

Chapter 10

HISTORICAL ORIGINS OF
THE SERGEANT MISSILE POWERPLANT*

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PART I

It is an understatement to say that solid propellant rocket technology advanced tremendously in the past three decades. From the small extruded cordite barrage rockets of the Second World War, a kaleidoscope of solid propellant powerplants has emerged, with capabilities once thought by many to be impossible with solid propellants. Modern solid propellant charges commonly weigh a great many thousands of pounds and are cast into a variety of different motors, often with diameters in the hundreds of inches, and provide full thrust vector control and superb thrust-curve reproducibility, to name just a few salient features. The list of available designs and performance characteristics is seemingly endless. A great many agencies in many countries have contributed significantly to these developments.

But despite the diversity in solid propellant rocket motor design, the basic design concept behind nearly all of today's most advanced solid propellant powerplants is, in a sense, of roughly the same genus when compared to the basic design of World War II. Generally speaking, the solids of that earlier period had heavy steel cases, burned extruded cordite charges of various designs, and rarely, if ever, employed the propellant itself for structural strength or for insulation of the casing from the combustion gases. The present generation of solid propellant motors, in contrast, almost uniformly incorporate castable composite propellants into a lightweight case and depend heavily upon the propellant itself for both structural strength and insulation from the heat of combustion. Achievement of the conceptual shift from the earlier archetype to the later model was one of the principal stepping stones, if not *the* principal stepping stone, to modern solid propellant rocket motor hardware. The ultimate cause of this conceptual shift can be traced to some engineers in the immediate postwar period who sought to "scale-up" small solid rockets of the war to comparatively large solid boosters.

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One of the earliest exemplars of the new concept was the powerplant for the U.S. Army's Sergeant guided missile (Figure 1). Developed by the California Institute of Technology's Jet Propulsion Laboratory (JPL) between 1954 and 1961, the 31-inch diameter Sergeant powerplant was the first operational motor of such size to emerge from a whole series of experimental solid propellant motor research conducted by JPL and other institutions in an effort to break away from the conventional and limited designs of World War II. In the course of this experimental research, the significant conceptual advances described above were combined successfully for the first time in actual hardware.

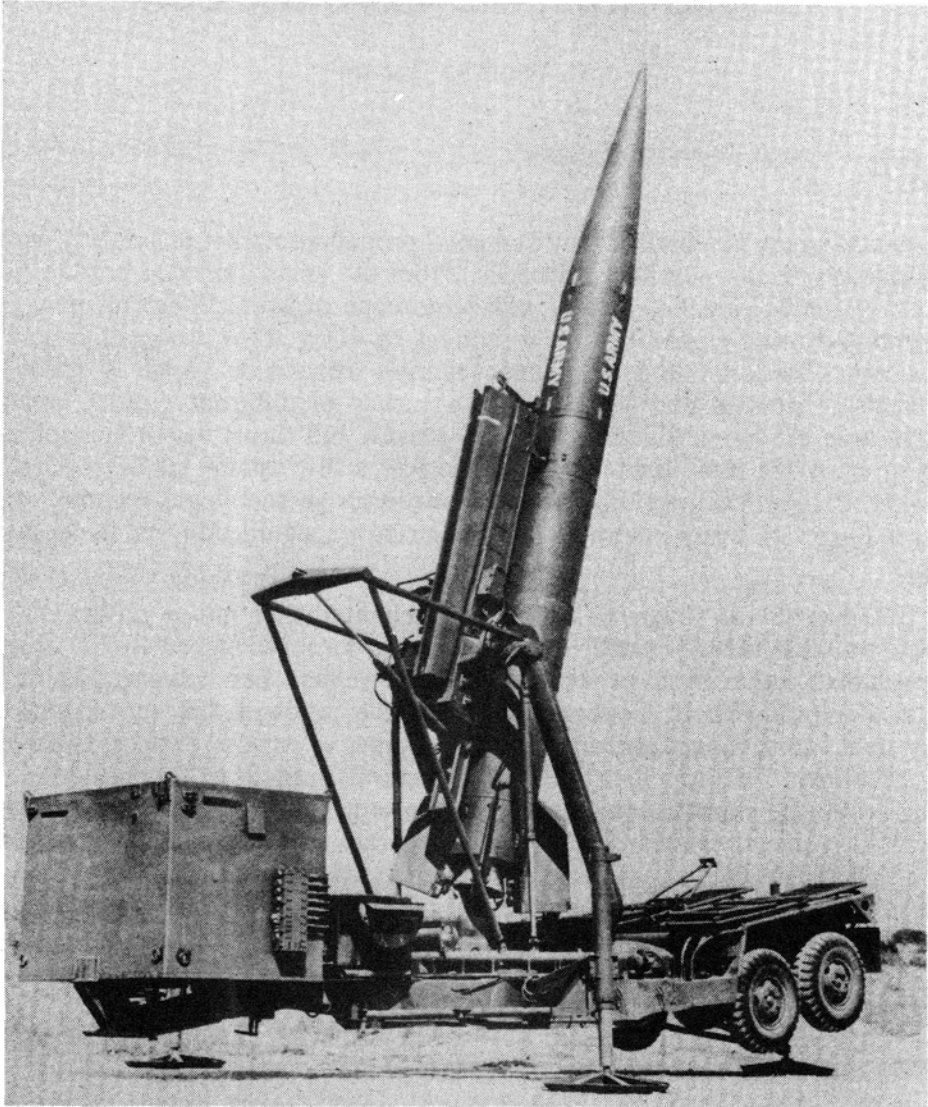


Figure 1 The Sergeant guided missile.

This paper presents an account of the early projects at JPL which led to the Sergeant missile powerplant, and of the key men involved in the most crucial aspects of this research and development. It has three objectives: 1) to make at least some of the origins of the Sergeant missile powerplant a matter of historical record, however sketchily; 2) to demonstrate that the solid propellant engineers at JPL in the immediate postwar period were among the first, if not *the* first, to accomplish the conceptual shift to the modern generation of solids; and 3) to illustrate by this case study the mechanism by which integrative research proceeds through fundamental shifts of conceptualization.

PART II

The historical origins of the Sergeant missile powerplant are inextricably intertwined with the history of the Jet Propulsion Laboratory, which had its beginnings in 1936 at Caltech's Guggenheim Aeronautical Laboratory, or GALCIT. In that year, a small group of Caltech students and co-workers led by GALCIT graduate student Frank J. Malina began to study rockets as a means of propulsion. For Malina, the work was nominally a doctoral research project under the direction of GALCIT Director Theodore von Kármán, but the ultimate goal of the project in the eyes of all concerned, according to Malina, was the development of a high altitude sounding rocket capable of exceeding an unprecedented altitude of 100,000 ft. Designated the GALCIT Rocket Research Project, the student group pursued these studies for three years, using funds from a small private grant.¹

With the advent of war in Europe in 1939, the project undertook fundamental research on rocket motors designed to provide jet-assisted take-off, or JATO, for heavily-laden aircraft. With the help of von Kármán, and supported first by the National Academy of Sciences and later by the Army Air Corps, work was diverted away from the original sounding rocket research--primarily liquid propellant--and redirected toward the development of small solid propellant motors with long burning times.

When the effort began on JATO development under the National Academy of Sciences contract, a solid propellant rocket that would burn longer than a few seconds had never been successfully built. Indeed, project experiments aimed at extending burning times using black powder rockets consistently resulted in failure. As with its fireworks counterpart, each rocket that was tested ignited and burned successfully for but a brief moment; after that, the pressure inside the combustion chamber continued to rise uncontrollably until the rocket exploded. This was in keeping with the contemporary orthodoxy of the internal ballistics of solid propellant rocket motors; solids with burning durations of more than three seconds, it was believed, were simply impossible.

Discouraged by the repeated failures, and thus concerned that explosions would make the end of the fledgling project, von Kármán determined to analyze the problem theoretically before ordering discontinuation of the experiments. In the spring of 1940, he and Malina derived and solved four differential equations describing the theoretical operation of an ideal restricted-burning solid propellant

rocket motor, metaphorically known as a cigarette-burning motor. The calculations showed that if the ratio between the area of the burning surface of the propellant and the area of the nozzle at the smallest diameter were constant, then the pressure inside the motor during combustion also would be stable and constant. This implied that the explosions of the GALCIT test motors were caused by an increase in the burning surface of the propellant as the hot combustion gases infiltrated the combustion chamber. According to the von Kármán-Malina theory, then, the explosions would cease if contact between the hot combustion gases and the propellant charge could be limited to a desired area.

