.

One igniter development, the consumable igniter, improved the mass fraction. The consumable igniter is designed to be (mostly) pyrolyzed by the internal environment once it has performed its function.

IHPRPT Program

To counter the sharp decline in U.S. solid rocket development program funding after the end of the Cold War, the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) Program was formed. This is a joint government-industry effort to sustain the U.S. rocket propulsion capability and expertise. The program is patterned after the highly-successful Integrated High Performance Turbine Engine Technology program (IHPTET). High performance SRM development from the early 1990s to the present has chiefly been under this IHPRPT Program.

The goal of IHPRPT is to significantly improve solid rocket propulsion capabilities by 2010.[89] Specific goals have been established to increase specific impulse by 8%, increase mass fraction by reducing the inert fraction 35%, increase reliability by reducing stage failure rate 75%, and reduce both hardware and support cost by 35%. Test firings demonstrating interim goals have been conducted successfully. As motors age out and require replacement, ICBM planners are considering Minuteman silo-based missile upgrades as well as a new FBM. IHPRPT is supporting the needed technologies. The U.S. solid rocket community is also giving high priority to environmentally-friendly materials and ultimate rocket disposal in the early planning and design stages of new SRMs.

Some innovations were compelling at the time of their first demonstration, but took decades before acceptance. An example is the technology of winding the case on the live propellant grain, i.e., case-on-propellant. The highly successful HiPADS (High Performance Air Defense Propulsion System) programs demonstrated unprecedented mass loading fractions in 1965 (see Fig. 11). Such applications involving case curing with live propellant required special low-temperature resin. The low-temperature resin prompted concerns over such items as aging during field storage and loss of strength under aerodynamic heating conditions.

4) Large Motor Technology

Large Segmented and Monolithic Boosters

An important thread in the advance of solid rocket motors was the continuous increase in size, burning time, thrust vector angle, and thrust level. A key early step in this direction started with a JPL test vehicle named the Sergeant, not to be confused with either the later missile of that name or the JPL Scale Sergeant used to place the first U.S. satellite in orbit.[90] Army Ordnance had authorized its development. It was a sounding rocket with a diameter of 15 in. (381 mm), which was about twice as large as any existing solid-propellant motor. Designed by JPL researchers (including Charles E. Bartley, J. I. Shafer, and H. L. (Larry) Thackwell) to launch a 23-kg payload to 213 km, it had an extremely thin steel case thickness of 1.65 mm and a star-shaped perforated grain. Static tests with a thicker case in February 1949 showed a polysulfide grain of that diameter could function without significant deformation. The result was twelve successive explosions, the last on 27 April 1950. At

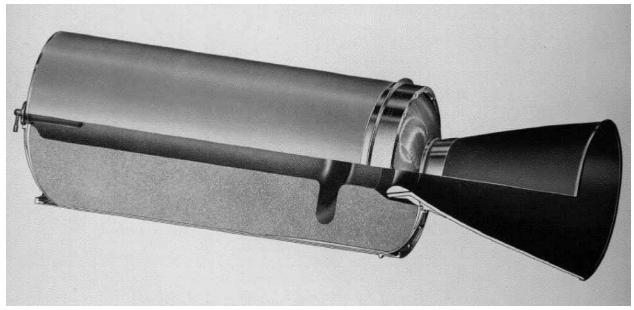


Fig. 11 The mid 1960s Thiokol Huntsville HiPADS case-on-propellant motors demonstrated a mass fraction greater than 91%. The techniques enabled more versatile grain designs, in-process inspection and repair, and higher loading densities. (ATK/Thiokol.)

this point, JPL Director Louis G. Dunn canceled the project for the sounding rocket and cut back all solid propellant work at the JPL to basic research. With Dunn's cancellation of the project, Thackwell took his knowledge of solid propellant rocketry to Thiokol's Redstone Division in Huntsville, Alabama.[91]

The year 1950 marked the start of an ambitious development program that provided a historic demonstration of the potential for case-bonded solid propellant rocket design and scale-up. At the time, the concept of using an internal-burning, case-bonded composite propellant was still in its infancy. The project, known by the test vehicle designation RV-A-10, was part of the Army's larger Hermes[92] low-cost missile development program. To the staff of propulsion contractor Thiokol at Redstone Arsenal it was just Hermes, which was to become the largest SRM of its time and have an impact on large motor development for years to come. Thiokol teamed with General Electric on the Army-sponsored Hermes project to produce a solid propellant rocket much larger than JPL's Sergeant sounding rocket. Work on the Hermes A-2 solid rocket version began at Redstone Arsenal in 1950. By current standards, the Hermes motor was small—just 31 in. in diameter and 108 in. long—but it represented a significant step in scale-up at the time.

The initial requirement for the Hermes was to carry a 500-pound (227-kg) warhead 140 km. Then the requirement changed to a 1500 lbm (680 kg) payload. A full-scale, heavy-wall motor was successfully static tested on 2 December 1951, just 18 months after program start. Then, over the period from January 1952 through March 1953, there were 20 more static tests at Redstone Arsenal and four flight tests of the missile at Cape Canaveral. Of the four flight tests, one flight achieved a maximum range of 84 km and a maximum altitude of 60 km. In the course of the program, the missile came to be designated the RV-A-10. During the testing, project engineers encountered and overcame unanticipated problems with nozzle erosion and combustion instability. In February 1953, the RV-A-10 became the first known solid propellant rocket motor of such a large size—31-in. (787-mm) diam and 4.4-m long—to be flight tested. Among its other firsts were scaling up the mixing and casting of polysulfide propellants to the extent that more than 5,000 lbm (2268 kg) could be processed in a single day.[90] The final design contained 4,690 lbm (2,127 kg) polysulfide composite propellant and produced an average thrust of 35,400 lbf (157,467 N) during a web burning time of 24 s.

The Hermes program at Thiokol produced a number of firsts and significant accomplishments enabling the progression of the emerging science of solid propellant rocketry into a dynamic, multicorporate industry by the late 1950s. Among these milestones were: the first successful static and flight tests of a large, long-duration, internal-burning, case-bonded solid rocket motor; routine use of multiple mixes for a single large motor; progressive pressure cure of the propellant grain to control physical properties; and the first use of jet vane thrust vector control in a large SRM. The technology developed during the Hermes program was applied to the subsequent 31-in. (787-mm) Sergeant missile propulsion system and first-generation Castor booster motors.

The Big Booster Early Years

Recognizing the potential for business growth in the development and production of large solid motors, Thiokol began construction of its Utah plant near Promontory in late 1956. By December 1957, the new plant had manufactured its first large motor, known by the Thiokol designation TU-100 and nicknamed Big B. The Big B contained 22,000 lbm (9,979 kg) propellant, four times as much as Hermes, and was successfully static tested in February 1958. The Big B demonstrated yet another level of design and processing scale-up that served as progenitor technologies for the Air Force's all-solid-propellant Minuteman ICBM.

Big Boosters Following the Space Race

Just as the demonstration of Thiokol's Hermes RV-A-10 and Big B motors spurred development of Minuteman, the quest for space and the Space Race of the 1960s fueled even bigger ambitions of solid rocket motor scale-up. Aerojet, Thiokol, United Technology Center (UTC), and Lockheed Propulsion all became involved in various large motor feasibility, demonstration, and development programs.

In 1959, the Air Force awarded Aerojet funds to demonstrate a 100-in. (2.54-m) diam motor generating a thrust of one million lbf (4,480,000 N) for a minimum of 20 s.[71] Six motors were successfully ground tested by early 1963, demonstrating case segmentation with various joint designs and several different forms of thrust vector control. UTC, meanwhile, invested company funds to demonstrate 87-in. (2.2-m) diam motors with its new polybutadiene-acrylic acid-acrylonitrile (PBAN) propellant in 1960 and 1961.

Beginning in late 1962, the Air Force's Large Solid Rocket Motor Program (623A Program) became the catalyst for several years of intense national effort to advance technologies applicable to potential NASA and DoD missions. Both Thiokol and Lockheed Propulsion built and tested 120-in. (3.05-m) and 156-in. (3.96-m) diam monolithic and segmented motors between 1962 and 1968. On 13 May 1966 Thiokol successfully tested a 156-in. (3.96-m) diam segmented fiberglass case motor, the largest diameter composite case ever fired. Segmentation enabled processing in existing facilities and land transport of large motors.

NASA eventually assumed management responsibility for the largest of the motors built and tested, the 260-in. (6.6-m) diam motor, as a backup for the first stage of the Saturn V manned launch vehicle.

Nearly in parallel with its 623A program, the Air Force began development of the Titan III launch vehicle, which incorporated two 120-in. (3.05-m) diam strap-on boosters (zero stage) developed and manufactured by UTC. The five-segment SRMs boosted the first of 64 Titan IIIC flights on 18 June 1965, and a $5\frac{1}{2}$ segment SRM was qualified and used for 15 flights of the commercial Titan 34D vehicle. The failure of a Titan IIIC SRM a few months after the *Challenger* accident caused a major delay in Titan IIIC launches. The failure resulted from unbonded case insulation in the joint area of one of the SRM boosters. One result was the Air Force required that future static tests of the booster be conducted in a nozzle down, vertical flight attitude. Titan IIIC SRMs had been qualified in vertical, but nozzle-up firings. This led to construction of a new large SRM vertical test stand test facility at AFRPL for return-to-flight testing and for future Titan IV-A SRM and Titan IV-B SRMU boosters. UTC developed and tested a seven-segment version of the Titan III SRM between 1969 and 1970 for the later-canceled Manned Orbiting Laboratory (MOL) program. The seven-segment SRM design was revived in 1985 and qualified for the heavy-lift Titan IV-A in February 1988. The first launch for Titan IV-A was on 14 June 1989.

The Air Force's desire for greater performance and exploitation of more modern technologies led to the development of the Titan IV SRMU by Hercules (later ATK) from 1987 to 1993. The twin SRMU strap-ons increased the payload capability of the Titan IVB vehicle by 25% over the heritage Titan IVA by increasing the diameter to 126 in. (3.2 m) and using a three-segment graphite composite case for higher propellant mass fraction and higher operational pressure capability. The SRMU is loaded with nearly 700,000 lbm (317,500 kg) of HTPB propellant.

The failure of the first SRMU development motor in 1991 during static testing at Edwards AFB led to grain design modifications. Subsequently, the SRMU was qualified with four successful static tests between 1992 and 1993. The inaugural launch of the Titan IVB with SRMU boosters took place on 23 February 1997 from Cape Canaveral. The SRMU is the largest composite-case motor ever flown.

Thiokol applied much of the technology gained from the large motor demonstration and ballistic missile development programs of the 1960s to the Space Shuttle SRM, the development of which began in 1974. This largest program in Thiokol history developed a land-transportable, 146-in. (3.7-m) diam motor containing over 1 million lbm (454,000 kg) propellant and delivering an average thrust of 2.3 million lbf (10.2 million N) over a 120 s burning time. These SRMs also featured the first reusable rocket motor cases and nozzles, recovered from the waters off Cape Canaveral following separation from the vehicle and a parachute-slowed descent into the Atlantic Ocean. The first development motor, DM-1, was tested on

18 July 1977 and the first use of the twin standard SRMs took place with the maiden flight of *Columbia* on 12 April 1981. Several design changes were later made to the SRM to gain an additional 3000 lbm (1361 kg) payload. The resulting improved high performance motor was first flown on 30 August 1983.

The tragic *Challenger* accident on 28 January 1986 forced a major redesign effort for the Space Shuttle SRM to return the Shuttle to flight. The program to fix the Thiokol SRM was designated the Redesigned (later Reusable) Solid Rocket Motor (RSRM). Design margins were increased in nearly all areas of the motor, particularly in the field joint. The accident was caused by the failure of the redundant o-rings to seal one of the SRM field joints due to the cold temperature at the time of launch. This failure required a total redesign of the field joint and an increase in safety margins in many other areas. This redesign program was the most extensive and comprehensive design, test, and analysis program in the history of the solid rocket motor industry. Oversight was provided by the longest-standing committee in the history of the National Research Council (NRC). The test program involved six times more testing and orders of magnitude more analyses than the original development and qualification program for the SRM. The original development and qualification program took 7 years whereas the redesign program took 32 months. The redesign program established a new standard for the SRM industry. Two full-scale Shuttle SRMs were tested at the temperature extremes (4 to 32 C) with full pre-launch, launch, and max Q flight loads applied during static test. These loads were applied through a set of hydraulic actuators attached to the external tank attach ring on the RSRM. One RSRM, designated as PV-1, was designed with intentional flaws incorporated in all of the joints. These flaws included holes through the stress-relieved and sealed insulation, a hole drilled through a capture-feature o-ring, and joint insulation intentionally separated from the joint area steel case wall, allowing hot gas to penetrate the redesigned field joint and case-to-nozzle joint. PV-1 was successfully tested—demonstrating the greatly improved safety margins of the RSRM—in August 1988, one month before return to flight of the Space Shuttle Discovery. This flaw testing was unprecedented in the solid rocket industry.[93] The redesign resulted in an inert weight penalty of about 3000 lbm (1361 kg).

