Chapter III

Crafting Rockets and Rovers: Apollo Engineering Achievements

The most dramatic events at Marshall during the Apollo Program were the static firings of the enormous first stage of a Saturn V rocket. The five F–1 engines of the S–IC stage produced over 7.5 million pounds of thrust, enough to generate 119 million kilowatts, twice the power of all hydroelectric turbines on American rivers. The stage burned 4 million pounds of fuel in two-and-a-half minutes, and three trucks could park side by side in its fuel tank. The engines had valves as big as suitcases and pumps as big as refrigerators.[1]

First S–IC full five engines firing on 16 April 1965.

Test structures for the stage and its engine cluster were also gigantic. The S–IC Test Stand, first used by Marshall's Test Laboratory in April 1965, had a superstructure and derrick that rose 406 feet. Built massive to secure the huge rocket stage, it was anchored in bedrock 45 feet below ground and had as much concrete underground as above.[2] To dissipate heat and dampen sound, the stand's pumps fed 320,000 gallons of water per second from an adjacent reservoir into the flame bucket. Each test generated a white cloud of vapor and a thunderous roar that echoed (and even shook buildings) throughout Huntsville. Engineers claimed that as a noisemaker the S–IC was third only to atomic bomb blasts and the Great Siberian Meteor of 1883. One Marshall official recalled that before the first test people feared broken windows at the Center; unable to finish an important telephone call when the test began, he crawled under his desk and shouted in the receiver.[3] Von Braun liked to interrupt meetings so that everyone could witness the spectacle from the top floor of Marshall's administration building.

The sound and fury of such tests bore witness to Marshall's contributions to the space program in the 1960s. The Center's laboratories helped design, develop, and test crucial hardware for the Mercury and Apollo programs. Marshall's project offices oversaw dozens of contractors and forged individual efforts into a collective whole. The Center's step-by-step efforts on space vehicles helped NASA achieve a series of "firsts" in space flight: the Mercury-Redstone boosters lifted American astronauts on their first suborbital rocket flights, the Saturn rockets powered humans on their first trips to the Moon, and the lunar roving vehicle (LRV) first transported people across its surface.

Mercury-Redstone

Marshall's initial triumphs as a NASA Center came in Project Mercury, America's first entry in the manned "space race" with the Soviet Union. The Center contributed Redstone boosters for the early flights, helped the STG with integration of the booster and crew capsule, and oversaw the launch process. Involvement in the program began in October 1958, when NASA and the Army Ordnance Missile Command agreed that the ABMA would provide 10 Redstone and 3 Jupiter missiles for the space program. In the next year ABMA modified the Redstones to prolong the time of engine burn. Working with the Chrysler Corporation, the prime contractor, and the Rocketdyne Division of North American Aviation, the engine contractor, ABMA personnel elongated the propellant tanks.

Modifying the Redstone tanks was straightforward, but "man-rating" the rocket was not. Man-rating meant verifying the rocket's safety for human flight. Although the Redstone had many successful launches as a ballistic missile, man-rating led to technical disputes between Huntsville personnel and the STG. Huntsville's experience with missiles led them to consider the "payload" as a passive package. But members of the STG were "old NACA hands" who were experienced with airplanes and pilots.

The contrasting perspectives of Marshall and the STG led to quarrels over automatic flight abort procedures. According to Joachim P. Kuettner, ABMA's and later Marshall's manager for Project Mercury, Huntsville preferred "positive redundancy" which provided for automatic aborts whenever required; automation would ensure astronaut safety by restricting his role. Kuettner thought the STG wanted "negative redundancy" which avoided aborts unless necessary; with more control, astronauts would have more opportunities to finish missions. Panels of technical experts from Marshall and the STG worked out the differences, balancing pilot safety and mission success, machine automation and human control. Their contrasting perspectives improved the Mercury design and helped ensure success, but put the program behind schedule.[4]

Delays came from other sources. The STG often changed its designs, forcing Marshall to adapt its work on the Redstone. The McDonnell Company, contractor for the Mercury spacecraft, fell behind, slowing Marshall's ability to integrate the hardware of spacecraft and Redstone. But the Center's extensive hardware testing also took longer than expected and caused delays.[5]

