THE HISTORY OF SOLID-PROPELLANT ROCKETRY: WHAT WE DO AND DO NOT KNOW

J. D. Hunley*
NASA Dryden Flight Research Center
Edwards, California

Abstract

Contributions to the evolution of solid-propellant rocketry have come from a variety of sources. World War II research on large solids enabled one company to capitalize on work in the area of castable double-base propellants. Separate development of castable composite propellants led to production of Polaris and Minuteman powerplants. Pivotal to the development of these missiles were Edward Hall's advocacy of the Minuteman missile within the Air Force and contract funding to resolve problems. The discovery that adding large amounts of aluminum significantly increased the specific impulse of a castable composite propellant further aided large-missile technology. These separate lines of research led to the development of large solid-propellant motors and boosters. Many more discoveries went into the development of large solid-propellant motors. Ammonium perchlorate replaced potassium perchlorate as an oxidizer in the late 1940's, and binders were developed. Discoveries important in the evolution of large solid-propellant motors appear to have resulted from innovators' education and skills, an exposure to contemporary problems, an awareness of theory but a willingness not to let it dictate empirical investigations, and proper empirical techniques. Other important contributions are the adequate funding and exchange of information. However, many questions remain about these and other innovations.

Nomenclature

Al	aluminum
AP	ammonium perchlorate
CMDB	composite-modified double base
CTPB	carboxyl-terminated polybutadiene
HMX	tetramethylene tetranitramine
HTPB	hydroxyl-terminated polybutadiene
Isp	specific impulse, lbf-sec/lbm
JANNAF	Joint Army Navy NASA Air Force (an Interagency Propulsion Committee)
JPL	Jet Propulsion Laboratory
PBAA	polybutadiene–acrylic acid
PBAN	acrylic acid, acrylonitrile, and butadiene terpolymer
psi	pounds per square inch (lbf/in^2)

Introduction

The history of solid- and liquid-propellant rocketry is particularly difficult to write for a variety of reasons, including the technical complexity of the subject and the resultant division of labor among rocket engineers into a variety of disciplines and subdisciplines. Other reasons include the comparatively large number of firms that have contributed various technologies to a very large number of large and small rockets and missiles; the fact that customers for rockets and missiles have included the U. S. Army, U. S. Navy, U. S. Air Force, NASA, and a growing commercial sector; and the fact that most people with technical expertise in rocketry know only a part of the history of their subject, and many of them disagree regarding technical details or matters of interpretation such as the origins of a particular technology or its relative importance.

For several years, I have been engaged in an effort to produce a general, technical history of the origins and evolution of both solid- and liquid-propellant rocketry in the United States with the intent to publish my findings in a book in the NASA History Series. Initially, while working in the History Office at NASA Headquarters (Washington, D. C.), I was able to devote quite a bit of time to my research and writing. For the past four years,

*NASA Dryden Flight Research Center Historian.

I have been the historian at the NASA Dryden Flight Research Center (Edwards, California) and have had to devote approximately 50 hours each week to the history of aeronautics. I now pursue my rocket research in the wee hours of the morning and on weekends.

I have also studied the history of liquid-propellant rocketry in Germany through the end of World War II because members of the von Braun group in Germany emigrated to the United States after the war and eventually formed the nucleus of the NASA Marshall Space Flight Center (Huntsville, Alabama), whence they made important contributions in overseeing the development of liquid-propellant rocketry. In the United States, I have studied the work of Robert Goddard; the group that founded Reaction Motors, Inc. (Dover, New Jersey); and especially the work of the California Institute of Technology (Caltech; Pasadena, California), the Jet Propulsion Laboratory (JPL; Pasadena, California), Aerojet General Corporation (Azusa, California), Thiokol Chemical Corporation (Trenton, New Jersey), Hercules Powder Company (Wilmington, Delaware), Lockheed Aircraft Company (Burbank, California), Atlantic Research Corporation (Vienna, Virginia), United Technology Corporation (now the Chemical Systems Division of Pratt & Whitney; Sunnyvale, California), and many other contributors to rocket technology. But a vast amount of work still needs to be done.

I have been asked to present my major findings thus far about the history of solid-propellant rocketry at this session and also to present the major questions I have that are unanswered as well as the major areas that remain to be explored. Table 1 shows key missiles and rocket boosters studied. Hopefully, members of the solid-propellant history group could suggest where I could devote my limited time to the best advantage.