A graphite-composite filament-wound case (FWC) upgrade of the Space Shuttle SRM was also undertaken in the mid 1980s to support eventual launches from Vandenberg AFB. Thiokol cast propellant in Hercules-manufactured composite case segments. Two of three manufactured FWC motors were assembled and successfully static tested on 25 October 1984 and 9 May 1985, respectively. However, Shuttle flights from Vandenberg AFB were canceled after the *Challenger* accident and the FWC effort was abandoned. Nevertheless, the FWC-SRM remains the largest composite case motor ever built and tested.

Smaller monolithic solid boosters such as Thiokol's Castor and ATK's GEM series also have an extensive record of service for both strap-on applications and as conventional stages. Thiokol's Castor I was the first strap-on booster used on an orbital space launch vehicle.[94] On 28 February 1963 the first launch of a Thrust Augmented Thor (TAT)-Agena D with three 31-in. (797-mm) diam Castor I strap-ons took place from Vandenberg AFB. This marked the beginning of the routine use of monolithic solid strap-ons that have established their place in at least one configuration of every major U.S. launch vehicle to date.

Upgrades in propellant and nozzle technology resulted in subsequent versions designated Castor II, IV, IVA, and IVB. These metal-case Castor series of motors have been used as strap-ons for several generations of the Delta launch vehicle since the 1960s. Four Castor IVA motors also boost Lockheed Martin's Atlas IIAS vehicle. The 93-in. (2.36-m) diam Castor 120, qualified by Thiokol in 1993, is a commercial derivative of its Peacekeeper first stage design and is the booster for the commercial Taurus® and Athena launch vehicles.

Pursuant to a string of launch vehicle failures in the mid 1980s, as well as the *Challenger* accident, the Air Force opened competition for a medium launch vehicle (MLV) system to orbit the Navstar GPS constellation. In 1987, McDonnell Douglas won the MLV competition with a proposed Delta II series of vehicles that used either nine Castor IVA strap-ons or nine new 40-in. (1-m) diam GEM-40 motors. The GEM-40 boosters, manufactured by Hercules, represented a bold step to provide a 25% increase in liftoff thrust of the Delta II—by using graphite composite-case motors with high-solids HTPB propellant. The first launch of the Delta II 7925 configuration on 26 November 1990 marked the first use of a composite-case motor in a launch vehicle strap-on application. Later, Delta II configurations with three and four GEM-40 strap-on boosters emerged as payload requirements necessitated.

The success of the GEM-40 throughout the 1990s spawned the larger derivative GEM-46, initially for use with the Delta III vehicle. The GEM-46 was qualified in 1997 and was first flown on 5 May 1999. Nine GEM-46 strap-ons were also used, for the first time, on a new Delta II Heavy configuration on 7 July 2003.

When the Air Force awarded concurrent contracts in late 1997 to Boeing and Lockheed Martin for the final phase of development of the EELV, neither of the proposed launch vehicle baselines included solid propulsion. As the EELV concepts matured into what became known as Delta IV and Atlas V, the prime contractors turned to solid strap-on boosters to increase the versatility of their medium and medium-plus configurations. ATK qualified the third generation GEM-60 for Delta IV in 2000 and Aerojet began the development of the 62-in. (1.57-m) diam Atlas V SRM in 1999.

With a length of 55.4 ft (16.9 m), Aerojet's Atlas V SRM is the longest monolithic graphite composite case motor manufactured and flown to date. It has a mid-case attachment feature, contains about 94,000 lbm (43,000 kg) of HTPB propellant, and provides about 250,000 lbf (1,100 kN) of average thrust over a 92-s burning time. Up to five SRMs can be mounted to the Atlas common core booster (CCB). The first two Atlas V SRMs flew successfully on the maiden launch of the Atlas V 521 configuration from Cape Canaveral on 17 July 2003.

Big Booster Effort at AFRPL

The Large Motor Branch of the AFRPL Solid Rocket Division in the late 1960s was a hard-charging group with high *esprit de corps*.[71] The Branch was led by Major Orval (Cruiser) Krone and the program was kept alive under the strong advocacy of Major William C. Rice of the division office and Colonel Harold W. Robbins of the Director's office. These men maintained a constant presence at the USAF chain of command in Washington to keep the program alive. At one point, when NASA and others were lobbying for the same funds, AFRPL disguised the requested funds as money for an "extended environment" air-launched propellant program. The local rocket company technical representatives always seemed to have a good handle on the AFRPL budget, but even they were fooled into thinking the lab had developed an inordinate interest in wide temperature capability tactical propellants. They were subsequently confounded when they found the money had been applied to the start of the large booster program.

The key young civilian AFRPL engineers managing these large booster programs included Wilbur C. Andrepont and Ralph M. Felix. The large booster effort sparked an unavoidable move toward analysis at AFRPL and within the U.S. propulsion industry.[95] Suddenly, as motors grew to 100 in. (2.54 m), 156 in., (3.96 m), and 260 in. (6.6 m) in diameter,[96] the old cut-and-try methods of motor design and development became impractical. This prompted daily crises and many unanswerable questions such as; How do we size large igniters?; Will the large grains transfer heat from the exothermic propellant cure reactions rapidly enough to prevent autoignition?; How well will large multi-day batch castings displace each other and knit together to give uniform ballistics and properties in large monolithic grains?; What two-phase-flow losses should we expect from motors with throats over a meter in diameter?; How do we fabricate gigantic cases and nozzles and estimate their structural margins?; How do we non-destructively test (NDT) the grains and motor components?. These and a myriad of other questions sparked a host of new AFRPL in-house and contractual programs, which lasted several decades and, in many cases, were the genesis for the solid rocket community modeling and simulation capability. These

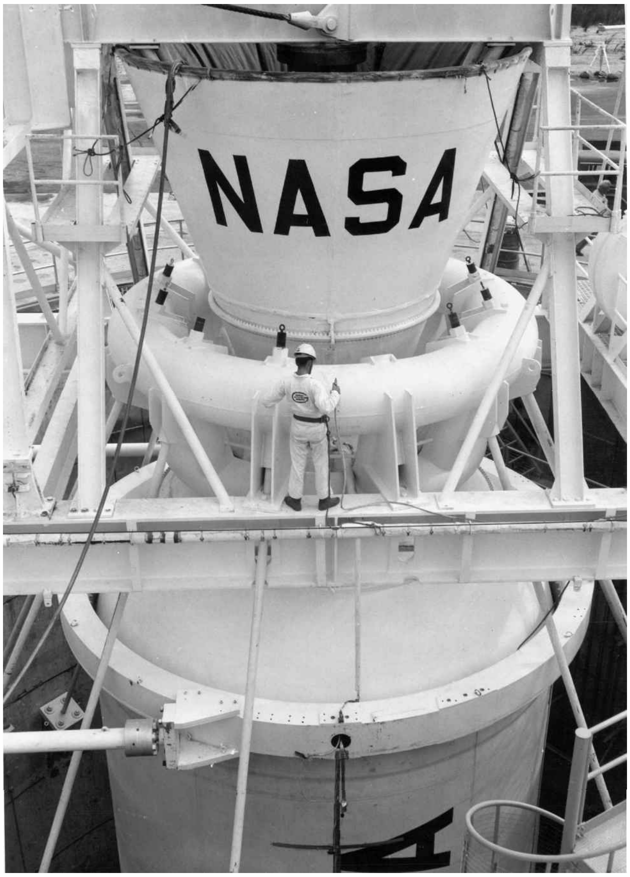


Fig. 12 One of the three 260-in. (6.6-m) diam motors (length of 80.7 ft, 24.6 m) fabricated in the Aerojet Dade County, Florida facility, under a NASA contract. The motors were successfully static fired in 1965–67. SL-1 and SL-2, loaded with 1.68 million lbm (763 Mg) of propellant, produced 3,600,000 lbf (16,000 kN) thrust.

are many of the contributions that are not often recognized as resulting from the big motor efforts.

The 260-in. Motor

In the mid 1960s Aerojet, under contract to the NASA Lewis Research Center to demonstrate the feasibility of utilizing large SRMs for space exploration, built and static-fire tested the largest solid rocket motor[97] in history (see Fig. 12). Aerojet established motor processing and test operations at a new facility in Homestead, Florida. To process a motor of this enormity, case preparation, insulation, casting, and static testing all took place in an in-ground vertical silo. With one continuous and two batch mixers employed, casting took over two weeks. The spectacular 260 SL-1 and SL-2 static test firings were conducted on 25 September 1965 and 23 February 1966 (at night) and were totally successful. Performance was nearly identical for the two firings with the maximum thrust and total impulse 3.6 million lbf (16,000 kN) and 372,000,000 lbf-s (1,650,000 kN-s), respectively.

SL stands for short length (24.6 m); the full-length motors would have been 38.6 m long and loaded over twice the propellant. SL-3, a modified version, tested the full size nozzle on 17 June 1967 producing 5,884,000 lbf (26,173 kN) thrust, an unmatched record.

Thiokol in the same period established a Space Booster Facility in Brunswick, Georgia and conducted a very successful 156-in. motor test.[96] However, the 156-in. prototype to their 250-grade-maraging-steel 260-in. case ruptured during hydrotest, prematurely ending their 260-in. aspirations. Both the Aerojet and Thiokol programs were important proving grounds for the eventual Shuttle SRM.

The NASA program put Aerojet in the lead for the highly coveted Space Shuttle booster contract. However, Aerojet championed a monolithic vs. segmented rocket motor design philosophy, a misinterpretation by Aerojet of the NASA proposal requirements. Aerojet filed a protest and won the right to propose a monolithic design.[10] This issue was claimed to be partially responsible for Aerojet not being selected for the Space Shuttle Solid Rocket Booster contract. In the words of Aerojet,[97] "The rest is space history."

5) Interceptors

Nike

In the late 1940s and early 1950s, the Army rapidly developed the Nike series of surface-to-air missile (SAM) interceptors with explosive warheads. The low-mass-fraction and low-specific-impulse (less than 200 s) boosters required these systems be two stage. By contrast, the ensuing enabling technologies make modern hit-to-kill systems effective with only one high-performance booster stage and without a massive explosive warhead. The resulting mass and volume reductions are striking.

The Nike system is the subject of several in-depth books (e.g., Ref. 98) and official websites (e.g., Ref. 99). The thousands of people who staffed the hundreds of Nike sites in the 1950s and 1960s keep the lore surrounding these Nike systems vibrant. In 1945, Douglas Aircraft Company became the Nike-Ajax airframe contractor. Initially Aerojet supplied both the liquid-fueled sustainer engine and the solid-fueled booster rockets. The initial design called for eight booster rockets wrapped around the tail of the missile. However, booster-cluster reliability problems forced designers to adapt an ABL booster (a single solid, 0.44-m diam) designed for the Navy. Douglas Aircraft built 13,714 missiles in Santa Monica, California and at the Army Ordnance Missile Plant, Charlotte, North Carolina. The NC/NG based extruded solid propellant boosters were produced by Hercules Powder Company, Radford Arsenal, Virginia. The Nike-Ajax, with an effective range of 40 km, was deployed in the U.S. from 1954 to the early 1960s.

In 1953, the extended-range Nike-Hercules was authorized. Again, Douglas was the airframe contractor and the solid boosters were provided by Hercules. To build Nike-Hercules the design team simply took the components of the Ajax missile and multiplied by four. Four 0.4-m (16-in.) diam M88 solid booster rockets were strapped together and four liquid-propellant sustainer engines strapped together. Following a fatality in a static test failure of the liquid rocket sustainer cluster, a solid rocket sustainer was specified. The XM30 sustainer was developed by Thiokol in Huntsville and produced by the Thiokol Longhorn Division, Marshall, Texas. The 27.5-in. (0.7-m) diam XM30 was one of the first production case-bonded motors; it used an ammonium perchlorate/polysulfide binder. The XM30 was among the first to use the highly reliable Pyrogen igniter. The ~80-in. (~2.0-m) motor was connected to an ~90-in. (~2.3-m) subsonic blast tube. The 45-kg blast tube was a performance-robbing contrivance used to manage the center of gravity on several of the 1950's and 1960's systems. The Nike-Hercules, with an effective range greater than 75 km, was deployed starting in 1958. Over 25,000 missiles were produced. In 1963, there were 134 Nike-Hercules and 77 Nike-Ajax batteries defending the U.S.

Surplus M88s have been widely used by NASA and university research programs for space science research. The NC/NG based propellant delivered a specific impulse of less than 200 s with a system mass fraction of 0.63. Clearly in 1955, the prospect for success via enabling technologies was bright.

In response to Sputnik in January 1958, the Army's Nike-Zeus Antimissile Missile development program was given the highest priority. The two-stage Nike-Zeus A is aerodynamically similar to the Nike-Hercules, just scaled up. Its new TX-135 booster, which was then the largest single chamber (~1-m diam) solid rocket motor produced in the U.S., delivers over 450,000 lbf (2002 kN) of thrust. The TX-135 uses several innovations and new technologies. To sharpen the tail-off and reduce mass, its grain is cast on top of low-density inert slivers. Its pioneering composite nozzle has over 50% less mass compared to a 1960s conventional heat-sink steel nozzle. The Pyrogen's spent parts are retained in the launcher, reducing inert mass. Its short burning time and brute force are marvels.