Unfortunately more delays came from the failure of the first flight test of Mercury-Redstone. The crewless launch of Mercury-Redstone 1 (MR–1) on 21 November 1960 began with the rocket engine burning normally. After a flight of a few inches, however, the engine abruptly shut off. MR–1 fell back on its pad, resting upright and inert but for an escape parachute which released from the capsule and flopped limply in the breeze. An investigation traced the engine failure to the booster's tail-plug prongs, which connected the booster via an electrical cord to ground equipment. The prongs were too short to compensate for changes in the payload and thrust of the modified Redstone, and the tail plug pulled out, prematurely turning off the engines.[6]

After the failure, and a malfunction which caused the MR–2 engine to operate at higher than planned thrust level, von Braun wanted to avoid unnecessary risks. He therefore insisted on one flawless Mercury-Redstone flight before any manned mission and convinced NASA to insert an extra "booster development" mission. This mission with a boilerplate Mercury spacecraft (MR–BD) flew successfully on 24 March 1961. The extra mission, however, pushed back the schedule for America's first manned Mercury-Redstone flight (MR–3) and allowed the Soviet Union to capture prestige with Yuri Gagarin's first orbital flight on 12 April. This Soviet triumph overshadowed the success enjoyed by the United States, NASA, and Marshall on 5 May 1961 with the suborbital flight of astronaut Alan Shepard aboard MR–3. The final Mercury-Redstone mission occurred in July.[7]

During these first steps in human space flight, Marshall experienced some problems that would recur in later programs and learned important lessons. Kuettner noted several difficulties in relations with the STG. He observed that the group's control over funds "resulted in a tight technical control of the total vehicle by the payload people." The group tried to tell Marshall what to do even though they had less experience in managing complex projects. Rather than directives coming from one Center, Kuettner thought that "broad program control" should come from NASA Headquarters or negotiations between Center directors.

Kuettner also expressed chagrin at how the STG and NASA had handled publicity and had failed to promote Marshall's role. "Handling of Public Information affairs," he lamented, "has been considered unfair by most every participant in this program."[8] Eberhard Rees, Marshall's deputy director for research and development, thought that STG publicity for Shepard's flight merely mentioned Marshall's role without praise. Rees wrote to von Braun that "this is significant how STG thinks. Under these conditions we can not work in the 'Manned Lunar Program.'"Von Braun responded, "I agree."[9]

Although wounded pride had caused Center personnel to blame the STG, larger circumstances explain Marshall's lack of celebrity. The media and the public idolized the STG's astronauts, seeing them as heroic explorers, but largely took for granted the more prosaic contributions of engineers and managers; unfortunately for Marshall, the Center had no astronauts. NASA used this public fascination with the astronauts to bolster its image, attract political support, and justify big budgets for human space flight. Consequently press coverage of MR–3 mentioned the "Old Reliable" Redstone but seldom attributed it to Marshall. Even the *Huntsville Times* lionized Shepard with very little mention of local people.[10]

Regardless of such slights, Marshall personnel had contributed to the success of Project Mercury. Moreover they had learned about man-rating rockets and working with another NASA Center, lessons they applied to the Saturn project.

"Stages to Saturn"

Marshall's primary effort in the 1960s was the design, development, and testing of the Saturn launch vehicles.[11] The work helped lead to the extraordinary first human explorations of the Moon.

The three basic Saturn configurations fit into the Center's conservative "building block concept" in which less powerful and sophisticated launch vehicles preceded and tested designs of more advanced models. The Saturn I, originally called the Juno V and Saturn C–1, was a two-stage booster used to test multi-engine clusters, to qualify Apollo spacecraft, and to launch the Highwater and Pegasus experiments. The Saturn IB, also called the C–1B and Uprated Saturn, had more advanced upper-stage engines than the Saturn I. NASA used it to continue propulsion and spacecraft testing, and to launch the Earth orbital missions in the Apollo and *Skylab* programs. By far the most powerful was the Saturn V, also known as the Saturn C–5. It was NASA's largest launch system, and its three stages propelled the Apollo lunar missions and the *Skylab* workshop.[12]

Building the Saturns was a tremendous challenge for the Marshall team. During the less than 10-minute burn of launch, the engines had to generate tremendous thrust. The rocket structure, with all its seams and connections, had to withstand changing stresses. All the mechanical and electrical systems had to work to near perfection. Any breakdown could result in a fiery disaster.