This was indeed heartening news. The motor that produced the explosions of 1939 and 1940 was a restricted-burning design, conceived by charter project member John W. Parsons, that should have had a constant propellant surface area exposed to combustion; thus, theoretically at least, it should have burned stably. The reasons for its failure to do so in practice, therefore, were suspected to be mechanical and not fundamental in nature. For example, the propellant charge may have been cracking under pressure and then igniting along the cracks; the hot combustion gases may have been seeping between the side of the charge and the walls of the combustion chamber, resulting in ignition along the sides of the "cigarette"; or the motor case may have become hot enough during firing to ignite the side of the charge. Reasoning that all such mechanical problems could be overcome as long as the underlying theory was sound, Parsons and his colleagues conducted hundreds of empirical tests during 1940 and 1941 with a variety of black powder mixtures, with different propellant loading processes, and with a score of unique motor designs.

By the spring of 1941, the explosions had become less frequent and a reasonably reliable long-duration restricted burning motor evolved from the tests. Having a heavy steel case and an acetate-impregnated blotting paper liner to protect and insulate the combustion chamber walls, it carried a two pound charge of an amide black powder propellant. Pressed into the case in small increments under a load of several tons, this propellant burned steadily for a record 12 seconds. During August, 1941, the new motor was successfully tested as a JATO unit on an Ercoupe airplane at March Field in California (Figure 2). Because of these tests, the Bureau of Supplies and Accounts of the Navy Department, on behalf of the Navy's Bureau of Aeronautics, awarded Caltech a small contract (NSx-5879) to develop a 200-pound thrust solid propellant JATO unit with an eight second duration.²

The Project personnel were understandably ecstatic over this development, but the high spirits soon subsided. During the Ercoupe tests in December, it was discovered that the JATOs exploded upon ignition after a brief period of storage because of an unknown degeneration effect. Failure of the motor because of the decomposition of their chemical constituents over time was suspected, as were the assembly procedures. A new series of empirical experiments in late 1941 and early 1942, in which the propellant composition, the acetate blotter liner composition, and the loading procedure were altered, failed to eliminate the explosions after storage, and the summer of 1942 dawned at the Project with little optimism that the Navy contract could be fulfilled.

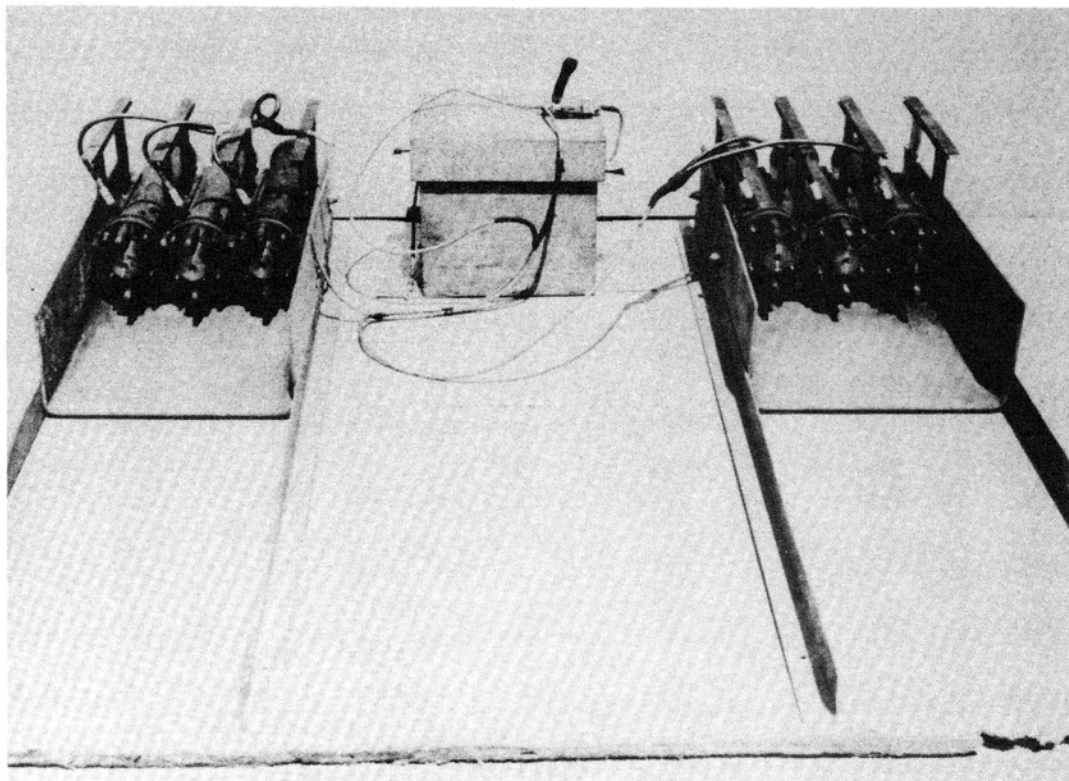


Figure 2 Ercoupe JATO units prior to installation on the aircraft.

Desperate, John Parsons in June suggested a novel solution to the degeneration problem. While watching the construction of a tarpaper roof at the GALCIT Project with a colleague, Fred Miller, it occurred to him to use asphalt, the roofing material, as a rocket fuel. He theorized that by heating the asphalt to a liquid state, stirring in potassium perchlorate as an oxidizer, pouring the mix into a rocket motor, and then cooling it into a solid mass, a sturdy, reliable, and, above all, storable propellant charge could be produced. Experiments with this new propellant were conducted immediately, and the results were promising enough to warrant discontinuation of research on all other solid propellants.

The asphalt-perchlorate propellant Parsons conceived and developed was unique in its day. In time, it came to be called a "castable composite solid propellant" -- castable because it could be poured or cast into the rocket motor as a liquid, rather than pressed, extruded, or molded into a solid charge, and composite because it had two components: a fuel matrix and a granular oxidizer dispersed throughout the matrix. Its introduction produced a new solid propellant paradigm at the project that spread, with much modification, throughout the solid propellant industry.

Using asphalt propellant, the GALCIT Project developed a 200-pound thrust, eight-second duration JATO for the Navy during 1942 (Figure 3). Since Caltech

had no interest in mass production, fabrication of the unit in large quantities for wartime use was begun by the Aerojet Engineering Corporation, founded in March, 1942, by the GALCIT Project personnel for the express purpose of producing the JATO. By the end of the war, with GALCIT Project consultation and manpower, Aerojet had mastered the art of asphalt JATO development and production. Indeed, in 1944, Parsons himself left the GALCIT Project permanently to become a full-time employee at Aerojet, and by that time an entire line of production asphalt JATOs was available.³



Figure 3 Typical Aerojet JATO units end-burning rockets using asphalt-based propellant.

Thus, in a few short years, the GALCIT Project members had achieved what many had once believed impossible: a useful theory describing the dynamics of a long-duration solid propellant rocket motor. In the bargain, they had invented asphalt-perchlorate propellants, a radical new approach in solid rocket propellant technology which would later free propellant developers from thinking along traditional lines.

PART III

No sooner had the GALCIT Project achieved its first wartime objective of inventing and perfecting a long-duration solid propellant JATO, than the events of World War II once again brought about a redirection of their efforts. British intelligence reports indicating the existence of a Nazi missile development program were circulated for the first time in the United States in 1943, and copies of some of these reports found their way into the hands of GALCIT Director von Kármán. Like most of his Allied colleagues, von Kármán concluded from the reports that the Germans were developing a long-range rocket weapon. But to the far-sighted European-born professor, the reports also had ramifications relating to the GALCIT rocket research. Now that the bulk of the JATO ground work was finished, he reasoned, the GALCIT Project was ready to tackle newer, larger problems. Concluding that a program to develop long-range missiles similar to the Nazi weapon would be an ideal avenue of research for the developers of the JATO, he took steps to convert the project into a long-range rocket research effort.⁴

To obtain approval and support for a long-range rocket program at Caltech, von Kármán, Malina, and the noted theoretical aeronautics expert Hsue-Shen Tsien, prepared a combined memorandum and analysis of long-range rocket research which could be performed in the United States. The document was a watershed in the history of JPL. First of all, it carried for the first time the name "Jet Propulsion Laboratory"; eventually this became the official name for what had begun as the GALCIT Rocket Research Project. Second, a copy of the document was sent to Colonel George W. Trichel of the Rocket Development Branch of the Army Ordnance Department, who replied by requesting the GALCIT Project undertake a program of long-range rocket research even broader than that outlined in the JPL memo. The request cemented the immediate future of the Laboratory.⁵

Arrangements for the new project were concluded on January 16, 1945, when a contract called ORDCIT (for Army Ordnance-California Institute of Technology) was signed between Caltech and U.S. Army Ordnance to cover the expenses of the missile program. It authorized "research, developmental, experimental, and engineering work and investigation on long-range rocket missiles and ramjets," and it set the following preliminary specifications for a typical long-range missile:

1. Maximum weight of high explosive payload, 1000 pounds;
2. Maximum weight of missile not to exceed a weight consistent with good design and a maximum payload;
3. Range of missile, 75 to 150 miles;
4. Dispersion at maximum range not in excess of two percent, or missile suitable for direction by remote control; and
5. Velocity sufficient to afford protection from fighter aircraft.