Table 1. Key missiles and rocket boosters.

Missile or booster	Motor manufacturer	Propellant	*Isp*[*]	Grain configuration	Operational date
Sergeant	Thiokol	AP/polysulfide	ca. 185	5-point star	1962
Polaris A1					
Stage 1	Aerojet	AP/Al/polyurethane	ca. 230	6-point star	1960
Stage 2	Aerojet	AP/Al/polyurethane	ca. 255	6-point star	1960
Polaris A2					
Stage 2	Hercules Powder Company	AP/nitrocellulose/ nitroglycerine/Al	ca. 260	12-point star	1962
Polaris A3					
Stage 2	Hercules Powder Company	HMX/Al/AP/nitrocellulose	ca. 280	slotted cylindrical center port	1964
Minuteman I					
Stage 1	Thiokol	AP/PBAA/Al	ca. 245	6-point star	1962
Stage 2	Aerojet	AP/polyurethane/Al	ca. 270	4-point star	1962
Stage 3	Hercules Powder Company	AP/HMX/nitrocellulose/ nitroglycerine/Al	ca. 275	core and slotted tube-modified end burner	1962
Titan 3 solid-rocket motor	United Technology Corporation	AP/PBAN/Al	ca. 265	8-point star and circular perforations	1965
Space Shuttle solid-rocket booster	Thiokol	AP/PBAN/Al	ca. 245	11-point star and tapered perforations	1981

*Under firing conditions, expressed in terms of lbf-sec/lbm (pounds of thrust per pound of propellant burned per second).

Perhaps promotion of a collaborative effort to gather the history of rocketry before it is lost to shredders and trash heaps throughout the country is possible.

Use of trade names or names of manufacturers in this document does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

Major Findings

The major findings of this research to date include the following:

- Goddard began investigating the use of solids for propulsion but spent most of his life exploring liquid propellants. His secrecy and penchant for patents rather than sharing his discoveries with others interested in the development of rocketry left little in the way of a legacy. Most of his findings had to be rediscovered by others.[1]
- During World War II, important work on tactical missiles occurred at the Naval Proving Ground (Indian Head, Maryland), Caltech (Eaton Canyon, California), Allegany Ballistics Laboratory (West Virginia), the Explosives Research Laboratory (Bruceton, Pennsylvania), and elsewhere.[2–6]
- The Hercules Powder Company appears to have been the major beneficiary of this research in the area of large solids, especially capitalizing on the work of John Kincaid and Henry Shuey in the area of castable double-base propellants.
- The Hercules Powder Company also participated in the development of several tactical missiles for the U. S. Department of Defense, including the Nike, Honest John, Sparrow, and Terrier missiles.[7] Much less seems to be known about these developments.
- ln a separate line of development, a group of researchers at the Guggenheim Aeronautical Laboratory at Caltech (which formed the nucleus of what became JPL in 1944) was working on jet-assisted takeoff units. In June of 1942, a chemist named John Parsons had the idea of combining asphalt (as a binder and fuel) with potassium perchlorate (as an oxidizer) to make the first castable composite solid propellant.[8]
- JPL engineer Charles Bartley improved on Parsons' basic discovery by replacing the asphalt with a Thiokol polysulfide polymer, LP-2. Combining LP-2 with an internal-burning, star-shaped grain and case-bonding the combination in a thin case led to the Sergeant missile powerplant and later, with different ingredients, the Polaris and Minuteman missiles.[9] Figure 1 shows a Polaris A2X test missile.
- Aerojet (which was founded by some of the leaders at JPL), Thiokol (which had links to JPL because of LP-2), and United Technology Corporation (which was founded by people with ties to JPL and elsewhere) all used this basic technology.
- These companies might not have made the contribution to rockets and missiles that they did had it not been for the vision of a U. S. Air Force officer, Edward N. Hall. Hall ensured funding of contracts to resolve problems with long-duration firings of solid propellants, thrust termination, thrust-vector control, and the exposure of nozzles to the heat associated with high specific impulses. He also advocated the Minuteman missile within the U. S. Air Force.[†, ‡, 7, 10–13]
- A further line of development that enabled large-missile technology started at Atlantic Research Corporation, working under contract with the U. S. Navy. Two young engineers named Keith Rumbel and Charles Henderson found that the addition of large amounts of aluminum significantly increased the specific impulse of a castable composite propellant. The propellant they used was 21 percent aluminum, 59 percent ammonium perchlorate, and 20 percent plasticized polyvinyl chloride.
- These separate lines of research led from development of the Polaris and Minuteman missiles to development of the large solid-rocket motors on Titan 3 and Titan 4 rockets and the solid-rocket boosters on the Space Shuttle.[14] Figure 2 shows a Titan 3E launch vehicle, and Figure 3 shows the Space Shuttle.