To avoid this fate, the Center and its contractors drew from their experience in military rocketry. Ancestors of the Saturns included the von Braun team's V–2 and the liquid-fueled military rockets that North American Aviation's Rocketdyne Division developed for the Navaho cruise missile. Lessons from the Air Force's Thor and Atlas and the Army's Redstone and Jupiter contributed to the Saturn's engine, fuel, guidance, and launchpad checkout systems. The Saturns, like the Navy Vanguard, used gimballed, or swiveling, engines to control flight direction. The engine that powered the Saturn V's first stage, Rocketdyne's mighty F–1, began as an Air Force research project. Drawing on this military technology, Marshall and its contractors transcended it by increasing rocket size and thrust, reducing the weight of components, improving reliability, raising engine pressures, and developing faster fuel pumps.[13]

The military influence was especially strong on the first stage of the Saturn I (called the S–1) because the Center's rocket experts largely designed and developed the S–1 while still a part of ABMA. In April 1957 the Army began studies of a super-Jupiter. Recognizing the potential political liabilities and financial costs of a new booster, the goal was to maximize lift but build on current technology. The plan called for using the H–1 engine, an improved version of Rocketdyne's Thor-Jupiter S–3D engine, in a "cluster" configuration of eight engines to achieve 1.5 million pounds of thrust. Clustering engines was an untried concept; von Braun recalled that skeptics doubted that eight engines could fire simultaneously and called the S–1 a "plumber's nightmare" and "Cluster's Last Stand." The vehicle's structure also used existing technology, positioning eight Redstone tanks around one Jupiter tank. Not only would this save money, but multiple fuel tanks offered technical advantages; easy dismantling and reassembly would facilitate transportation, its RP–1 kerosene fuel and its oxidizer would reside in different tanks, and the number of interior fuel slosh baffles would diminish.


Saturn second stage acceptance test.

Following the August 1958 authorization to develop the Saturn I first stage, ABMA built the first eight vehicles in-house and then the Chrysler Corporation took over the work. With these measures, work on the S–1 proceeded quickly. Marshall began static firing of the first test booster on 28 March 1960, only three years after the project's conception and 19 months after its authorization. An improved, more powerful version of the S–I, designated the S–IB, provided the first stage of the Saturn IB.[14]

Because the S–IV and its more advanced progeny, the S–IVB, were the upper stages for the Saturn missions, they were the next boosters completed. In 1959 ABMA's initial designs for an upper stage called for using current military boosters with conventional rocket fuel. But the Jupiter, Altas, and Titan lacked the power needed for high altitude second stages. Using them with the S–1, observed Willie Mrazek, director of the Structures and Mechanics Lab, "was like considering the purchase of a 5-ton truck for hauling a heavy load and finally deciding to merely load a wheelbarrow full of dirt." Army and NASA planners began considering more powerful, innovative engines with liquid hydrogen fuel. This fuel was extremely volatile and flammable and had to be controlled with great caution, but it could boost heavier payloads.[15]

The rocket engineers at ABMA and Marshall drew on the work of others with liquid hydrogen engines. The United States Navy and Air Force, the Jet Propulsion Laboratory, Aerojet Corporation, and especially NACA's Lewis Research Center had developed the technology in the 1940s and early 1950s. In the late 1950s the military contractor General Dynamics worked on the Centaur upper stage with liquid-hydrogen engines developed by Pratt and Whitney. Marshall took over management of the Centaur contract in July 1960 and in August had Pratt and Whitney begin upgrading its propulsion for the Saturn project. After Marshall finished its designs, the S–IV had a cluster of six Pratt and Whitney RL–10 engines in a vehicle built by Douglas Aircraft. The Center made major contributions by conducting metallurgy studies to guide the selection of materials for the fuel tanks.

The S–IVB emerged from NASA's quest for even more powerful upper stages. A propulsion study committee headed by Abe Silverstein recommended a liquid-hydrogen engine of 200,000 pounds of thrust, far above the RL–10's 15,000 pounds of thrust. Marshall worked on the design and awarded a research contract to Rocketdyne in 1960. The final configuration awaited the outcome of NASA mission planning, and in 1962 the agency decided on one J–2 engine for the S–IVB. To increase tank capacity, Douglas Aircraft would widen the S–IV frame by a meter in diameter. A major challenge was developing technology for restarting the S–IVB in orbit for the reboost to the Moon. Since the liquid fuel would float freely in the microgravity, the Center and its contractors devised systems to position the fuel in the tanks, using pressurized mechanisms and small rockets to give the stage an initial boost.[16]