Despite these details, however, all parties to the contract did not expect development of an actual missile per se; rather, they interpreted the contract as authorizing basic research on some of the technical problems connected with long-

range missile development through theoretical and experimental investigations, as well as the design, construction, and testing of research vehicles.⁶

Initial work began on a test vehicle named Private. Two versions of this small unguided solid propellant missile were flight-tested at two locations between December 1, 1944, and April 13, 1945 (Figure 4). Designed to investigate the usefulness of adding wings to extend range, to gain experience with launching facilities, launching boosters, and tracking, and to gather data on the sustained flight of a fin-stabilized missile, the Privates did little to further the state of the art of solid propellant rocket motors. In fact, both versions of Private employed identical Aerojet-General solid propellant powerplants adapted from off-the-shelf JATO hardware. Workhorses for the more fundamental research at hand, they marked a transition between the old and the new in solid propellant motor development at JPL, serving both as a tribute to the achievements of the GALCIT group and as a challenge to those solid propellant experts who would later participate in the ORDCIT Project.

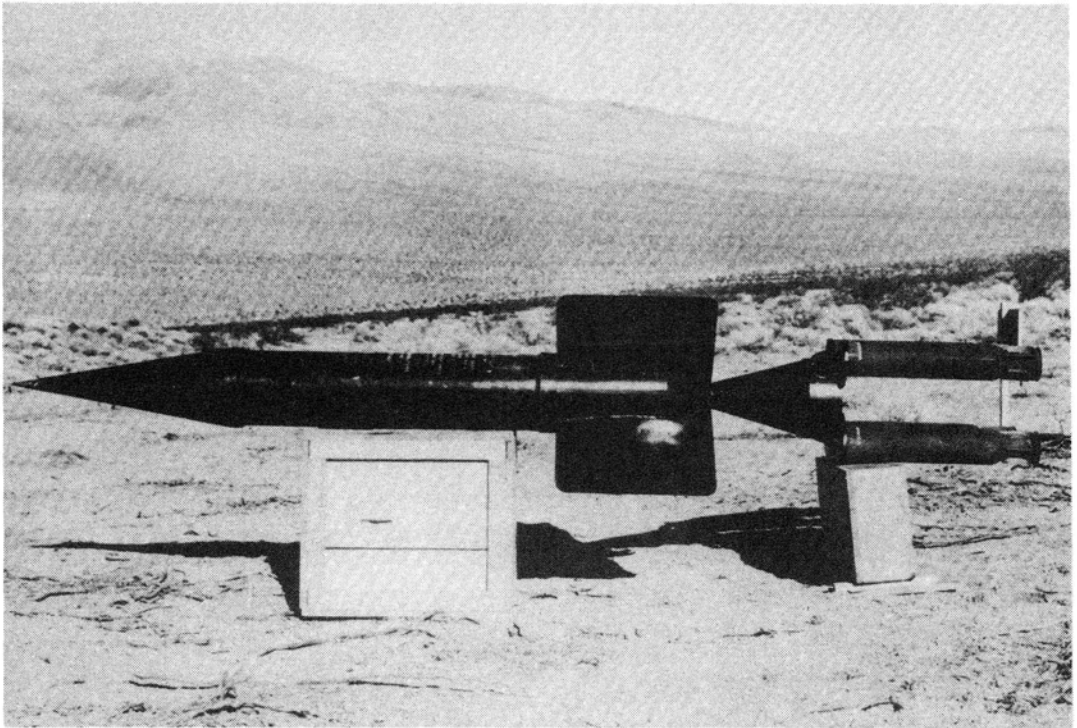


Figure 4 Private A with booster - one of two versions of the Private to be flight-tested by JPL.

Upon conclusion of the Private tests in April, 1945, the ORDCIT Project moved on to work of a more advanced nature. Turning to storable liquid-propellant powerplants, JPL continued development of the WAC Corporal, a 12-inch-diameter sounding rocket not unlike the ultimate GALCIT Rocket Research Project vehicle envisioned by Malina in 1936, since it was originally designed to

reach altitudes in excess of 100,000 feet (Figure 5). Development of this vehicle, once again derived from an Aerojet JATO, albeit this time a liquid-propellant unit, had actually begun some four months before, when Malina and his associates conducted preliminary design studies of the vehicle in support of the recommendations sent to Colonel Trichel. Once the Private tests were completed, development of the WAC Corporal became the principal objective of the Project. It occupied most of the JPL personnel and began a period of emphasis upon liquid propellant rockets that followed the world-wide trend toward liquids; the research resulted, eventually, in the development of the Corporal tactical missile.⁷

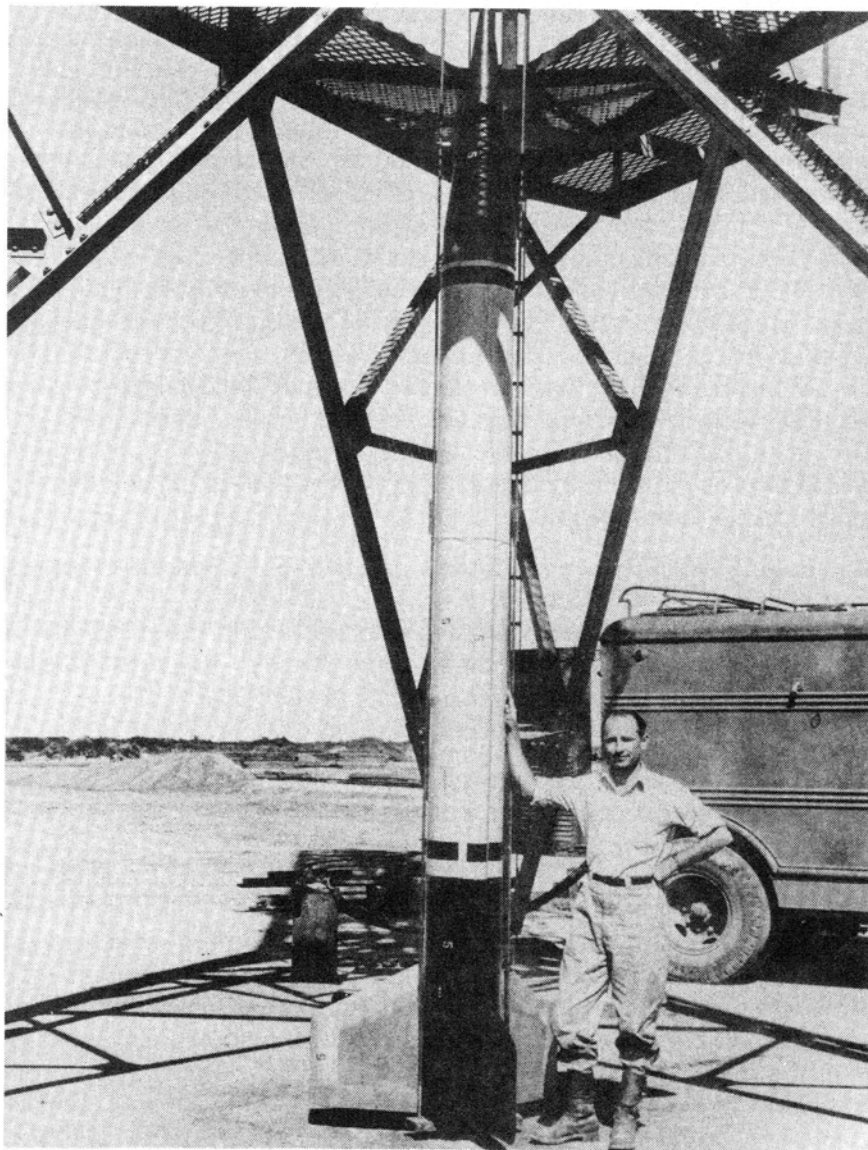


Figure 5 The WAC Corporal liquid-propellant sounding rocket and JPL Director Frank J. Malina.