On 7 October 1961, the three-stage Nike-Zeus vehicle achieved an apogee of 200 km. It used three new stages, the Thiokol Huntsville

TX-135, TX-238 and TX-239. The innovative final stage TX-239, referred as *the Canard*, provides steering by four movable exhaust ports. The Canard enables maneuvers without momentum-degrading aerodynamic surfaces. Nike-Zeus is an imposing 1960s system: 10,300 kg, 0.91 m core diameter, 14.60 m length, and ~400 km range.

Sprint and HiBEX

The pursuit of ever-shorter time-to-target placed great premiums on decreasing burning time of boosters and increasing I_{sp} and mass fractions of the second stage. The urgency of early 1960 requirements accelerated propellant, nozzle, and case development.

The 1960's focus on missile defense led to the rapid development and testing of two extraordinary systems, Sprint and HiBEX. They, along with Nike-Zeus, which evolved into Spartan, would become the components of a series of ballistic missile defense programs. In 1975, Spartan and Sprint became the two-tier components of the short-lived Safeguard anti-ballistic missile system.

Sprint is a phenomenal missile. Martin began its development in 1962. Sprint is a two-stage conical missile that accelerates at ~100 g to Mach 10 in 5 s. The inferno on its outer skin rivals the one in its chamber. A thick ablative coating is needed to fend off the ~3600 K aeroheating. Flight control during the first stage burning is via fluid injection. Second stage control is obtained via small aerodynamic fins. Sprint is over 8-m long and 1.4-m diam at the base.

The high burning rate demanded by Sprint energized the industry. Hercules, Aerojet, and Thiokol competed to more than double propellant burning rate. All of the initial approaches were troublesome. In many instances understanding of flame science revealed why intuitively-appealing approaches would not succeed. Nevertheless, many dead-end approaches were attempted. The basic task was to achieve the high burning rate through particle size control. This led to new techniques for producing ultra-fine ammonium perchlorate (UFAP). Attempts to make ultra fine aluminum (UFAL) and treated aluminum capable of enhancing burning rate were disappointing. Thin metal fibers (e.g., 20-μm thick), blended into high-burning-rate-matrix propellants, gave encouragingly-high burning rates in strand burners. However, the inability to control the alignment of the fibers during casting led to nonuniform burning, producing weird hay-stack (versus desirable flat) pressure-time traces in motors of all sizes. No amount of grain design cleverness or process control to align the fibers could produce predictable burning patterns to achieve even a semblance of flat pressure-time traces. Chemical approaches such as the ferrocene burning-rate enhancers required concentrations that pushed the limits of loading and safety; thus, they were unattractive. However, after less than two years of vigorous work, the required fast burning times were achieved through a combination of thin-web grain designs and greatly increased burning rates, in turn achieved by a combination of means. The initial Sprint demonstration contracts were awarded to Thiokol, Aerojet, and Hercules. The first Sprint launch occurred in November 1965. Eventually, Hercules received the production contract and subsequently developed an improved motor set containing composite modified double-base (CMDB) propellant. Being impressed with the amazing success of the Sprint motors was short lived. HiBEX was bolder.

Initially HiBEX was part of DARPA's Project Defender for terminal layer BMD, e.g., missile defense below 3 km. HiBEX was 5.2 m long and 1.22 m in diameter at the base. The HiBEX experiment required acceleration in the 400-g range. Boeing was the airframe contractor and Thiokol Huntsville developed the propulsion. Observing the first HiBEX static test was surreal. From an excellent Redstone Arsenal vantage point, the action time was so fast and the exhaust fireball so intense, a motor success and an explosion appeared the same. A quick trip to the blockhouse confirmed that HiBEX operated successfully. The first launch was on 25 February 1965.

The short development times for the Nike, Sprint and HiBEX series reflect more than the urgency of the era. Ample up-front budgets and get-out-of-the-way DoD and corporate management enabled the technical teams to focus primarily on the technology. In the current era of instant communication and computers everywhere, lesser projects take much longer and cost much more.

Patriot

Patriot is the most advanced medium surface-to-air missile in the Army inventory, and is the only SAM to have intercepted ballistic missiles in combat. The Patriot system is complemented by the new Patriot Advanced Capability-3 (PAC-3) missile, which is smaller and has shorter range. Both missiles are single-stage solid rocket systems using mature technology enabled by the development programs associated with the more severe requirements of systems such as Sprint and HiBEX. The 0.4-m (16-in.) diam Thiokol TU-758 Malemute motor, sold commercially and used primarily for sounding rocket experiments, is a variant of the Patriot booster. University-conducted hypervelocity aerothermochemistry experiments have probed the greater than 4 km/s regimes using instruments boosted by Malemutes.

DACS

DACS propulsion for divert and attitude control provides short-duration thrust, typically 90 deg to the main flight-path axis. For some applications, impulse bits must be delivered in less than 0.01 s. Until recently, liquid propulsion systems using either rapid on-off cycles or fast-action valves were the principal approaches for exoatmospheric applications. Two types of solid propulsion impulse management approaches received the most attention: 1) fixed impulse bits using small solid rockets and 2) proportional control using valved nozzles (as shown in Fig. 13).

ARC is prominent in devising systems to provide fixed impulse bits using small rockets. For example, they achieve 360-deg control by placing an array of rockets on the outer circumference of a spinning system. As the system spins, the short-action-time rockets deliver impulse over a few degrees of rotation; thus, the impulse bit is highly directional. The Maneuvering Propulsive Array (MPA),[14] built by ARC in the 1980s, is an array of center-vented small-diameter rockets for a spin stabilized hit-to-kill interceptor for space. The short action time motors are fired at the precise time to move laterally move a prescribed distance to close with the target. A photograph of this innovative propulsion system is Fig. 13 in

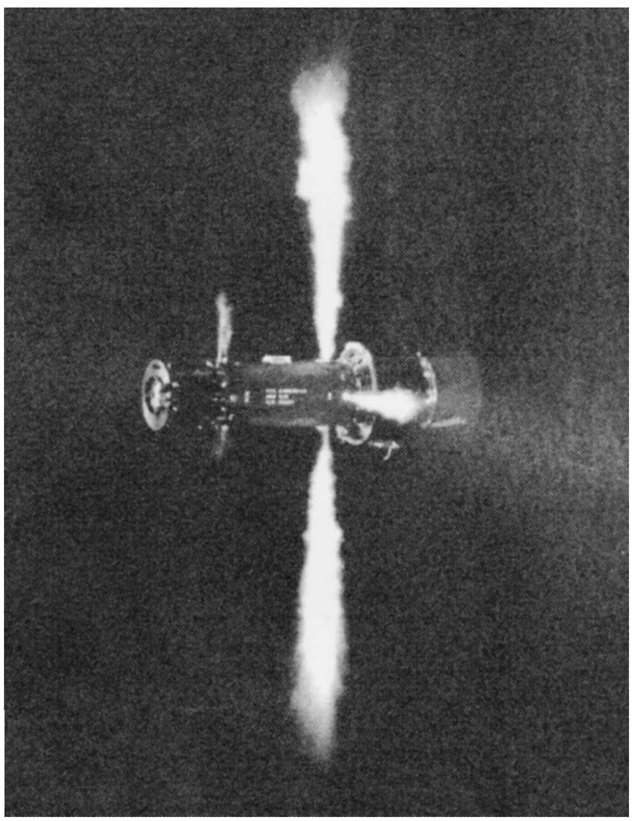


Fig. 13 Solid propellant Divert and Attitude Control System (DACS) hovering in 1990's free flight test. (ATK/Thiokol Elkton Division)

Ref. 16. ARC perfected variants of these circumferentially-mounted rockets for ground-to-air interceptors,[100] most prominently for use on the PAC-3 missile. Part of the innovation was the ignition and timing systems to achieve the high precision needed to simplify the seeking system.

Since 1990, ATK Elkton (formerly Thiokol Elkton)[101] and Aerojet[102] have been making rapid progress in developing miniature solid propellant, multi-pulse, gas-generator systems with fast-action valves. A typical configuration is four valves in a plane spaced at 90-deg. intervals (see Ref. 103 for general nozzle configuration). Thiokol received the majority of the funding for the series of programs led by John J. Walsh, Bart R. Olson, and William S. Prins. Solid propellant, with inherent characteristics of readiness, storability, and safety, offers solutions to concerns over the safety of toxic liquids. Each application is design specific, and in some situations, solid DACS (using the current propellants) can be mass competitive with bi-propellant liquid DACS. The smaller volume of the solid DACS offers new packaging options and may lead to mass savings on a total systems basis.

Among the most challenging propulsion designs are the DACS for the Lightweight Exo-Atmospheric Projectile (LEAP) and Solid Divert and Attitude Control (SDAC) system. Bi-propellant liquid propulsion DACSs were hover tested in the early 1990s. However, for some applications only solid propellants can meet the requirements for storability and non-toxicity, giving them another advantage over conventional bi-propellant liquids. The continuing challenge is achieving low-mass, fast-acting valves that survive the high temperature corrosive combustion products. The enabling technologies include improvements in carbon–carbon fabrication and the deposition of refractory coatings such as Re and HfC. Thiokol's Elkton Division solid DACS propulsion systems were hover tested in the mid 1990s (see Fig. 13) and operated successfully in three 2002[104] flight tests which intercepted their targets.

6) Thermochemical Modeling and Simulation Development

JANAF Thermochemical Tables

As part of the Space Race, ARPA initiated Project Principia to harness the U.S. chemical industry to make rapid advances in the performance of solid propellants. The goal was to deliver 280 s of I_{sp} at standard sea-level conditions. Despite the expenditure of over $120 million dollars and much good science over six years, little of the technology was suitable for near-term applications. This was mostly due to the hazards and $/kg imposed by the laws of chemistry and physics, and to the lack of interfaces with the pragmatic propulsion community.[105] Project Principia was criticized in later decades for not leading to miracles. However, it was the foundation for most future U.S. advanced energetic ingredients work. It uncovered a vast line of new chemistry and trained many successful chemists, e.g., Milton B. Frankel and Horst Adolph. They, in turn developed the next generation of national leaders (e.g., Joseph E. Flanagan and Francisco Q. Roberto) and ingredients, e.g., GAP and CL-20[2] energetic propellant ingredients. Having the benefit of over 30 years of experience, a revisit to some of the Project Principia materials will be fruitful.

A major contribution of Project Principia was the development of the JANAF Thermochemical Tables.[106] At the time, the availability of reliable thermodynamic functions for compounds of interest to solid rocket propulsion experts was sparse to non existent. The National Bureau of Standards was unable and unwilling to pursue this need in the short time available. Finally, ARPA convinced the Dow Chemical Company to have its renowned thermochemist D. R. Stull undertake a crash effort in his well-equipped lab in their Midland Michigan research center. Concerned about the credibility of the data and his reputation, Stull won a key concession from ARPA. A color-coding system was devised whereby Stull published the loose-leaf data on various colors of paper depending upon the certainty of the results. Progressing from pink, to gray, etc. the data went on white sheets only when it met his standards. The value of this effort should not be underestimated. The data proved so valuable to all fields of science and engineering that it is now the worldwide standard, and appears in every major technical library, university, and research laboratory on the globe. This achievement has stood the test of time as it approaches its 50th anniversary. A good historical account of the creation of this data is presented in the preface of the first edition of the JANAF Tables.

The evolution of the keepers of this national treasure is also of historical interest, along with some of the key individuals. The long-time manager of the efforts to produce and refine these tables was Curtis C. Selph of the AFRPL (who also wrote and maintained one of the widely used Isp calculation codes for the AFRPL). Many of those who served on the JANNAF Thermochemical Panel and Working group, and reviewers between 1959 and 1998, are listed in the current edition. The list reads like a Who's Who in Rocket Propulsion. The AFOSR, later joined by DoE, funded the effort from 1967 until 1985. In January 1986, the JANAF Thermochemical Tables project transferred from the Dow Chemical Company, who conducted the contracted work effort continuously from 1959 until 1986, to the National Institute of Standards and Technology. Funding since 1986 has come in large part from the Standard Reference Data Program, with additional contracts with NASA, the JANNAF Combustion Subcommittee, and the Army.

Shifting Specific Impulse Calculations

In 1951[107] investigators at the Lewis Research Center of the National Advisory Committee for Aeronautics developed an IBM 650 computer program for calculating the performance of propellants composed of combinations of carbon, hydrogen, oxygen, nitrogen, boron, chlorine, and fluorine.