Other Developments and Key Questions

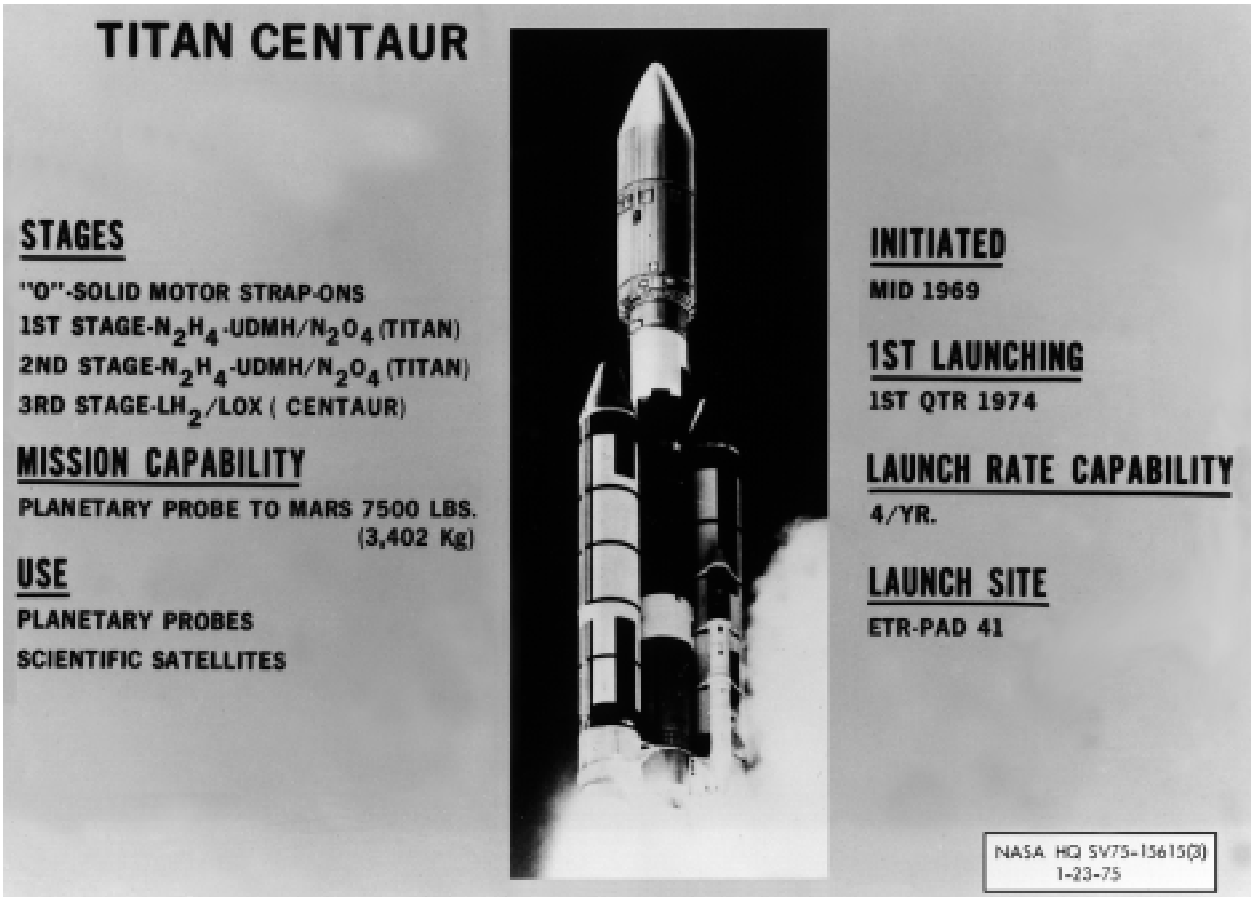
Many more discoveries were behind these large solid-rocket developments than just these propellant contributions. Integral to the stories of the propellants used on large rockets and missiles, smaller tactical missiles, and a host of smaller rockets for a variety of rockets and spacecraft were the various binders, fuels, and oxidizers that went into the propellants. For example, the motors for the Polaris A1 missile designed

[†]Telephonic interview of Col. Edward N. Hall (United States Air Force, Retired) by J. D. Hunley, Nov. 13, 1998.