While most of the Laboratory concentrated on liquid propellants, however, the solid propellant personnel continued an ongoing project to develop new solid propellants. Initiated by Mark M. Mills as part of the earlier Air Corps JATO Project, this new effort was an attempt to find a solid propellant with all the advantages of asphalt but none of its drawbacks. To be specific, asphalt was desirable as a solid rocket fuel because of its castability, its storability, and its elastic properties, but it also had an undesirable tendency to become liquid in hot tropical weather and crack in cold arctic climes. The new propellant research, therefore, was aimed primarily at finding a storable, elastic, and castable solid fuel for JATO applications that could withstand both hot and cold weather.⁸

This research led directly to synthetic rubber fuels. Beginning with investigations of butyl rubbers in February 1944, the research advanced through many other substances, until, in May, studies began with Buna-S, the new synthetic polymer developed by I.G. Farben in Germany and by Standard Oil and others in the United States. Under the direction of Charles E. Bartley (a young JPL engineer who fervently disbelieved that solid propellant motors were limited to contemporary pedestrian applications), several static tests of a Buna-S-based propellant called ORDCIT 21 were conducted between May and August, 1945, by Lawrence Settlemyre. Results indicated that the new propellant did not have the disadvantages of asphalt at high and low temperatures, but the bond between the propellant and the insulating liner that surrounded it proved unsatisfactory. Nevertheless, the ORDCIT 21 tests indicated that the solution to the temperature problem associated with asphalt might lie in the further development of polymer propellants. Bartley was thus encouraged to test other polymers, and to expand the scope of his polymer propellant investigations.⁹

Abandoning Buna-S, Bartley turned to other polymers and resins, including neoprene. During July and August, 1945, a series of static firings of end-burning cartridge charges of a neoprene-based propellant called ORDCIT 29 were conducted at high, low, and ambient temperatures. Results showed that neoprene was entirely satisfactory in terms of both the quality of the bond between propellant and liner and the ability of the charge to resist extreme temperatures.¹⁰

But another drawback became apparent: the method of manufacturing experimental neoprene propellant was not applicable to mass production. To incorporate the granular oxidizer into the propellant, it was necessary to soften the solid, raw neoprene fuel and then knead it like dough. In test batches made at JPL, this was accomplished by a costly and complicated three-step operation involving large roller mills, heavy steel molds, and high curing temperatures. Cost was virtually no object for these small batches, but mass production by this method would have been time-consuming and required exceptionally heavy, prohibitively expensive equipment. Seeking to eliminate these undesirable features, Bartley and his colleagues in the fall of 1945 found an alternate method of fabricating the neoprene charges.¹¹

The neoprene fabrication problem was solved in a most unexpected way. By now, fairly knowledgeable about the emerging science of synthetic rubber chemistry, Bartley concluded that many of the undesirable features of neoprene

propellant manufacture could be eliminated by utilizing a reactive plasticizer which would convert the solid neoprene into a liquid or paste during processing and thus eliminate the need for the heavy and expensive processing equipment. In search of this substance, or perhaps a liquid substitute for solid neoprene, Bartley toured various rubber industries on the West Coast during the summer of 1945. On one of these visits in July, Bartley met Frank M. McMillan, a polymer expert with the Shell Development Company in Emeryville, California. Like many others Bartley had interrogated, McMillan knew of several conventional plasticizers for neoprene, but none of these substances would alter the neoprene in the way and to the degree needed to simplify the neoprene propellant manufacture. When Bartley inquired if there were a possible liquid substitute for solid neoprene, McMillan suggested a synthetic polysulfide polymer called LP-2 produced by the Thiokol Chemical Corporation, and he directed Bartley to Walter Boswell, Thiokol's West Coast sales representative.

McMillan's tip proved invaluable to Bartley's research. As produced by Thiokol, LP-2 was an amber liquid polysulfide compound which became an elastomeric solid upon the addition of a polymerizer. In this form it was widely used in 1945 for such applications as the sealing of aircraft fuel tanks. Bartley reasoned that if a granular oxidizer could be incorporated into the mix before the polysulfide solidified, the result would be a solid propellant based on the burning of the polysulfide as fuel. A propellant based on LP-2, therefore, held great potential, since its manufacture did not involve any of the problems experienced in the manufacture of neoprene. Eager to test the bonding and ballistic properties of LP-2, Bartley instructed Settlemire to obtain a small quantity of the substance from Boswell.¹²

Tests of a propellant made from this sample by Settlemire in August 1945 were for the most part successful. They indicated that propellants made from this new substance would exhibit good performance at both high and low temperatures, have excellent bonding properties, and burn steadily at very low chamber pressures. Moreover, the tests indicated that fabrication of satisfactory rocket motor charges, or "grains", as they were called in the industry, would be both simple and inexpensive. Over the following two years, from mid-1945 to mid-1947, research on solid polysulfide propellants expanded steadily at JPL as Bartley's group tried to refine and perfect the new propellant and determine its physical and ballistic properties.

Though many problems surfaced during the initial research, all proved surmountable. Polysulfide solid propellants containing some additives, it was found, cured too quickly. Still others would not cure at all; they remained liquid indefinitely. It was also discovered that humidity played a part in the rate of curing, and so moisture had to be controlled. Polysulfide propellants using only the readily-available potassium perchlorate as oxidizer eroded nozzles excessively. When used as a liner, the polysulfide fuel material was found to be too thin when prepared in the usual manner, so a new liner processing technique had to be developed. In addition, the charge and the liner had to be cured simultaneously, rather than sequentially, so that proper bonding between them would occur. By various means, through empirical research, all of these problems were overcome.¹³

One very serious problem persisted, however. The "coning" phenomenon observed in conventional end-burning motors seemed immune to a technical solution. In November 1945, experiments showed that the chamber pressure of cigarette burning polysulfide charges rose steadily for a brief period before stabilizing at a higher-than-predicted level. In other words, the charges burned "progressively" for a while and then burned "neutrally." Utilizing the von Kármán-Malina theoretical analysis of 1940, which predicted that progressive burning indicated an increase in the burning surface area (assuming the nozzle throat area was constant and the propellant did not crack), Bartley's section surmised that the initially flat burning surface of each charge was transformed during firing into a convex cone. The burning surface area, then, grew steadily as the cone emerged, causing the progressiveness; once the cone was formed, however, burning became neutral. To test this, burning was artificially stopped midway through the firing of several polysulfide motors and the charge was inspected visually; as expected, a cone had formed at the exposed end of the cigarette charge.¹⁴

Several explanations for the coning phenomenon were advanced. Some of the engineers reasoned that an inferior bond between the propellant and the liner was somehow causing accelerated burning at the periphery of the charge. Others attributed the discrepancy to differences between the curing of the polysulfide at the edge of the grain and the curing at the center. The higher burning rate at the rim was also blamed on a proportionately higher concentration of either air bubbles or oxidizer at the periphery than at the center of the grain. Finally, some claimed that the liner conducted heat down the side of the charge, prematurely igniting the adjacent propellant.¹⁵

Investigation of these hypotheses was expensive, time-consuming, and only marginally successful. Research devoted to the coning phenomenon dragged on through the fall of 1947, when it was abandoned because other, more promising projects drew attention away from it. And, although several of the suggested causes of coning were proven to contribute to the problem, coning persisted through all of the remedies tried, albeit to a degree that decreased with time. At the time the coning investigation was discontinued, the best solution to the problem was to accept the phenomenon as inevitable, and manufacture the grain complete with a cone of the right shape to eliminate the progressive burning associated with its formation.¹⁶

Despite any delay they may have caused, the coning investigations moved JPL closer to the Sergeant missile powerplant. First, the accelerated activity on this problem required the expansion of the size and sophistication of the solid propellant research facilities at JPL. In particular, new personnel were acquired to work with the new propellant. Most notable among them, John I. Shafer, a mathematically-inclined design engineer who came to JPL with a commitment to large solid propellant rockets, and Henry Lawrence Thackwell, Jr., an aircraft structures expert; Thackwell was converted to big solids after discussing the state of the art with Shafer during his first week at the Laboratory. Second, the coning work provided voluminous data on the new polysulfide propellants; as Bartley, Shafer, and Thackwell became more familiar with this new group of compounds, they became con-

vinced that polysulfides held great potential for use in very large motors. Third, back in February 1946, experiments began with tubular, or unrestricted, charges of polysulfide rather than the usual cigarette, or restricted, charges in an effort to avoid the coning that occurred in the cigarette shape.¹⁷ Engineers found that the tubular charges, a common shape for the time, had a higher impulse-weight ratio than expected, exhibited no coning, and could be made to compete favorably with the standard asphalt JATOs produced at Aerojet. This new line of research led to investigations of other new grain designs for the polysulfide propellants and it eventually eclipsed all of the research on coning.