The largest of the Saturn boosters was the S–IC, the first stage of the Saturn V. Huntsville's propulsion experts began preliminary designs in the late 1950s, choosing RP–1 kerosene fuel because it would require less tank volume. Initial plans called for using four F–1 engines, but early in 1960 as the projected weight of the Apollo spacecraft continued to grow, NASA's engineers decided to add a fifth engine. Marshall's robust rocket structure with heavy cross-beams made addition of the fifth engine possible. The lifting capacity of five engines would prove invaluable when the weight of Apollo payloads increased.[17]

Installing S–IC–T stage in S–IC Test Stand in March 1965.

In December 1961 Marshall selected Boeing as the prime contractor for the S–IC, and for several reasons the two quickly formed an intimate relationship. Closeness was easier because, unlike other Saturn contractors, Boeing worked in Huntsville with offices at the center and in a converted textile mill called the HIC Building (Huntsville Industrial Center). Even when work moved to the Michoud Assembly Facility and Mississippi Test Facility, Boeing remained at Marshall sites. Moreover early design and development occurred in-house at Marshall. There the Center directly managed Boeing's work, integrating contractor personnel into Marshall teams and only gradually giving

Saturn S–II stage arrives at Marshall.

them independence. When manufacturing began in 1963, the Center used Boeing tooling to make the first three test models.[18]

Technical challenges also brought Marshall and Boeing together. The S–IC was so large, 33 feet in diameter and over 130 feet long, that its construction required new manufacturing methods. For example its bulkheads needed welds dozens of yards long to join the thin aluminum walls. To solve this problem Marshall helped its contractor devise new welding and inspection techniques. Center personnel invented an electromagnetic hammer to remove distortions in the bulkheads created by welding. The hammer functioned without physical contact, and technicians showed off its operation by inserting tissue paper between the electromagnetic coil and the metal part and removing the paper unscathed. Marshall also helped devise x-ray systems for inspecting the welds.[19]

Marshall's in-house activities for the Boeing contract sometimes led to problems. NASA Headquarters initially questioned the amount of arsenal work. During a visit to Marshall in 1962, one headquarters official "stated repeatedly that he believes Marshall should de-emphasize more the in-house operations in connection with S–IC development" and let Boeing handle the job. Marshall managers explained that the arsenal system saved money and time by allowing work to proceed while the contractor upgraded its skills and NASA constructed the facilities at Michoud and in Mississippi. Two years later the intimate relationship made it difficult for the Center to hold Boeing responsible for cost overruns. Marshall had so dominated the S–IC project that it was as responsible for the overruns as Boeing; one internal Center memo admitted that Marshall had "imposed our experience on their [Boeing's] minds to the point of their losing their identity as an independent contractor." Looking back after 30 years, Dr. William Lucas, then chief of the engineering materials branch in the Propulsion and Vehicle Engineering Lab, argued that the arsenal system provided Boeing with help it needed to solve the novel technical problems created by the Apollo mission; "there was not a contractor workforce out there willing and able to do the job."[20]

Marshall also had an especially close technical relationship with Rocketdyne for the F–1 engine. Saviero "Sonny" Morea, Marshall's manager for the F–1, recalled that the Center "used to drive them bananas with our technical prowess" and that "sometimes we penetrated more deeply than they desired us to penetrate" until Marshall was in Rocketdyne's "drawers quite deeply." Morea thought the Center and its contractor needed such a "team relationship" to solve technical problems and meet the end-of-the-decade deadline.[21]

Although the F–1 lacked the sophistication of the J–2, its size and thrust created new difficulties before 1965. To generate its 1.5 million pounds of thrust, its turbopumps and fuel lines had to deliver precise amounts of RP–1 kerosene fuel and liquid oxygen (LOX) to the combustion chamber. For each second of the two-and-a-half-minute burn, pumps provided 2 metric tons of LOX at minus-300 degrees Fahrenheit and 1 metric ton of RP–1 at 60 degrees. During operation the turbopumps warmed to 1,200 degrees and the combustion chamber reached 5,000 degrees.

One of the most severe problems addressed during the development of the Saturn V program was the issue of combustion instabilities in the F–1 engine. Combustion instability resulted from destructive pressure oscillations found in the engine's high-pressure, high-performance combustion chambers. The problem was so severe that some development engines were lost due to heat loads on chamber walls and damage to the injector; in several cases, instability caused catastrophic loss of entire engines.