[‡]Hall, Edward N., "USAF Engineer in Wonderland Including the Missile Down the Rabbit Hole," undated typescript provided by Hall.

(Photo courtesy of NASA.)

Figure 1. A Polaris A2X test missile on the launch pad at the Atlantic Missile Test Range, Cape Canaveral, Florida. The A2X is the prototype for the 1500-nmi Polaris A2 missile that became operational in 1962.



(Photo courtesy of NASA.)

Figure 2.A Titan 3E launch vehicle with a Centaur upper stage. This vehicle featured the five-segment solid rocket motors shown firing in this photograph together with three liquid-propellant stages, including the Centaur. This configuration launched the Viking, Helios, and Voyager spacecraft from 1974 to 1977.

by Aerojet featured a cast, case-bonded polyether-polyester-polyurethane composition with 15 percent aluminum and ammonium perchlorate. Karl Klager at Aerojet has been credited with being largely responsible for developing both the grain and the propellant for these motors, but the story of their development is evidently quite complex. Klager received the U. S. Navy Distinguished Public Services Award in 1958 for his work on the Polaris missile, but the development of some of the propellant ingredients predates when Klager joined Aerojet in 1950.

In 1948, Aerojet had replaced potassium perchlorate with ammonium perchlorate in certain aeroplex propellants to reduce smoke and increase specific impulse. Problems existed with combustion instability and the aeroplex binder was not case-bondable, leading Aerojet to convert to a polyurethane binder in 1953 and 1954. But the process had started.[§] JPL and Thiokol were also working with ammonium perchlorate as an oxidizer in the late 1940's and used it in the early 1950's on the RV-A-10 missile, an important precursor of the Polaris missile.[¶] A significant part of the history of rocketry involves the full details of how ammonium perchlorate successfully came to be used and how the various ingredients in the Polaris motors came to be combined in the proportions that ultimately were employed.

For subsequent missiles and rockets, similar questions exist about the development of the propellant grains. How, for instance, did polybutadiene–acrylic acid (PBAA); acrylic acid, acrylonitrile, and butadiene terpolymer (PBAN); carboxyl-terminated polybutadiene

[§]Klager, Karl and Albert O. Dekker, "Early Solid Composite Rockets," unpublished paper, Oct. 1972.

[¶]Wiggins, Joseph W., "The Earliest Large Solid Rocket Motor—The Hermes," presented at the AIAA 9th Annual Meeting and Technical Display, Washington, D.C., Jan. 8–10, 1973.

(NASA photo 81-HC-829.)

Figure 3. Space Shuttle Columbia climbs skyward on its second mission into space from NASA's Kennedy Space Center, Florida, on November 12, 1981. This photograph shows one of the two giant solid rocket boosters firing to provide the lion's share of the orbiter's lift for the first 24 nmi of ascent into space.

(CTPB); and hydroxyl-terminated polybutadiene (HTPB) come to be developed as binders? How did tetramethylene tetranitramine (HMX) come to replace at least some of the ammonium perchlorate in some high-energy propellants? The technical literature seems to leave these kinds of questions unanswered. More research is needed.

Ernie Sutton's privately printed and very useful history of Thiokol[#] provides partial answers to some of these questions. According to Sutton, Thiokol began searching in 1952 for propellants that would raise performance while lowering temperatures of the burning grain. Funded by the U. S. Army, Thiokol chemists sought to reduce or eliminate the sulfur content of its polysulfides by preparing liquid hydrocarbon polymers. The chemists tried several polymers and combinations of copolymers but found adding functional groups that would cure readily was problematic. Eventually, in 1954, the chemists in Huntsville, Alabama, discovered a copolymer of butadiene and acrylic acid—PBAA. Using 32-oz soda bottles for mixing, the chemists succeeded in getting a liquid epoxide resin to react with the carboxyl groups yielded from the acrylic acid and thus produced a cured polymer binder. Sutton does not reveal, however, who the chemists were or exactly how they arrived at their discovery, although his narrative suggests that they did so by trial and error with likely polymers.