At JPL, by March 1947, all of these elements converged to generate the self-conscious development of large solid motors. Army Ordnance, by this time very much interested in checking the adaptability of Thiokol propellants for use in high-thrust, short-duration boosters, requested that the JPL Solid Propellant Rockets Section begin research into the "possibility" of large solid-propellant motors. In addition, the Navy expressed interest in using a polysulfide propellant in a booster for its Bumblebee Project; this project, which ultimately led to the Polaris missile, was only one of the many ongoing solid-propellant powerplant projects then in progress in America and elsewhere, was one of the earliest to tap the developments at JPL, and it stimulated further interest in the polysulfide work.

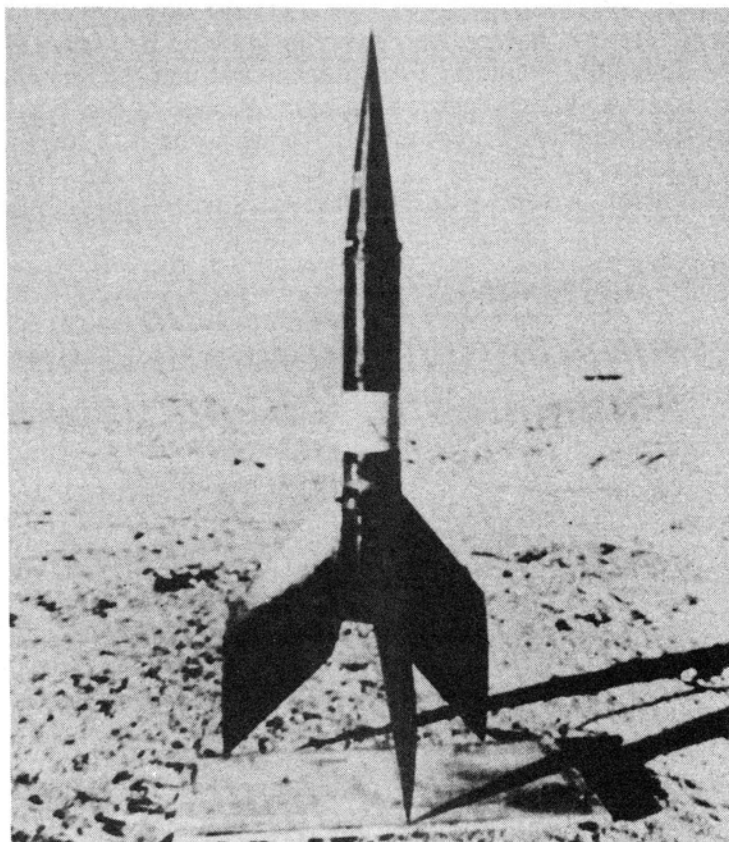


Figure 6 The Thunderbird experimental rocket.

Although most of the ballistic and physical properties of polysulfide propellants had been determined by early 1947, it was still unclear whether these rubbery compounds could withstand the stress of high acceleration at launch. Shafer and Thackwell, who had just arrived at JPL, saw these events as an immediate opportunity to branch out into the development of large solid propellant motors. They used the Army request as authorization and the Navy request as justification for the development of a six-inch-diameter high-acceleration test vehicle called "Thunderbird" (Figure 6).¹⁸

Officially known as the Solid-Propellant Flight-Test Booster Rocket, Thunderbird was unique. Its official mission was to test the ability of polysulfide 3 propellants to withstand the stress of high acceleration, and it was designed to produce an unprecedented acceleration in excess of 120 g, or 120 times the acceleration of gravity. But more important, in the eyes of Shafer and Thackwell at least, Thunderbird represented a positive step toward very large solid-propellant rockets, for in addition to the new polysulfides, it also incorporated a new design: the internal-burning star grain.

PART IV

Although new to JPL in 1947, the idea of an internal-burning star grain design was quite a mature one, having been invented in Great Britain in the late 1930's. In 1935, as one method of preparing for a possible war with Germany, the British War Office established a military rocket development team at the Woolwich Royal Arsenal called the Reaction Group. Under the leadership of Alwyn Douglas Crow, Director of Research at the Arsenal, the Group investigated a variety of rockets for military applications. An anti-aircraft rocket was the top priority item, and the star design was one result of that anti-aircraft rocket research.¹⁹

Working on a shoestring budget and under a growing threat of German air attack, the Group chose limited objectives for their anti-aircraft rocket research. At first only one weapon, a two-inch rocket, was selected for development, mainly because its calculated performance matched that of existing three-inch anti-aircraft guns which were in short supply. Cordite, a brittle solid propellant, was employed because of its ready availability and high energy content. A quantity of thin steel tubes were pirated from another application for use as rocket motor cases.

The two-inch cases presented an immediate problem to the British designers. Because the tubing was so thin, it had little chance of withstanding direct contact with the hot exhaust gases for the duration of burning; therefore, they sought a design that would provide insulation of the chamber walls from the products of combustion. The design eventually adopted was the internal burning star grain, so called because it burned on the inside only along a longitudinal star-shaped perforation (Figures 7 and 8). Its inventor, Harold James Pool, was an imaginative British government chemist who had been associated with cordite research since 1920.²⁰ The diameter of the extruded cordite star grain was slightly less than the inside diameter of the rocket case, and the space between the charge and the tube was filled with a thermoplastic cellulose acetate seal which bonded to both the

charge and the tube. Since combustion occurred only within and along the star perforation, the steel case was insulated from the high heat inside the motor.²¹

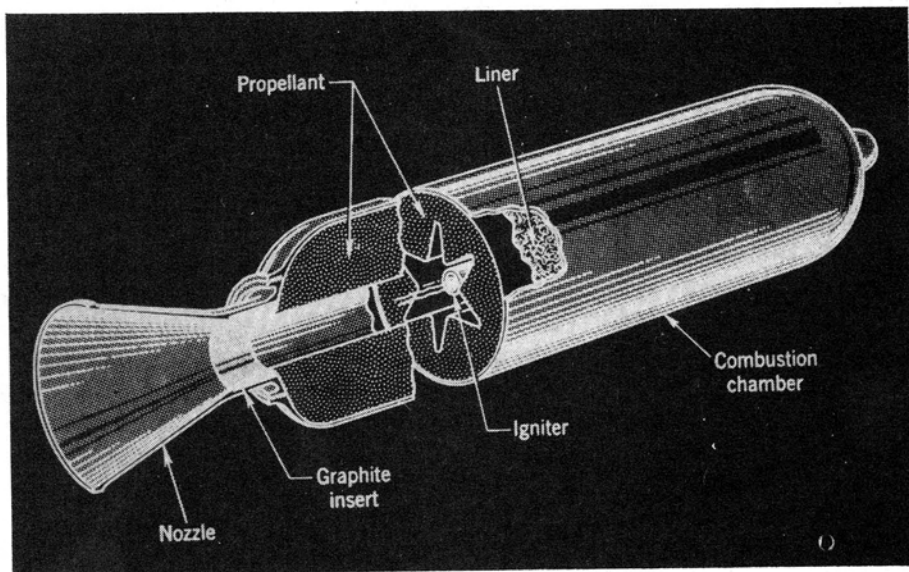


Figure 7 Cutaway sketch of a typical case-bonded internal-burning rocket of modern design.

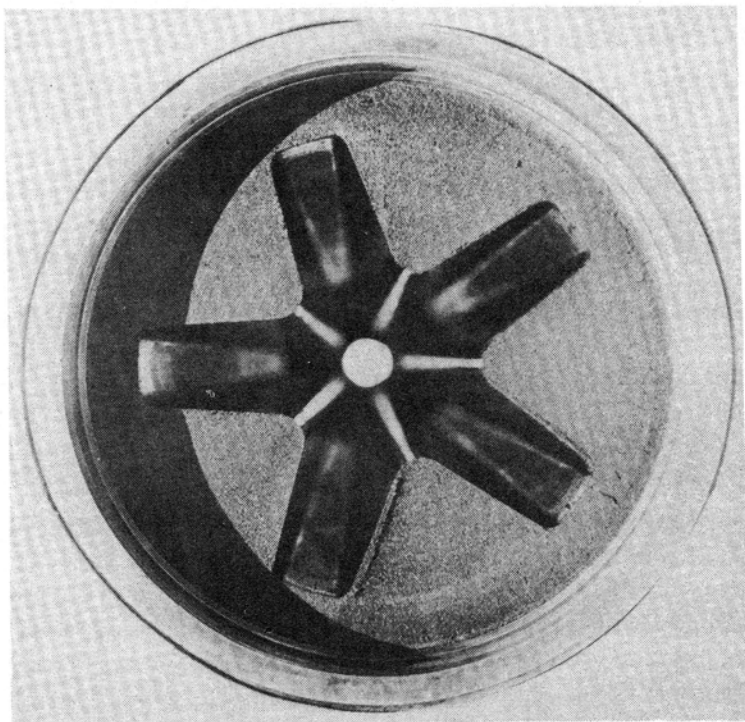


Figure 8 Typical cross-section of a case-bonded internal-burning rocket of modern design.