At the same time the JANAF Thermochemical Tables began to solidify in 1958, shifting-equilibrium rocket performance programs emerged. In 1959, to support the solid rocket activities at the newly-created AFRPL, a general computer program based upon a new concept of the minimization of free energy was established at Wright Air Development Center. For all practical purposes, any propellant system for which thermodynamic data are available may be evaluated. This achievement may be considered a logical outgrowth of the work of earlier investigators. This program was written and implemented on the WPAFB computer for his M.S. thesis by Lt. T. O. Dobbins of the Air Force Propulsion Lab.[108] So far as is known, this was the first application of the minimization-of-free-energy solution and the forerunner of the now-popular NASA Lewis shifting-I_{sp} computer code.[109] An improved version introduced in 1976[110] has remained the community standard under the dedicated care of Bonnie J. McBride and Stanford Gordon.

Solid Performance Program (SPP)

The Solid Performance Program (SPP) is the U.S. standard for prediction of solid rocket motor performance.[111–113] SPP was the culmination of over two decades of effort to understand and model the important processes in solid rocket motors. Key elements leading to this capability were the Bartlett and Delaney[114] work on two-phase-flow and the work under the AFRPL BATES program[115] by Lt. Palmer Smith, Charles Beckman, and Robert L. Geisler. A BATES accomplishment was to collect and size the oxide from every significant U.S. motor over a number of years. SPP was developed under the sponsorship of the Combustion Section of the AFRPL led by Daweel J. George. The contractor was Software and Engineering Associates, Inc (SEA) of Carson City, Nevada led by Douglas E. Coats and with notable contributions on real motor data and particle sizes from R. W. Hermsen[116] and J. T. Lamberty of CSD. The AFRPL-sponsored version was completed in 1975.

SPP uses a collection of analyses based on the standard JANNAF methods for performance predictions. The analysis consists of two parts: nozzle performance and motor performance. The nozzle module analyzes the performance loss mechanisms in four categories: combustion chamber, boundary layer, chemical kinetics, particle, and divergence. The motor performance analysis is a generalized 3-D grain design module coupled to an internal ballistics module. Several macros help the user specify complex grain shapes, such as Star, Wagon-Wheel, Dog-Bone, Dendrite, Finocyl, Conocyl. These macros include a head-end and aft-end domes treatment, which allows a head-end or aft-end taper or transition. The grain-design module is internally linked with the one-dimensional motor ballistics modules. Motor stability can be analyzed with the axial-mode Standard Stability Prediction (SSP) package that is internally linked with the 3-D grain design and ballistic modules to define burning rates, motor surface, and port areas.

SPP is fast and robust enough to provide performance predictions for extensive parametric studies and sufficiently accurate to provide flow field and performance solutions for detailed studies. The features and capabilities of SPP include the ODE (NASA LeRC CET)[110] module to calculate ideal nozzle performance; ODK module to calculate the finite-rate gas-phase chemistry losses; TD2P module to calculate divergence and particle losses; and BLM finite difference Boundary Layer Module to calculate boundary layer losses. The axial mode SSP is linked to the 3-D Grain Design and Ballistic Module.

SEA continues to support and upgrade SPP on a commercial basis. The development and care of this valuable U.S. asset over the past four decades is the singular and dedicated effort of Douglas E. Coats.

Combustion

The application of practical combustion research has been a cornerstone of solid rocketry. The AIAA coverage of this topic is continuous, ample, and current, e.g., references 27, 117, and 118 range from the ARS to the current AIAA Progress Series. Since so much effort has been devoted to combustion instability, the sustained contributions of several researchers to the practical aspects of that pathology are noteworthy. Frederick E. C. Culick is prominent in the community and perennially offers broad treatments of the theoretical[119] and experimental issues. Others such as Leon D. Strand and Robert S. Brown nurtured a range of useful experimental techniques.[120] The keepers of the research on combustion instability are at China Lake where Edward W. Price established his Aerothermochemistry Division as the Nation's *de facto* center for overcoming difficult combustion instability problems. Ronald L. Derr, Thomas L Boggs, and (presently) Fred Blomshield[121] continued the rich tradition of Price. After five decades of research, the industry still lacks the experimental tools to anticipate acoustic stability problems, and an adequate set of techniques, chemical additives, etc., to economically overcome it. One can only imagine the advancements that might have been made if the brainpower that went into studying acoustic instability had been focused on rocket motor concepts and design. The insights and training from combustion instability research have had significant spins-offs. For example, Gary A. Flandro's ingenious explanation of roll torques produced by mismatched vortex pairs[122] in motors with star points draws on combustion instability experience.

7) High Area Ratio Nozzle Technology

The carbon–carbon exit cone is a key technology as it enabled high-performance upper stage solid rockets. The pioneering work on this technology was performed by R. L. Bailey and J. I. Shafer of JPL. They successfully test fired a 1.65-mm (65-mil) thick carbon–carbon exit cone with an expansion ratio of 53.5:1 in ambient air at Edwards AFB in March 1970.[123] After firing, the nozzle was judged to be in such good condition it was subjected, without refurbishment, to a second ambient-air static test firing. A second nozzle of similar design was subsequently test fired twice in an altitude chamber. The tested nozzles were half the weight of the ablative nozzle they were derived from, the JPL Syncom apogee kick motor nozzle. Attendant studies concluded energy losses from radiation and gas leakage through the somewhat-porous carbon–carbon wall were no greater than losses with ablative nozzles. These demonstrations and studies concluded carbon–carbon exit cones could make feasible long-burning and very high-performance nozzles.

Success in this pioneering effort at JPL was soon followed by application in STAR motors by Thiokol, and in the IUS large and small nozzles by CSD. Application to IUS enabled development of the longest burning boost or upper stage SRM ever produced in the U.S., the large IUS motor (Orbus 21) with a nominal duration of 152 s. The small IUS motor (Orbus 6) incorporated the first production extendible exit cone (EEC), with two carbon–carbon cones nested around a fixed carbon–carbon exit cone. The two nested cones were extended and latched following separation from the large IUS motor stage, prior to small motor ignition. This packaging technique allowed an expansion ratio of 181:1 within the stage length limit. IUS motor nozzles also featured the first production use of three-directionally-reinforced (3D) carbon–carbon ITEs.

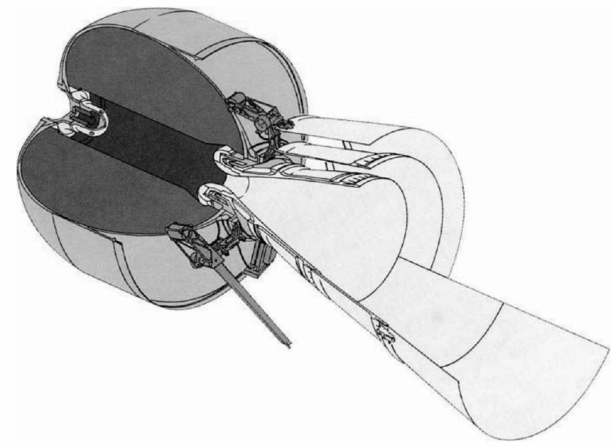


Fig. 14 The IUS length was limited to fit in the Space Shuttle payload bay. The extendible exit cone (EEC), shown both stowed and deployed on the IUS Orbus® 6 small motor, allowed extra payload within that constraint, deploying in space to increase expansion ratio from 49.1:1 to 181.1:1. (Pratt & Whitney Chemical Systems Division, Ref. 88)

EEC application to SRMs was apparently a spin off of earlier work on liquid rockets. Aerojet began IR&D work on elastomeric and metallic EECs in 1960, conducting a bi-propellant engine test. Subsequent work and tests included a refractory metal cone, convoluted into a cylinder, tested attached to the exit cone of a BATES-type motor. A scale-up test of the same concept by Aerojet on a Skybolt motor followed in 1967. In the early 1970s Bell Aerospace developed and demonstrated metallic rolling diaphragm and gas-deployed skirt concepts.[124]

Carbon-carbon materials were applied to the EEC concept, and, under AFRPL funding, Hercules, and CSD demonstrated carbon–carbon nested cone EEC systems during the 1977–1978 period. Thiokol tested a phenolic nested-cone EEC in 1977.[125] As noted earlier, the carbon–carbon nested-cone EEC was the first used in a production SRM, the IUS small motor (see Fig. 14). Nested-cone EECs were later employed in production on Peacekeeper second and third stage motors. The Peacekeeper second stage nested cones were of carbon-phenolic construction, whereas the third stage nested cones (like IUS) are of C-C construction. Many other EEC concepts were evaluated, developed and tested, but only the nested-cone system has gone forward into production systems.

8) Air-Launched Missile Technology

Sidewinder

The development of jet aircraft in the 1940s prompted innovative weapons design, including the need for guided, highly-maneuverable air-launched missiles. It was with this challenge that William B. McLean and a visionary team at NOTS conceived the design concept that would place the fire control system in the missile instead of the aircraft.[4,8] The result was the infrared-seeking Sidewinder missile. With various configurations and modifications, the 5-in. (127-mm) diam Sidewinder has been used for short-range air-to-air protection by the U.S. since 1956.[126] An interesting aspect of this family of missiles is the basic name remained unchanged, whereas the propulsion and other missile characteristics were modernized to "maintain the winning edge." As the next few paragraphs reveal, these systems evolved and remained operational with a mix of old and new propulsion components. Re-competing the propulsion contracts over several decades led to reduced cost and improved performance. The NOTS team overcame a series of technical and bureaucratic challenges during development and succeeded in producing this first guided missile used successfully in air-to-air combat. The first Sidewinder, designated AAM-N-7 for the Navy and the GAR-8 for the Air Force (later AIM-9), included many innovative features. A compact gas generator containing N-8 double-base propellant provided energy for control surface actuation and electrical components. The Sidewinder 1A contained a 43-lbm (19.5-kg) extruded grain of N-4 double-base propellant in an internal-burning, 8-point star configuration and an aluminum motor case. Other outwardly-distinguishing features of Sidewinder include the double-delta canards used to steer the missile and wing rollerons that control the roll rate during flight.

As the Sidewinder evolved, efforts to make it more effective led to a higher-energy rocket motor. The new cast propellants of the late 1950s and 1960s made it possible to greatly increase the energy in the same motor envelope. The redesigned Sidewinder 1C (AIM-9C) used a high-strength steel motor tube and a new nozzle designed to withstand the higher-temperature exhaust gases. The first Sidewinder 1C motors were loaded at B. F. Goodrich and at NOTS with C-509 PBAA composite propellant. The Rocketdyne solid rocket plant at McGregor, Texas (acquired by Hercules in 1978) assumed production in the mid 1960s and loaded motors with its signature Flexadyne® carboxyl-terminated polybutadiene (CTPB) propellant. Bermite Powder Company in California and the Naval Ordnance Station, Indian Head, Maryland also produced the "smoky" motor, as did Norway's Raufoss Ammunisjonsfabrikker (currently Nammo Raufoss AS) for the NATO countries.

The present reduced-smoke HTPB propellant used in the Sidewinder Mk 36 Mod 9 and Mod 11 motors was developed to reduce the vulnerability of the attacking aircraft to retaliatory fire. In the late 1970s, Thiokol Huntsville initially qualified the reduced-smoke Mk 36 motor, while Hercules ABL qualified the SR116 version with its own reduced-smoke propellant, both as part of AFRPL programs managed by Peter Huisveld and Lee G. Meyer. Hercules McGregor was also established as a second production source for the Mk 36 motor. Following the closings of the Huntsville and McGregor solid rocket plants in the 1990s, Atlantic Research and ABL produced the Mk 36 Mod 11 Sidewinder and the Mk 112 motor for the Rolling Airframe Missile (RAM), a ship-launched version of Sidewinder. In 1999, ATK completed the engineering and manufacturing development (EMD) of a jet vane thrust vector control system to further improve the maneuverability of the latest version of Sidewinder, the AIM-9X.

Sparrow

The 8-in. (203-mm) Sparrow is a medium-range air-to-air missile that was designed to neutralize high-performance enemy aircraft by radar-guided interception. Like Sidewinder, the Sparrow missile has a long history of design iterations and modifications. Among the rocket motors produced for Sparrow propulsion are the Hercules McGregor Mk 38, the Aerojet Mk 52, and the prolific Mk 58 produced by Hercules and ATK/ABL for the air-launched AIM-7 and the RIM-7 Sea Sparrow variant. The Mk 58 Sparrow rocket motor is a dual-grain, dual-thrust design that contains aluminized CTPB propellant and has been in production since 1969. It was among the first tactical motors to tailor the thrust profile using post-cure-machined radial slots.

AMRAAM

The AIM-120 Advanced Medium Range Air-to-Air Missile (AMRAAM) was designed as a successor to Sparrow and represents the beyond-visual-range, fire-and-forget, multiple launch capability for the U.S. and NATO countries. Hercules McGregor originally developed and qualified a radially-slotted, reduced-smoke boost-sustain grain in the late 1980s, while Aerojet qualified and produced a dual-grain motor. In 1995, ATK moved production of AMRAAM from McGregor to ABL, which became the sole producer after 2000. ATK currently produces the baseline rocket motor and an enhanced all-boost design that delivers a 13% increase in performance within the same missile envelope.