Sutton notes that PBAA was a definite improvement, but that it did not possess good tear strength.[#] Hence, Thiokol introduced PBAN, which offered better physical properties, in 1954. According to Sutton, although Thiokol originally developed PBAN, the American Synthetic Rubber Corporation in Louisville, Kentucky (later known as Kentucky Synthetic Rubber Corporation), somehow—he doesn't say how—began producing the binder in the late 1950's. Used in Minuteman missiles, Space Shuttle solid rocket boosters, and Poseidon missiles, PBAN has accumulated the largest production tonnages in the industry.[#]

Later in the 1950's, Thiokol developed CTPB, although Sutton does not say how. He notes CTPB has better mechanical properties than PBAN but never fully supplanted the latter, partly because of its higher cost and partly because of the emergence of a better polymer, known as HTPB.[#]

Karl Klager, who is credited with the development of HTPB, was asked how he came to develop this low-cost, low-viscosity propellant that has become an industry standard. He said only that he started development in 1961 but waited until 1969 to propose the propellant to NASA for the Astrobee D and Astrobee F sounding rockets on which it flew successfully. Perhaps, however, Klager's response regarding how he came to discover unsymmetrical dimethylhydrazine (UDMH) (which is a liquid propellant used on the Bomarc missile, Titan 2 missile, Titan 3 and Titan 4 rockets, and other missiles and rockets) applies equally to HTPB. Klager said that he simply brought his knowledge of the science of chemistry to bear on the need for a propellant. He had earned a Ph.D. in chemistry from the University of Vienna in 1934 and had worked for several chemical firms in Europe from 1931 to 1948 before moving to the United States and starting work for Aerojet in 1950.[#, **, ††]

Klager's explanation is similar to the answer given by Charles Henderson about the discovery that large amounts of aluminum—on the order of approximately 16–20 percent—substantially added to the specific impulse of solid propellants. Henderson and Keith Rumbel, both chemical engineers trained at the Massachusetts Institute of Technology (Cambridge, Massachusetts), were aware that other researchers, including some at Aerojet, had calculated that the specific impulse of composite solid propellants could be raised by including aluminum in the ingredients. These other researchers' calculations, following contemporary theory, had showed that the aluminum would increase the specific impulse only within a narrow range. When the amount of aluminum in the propellant exceeded the level of 5 percent of the total content, the calculations indicated that the specific impulse again declined.

Rumbel and Henderson apparently had better information about the actual nature of the combustion process and went well beyond the 5-percent level, finding that the specific impulse of the Atlantic Research polyvinyl chloride propellant climbed significantly as that level was exceeded. In addition to a lack of false assumptions about the then–still largely unexplored nature of the combustion process, what permitted Rumbel and Henderson to make their discovery was

[#]Sutton, E. S., "How a Tiny Laboratory in Kansas City Grew into a Giant Corporation: A History of Thiokol and Rockets, 1926–1996," privately printed, Jan. 1997.

[**]Short biography of Dr. Karl Klager, provided by him to J. D. Hunley, Mar. 1997.

[††]Telephonic interview of Dr. Karl Klager by J. D. Hunley, Mar. 15, 1997.

good empirical technique. They and their colleagues at Atlantic Research apparently had the proper mix of skills and knowledge to employ the correct procedures for testing the effects of a 21-percent concentration of aluminum combined with 59 percent ammonium perchlorate and a binder of 20 percent plasticized polyvinyl chloride in test stands at Atlantic Research. Aerojet later verified their findings in an actual 100-lb rocket in early 1956.

Rumbel and Henderson had found that several conditions were necessary for good combustion of aluminum: small particles (fortunately available from both the Aluminum Company of America, Alcoa, Tennessee; and Reynolds Metals Company, Richmond, Virginia), proper chamber pressure (approximately 725–889 psi with measured specific impulse at those two pressures being 230 and 247 lbf-sec/lbm, respectively) and oxidation ratio, and sufficient energy content in the propellant mixture to ignite the aluminum. They used test motors 5 in. in diameter and 14 in. long with a star perforation.[‡‡, §§, ¶¶]