From a theoretical standpoint, the star design had many advantages. First, it insulated the chamber walls, and case materials did not need to be heat-resistant. Second, it provided a high and nearly constant thrust because the relatively large burning surface area of this design remained constant with time as the initially star-shaped hole burned away and became nearly cylindrical. Third, the design permitted the loading of most of the volume of the combustion chamber with propellant, thereby insuring a greater total impulse for a given propellant and a given overall diameter and length than with most other charge designs.

Preliminary firing trials conducted with a rocket incorporating the new star design during late 1935 demonstrated promising, reliable performance (Figure 9). In later tests, however, the case-bonded prototype began failing. British researchers discovered that nitroglycerin from the extruded cordite grain was being absorbed by the thermoplastic seal, causing it to deteriorate while stored. In addition, the seal became fluid at high ambient temperatures, while at low temperatures it lacked plasticity and became tacky. These adverse conditions resulted in insufficient insulation of the chamber walls on the one hand, slippage of the grain under acceleration on the other, or both, with motor failure the outcome. No technical solution could be found for these problems, and the internal burning star design was abandoned in late 1937 in favor of a more conventional burning arrangement which, although less efficient, could be readied for production on short notice.

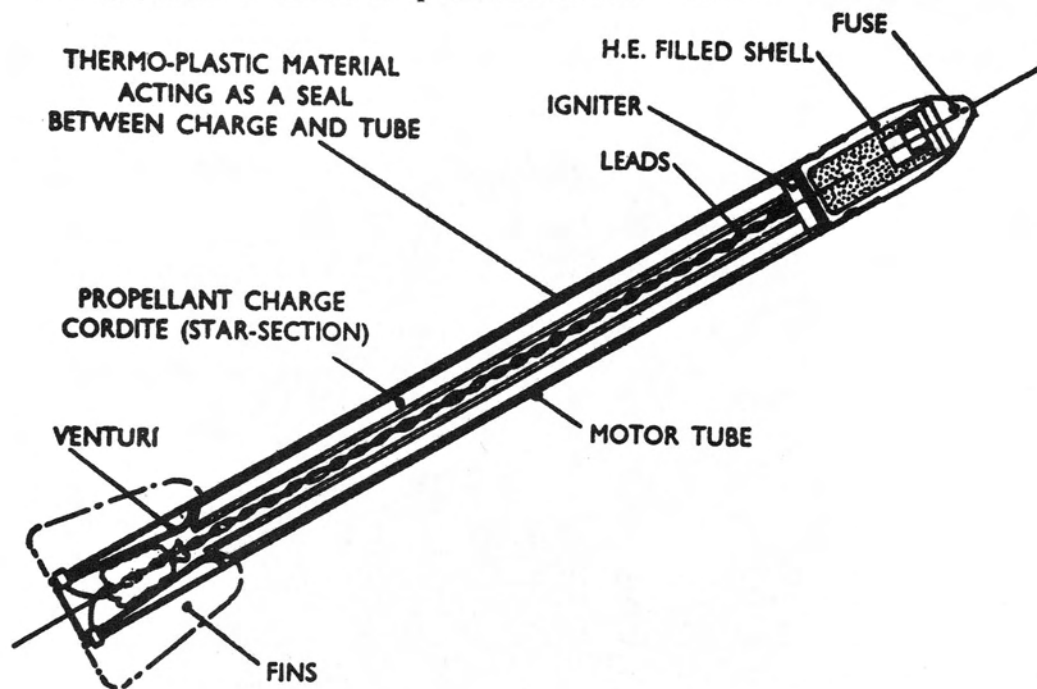


Figure 9 Two-inch prototype British anti-aircraft rocket tested in late 1935; propellant was extruded in an internal-burning star configuration (British Crown copyright, reproduced by permission of Her Majesty's Stationery Office and the Institute of Mechanical Engineers).

Although of no immediate practical usefulness, the British continued to investigate the internal-burning star as a promising idea. While Crow's group was involved with the more mundane and empirical development of mass-produced cordite anti-aircraft rockets between 1937 and 1940, Poole designed various internal burning grain configurations, including those with 3-, 8-, 10-, and 12-pointed star perforations. Using simple geometric analysis, he proved that these designs, theoretically at least, would maintain a nearly constant burning surface area during firing. Although the von Kármán-Malina analysis had not yet been done, he apparently took it for granted that a constant burning surface area was a prerequisite for constant thrust. In April 1941, Poole's investigations were summarized in a brief ten-page report.²²

Before the end of World War II, word of the star-shape had reached the United States. Through channels established in 1940, the document by Poole, along with other British reports dealing with the star design,²³ was distributed to several American jet propulsion facilities working on military projects. In March 1945, the Allegany Ballistics Laboratory (ABL) in Pinto, West Virginia, initiated development of a high-velocity rocket called Vicar with a star grain adapted from Poole's work. Although the Vicar project was never completed, the Curate, a scaled-down version of the Vicar, was flight-tested successfully, and documentation of the unfinished research was published. According to ABL, this was the first time the star grain was used in America: citing the original summary by Poole, the Vicar final report stated that "the star-center granulation was developed by the British for use in long-burning rockets propelling mine-clearing devices [sic], but has not been used hitherto in this country."²⁴

Shortly after the Vicar and Curate work was terminated at ABL in November 1945, the analysis that had gone into the Vicar charge design was consolidated into a technical memorandum written by John Beek, the Vicar project manager, and a colleague, Henry Siller. This memorandum reached JPL as an appendix to another document intended as an introductory text on the design of solid propellant rocket charges.²⁵ Containing general design equations for constructing star grains, this text served as the principal reference for constructing solid propellant charges with a star geometry at JPL for the rest of the 1940's. Bartley had first learned of the star design in late 1946 by reading of it in a British report, and he instructed Shafer to investigate the work. At first using his own calculations, and later, the Beek and Siller equations, Shafer derived a number of star designs in 1947 and in later years.²⁶

The star design was perfectly compatible with the earlier solid propellant achievements at JPL. Because it maintained a more-or-less constant burning surface area during firing (thus satisfying the requirements of the von Kármán-Malina theory), it could be used in a long-burning rocket. The gap-filling problem that plagued the British in 1936 was eliminated by the simple technique of casting the propellant in the case and bonding the charge directly to the chamber walls--a technique now commonly known as case-bonding. Finally, a polysulfide charge cast in this design maintained the advantages of the polysulfide, namely, ease of manufacture, storability, and the ability to withstand adverse ambient temperatures. For

Shafer, Thackwell, and Bartley, all of these technical properties translated into a forceful conclusion: polysulfides and the star design made possible a practical, large, solid-propellant rocket.

The introduction of the star grain at JPL in 1947 made the Thunderbird project doubly significant. Not only was Thunderbird (Figure 6) an opportunity for Shafer and Thackwell to expand their experiments to hardware development, it was also a first opportunity to marry polysulfides to the star design in a prototype of the modern solid combination. Indeed, Thunderbird was the first polysulfide rocket with a star grain to be flight-tested. These Thunderbird tests, conducted in late 1947 and early 1948, proved highly successful. And these successes tremendously accelerated the interest at JPL of Bartley, Shafer, and Thackwell in large solid rocket development.²⁷

Further encouragement was soon at hand. The Hughes Aircraft Company, in need of a booster for an air-to-air missile they had named Falcon, adapted Thunderbird to their needs in 1947, making Falcon the first operational polysulfide missile weapon. Shafer, meanwhile, applied the polysulfide star design to the spin rockets for General Electric's Bumper vehicle, a two-stage combination of the V-2 and the WAC Corporal that two years later set a historic altitude record.²⁸ Each application brought more experience with the new tandem configuration of polysulfide and star, and added impetus for more research on still larger vehicles. By mid-1947, the stage was set for the new, large, solid rocket.