Falcon

The development of another early air-to-air solid propellant missile, Falcon, served to advance and mature the case-bonding process that subsequently became common practice in the industry. With initial development beginning in 1949, the reliable Falcon went on to become one of the longest tactical missile programs in Air Force history until its succession by the AGM-65 Maverick in the 1970s. The Falcon contained a Thiokol polysulfide composite propellant and was the company's first production rocket motor. The Falcon went through many modifications and improvements, and was in production at three different Thiokol locations: Huntsville, Elkton, and Longhorn. As of 1959, the M58 Falcon polysulfide motors had achieved a wider operating-temperature range [−65 to 165°F (−54 to 74°C)] than any other tactical weapon system of its day, and field-stored units demonstrated satisfactory performance over 22 years after manufacture.[7]

SRAM

While simplicity, reliability, and storability have made solid rocket motors the propulsion system of choice for tactical missile systems, thrust-magnitude control has been an issue. Once a solid grain is ignited, combustion typically continues uninterrupted until the propellant is expended. In the early 1960s, the Air Force and Navy desire to establish controllability in solid rocket motors led to a series of solid propellant pulse motor programs at ARC, Aerojet, and Lockheed Propulsion Company. These early demonstration programs soon led to the development of the propulsion system for the Air Force's AGM-69A Short Range Attack Missile (SRAM). SRAM was the first pulse motor to be developed, qualified, and placed into service.

Under contract to Boeing, Lockheed Propulsion began the formal development of SRAM in 1966. The SRAM's unique two-pulse end-burning grain configuration permitted a pre-planned delay between thrust pulses to provide a degree of performance control and mission flexibility. The high burning rate required of the end-burning configuration was obtained by the use of ultra-fine ammonium perchlorate (UFAP) and the liquid burning rate modifier alkyl ferrocene. A greater operating pressure than was state-of the-art at that time was required to meet performance requirements.

The challenges presented to the Lockheed Propulsion Company by the high operating pressure were substantial, particularly in the areas of nozzle design and pressure equalization along the length of the motor. To ensure adequate flow area, three pressure-differential spacers containing multiple-rectangular-flow channels were installed along the length of the inner case wall of each motor.[127] The manufacturing process for the SRAM motor was labor intensive.

Development of the 17.7-in. (450-mm) diam, 168-in. (4.267-m) long SRAM rocket motor by the Lockheed Propulsion Company was extremely challenging. Qualification of SRAM was accomplished in 1971 and a single production run of 1,500 missiles was produced by 1975. The AGM-69A SRAM remained on ground alert status until 1990 and entered initial phase-out from the DoD inventory in 1995.

9) Mastery of Hazards

SOPHY

As the prospect of building and flying large solid rocket boosters (e.g., the 120-in. (3.05-m) diam Titan III segmented strap-ons and the 260-in. (6.6-m) space booster) emerged in the 1960s, the explosive hazards of such large boosters was an issue. The magnitude of hazards associated with potential mishaps during handling, transportation, storage, or launch had to quantified. The central issue was to determine the critical diameter and explosive yield of these relatively benign ammonium perchlorate, polybutadiene-acrylic-acid-acrylonitrile (PBAN) binder, and aluminum propellants as the motors grew to unprecedented sizes. The crude shock-hydrodynamic codes of the day suggested the critical diameter to sustain a detonation would be between 60 in. (1.5 m) and 96 in. (2.4 m). In order to test and calibrate the models, the Air Force funded what became a classic landmark series of tests under project SOPHY,[128] the Solid Propellant Hazards Program. The program was conducted by Aerojet-General Corporation at the AFRPL 1-36D Hazard Test Area, which is sited for a million pound (454,000 kg) TNT detonation. The tests involved a number of right-circular cylinders of propellant. Test of these cylinders, initiated by an on-top cone of TNT with a base the same diameter as the propellant specimen, was quite spectacular. By systematic testing the critical diameter was determined to be between 60 in. (1.5 m) and 72 in. (1.8 m). One cylinder that detonated was an unconfined specimen 6-ft (1.5-m) in diameter, 24-ft (7.3-m) in length, and 74,000 lbm (34,000 kg) mass. It was capped by an initiation cone of TNT with a mass of 18,000 pounds (8164 kg). The steel witness plate under the specimen was 6 in. (152 mm) thick and 10 ft (3.05 m) square with a mass of 24,000 lbm (11,000 kg). The witness plate was shattered and a crater 32 ft (9.8 m) in diameter and 10-ft (3.05-m) deep was produced. These tests led to the refinement of the shock-hydrodynamic codes and provided the U.S. with the ability to reliably estimate the hazards of future generations of solid propellants. To this day, the SOPHY program and results are revered by the worldwide explosive safety community and have served as the basis for launch and range safety evaluations of solid rocket motors of all types.

DDT, IM, and ESD

In the 1970s, the U.S. was the first to introduce advanced cross-linked double base (XLDB) propellants in solid rocket motors, however a number of motor hazards and detonation issues ensued. On 5 May 1974 a large DoT-ICC/Military Explosives Hazard Class 1.1 rocket motor experienced a case failure about 20 s into a planned 60 s test and transitioned to a detonation. As a result, the Navy SSPO formed a unique team, drawing from U.S. propulsion and explosives communities, to learn each other's technologies and terminology to eventually resolve the problem. This large DoD-DoT/contractor team required over three years to understand what had happened and additional time to fully appreciate and master the design and material nuances required to harness these high-performance propellants. This effort enabled the industry to build the Trident, Peacekeeper and Small ICBM missiles with unprecedented performance capability. The mastery of this technology truly enabled the move to the next generation of solid rocket motors. This collaboration between shock hydrodynamicists from the weapons community and propulsion engineers was a key enabling step for the future generations of high-performance motors, and has become a unique, unequalled asset to the U.S. solid rocket program. These efforts involved the understanding and development of tests and analyses for Deflagration-to-Detonation Transition (DDT), Shock-to-Detonation Transition (SDT), and motor implosion.[129–131] Key participants in these efforts included John F. Kincaid and Henry M. Shuey, consultants; Sig J. Jacobs and Donna Price of the Naval Surface Weapons Center; Robert L Geisler of AFRPL; Thomas L. Boggs of NAWC; Edward Lee of Lawrence Livermore National Laboratory; R. Craig of Los Alamos National Laboratory; Leroy Throckmorton of Navy SSPO; and McKay Anderson, James H. Thacher, and Gary Muir of Hercules, Inc.

Another serious hazards problem became evident with a severe 1985 accident during the assembly of a Pershing II missile. An SRM was being separated from its container when, without apparent reason, autoignition happened inside the propellant grain. The accidental ignition was related to an internal electric field buildup inside the propellant grain in an electrically-insulating Kevlar case. William D. Stephens of the Army MICOM led a national effort, which traced the problem to a unique ESD hazard regarding the use of HTPB propellants in Kevlar-case motors.[2] The French propulsion community had earlier encountered this problem and provided great insight into the mechanism and solution to the problem.[132] The solution involved the recognition that HTPB propellants are less tolerant of ESD than earlier propellants that are also rubber based, and must be formulated with more care to limit their sensitivity. This understanding, combined with rigorous grounding of non-conductive casting tooling and non-conductive cases such as Kevlar, solved the problem. This problem became less severe when Kevlar cases were replaced with the more conductive graphite-epoxy cases in later motors. The companion Davenas article[2] in this issue further explains this Pershing II ESD problem, how it was conquered, and a myriad of efforts in the tactical motor arena to achieve Insensitive Munitions (IM) goals to facilitate safe transportation and storage of tactical rounds.

The primary hazards issue for tactical solid rocket motors in recent years has been that of developing Insensitive Munitions. The focus of this technology is to develop motors that do not explode violently or become propulsive when encountering fire or impact of a bullet or fragment.[133] A large impetus for this area has been the safety of motors during storage in the field, particularly on aircraft carriers and in magazines. Leading authorities in this field include Alice I. Atwood of NAWC, China Lake, California and the late Benjamin (Bo) B. Stokes[134] of Thiokol Huntsville and later, NATO's NIMIC.[135]

One of the most important tests for guiding the work of the propellant chemists in developing advanced nitramine propellants was the "Shotgun" test. This test, as discussed by Davenas,[2] measures the relative friability of the propellant under high-rate shear to judge its toughness and resistance to DDT. A 10-in. (254-mm) diam and several foot-long (over a meter) sample was required at $10,000 per test. When Robert L. Geisler was asked his opinion of the test by Admiral Levering Smith, Geisler suggested the rocket community would not routinely use such a test unless it could be done for less than $125. Several months later Hercules presented the shotgun test. This test uses a few grams of propellant fired against a steel plate; the resulting pieces of fractured propellant are subjected to a test similar to the classic gunpowder relative quickness test. The acceptance criteria are based on such observable data as the pressure rise rate, which is an indirect measure of the fracture propellant's surface area. Admiral Smith was quick to seek out Geisler and remark, "Is this one cheap enough for you?" This inexpensive test became a standard for the industry.

10) Small Tactical Motor Technology

Advancements such as case-bonded grains, composite cases, and refractory nozzle materials enabled many innovations in man-portable and small propulsion systems. However, progress was slow. For example, the venerable M28 Super Bazooka for WW-II used 16 sticks of NC/NG propellant trapped in the chamber by a perforated steel plate. Its performance robbers include propellant loss through perforations, heating of metal parts, and inert component mass. Nevertheless, well into the 1980s new designs still used variants of this NC/NG stick propellant propulsion. Developing high-burning-rate composite propellants capable of configurations that can withstand launch loads is a continuing challenge. Indeed, several promising systems quietly faded away after years of development, e.g., Viper.

In some systems, e.g., the M-72 LAW, the motor burns out before leaving the tube. However, most modern tube-launched small tactical systems use two propulsion stages and share several constraints. A launch motor is used to eject the flight motor and warhead from a meter-long tube in less than 0.02 s. The flight motor must have sufficient velocity (and, in some cases, spin) to insure an accurate trajectory. In other cases, the launch motor is packaged as an integral part of the flight motor. The primary propulsion is the flight motor, which ignites at a safe distance from the launcher and typically burns for a few seconds. The launch motor must burn out in ~0.1 s to avoid blasting the operator. Burnout must occur in the tube even at the lowest ambient temperature, e.g., −43°C (−45°F) while not over-pressurizing components at the highest ambient temperature, e.g., 43°C (145°F). To achieve the short action time, these systems often operate in the 20 to greater than 30 MPa (30 to greater than 45 kpsi) range. An additional constraint is avoiding noise spikes that damage hearing. Modern composite materials have reduced the mass of tube-launched systems, but moving beyond the low-flash and low-smoke NC/NG stick propellants for short-action-time propulsion for systems (such as TOW) is still a work in progress.

One of the minimum smoke flight propulsion variants for the Army's Hellfire system is shown in Fig. 15. The ATK/ABL[136] rod-in-tube grain design, developed and qualified in the late 1980s, is

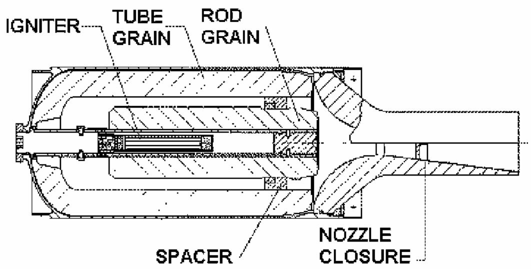


Fig. 15 A variant of the Hellfire flight propulsion system. The motor is 590-mm long with a 178-mm diam and uses a cross-linked double-base propellant in a case-bonded grain. (ATK web site, Ref. 136.)

an intrinsically simple way of achieving high burning surface area, thin web, and sharp tail-off.

1990–2003: New Needs, New Developments

From 1976 to 1989, attention was focused on the development and fielding of the new generation of land- and sea-based ballistic missiles and the advanced EELV strap-on space boosters. The systems include Pershing II, Peacekeeper, Trident I/II (C4/D5), SICBM, Titan-IV SRMU, and the first Delta GEM motors.

On 6 July 1989, the 169th and last Pershing 1A intermediate-range ballistic missile was destroyed at the Longhorn Army Ammunition Plant near Karnack, Texas, under the Intermediate Nuclear Forces treaty. Systems labored over were being deliberately destroyed! Hard to watch, but good news for the SRM industry since fewer motors would be available for "cheap launches."

At the end of the 1980s tremendous changes appeared in the world landscape following the disappearance of the Soviet Union. Defense strategies and systems appropriate to the new era are still being redefined. Another important factor of change was the development of a national and international conscience on issues like the environment, hazards, the use of technology for the welfare of humanity, and the nature of the industry in general.

The process of adapting what was learned on defense systems to commercial applications is continuous. As an example, the Orbital Sciences Corporation (OSC) Pegasus® air-launched space booster uses three stages (1.22-m diam) that evolved from Hercules Small ICBM designs. Using internal funding, Hercules and OSC made several cost-saving modifications, e.g., replaced the DoT-ICC/Military Explosives Hazard Class 1.1 propellant with a non-detonable Class 1.3 propellant and removed the TVC from the lower stages. The resulting commercial derivatives used for Pegasus are known as the Orion® series of motors. The Pegasus first flew in 1992. Discussions of the Pegasus stages are in the paper[137] describing Taurus. Taurus is essentially Pegasus ground boosted by a Thiokol TU-93 (Peacekeeper first stage), yet another defense-to-commercial adaptation.