Henderson, after consulting with Rumbel, also provided a description of Atlantic Research's development of composite-modified double-base (CMDB) propellants,[##] which later became important in rocketry. Although Henderson's short narrative does not answer precisely how the discovery occurred, it does provide many of the details. He says the development began at Atlantic Research with a laboratory process for the preparation of plastisol-grade nitrocellulose. The individuals responsible for that process were Arthur Sloan and D. Mann, who, Henderson says, patented it with the rights assigned to Atlantic Research. Nitrocellulose was not suitable in its manufactured state as an unmodified additive to other propellant ingredients being mixed together because of its fibrous nature. Sloan's process consisted of dissolving the nitrocellulose in nitrobenzine and then separating the nitrocellulose out again using water under high shear.[##] This process resulted, Henderson adds, in a compact and spherical product with a particle diameter in the range of approximately 1 to 20 microns. In this form, the nitrocellulose could readily be combined with liquid nitroplasticizers and crystalline additives and then be mixed with other propellant ingredients and cast in either cartridge-loaded grains or case-bonded rocket casings because, when subjected to moderate heat, the nitrocellulose converted into a solid.[##]

Henderson did not furnish a date for this development, but he said that in 1955 he and Rumbel began scale-up work and propellant development based on Sloan and Mann's discovery. Atlantic Research constructed a pilot plant and began development of two CMDB formulations in 1956. Table 2 shows what comprised the two formulations.

Table 2. CMDB formulations.

	Content (percent by weight)	
Ingredients	40-percent binder	50-percent binder
Pyro nitrocellulose	20	25
Nitroglycerin	14	17.5
Dibutyl phthate	6	7.5
Ammonium perchlorate	32.8	25.45
Aluminum powder	27.2	24.55
Calculated specific impulse (lbf-sec/lbm) at 1000 psi to 1 atm	261	262

Henderson remembers casting the propellant grains and doing static firing, but because his records do not include the dates, he guesses the work occurred in 1957. Henderson says that as Atlantic Research's activities grew, its pilot plant became too small for its needs and the Naval Proving Ground at Indian Head, Maryland, began to produce CMDB at some point. Atlantic Research and other firms in the rocket industry obtained the product from the U. S. Navy. Because the Atlantic Research plastisol process was much simpler, safer, and cheaper than other processes being used, the Hercules Powder Company and other facilities using double-base propellants adopted it.[##]

From the examples of discoveries by Klager and Atlantic Research, the conditions necessary for innovation in rocket technology would seem to include proper education and skills, an exposure to contemporary problems, awareness of theory but a willingness not to let it dictate empirical investigations, and proper empirical techniques. Another condition would seem to be adequate funding and exchange of information such as has been provided by the Joint

[‡‡]Letter from Karl Klager to J. D. Hunley, Oct. 7, 1997.

[§§]Letter from Charles B. Henderson to J. D. Hunley, Oct 16, 1997.

[¶¶]Telephonic interview of Charles Henderson by J. D. Hunley, Oct. 15, 1997.

[##]Narrative by Charles Henderson and Keith Rumbel dated Sept. 30, 1998, sent to J. D. Hunley as an enclosure to a letter from Charles Henderson dated Oct. 8, 1998.

Army Navy NASA Air Force (JANNAF) Interagency Propulsion Committee and its predecessors, which date back to the Rocket Propellant Information Agency within the Applied Physics Laboratory at Johns Hopkins University (Baltimore, Maryland) in 1946.[15, 16]

In addition to propellants themselves, other issues exist, such as testing the propellant grain, materials research for motor cases and nozzles, techniques for ignition of the grain, grain configurations, thrust-vector control and thrust termination, mixing techniques, liners, bonding agents, stabilizers, catalysts, and guidance and control, that still need to be researched. I have read a lot of the literature on research into the issue, but still don't have a crystal-clear notion of exactly what combustion instability has contributed to solid-propellant rocketry beyond a greater understanding of internal ballistics.

As mentioned above, one other area needing much more extensive research is the contribution of work on tactical missiles to solid-propellant technology. This paper mainly concentrates on large rockets and missiles, but Edward Price has stressed that smaller missiles have made many important contributions. I have not had time to pursue some leads Price has given me regarding his own work outside the general area of combustion instability, but some suggestions are in more readily available literature.