PART V

Until mid-1947, all of the solid propellant development work at JPL had been directed either toward improving rockets for JATO and other small booster-related applications, or for boosters several inches in diameter and of admittedly high thrust, but with exceedingly short burning durations. Now, suddenly, very large, long-duration solid propellant missiles appeared to be a distinct possibility in the very near future. John Shafer was the first to grasp the possibility apparent in the polysulfide, star-grain, Thunderbird rocket. After laboratory tests on the Thunderbird motor began in June, he speculated on a polysulfide solid-propellant rocket the size of the liquid-propellant German V-2. During his spare time, Shafer analyzed the performance of his theoretical rocket and found, on paper at least, that his hypothetical rocket vehicle could deliver a nine-ton payload as far as the German V-2 could deliver a one-ton payload! Shafer's colleagues, especially Martin Summerfield, then Chief of the Rockets and Materials division at JPL, were initially and understandably skeptical of these astounding findings, but checks of his calculations verified their accuracy and converted them to believers.²⁹

Shafer's preliminary analysis, nonetheless, increased the enthusiasm for large solids shared by Thackwell and Bartley, and precipitated a more formal study of Shafer's work. Released in October 1947, JPL Memorandum No. 4-17, *The Applicability of Solid Propellants to High-Performance Rocket Vehicles* discussed the design of a high-altitude sounding rocket called the XSPV (experimental solid-propellant vehicle), a proposed 12-inch diameter solid rocket with a case-bonded

internal-burning polysulfide charge--the first proposal for a polysulfide design of such size (Figure 10). More sedate than Shafer's original calculations, the memo affirmed that the XSPV could carry a 25-pound payload to an altitude of 810,000 feet, nearly three times the altitude calculated for a similar payload boosted by a contemporary liquid propellant rocket of similar size, JPL's WAC Corporal B.³⁰

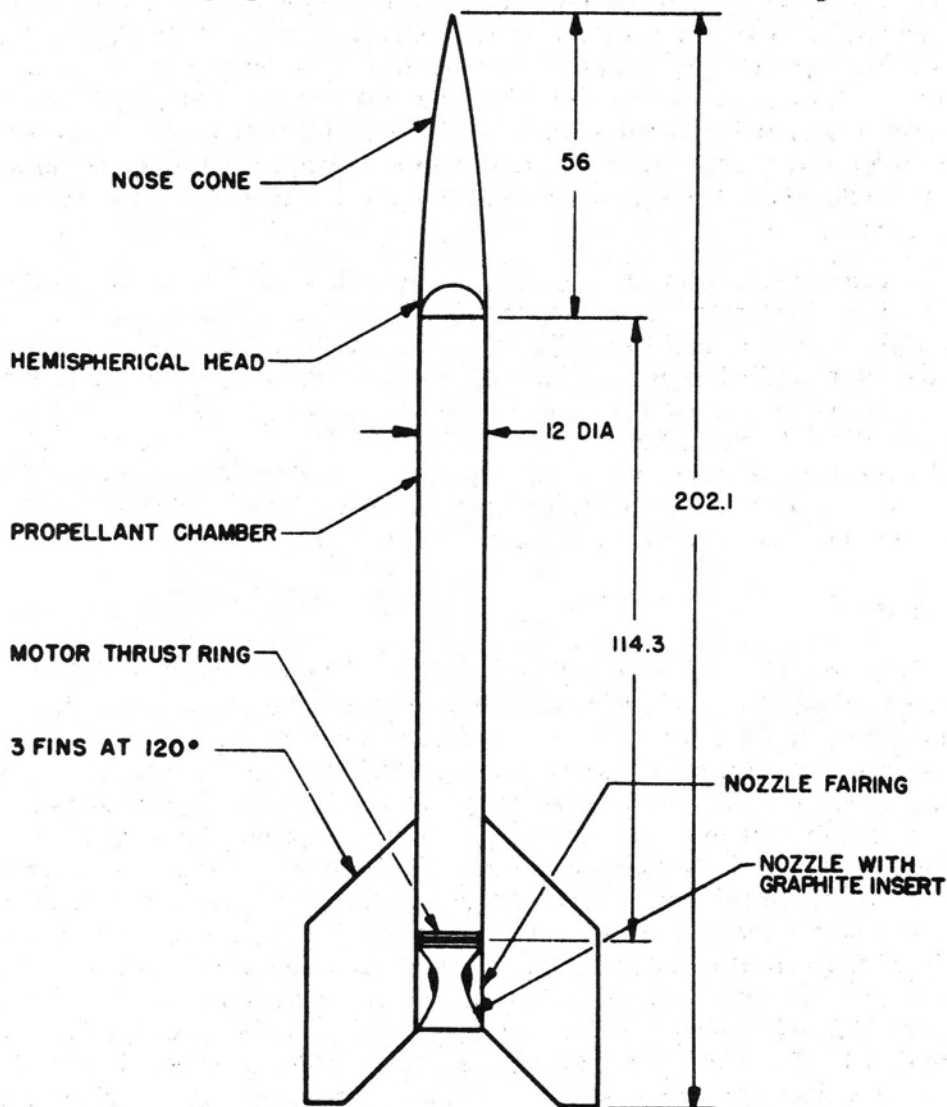


Figure 10 The XSPV solid-propellant sounding rocket.

Confirmation of these astounding calculations proceeded apace. In April 1948, JPL released Memorandum No. 4-25, *The Applicability of Solid Propellants to Rocket Vehicles of V-2 Size and Performance*. More ambitious than the first study, this second report confirmed Shafer's original V-2 calculations, expanding the earlier

design study to consider large solid rockets with what were then incredible diameters of 34- and 60-inches.³¹ Besides formulating long-range plans and legitimizing the commitment of Shafer, Thackwell, and others to the ambitious development of large solid-propellant rockets, these two reports served as proposals for the next stage of polysulfide rocket development and justification for detailed design studies on a large polysulfide vehicle akin to the XSPV.

Enticed by these findings and encouraged by the promotional zeal of Shafer and Thackwell, Army Ordnance authorized development of a test vehicle similar to the XSPV late in the spring of 1948. Now called Sergeant, but remembered by all concerned as the Sergeant sounding rocket to distinguish it from the larger, later Sergeant missile, this 15-inch-diameter vehicle was considered by those who built it to be an ambitious step forward in the state of the art (Figure 11). Engineers designed the vehicle to have a diameter about twice that of existing solid propellant motors, use an unprecedently thin steel case (0.065 in.), and attain an altitude of up to 700,000 feet with a 50-pound payload. In addition, Sergeant was to carry instrumentation that would telemeter data on motor performance during flight. (The autopilot designed for this system, incidentally, was later adapted for use on the Corporal missile.) In sum, it was a giant first step into large solid motor development.³²

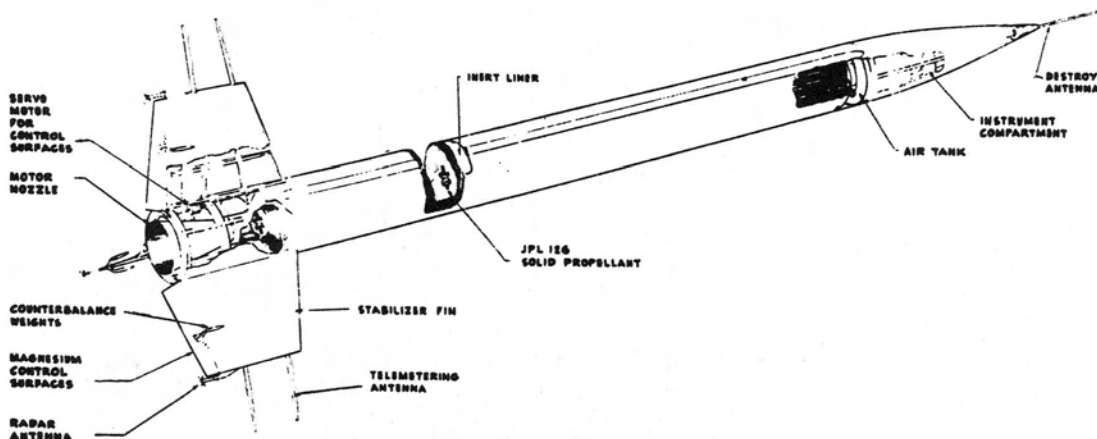


Figure 11 The Sergeant sounding rocket.