Insensitive Munitions (IM)

The elimination of accidents and hazards associated with rocketry has always been a major consideration in the U.S. However, in the 1960s only minor modifications were made because of the demand for greater performance. More frequent problems occurred as the demands for performance increased, e.g., lighter delivery platforms and launch systems reduced the protection afforded by the platforms to weapons systems. In the late 1970s, DoD and DoE formed an interagency Group on Insensitive Explosives, which met at Los Alamos National Laboratory. Their report led to the term insensitive munitions (IM) becoming more central to the rocketry lexicon and an IM specification for new solid rockets. At first, IM meant giving up performance, a notion alien to those pursuing higher performance. During the 1980s, Ronald L. Derr and his U.K. and French counterparts led a multi-nation process of achieving greater safety through innovation applied to missile configuration and propellant formulations. This process ameliorated some of the dreaded performance losses. In 1991, the partnerships formed during this period led to the NIMIC.

One of the challenges in putting insensitive munitions (IM) requirements into proper perspective is design criteria. The essential selection criteria is the ability of a company to balance safety (including IM) with achieving goals for performance and life-cycle cost in a very competitive industry. Some of the gains are enabled through clever use of new composite materials and no loss in performance; for example novel composite cases designed[138] to lose structural capability before reaching 200°C (392°F), too low to ignite the propellant. IM requirements are not universally agreed to. For example, even within the U.S., IM requirements and specifications are viewed very differently by the Army, Navy, and Air Force. Even within the Navy, the importance of IM varies among the several Navy centers.

The strongest advocate of IM as a primary design criterion is the leadership at NAWC. The NAWC focus stems from the incidents on the flight decks of aircraft carriers several years ago. In the late 1980s, the Army and Air Force position on IM began to moderate and diverge from the Navy and, in particular, the emphasis of NAWC. For example, Air Force propulsion experts also emphasize safety, but are less likely to accept safety as a reason to reduce overall system performance.

Over the last twenty years, important and practical means have been achieved to improve IM and safety. Many rocket motor team leaders make the distinction between IM and safety and consider IM as part of the broader approach to safety. Under this type of interpretation, the specifications from the NIMIC are modified to achieve more pragmatic specifications for IM testing and qualification. For example, many propulsion engineers consider it more important for safety to have the propellant tailored to a low cook-off temperature, than to have motors cases that, when exposed to serious fires, weaken in hoop-stress capability (or even split open) to prevent explosion.

Controllable Solid Rockets

Over the decades attention several promising techniques for throttling solid rockets were demonstrated. To some extent this was to counter the claims that liquids could be throttled and solids could not be. The primary motivation was to improve on the impulse management achieved by grain designs. The leading contenders are the variants of the pintle nozzle, but trade studies were seldom favorable to the higher mass and cost of this system. However, interest and static tests continue.[139] Recently, a convincing flight validation using an Aerojet pintle nozzle that operated for 50 s was accomplished.[140]

Missile Defense Propulsion

The missile defense requirements for new systems will continue to drive advanced boosters and DACS propulsion systems. This underscores the need for continual advancement of affordable, controllable motors and low-mass inert parts as well as higher-performance propellants.

Projection

Other authors have analyzed, projected, and commented on the future of SRMs. In particular, an International Astronautical Federation paper[141] in 2000 summarized the findings of several international working sessions on space propulsion. They beckon another wave of enablers to achieve the performance gains attendant to higher chamber pressure, lower mass thermal insulation, lower cost nozzles, etc. The payoffs described warrant continued large investments in SRM R&D. International space exploration will continue to nurture innovation for such SRM functions as deceleration, soft landing, and gas actuation. The military applications will sustain the drive for new technology to enable even higher performance, agility, and robustness, i.e., the winning edge. Aspirations to improve SRM capabilities are shared by an increasing number of countries.

Conclusion

Modern solid rocket motors have a rich, colorful, and instructive legacy. The solid rocket industry's rapid pace and many trials by fire fostered its amazing problem-solving capability. Readers desiring to dig deeper into the personalities and traits of the pioneers, do well by starting with all of the 1950s issues of the American Rocket Society

Journals. Subscribers to those professional and well-edited journals received bonuses. They were never far from practical topics and industry tempo since the journal included hardware and employment ads, patent summaries, technical report synopses, book reviews, etc. In those issues, important history is waiting to be rediscovered, as in the case of Geoffrey Robillard in Ref. 28 relating the series of innovations leading to qualifying the solid rocket stages to propel Explorer 1. The company and laboratory histories include unexpected disclosures. Reference 10, written by Aerojet retirees—free of corporate constraints, proudly report new aspects of their accomplishments. As an example of a "I didn't know that," Charlie Thies in Ref. 16 divulges why 3000 kg of R&H propellant, loaded in a Nike-Zeus second stage, exploded after 70 ms giving Huntsvillians anecdotes and recriminations since 1959.

This paper has focused on ten enabling technologies or technological areas deemed by the authors to have made the most significant impact on the U.S. modern solid rocket program. The story of the achievements of this vibrant community is the efforts of organizations, teams, and individuals as well as advancements in materials and analytical capability. The effort has been driven by critical national needs and the contributors undertook the effort with a sense of purpose and dedication consistent with the urgency and importance. The effort could not have been accomplished as well without the contributions of several government labs and universities as well as the industrial propulsion community. Of key importance has been the broad U.S. industrial base in petrochemicals and materials. The story of solid rockets is one of creating and harnessing 3600–4100 K corrosive exhaust products for up to two minutes at pressures exceeding 7 MPa (∼1000 psi) in structures that are incredibly light in weight, having minimal margins of safety in order to maximize performance. These difficult achievements have also included the vectoring of the exhaust and the ability to precisely predict the myriad of details involved in the process of solid rocket operation, which even extend to a precise estimate of the observable properties of the exhaust plume. Furthermore, the solid rocket community learned how to integrate its technology with liquid and air-breathing propulsion systems to best achieve the overall goals of the systems designers.

Given these achievements, it has now become routine to rapidly and economically develop and field new weapons and space boosters as the needs arise. If the past is prologue, then the solid rocket industry will fulfill future propulsion needs with even higher-performing materials, concepts, and designs.

Acknowledgments

Firstly, the authors acknowledge all those worthy people and contributions not cited because of space limitations. This paper benefits from the experience of the authors while working at various organizations. LHC worked at ATK/Thiokol's Huntsville Division, Princeton University Guggenheim Laboratories, and the Air Force Office of Scientific Research. RLG spent 40 years at the AF Rocket Propulsion Laboratory at Edwards AFB. RAE worked for Pratt & Whitney Chemical Systems Division and ATK/Thiokol's Wasatch Division. TLM worked at ATK's Allegany Ballistics Laboratory before joining CPIA. The authors gratefully acknowledge William L. Hufferd's contributions to the discussions of structural analysis and mechanical properties. David K. McGrath's (ATK/Elkton) replies to specific questions and research on historical precedent of over a dozen issues are especially appreciated. The authors acknowledge the AIAA Solid Rockets Technical Committee for their generous logistical support during the preparation of this article. Finally, the authors appreciate the help of colleagues at the propulsion companies and the DoD laboratories in fielding questions and commenting on the manuscript.

References

[1]Morey, L. E., *The Powder Rockets*, Sunflower Univ. Press, Manhattan, KS, 1982.

[2]Davenas, A., "The Development of Modern Solid Propellants," *Journal of Propulsion and Power*, Vol. 19, No. 6, 2003, pp. 1108–1128.

[3]Malina, F. J., "Origins and First Decade of the Jet Propulsion Laboratory," *The History of Rocket Technology*, edited by Eugene M. Emme, Wayne State Univ. Press, Detroit, MI, 1964, pp. 46–66.

[4]Christman, A. B., *Sailors, Scientists, and Rockets*, Volume 1 of the history of the Navy at China Lake, by Washington, DC, Naval History Division, 1971.; also Gerrard-Gough, J. D. and Christman, A. B. *The Grand Experiment at Inyokern*, Vol. 2 of the History of the Navy at China Lake, Washington, DC, Naval History Division, 1978; also, Babcock, B., *Magnificent Mavericks: Evolution of the Naval Ordnance Test Station from Rockets to Guided Missiles and Underwater Ordnance (Time span: 1948 to 1958)*, Vol. 3, (to be published).

[5]Malina, F. J., "A Short History of Rocket Propulsion up to 1945," *Jet Propulsion Engines*, edited by Lancaster, O. E., Vol. XII, High Speed Aerodynamics and Jet Propulsion, Princeton Univ. Press, Princeton, NJ, 1959, Section A, pp. 3–19.

[6]Price, E. W., "History of Solid Rocket Motors (1940–1960)," AIAA Paper 1998-3978, July 1998.

[7]Sutton, E. S., "From Polymers to Propellants to Rockets, a History of Thiokol," AIAA Paper 99-2929, June 1999.

[8]Robbins, J. M., and Feist, R. W., "The China Lake Propulsion Laboratories," AIAA Paper 92-3612, July 1992.

[9]Umholtz, P. D., "The History of Solid Rocket Propulsion and Aerojet," AIAA Paper 1999-2927, June 1999.

[10]Aerojet History Group, *Aerojet: The Creative Company*, Stuart F Cooper Company, Los Angeles, CA, 1995.

[11]Dyer, D., and Sicilia, D. B., *Labors of a Modern Hercules, The Evolution of a Chemical Company*, Harvard Business School Press, Boston, MA, 1990.

[12]Thacher, J. H., and Wetherell, R. B., "Solid Rocket History at Hercules," AIAA Paper 91-2188, June 1991.

[13]Reily, P. K., *The Rocket Scientists, A History of Achievements at ARC*, Vantage Press, New York, 1999.

[14]Sparks, J. F., and Friedlander, M. P. III, "Fifty Years of Solid Propellant Technical Achievements at Atlantic Research Corporation," AIAA Paper 99-2932, June 1999.

[15]Bartley, C. E., and Bramscher, R. G., "Grand Central Rocket Company," *History of Rocketry and Astronautics*, AAS History Series, Volume 23 (IAA History Symposia, Volume 15), edited by D. C. Elder and C. Rothmund, Univelt Inc., San Diego, CA, 2001, pp. 267–277.

[16]Thies, C. E., "A Personal History of the Rohm and Haas Company's Redstone Research Laboratories at Redstone Arsenal, AL," AIAA Paper 96-3149, July 1996.

[17]Hunley, J. D., "The History of Solid Propellant Rocketry: What we do and what we do not know," AIAA Paper 1999-2955, June 1999.

[18]Neal, R., *Ace in the Hole*, Doubleday & Company, Inc., Garden City, NY, 1962.

[19]Neal, R., "The Minuteman," *Rocket and Missile Technology*, edited by Gene Gurney, Franklin Watts, Inc., New York, 1964.

[20]Dailey, C. L., and Wood, F. C., *Computation Curves for Compressible Fluid Problems*, Wiley, New York, 1949.

[21]*Jet Propulsion Engines*, edited by Lancaster, O. E., Vol. 12, High Speed Aerodynamics and Jet Propulsion, Princeton Univ. Press, Princeton, NJ, 1959.

[22]Huggett, C., Bartley, C. E., and Mills, M. M., *Solid Propellant Rockets*, Princeton Univ. Press, Princeton, NJ, 1960, (Section H from Ref. 21).

[23]Sutton, G. P., *Rocket Propulsion Elements*, John Wiley and Sons, New York, 1949; also 2nd ed., 1956.

[24]Penner, S. S., *Chemistry Problems in Jet Propulsion,* Pergamon Press, New York, 1957.

[25]Barrère, M., Janmotte, A., de Veubeke, B. F., and Vandenkerckhove, J., *Rocket Propulsion*, Elsevier Publishing Company, Amsterdam, Netherlands, 1960.

[26]Shapiro, A. H., The Dynamics and Thermodynamics of Compressible Fluid Flow, Vol. 1, Ronald Press, New York, 1953.

[27]Summerfield, M. (Ed.), *Progress in Astronautics and Rocketry*, Vol. 1: *Solid Propellant Rocket Research*, Academic Press, New York, 1960.

[28]Robillard, G., "Explorer Rocket Research Program," *ARS Journal*, Vol. 29, No. 7, July 1959, pp. 492–499; also, Stewart, H. J., Small, J. G., and Robillard, G., *The Explorer Rocket System*, Publication No. 129, Contract DA-04-495-Ord 18, Jet Propulsion Laboratory, California Inst. of Technology, CA, May 1958.

[29]Bartz, D. R., "A Simple Equation for Rapid Estimation of Rocket Nozzle Convective Heat Transfer Coefficients," *Jet Propulsion*, Vol. 27, No. 1, 1957, pp. 49–51.

[30]Green, L., "Erosive Burning of Some Composite Propellants," *Jet Propulsion*, Vol. 24, No. 1, Jan. 1954, pp. 9–15.