For example, Edward Hall has written that by 1950, the Falcon missile had contributed "quality control techniques for rubber-base propellants, design data for case-bonded grains, [and] aging characteristics of rubber-base propellants."[17] Exactly how the Falcon missile contributed these techniques and data, however, Hall does not say. We do know that although the Falcon missile was built by Hughes Aircraft Company (Culver City, California), Thiokol developed its motors.[10, 18]

Some information exists in Sutton's history of Thiokol about the processes that Hall mentions. At the time that Thiokol was working on the Falcon missile, the company was also working on a jet-assisted takeoff motor designated T-40, which used a JPL propellant formulation, and the RV-A-10 missile. Without explaining how the development occurred, Sutton quotes an early Thiokol employee, Jack Buchanan, as stating, "The T-40 was probably the first successful demonstration that internal-burning, case-bonded motor designs using polysulfide propellants could be successfully scaled up to larger diameters."[#] Sutton reveals that the development occurred in 1949 under the technical direction of Harold W. Ritchie, a chemist trained at Purdue University (Lafayette, Indiana).

Sutton also quotes Ritchie himself with regard to the Falcon missile: "[Liquid polysulfide]-bonded propellants gave me one of my greatest lifetime headaches because of the cure exotherm and resultant shrinkage on curing—just before [the propellant grain] became solid. Propellant voids from shrinkage and from (air) bubbles were at first two of our greatest problems. I initiated the temperature-programmed cure cycle and also the slit-plate casting system to remove mixing bubbles."[#] Sutton adds, "Later on, pressurized curing was introduced to allow propellant to flow back into the motor from the head cap area."[#]

These points by Sutton address the quality control and aging issues raised by Hall, and no doubt the design data for case-bonded grains resulted from this work by Thiokol not only on the Falcon missile but also on the jet-assisted takeoff motor. However, the developments clearly resulted in some degree from interactions between JPL and Thiokol, not strictly from internal Thiokol discoveries.[#, 10, 14] A great deal more research is needed to clarify and provide the details of the development process outlined by Hall and Sutton.

Sutton does discuss an improvement in grain design that Thiokol provided. JPL had been working on a Sergeant sounding rocket but had cancelled its development in 1950 because cracks in the star-shaped internal cavity had resulted in explosions.[9] Thiokol overcame this problem as a result of photoelastic grain studies performed by the Armour Institute, later known as the Illinois Institute of Technology (Chicago, Illinois). These studies led Thiokol to round the star points on the RV-A-10 missile to prevent cracks from forming during sub- and full-scale motor firings.[#, ***]

Concluding Remarks

These details constitute some aspects of rocket development that I have been able to find out from existing literature and the comparatively small number of interviews that I have found time to conduct. But a vast amount of research is still needed, much more than I ever expect to have time to do—especially as I am researching liquid- as well as solid-propellant rocketry, and liquids have their own separate issues and complexities.

[***]Telephone interview of Lawrence Thackwell (who worked in succession for JPL on the Sergeant sounding rocket, for Grand Central Rocket Company, and then for Thiokol on the RV-A-10 missile) by J.D. Hunley, Dec. 17, 1995.

Consequently, I solicit your suggestions and even your assistance. Assembling a group of people who are already experts in specific areas of solid-propellant rocketry and are willing to write chapters on the history of their areas of expertise should be possible. The group could address the major innovations in their area; attempt to find out where, when, and how the innovations occurred; and discuss which rockets and missiles have employed those innovations. Someone, possibly myself, could edit the volume for consistency and write introductory and concluding chapters that would cover the background, indicate the nature of the enterprise, and summarize the principal findings. I would welcome hearing from anyone who might be willing to participate in such an effort or can suggest other possible participants.

Acknowledgments

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13. ABSTRACT (Maximum 200 words)

Contributions to the evolution of solid-propellant rocketry have come from a variety of sources. World War II research on large solids enabled one company to capitalize on work in the area of castable double-base propellants. Separate development of castable composite propellants led to production of Polaris and Minuteman powerplants. Pivotal to the development of these missiles were Edward Hall’s advocacy of the Minuteman missile within the Air Force and contract funding to resolve problems. The discovery that adding large amounts of aluminum significantly increased the specific impulse of a castable composite propellant further aided large-missile technology. These separate lines of research led to the development of large solid-propellant motors and boosters. Many more discoveries went into the development of large solid-propellant motors. Ammonium perchlorate replaced potassium perchlorate as an oxidizer in the late 1940’s, and binders were developed. Discoveries important in the evolution of large solid-propellant motors appear to have resulted from innovators’ education and skills, an exposure to contemporary problems, an awareness of theory but a willingness not to let it dictate empirical investigations, and proper empirical techniques. Other important contributions are the adequate funding and exchange of information. However, many questions remain about these and other innovations.

14. SUBJECT TERMS
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