But it was too big a step from a technical standpoint. Beginning with tests of scaled-down models, the Sergeant project graduated to full-scale static tests of a version of the motor having a thick case in February 1949. Up to this point the program was successful, proving in the process that a polysulfide grain of 15-inch diameter could support itself. But in the next phase, static tests of the motor incorporating the steel case with only a 0.065-inch diameter resulted in repeated explosive failures. Examination of fragments of the exploded motors showed that burning had occurred within cracks which had developed between the points of the

star perforation and the chamber wall; the problem was one of excessive efficiency expected from the design, not one of excessive size.³³

Still, the problem was serious. After the twelfth full-scale static-test motor exploded in April 27, 1950, a disgusted JPL Director, Louis G. Dunn, wary of the seemingly wild-eyed promoters in Bartley's solid propellant section, cancelled all further development of the Sergeant sounding rocket and reduced work on solid propellant motors at the Laboratory to a more conventional role of fundamental research.³⁴

Thackwell, now one of the most outspoken supporters of the Sergeant sounding rocket at JPL, was greatly agitated by this policy decision. No sooner had Dunn ordered termination of the project than the cause of the disastrous cracking phenomenon was found: internal stress produced by the high chamber pressure, was simply too great for the thin-walled steel case, which expanded under the pressure, strained the propellant charge, thus creating the cracks. The solution involved reversion to a thicker case, development of a more elastic propellant, and alteration of the star perforation to relieve stress points. But that course and further testing at JPL were now precluded. Thackwell could not accept the cancellation of this work, especially when he felt he was so close to success; his solution was to relocate.³⁵

Taking his commitment to big solids and all he had learned about such vehicles with him in 1950, Thackwell accepted employment with the Redstone Division of the Thiokol Corporation, the manufacturers of polysulfide polymers. There he urged development of a large polysulfide motor with slightly lower performance requirements than those of the Sergeant sounding rocket. Located at the Redstone Arsenal (then the center of large rocket development in the U.S.), and basking in the prosperity that followed the marriage of polysulfide to solid propellants at JPL, Thiokol management eagerly supported Thackwell's plans. Back on the West Coast, now out of the large solid motor development business, JPL engineers concentrated on converting their liquid propellant Corporal research vehicle into a guided missile for the U.S. Army.

In Pennsylvania, meantime, the General Electric Company (GE) encountered some minor difficulties with its liquid propellant Hermes A2 rocket. Sensing that these troubles might afford an opportunity to see a solid motor development program begin--especially because such a program promised a cheaper missile with a simpler guidance system--Thackwell contacted Richard W. Porter, then GE project manager on Hermes. Porter absorbed Thackwell's praise of solids and decided to try them; together they drew up a proposal for huge solid propellant vehicle called RV-A-10 to replace the liquid A2 Hermes. Army Ordnance perceived that the RV-A-10 would demonstrate a significant advance in rocket weapons design above and beyond the liquid propellant Corporal. Among other virtues, the field logistics for an operational version of RV-A-10 would be far simpler and less costly than those for the liquid-propellant Corporal. Ordnance quickly approved GE-Thiokol development of the RV-A-10.³⁶

RV-A-10 embodied both advanced and conservative features at the same time (Figure 12). With a diameter of 31 inches, twice that of the Sergeant sounding rock-

et, it was advanced for its time by anyone's standards. Moreover, with an overall length of 244 inches and a total propellant weight of almost 5000 pounds, RV-A-10 could deliver a 1500-pound payload to a range of 75 nautical miles, an astounding feat for the day. To avoid the cracking problems experienced with the Sergeant sounding rocket, on the other hand, RV-A-10 had to be somewhat conservative in design; thus, it featured a 0.2-inch-thick steel case (which, although not excessive, was much thicker than the 0.065-inch case for the flight-weight Sergeant), a more elastic polysulfide propellant than that used in Sergeant, and a star perforation designed not only for performance but also to relieve stress points. In short, the RV-A-10 design compromised somewhat on performance to ensure success, but it was large enough in size to guarantee impressive results.

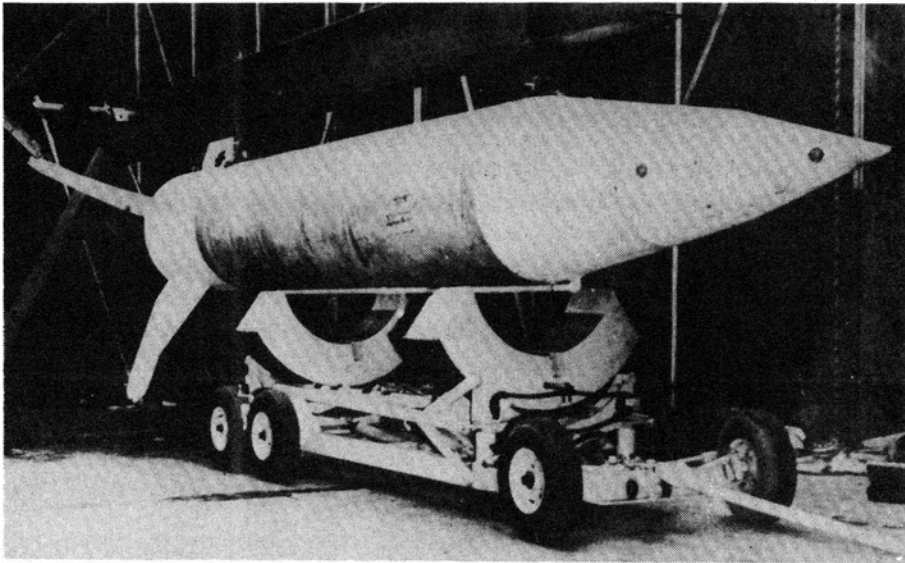


Figure 12 The RV-A-10 rocket (courtesy of Thiokol Chemical Corporation).

The conservatism paid off. Development of the RV-A-10, in contrast to that of the 15-inch Sergeant, was almost trouble-free. The only serious problem, a resonant burning phenomenon, was eliminated by modifying the propellant composition. During February-March 1953, four RV-A-10 vehicles were successfully launched and flight-tested from the Air Force Missile Test Center (AFMTC) at Cape Canaveral, Florida.³⁷

The success of the RV-A-10 test rockets in 1953 marked the beginning of the era of large solid-propellant rocket powerplants. Although crude and inefficient by present standards, RV-A-10 was the first flight-proven solid-propellant rocket

powerplant suitable for use as a long-range guided missile sustainer. Its successful flight tests stimulated further military development.

PART VI

The Sergeant missile followed closely on the heels of the RV-A-10, but the scene of action now returned to JPL. From 1952 through 1954, the General Electric Company prepared several proposals for a military missile based on the RV-A-10 design, called Dobbin and Phoenix. Although Army Ordnance remained most interested in developing a solid-propellant long-range missile, it did not accept the proposal, for reasons apparently unrelated to a RV-A-10 development.³⁸ A few weeks before the first RV-A-10 test flight, in January 1953, Ordnance asked JPL to study the feasibility of a tactical solid-propellant guided missile to replace the Army's temperamental liquid-propellant Corporal, then being readied for deployment in Europe. The resultant study, of course, indicated that such a vehicle was technically practical, and Army Ordnance requested from JPL a proposal for development of the new weapon.³⁹

Led by James D. Burke, a six-man design team prepared the JPL proposal between mid-1953 and the spring of 1954. It contained a preliminary study of a rocket weapon based on the RV-A-10, but using a lighter stainless-steel case about half as thick as the RV-A-10 case. Longer and heavier, but having the same diameter as the RV-A-10, the new vehicle was called the Sergeant missile. With Ordnance approval, it was developed between April 1954 and June 1960 as a surface-to-surface tactical guided missile. With a total propellant weight of over 5000 pounds, the Sergeant motor combined a case-bonded internal-burning star design with a polysulfide propellant.⁴⁰ Withal, the historical origins of the Sergeant missile powerplant can be traced through the work at GE and JPL, and the British innovations that dated back to 1935.

PART VII

By the time the Sergeant missile became operational in 1961, the technical breakthroughs in solid-propellant motor design had been incorporated in still more exciting vehicles. The solid-propellant Polaris and Minuteman intercontinental ballistic missiles were in testing. Preliminary planning for the giant, segmented solid motors of the later 1960s were already underway, and the Sergeant missile powerplant was no longer a novelty.

Although many critical problems had to be overcome on the road to the Sergeant missile, by far the most complex was the integration of all the elements that comprised the modern gestalt: castable composite propellant, case-bonding, an internal-burning cavity, and a thin case, insulated and supported by the grain. Many engineers successfully demonstrated the feasibility of some or all of these features in the 1940's, but it appears that Shafer and Thackwell were the first to realize the full scaling potential of their combination into a unified design (as demonstrated by

the XSPV design studies of 1947), and to act upon this realization (by developing the Thunderbird and the Sergeant sounding rocket).

The process of realizing the potential of large solid rocket motors illustrates a seemingly basic element of modern technological development. Although most JPL research drew heavily upon the preceding developments at the laboratory, it also incorporated, on a regular basis, salient features from among diverse experimental studies conducted in many other locales. In particular, JPL engineers often adapted related developments, such as the Thiokol polymers, to the JPL research at hand. Frequent searches outside the state of the art of the technological discipline under study, in the hope of finding solutions to specific problems, thus appears highly conducive to conceptual advances. The Sergeant missile powerplant bespoke an important conceptual breakthrough in solid motor design, and represented the end of one chapter in the history of rocket technology. It should also remind modern engineers that the blending of theoretical and applied research, and the adaptation of the successes of others, is indeed sound policy.

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END NOTE

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