[31]Geckler, R. D., and Sprenger, D. F., "The Correlation of Interior Ballistic Data for Solid Propellants," *Jet Propulsion*, Vol. 24, No. 1, Jan.–Feb., 1954, pp. 22–26.

[32]Geckler, R. D., "Thermal Stresses in Solid-Propellant Grains," *Jet Propulsion*, Vol. 26, No. 2, Feb. 1956, pp. 93–98.

[33]Anderson, W. H, and Chaiken, R. F., "Detonability of Solid Composite Propellants," *ARS Journal*, Vol. 31, No. 10, Oct. 1961, pp. 1379–1387.

[34]Barrett, D. H., "Solid Rocket Motor Igniters," NASA Space Vehicle Design Criteria (Chemical Propulsion), NASA SP-8051, March 1971, pp. 31–32.

[35]Price, E. W., "One-Dimensional, Steady Flow with Mass Addition and the Effect of Combustion Chamber Flow on Rocket Thrust," *Jet Propulsion*, Feb. 1955, Vol. 25, No. 2, pp. 61–68.

[36]Graves, A., "Improved Safety Through the Use of Exploding Bridgewire Ordnance Devices, *Proceedings of Fifth Explosives Safety Seminar*, AD 346-196, Santa Monica, CA, 20 Aug. 1963, pp. 258–272.

[37]Landsbaum, E. M., "Thrust of a Conical Nozzle," *ARS Journal*, Vol. 29, No. 3, March. 1959, p. 212.

[38]Landsbaum, E. M., "Analysis of Ballistic Anomalies in Solid Rocket Motors," *Journal Propulsion and Power*, Vol. 7, No. 6, Nov.–Dec. 1991, pp. 887–893.

[39]Landsbaum, E. M., "Erosive Burning Revisited," AIAA Paper 2003-4805, July 2003.

[40]Hart, R. W., and McClure, F. T., "Combustion Instability: Acoustic Interaction with a Burning Propellant Surface," *Journal of Chemical Physics*, Vol. 30, No. 6, 1959, pp. 1501–1514.

[41]McClure, F. T., Angelus, T. A., Berl, W. G., Green, L., Hart, R. W., Landsbaum, E. M. W., Price, E. W., Shuey, H. M., and Summerfield, M., "First Report of the Working Group on Solid Propellant Combustion Instability," Applied Physics Lab., The Johns Hopkins Univ., TG 371-1, July 1960.

[42]Moore, T. L., "Solid Rocket Development at Allegany Ballistics Laboratory," AIAA Paper 99-2931, June 1999.

[43]Rumbel, K. E., and Cohen, M., "Propellant Grains," U.S. Patent 3,109,374, Nov. 1963; also, Rumbel, K. E., and Scurlock, A. C., "Propellant Grains," U.S. Patent 3,109,375, Nov. 1963; also, Rumbel, K. E., Cohen, M., Nugent, R. G., and Scurlock, A. C., "Propellant Grains," U.S. Patent 3,116,692, Jan. 1964.

[44]Baumgartner, W. E., "Combustion of Thermogens in Solid Propellants," First AIAA/ICRPG Solid Propulsion Conf., Washington, DC, July 1966.

[45]Waesche, R. H. W., "Comments on a 'Ballistic Bomb Method for Determining the Experimental Performance of Rocket Propellants,'" *ARS Journal*, Vol. 29, No. 5, May 1959, p. 375.

[46]Cockrell, B. L., "Ballistic Evaluation of Propellants in Micro-motors," Rohm and Haas, Technical Report No. S-49, Huntsville, AL, Oct. 1964.

[47]AIAA Solid Rocket Technical Committee, *Proceedings of Workshop on University Programs in Solid Rocket Propulsion*, AIAA 38th Aerospace Sciences Meeting, Reno, NV, Jan. 2000.

[48]Lt. Gen. Wilson's letter from the personal files of Robert L. Geisler.

[49]Colonel McKee's letter from the personal files of Robert L. Geisler, dated 4 March 1959.

[50]Personal communication from Donald M. Ross to Robert L. Geisler upon the occasion of Col. Robbins death, 24 Dec. 2001.

[51]Wimpress, R. N., and Sage, B. H., *Internal Ballistics of Solid Fuel Rockets—Military Rockets Using Dry-processed Double-base Propellant as Fuel*, McGraw–Hill, New York, 1950.

[52]Price, E. W., Horine, C. L., and Snyder, C. W., "Eaton Canyon: A History of Rocket Motor Research and Development in the Caltech-NDRC-Navy Rocket Program, 1941-1946," AIAA Paper 98-3977, July 1998.

[53]Gilbert, M., Allport, J., and Dunlap, R., "Dynamics of Two-Phase Flow in Rocket Nozzles," *ARS Journal*, Vol. 32, No. 12, 1962, pp. 1929–1930.

[54]Crowe, C. T., Babcock, W. R., and Willoughby, P. G., "Drag Coefficient for Particles in Rarefied, Low-Mach No. Flows," *Proceedings International Symposium on Two Phase Systems*, 1971.

[55]Crowe, C. T., Nicholls, J. A., Morrison, R. B., "Drag Coefficients of Inert and Burning Particles Accelerating in Gas Streams," *Ninth (International) Symposium on Combustion*, Academic Press, 1963, p. 395.

[56]Hermsen, R. W., Dunlap, R., "Nucleation and Growth of Oxide Particles in Metal Vapor Flames," *Combustion and Flame*, Vol. 13, No. 3, June 1969.

[57]Crowe, C. T., and Willoughby, P. G., "A Study of Particle Growth in a Rocket Nozzle," *AIAA Journal*, Vol. 5, No. 7, 1967, pp. 1300–1304.

[58]Dunlap, R., Blackner, A. M., Waugh, R. C., Brown, R. S., and Willoughby, P. G., "Internal Flow Field Studies in a Simulated Cylindrical Port Rocket Chamber," *Journal of Propulsion and Power*, Vol. 6, No. 6, 1990, pp. 690–704.

[59]McDonald, A. J., and Hedman, P. O., "Erosion of Graphite in Solid-Propellant Combustion Gases and Effects of Heat Transfer," *AIAA Journal*, Vol. 3, No. 7, July 1965, pp. 1250–1257.

[60]Delaney, L. J., Eagleton, L. C., Jones, W. H., "A Semi-quantitative Prediction of the Erosion of Graphite Nozzle Inserts", *AIAA Journal*, Vol. 2, No 8, Aug. 1964, pp. 1428–1433.

[61]Saderholm, C. A., "A Characterization of Erosive Burning for Composite H-Series Propellants," *Proceedings of AIAA Solid Rockets Conf.*, Jan. 1964.

[62]Baker, J. S., "Solid Rocket Motor Grain Configuration Development," AIAA Paper 78-986, July 1978.

[63]Sforzini, R. H., and Foster, W. A., Jr., "Monte Carlo Investigation of Thrust Imbalance of Solid Rocket Motor Pairs," *Journal of Spacecraft and Rockets*, Vol. 13, No. 4, 1976, pp. 198–202.

[64]Foster, W. A., Sforzini, B. W., and Shackleford, B. W., Jr., "Thrust Imbalance of the Space Shuttle Solid Rocket Motors," *Journal of Spacecraft and Rockets*, Vol. 19, No. 6. 1982, pp. 545–549.

[65]Billheimer, J. S., and Marshall, C. A., "Feasibility of Algorithmic Definition of Solid Propellant of Functional Design, AIAA Paper 69-432, June 1969.

[66]Browning, S. C., and Christensen, R. J., "A Multi-axial Failure Test Vehicle for Filament-wound Pressure Vessels," Hercules Inc., Bacchus Works, Magna, UT, Society for Experimental Stress Analysis, Spring Meeting, Dallas, TX, 15-20 May 1977.

[67]Ordahl D. D., and Williams, M. L., "Some Preliminary Photoelastic Design Data for Stress in Rocket Grains, *Jet Propulsion*, Vol. 27, No. 6, 1957, pp. 546–662.

[68]Williams, M. L., Landel, R. F., and Ferry, J. D., "The Temperature Dependence of Relaxation Mechanisms in Amorphous Polymers and Other Glassforming Liquids," *Journal of American Chemical Society*, Vol. 77, 1955, pp. 3701–3707.

[69]Muki, R., and Sternberg, E., "On Transient Thermal Stresses in Viscoelastic Materials with Temperature Dependent Properties," *Journal Applied Mechanics*, Vol. 28, No. 2, June 1961, pp. 193–207.

[70]Williams, M. L., "Structural Analysis of Viscoelastic Materials," *AIAA Journal*, Vol. 2, No. 5, May 1964, pp. 785–809.

[71]Andrepont, W. C., and Felix, R. M., "The History of Large Solid Rocket Motor Development in the United States," AIAA Paper 94-3057, June 1994.

[72]Herrmann, L. R., "Elasticity Equations for Incompressible and Nearly Incompressible Materials by a Variational Theorem," *AIAA Journal*, Vol. 3, No. 10, Oct. 1965, pp. 1896–1900.

[73]Dunham, R. S., and Nickell, R. E., "Finite Element Analysis of Axisymmetric Solids with Arbitrary Loading," Report 67-6, Univ. of California, Berkeley, CA, June 1967.

[74]Sackman, J. L., Taylor, R. L., and Murray, R. C., "Steady State Vibration of Orthotropic Linear Viscoelastic Solids," Mathematical Sciences Northwest Report No. 68-57-1, Part 2, Seattle, WA, 1968.

[75]Taylor, R. L., Pister, K. L., and Goudreau, G. L., "Thermomechanical Analysis of Viscoelastic Solids," Department of Civil Engineering Report No. 68-57-1, Univ. of California, Berkeley, CA, 1968.

[76]"Special Report: Filament Winding," *Missiles and Rockets, The Weekly of Space Systems Engineering*, 12 Aug. 1963, pp. 22–31.

[77]Bille, M., and Lishock, E., "NOTSNIK: The Secret Satellite," AIAA Paper 2002-0314, Jan. 2002.

[78]Scala, K. J., "Rocket's Red Glare," *Quest, The History of Spaceflight Magazine*, Vol. 3, No. 1, Spring 1994, pp. 58–61.

[79]Standard Missile-3, http://www.raytheon.com/products/standard_missile/ref_docs/standard_missile-3.pdf, Raytheon Company, Surface Navy Air Defense Systems, Tucson, AZ [cited 8 Sept. 2003].

[80]McGrath, D. K., "Thiokol Solid Rocket Motors on the Saturn V Launch Vehicle," AIAA Paper 96-3151, July 1996.

[81]McDowell, J., "Kick in the Apogee: 40 Years of Upper Stage Applications for Solid Rocket Motors, 1957–1997," AIAA Paper 97-3133, July 1997.

[82]Ellis, R. A., "Solid Rocket Motor Nozzles," NASA Space Vehicle Design Criteria (Chemical Propulsion), NASA SP-8115, June 1975.

[83]Kershner, R. B., "A New Method of Thrust Vector Control for Solid Rockets," JHU/APL, Laurel, MD, 9 Sep. 1958.

[84]Kershner, R. B., and Swain, F. H., "Jet Control by Rotatable Offset Nozzle," U.S. Patent No. 3,165,889, U.S. Patent Office, 19 Jan. 1965.

[85]Kennedy, W. S., Kovaciac, S. M., Rea, E. C., and Lin, T. C., "Solid Rocket Motor Development for Land-Based Intercontinental Ballistic Missiles," *Journal of Spacecraft and Rockets*, Vol. 36, No. 6, Dec. 1999, pp. 890–901.

[86]Herbert, J. T., Kovitch, F. J., and McCorkle, M., "Flexible Joint Means," U.S. Patent 3,390,899, 2 July 1966.

[87]Chase, C. A., (Editor) "Orbus Family of Space Propulsion Systems," (International Marketing Brochure), Pratt & Whitney Chemical Systems Division, San Jose, CA, 8 Sep. 2000.

[88]Chase, C. A., "Development Status of the Inertial Upper Stage Solid Motors—Chemical Systems Division," AIAA paper 80-1267, July 1980.

[89]DeGeorge, D., and Blair, M., "Overview of the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) Program," Second European Conf. on Launcher Technology: Space Solid Propulsion, Nov. 2000, Rome, Italy

[90]Launius, Roger D. and Jenkins, Dennis R., "To Reach the High Frontier: A History of U.S. Launch Vehicles," edited by Hunley, J. D., Chap. 6, *Minuteman and the Development of Solid-Rocket Launch Technology*, Univ. Press of Kentucky, KY, Nov. 2002.

[91]Carroll, P. T., "Historical Origins of the Sergeant Missile Powerplant," *History of Rocketry and Astronautics*, edited by Kristan R. Lattu and R. Cargill Hall, Univelt, Inc., San Diego, CA, 1989.
[92]Wiggins, J. W., "The Earliest Large Solid Rocket Motor—The Hermes," AIAA 9th Annual Meeting and Technical Display, Washington, DC, Jan. 1973.
[93]McDonald, A. J., "Fixing the Field Joint That Failed on the Challenger," *Journal of Propulsion and Power*, Vol. 7, No. 2, 1991, pp. 130–138.
[94]Moore, T. L., "Evolution of Intermediate Solid Boost Propulsion in the United States," Second European Conf. on Launcher Technology: Space Solid Propulsion, Rome, Italy, Nov. 2000.
[95]Klager, K., "Segmented Rocket Demonstration Historical Development Prior to their Use as Space Boosters," IAA 91-687, 42nd IAF Congress, Oct. 1991.
[96]McGrath, D., "Thiokol's 'BIG BOOSTER' Work at the Georgia Division During the 1960s," AIAA Paper 95-3131, July 1995.
[97]Crimmins, P., Cousineau, M., Rogers, C., and Shell, V., "The 260—The Largest Solid Rocket Motor Ever Tested—Gencorp Aerojet," AIAA Paper 2000-3690, July 2000.
[98]Morgan, M., and Berhow, M., *Rings of Supersonic Steel-Air Defenses of the United States Army 1950-1979*, The Fort MacArthur Military Press, 2nd ed., 2002.
[99]"The Nike Site," www.redstone.army.mil/history/nikesite/welcome.html, Redstone Arsenal AL [cited 20 Aug. 2003].
[100]"ARC to Build Rockets for Patriot Advanced Capability–3 (PAC3) Missile," www.atlanticresearchcorp.com/docs/pr_98aug27l.shtml, Atlantic Research Corporation (ARC), [cited 27 Aug. 2003].
[101]Prins, W., Spencer, A., and Roberts, J., "SM-3 SDACS Flight Test Successes," AIAA Paper 2003-4664, July 2003.
[102]West, L., and Carlson, R., "Solid Divert Propulsion Break-Throughs that Enable Mission Flexible TMD Interceptors" Paper 06-04, *Proceedings of 7th Annual AIAA/BMDO Technology Readiness Conference*, Aug. 1998, pp. 6-19–6-27.
[103]Campbell, J. G., and Ruttle, D. W., "Safe Propulsion for Missile Divert Thrusters and Attitude Control Thrusters and Method for Same," U.S. Patent 5,433,331, Kaiser Marquardt, Inc., Foster City, CA, 9 July 1996.
[104]ATK, Press Release, "Propulsion Systems Support Successful Sea-Based Missile Defense Test," Minneapolis, MN, 31 Jan. 2002.
[105]Geisler, R. L., "My Memoirs of Solid Propellant Development at the Air Force Rocket Propulsion Laboratory," AIAA Paper-93-1783, June 1993.
[106]Chase, M. W. Jr., (ed.), "NIST JANNAF Thermochemical Tables," *Journal of Physical and Chemical Reference Data, Monograph, No. 199, in 2-Volumes*, National Inst. of Standards and Technology U.S., Oct. 1998.
[107]Huff, V. N., Gordon, S., and Morrell, V. E., "General Method and Thermodynamic Tables for Computation of Equilibrium Compositions and Temperature in Chemical Reactions," NACA Report 1037, 1951.
[108]Dobbins, T. O., 1/Lt USAF, "Thermodynamics of Rocket Propulsion and Theoretical Evaluation of some Prototype Propellant," WADC Report TR-59-757, AD-0232465, WPAFB, OH, Dec. 1959.
[109]Zeleznik, F. J., and Gordon, S., "A General IBM 704 or 7090 Computer Program for Computation of Chemical Equilibrium Compositions, Rocket Performance, and Chapman-Jouguet Detonations," NASA Report TN D-1454, 1962.
[110]Gordon, S., and McBride, B. J., "Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance," NASA SP 273, NASA Lewis Research Center, OH, March 1976.
[111]Coats, D. E., Levine, J. N., Nickerson, G. R., Tyson, T. J., Cohen, N. S., Harry, D. P. III, and Price, C. F., "A Computer Program for the Prediction of Solid Propellant Rocket Motor Performance," Vol. 1, Ultrasystems, Inc., Irvine, CA, Final Rept., AFRPL-TR-75-36, Vol. 1, July 1975.
[112]Coats, D. E., Nickerson, G. R., Dang, A. L., and Dunn, S. S., "Solid Performance Program (SPP)," AIAA Paper-87-1701 June 1987.
[113]Coats, D. E., Colegrove, P. T., and Dunn, S. S., "A Critical Review of the SPP Loss Mechanisms," AIAA Paper-89-2781, July 1989.
[114]Bartlett, R. W., and Delaney, L. J., "Effect of Liquid Surface Tension on Maximum Particle Size in Two-Phase Nozzle Flow." *Pyrodynamics*, Vol. 4, 1966, pp. 337–341.
[115]Geisler, R. L., and Beckman, C., "The History of the BATES Motors at the Air Force Rocket Propulsion Laboratory," AIAA Paper-98-3981, 1998.
[116]Hermsen, R. W., "Aluminum Oxide Particle Size for Solid Rocket Motor Performance Prediction," AIAA Paper 81-0035, Jan. 1981.
[117]Kuo, K. K., and Summerfield, M., (eds.), *Fundamentals of Solid-Propellant Combustion*, Progress in Astronautics and Aeronautics Series, Vol. 90, AIAA, Reston, VA, 2000.
[118]Yang, V., Brill, T. B., and Ren, W.-Z., (eds.), *Solid Propellant Chemistry, Combustion, and Motor Interior Ballistics*, Progress in Astronautics and Aeronautics Series, Vol. 185, AIAA, Reston, VA, 2000.
[119]Culick, F. E. C., "A Review of Calculations for Unsteady Burning of a Solid Propellant," *AIAA Journal*, Vol. 6, No. 12, 1968, pp. 2241–2255.
[120]Strand, L. D., and R. S., Brown, "Laboratory Method for Measuring Combustion Response Functions," Chemical Propulsion Information Agency, Report 86-36, March 1986.
[121]Blomshield, F. S., "Historical Perspective of Combustion Instability in Motors—Case Studies," AIAA Paper 2001-3875, July 2001.
[122]Flandro, G. A., "Roll Torque and Normal Force Generation in Acoustically Unstable Rocket Motors," *AIAA Journal*, Vol. 2, No. 7, July 1964.
[123]Bailey, R. L., and Shafer, J. I., "An All-Carbon Radiating Nozzle for Long-Burning Solid Rocket Motors," *JPL Quarterly Technical Review*, Vol. 1, No. 2, July 1971.
[124]Carey, L., and Nixon, G., "Gas Deployed Skirt for Rocket Motor Nozzles," AIAA Paper 77-942, June 1977.
[125]Inman, F., and Trowbridge, J., "Nested Extendible Exit Cone Solid Rocket Nozzle Engineering Evaluation Program," AIAA Paper 78-1070, July 1978
[126]Blanchard, D. G., "A Brief History of Air-Intercept-Missile 9 (Sidewinder)," AIAA Paper 96-3154, July 1996.
[127]Dunn, B. M., Durbin, M. R., Jones, A. L., Lund, E. G., and Partington, R. L., "Short Range Attack Missile (SRAM) Propulsion, Three Decades of History," AIAA Paper 94-3058, June 1994.
[128]Elwell, R. B., Irwin, O. R., and Vail, R. W., Jr., "Project SOPHY–Solid Propellant Hazards Program," Air Force Rocket Propulsion Lab., AFRPL-TR-67-211, Vol. 1, Contract F04611-1019, Aerojet-General Corp., Downey, CA Research Div., Aug. 1967.
[129]Kincaid, J. F., "The Determination of the Propensity for Detonation of High Performance Propellants," *Proceedings of the 13th International Conference of ICT*, Karlsruhe, Germany, 1982.
[130]Brunet, J., and Paulin, J. L., "Study of the Deflagration to Detonation Transition of Missile Propellants," *AGARD Conference Proceedings No 367*, Neuilly-sur-Seine, France, May 1984.
[131]Weiss, R. R., Vander Hyde, N., and Merrill, C., "Review of USAF Treatment of Solid Propellant Rocket Motor Hazards," *AGARD Conference Proceedings No 367*, Neuilly-sur-Seine, France, May 1984.
[132]Kent, R., and Rat, R., "Static Electricity Phenomena in the Manufacture and Handling of Solid Propellants," *Proceedings of 20th DDESB Seminar*, Norfolk, VA, Vol. 1, Aug. 1982, pp. 885–889.
[133]Isler, J., "The Transition to Insensitive Munitions," *Propellants, Explosives, Pyrotechnics*, Vol. 23, 1998, pp. 283–291.
[134]Stokes, B. B., "Best Practices for IM Testing," NATO Insensitive Munitions Information Center, NIMIC Report TR19970151, Nov. 1997.
[135]"NIMIC, NATO Insensitive Munitions Information Center," www.hq.nato.int/related/nimic, Brussels, Belgium, 2003 [cited 20 July 2003].
[136]"Hellfire Propulsion System," www.atk.com/aerospace/descriptions/tactical-propulsion/hellfire.htm, ATK website, Minneapolis, MN, 2003 [cited 20 Aug. 2003].
[137]Stoecker, T., Frazier, S., and Padavano, J., "The Taurus, Launch Vehicle Design and Capability," AIAA Paper 92-3868, July 1992.
[138]Singer, V., and Graser, W. L., "High-Performance Structural Composite for Insensitive Munitions Applications–NIMIC Award Special Mention," 1997 Nation Defense Industry Association, *Proceedings of Insensitive Munitions and Materials Technology Symposium*, Oct. 1997
[139]Burroughs, S. L., "Status of Army Pintle Technology for Controllable Thrust Propulsion," AIAA Paper 2001-3598, July 2001.
[140]Aerojet GenCorp Company, Press Release: First Successful Flight Test of an Aerojet Controllable Thrust Solid Rocket Motor," Sacramento, CA, June 2003.
[141]Davenas, A., Boury, D., Calabro, M., D'Andrea, B., and McDonald, A. J., "Solid Propulsion for Space Applications: a Roadmap," 51st International Astronautical Congress, Paper IAA-00-IAA.3.3.02, Oct. 2000.

Glossary[a]

ABL	Allegany Ballistics Laboratory, Rocket Center, West Virginia
AFOSR	Air Force Office of Scientific Research, Arlington, Virginia
AFRPL	Air Force Rocket Propulsion Laboratory, Edwards AFB, California (renamed several times after 1980)
ARO	Army Research Office, Durham, North Carolina
ARS	American Rocket Society
ARPA	Advanced Research Projects Agency, Arlington, Virginia; at

[a]Items defined in text within section of use are not included.

DARPA	Various times Defense Advanced Research Projects Agency
BATES	Ballistic Analysis and Test System (BATES) series of solid rocket performance test motors established by AFRPL
C-C	Carbon-carbon composite material
CPIA	Chemical Propulsion Information Agency in Columbia, Maryland, part of John Hopkins University
DDT	Deflagration to Detonation Transition
DACS	Divert (propulsion) and Attitude Control System
EEC	Extendible Exit Cone
EELV	Evolved Expendable Launch Vehicle
EPDM	Ethylene propylene diamine monomer, an elastomeric insulating material
ESD	Electrostatic Discharge
FBM	Fleet Ballistic Missile
GALCIT	Guggenheim Aeronautical Laboratories at California Institute of Technology
GEM	Graphite Epoxy Motor
HTPB	Hydroxyl terminated polybutadiene polymer
ICBM	Intercontinental Ballistic Missile
IHPRPT	Integrated High Payoff Rocket Propulsion Technology
IM	Insensitive Munitions
ITE	Integral Throat Entrance
IUS	SRMs produced by Pratt & Whitney Chemical Systems Division
JANAF	Joint Army, Navy, and Air Force Interagency Propulsion Committee (pre-1958 and NASA)
JANNAF	Joint Army, Navy, NASA, and Air Force Interagency Propulsion Committee
JATO	Jet-assisted Take-off
JHU/APL	John Hopkins University/Applied Physics Laboratory, Laurel, Maryland
JPL	California Institute of Technology's (Caltech) Jet Propulsion Laboratory, Pasadena, California
MICOM	Army Missile Command, Redstone Arsenal, Alabama
MM	Minuteman strategic missile
NAWC	Naval Air Weapons Center, China Lake, California (From 1992)
NC/NG	Nitrocellulose plasticized by nitroglycerin plus stabilizers.
NIMIC	NATO Insensitive Munitions Information Center, in Brussels, Belgium
NOTS	Naval Ordnance Test Station, China Lake, California (Initial name in 1944)
NDRC	National Defense Research Committee (a 1940s organization that mobilized the academic talents)
Orbus	Series of space motors developed by CSD
R&H	Rohm and Haas Research Laboratories, Redstone Arsenal, Alabama
SRAM	Short Range Attack Missile
SRM	Solid Rocket Motor
SRMU	Solid Rocket Motor Upgrade
SOPHY	A Solid Propellant Hazards Program (Ref. 128)
SRM	Solid Rocket Motor
SSPO	Navy Strategic Systems Project Office, formerly Special Projects Office (SPO)
SSP	Standard Stability Prediction
STAR	Trademark name for a series of typically spherical space motors developed by Thiokol
TVC	Thrust Vector Control
WPAFB	Wright Patterson AFB, Dayton, Ohio