Marshall formed an "ad hoc" committee to solve the F–1 problems. The committee was made up of engineers and scientists from government agencies, industry, and universities; this approach of pulling together the right people and resources to solve such problems was a strong point of Marshall's approach during Saturn development. The "ad hoc" committee analyzed the problems and developed a test program to study alternative designs. They ignited small bombs in the engine exhaust to induce instability, and tested prototypes until they failed. After considerable trial-and-error engineering, they reached a robust design that could compensate for combustion instability. The solution was a set of baffles in the combustion chamber which dampened the acoustic oscillations if they began. The process took some time, and Marshall did not certify the engine until January 1965.[22]

The S–II stage was the last completed, and Marshall's relationship with North American Aviation, the prime contractor, was its most troubled of the Saturn era. The story of the S–II reveals what Marshall expected from its contractors and how the Center responded to problems.

The design for the S–II began in late 1959 when NASA's Silverstein propulsion committee recommended upper stages with liquid-hydrogen engines. ABMA, and later Marshall, began preliminary studies and in 1961 selected North American Aviation for the contract. Unfortunately, however, NASA's choices about Apollo missions and escalating concerns about payload weight increases in 1962 led to changes in the S–II's technical requirements. NASA chose a cluster of five J–2 liquid-hydrogen engines, and wanted both to increase size to accommodate more fuel and to contain weight to allow for greater payloads.

To meet the S–II's complex requirements, Marshall and North American had to overcome many challenges. To save weight, their design used a single bulkhead between the LOX and liquid-hydrogen tanks rather than two separate tanks. The common bulkhead, however, needed insulation to prevent the liquid-hydrogen from boiling away. The material for the tanks had to be lightweight and compatible with the fluids in them. Marshall chose a pre-existing aluminum alloy for the tanks that its developer said was impossible to weld. Even worse, long welds were required to join the segments of a stage 10 meters wide and 24 meters high. Marshall and its contractors therefore had to develop new welding and inspection technologies.[23]

North American Aviation began manufacturing the S–II in the fall of 1963, but quickly encountered problems. Recognizing the technical complexity of the project, Marshall nonetheless concluded that the primary problems were managerial. Indeed for the next three years, reports of Center officials offered a litany of North American's management weaknesses. They complained that the company lacked a management system necessary for a complex research and development project and so it could not integrate budgeting, engineering, manufacturing, quality control, and testing. This led to unclear authority, piecemeal design, communications failures, unanticipated problems, crash efforts, rework, haphazard documentation, cost overruns, schedule slips, and unresolved technical weaknesses. In one case, Marshall project officials were stunned to find that North American had purchased the same vehicle checkout system from the same subcontractor as had Douglas Aircraft, but had paid 70 percent more. From the Center's perspective, excessive pride and optimism made the company reluctant to accept Marshall's directions. James Odom, Marshall's chief engineer for the S–II, recalled that Marshall had more experience in welding large structures than its contractor, but the experts at North American doubted the Center's technical advice. In addition, Center officials believed that NASA's MSC contributed to the company's bad habits by lax management of North American's work on the Apollo Command Module.[24]

By spring 1965, the S–II had fallen so far behind that Marshall eliminated some test models so the contractor could work on flight stages. The structural failure of a stage during a load test in late September 1965, led General Edmund O'Connor, head of the Center's Industrial Operations, to warn von Braun that the project was "out of control" and "jeopardizing the Apollo Program." NASA Headquarters sent a team to investigate and advise. One Marshall engineer told the investigators that North American's "equipment is usually too complicated" and their work "is nearly always overpriced." "They accept direction readily if they agree with it. If they do not, they will stall, misunderstand, write, dither, and all the while continue along the same path until we are faced with a schedule impact if we force our position." Rees, the Center's technical deputy director, warned the company that failure to improve would result in transferal of the project to another contractor.[25]

Avoiding such a drastic step, Marshall sent managers and engineers to accelerate progress. North American changed project managers and reconfigured its managerial systems, but in May 1966 another stage was destroyed. Fortunately NASA's large Apollo budget and Marshall's arsenal system provided a wealth of money and expertise to throw at the problem. Even after 18 months of extensive assistance by Marshall, however, the S–II project remained in crisis. In December 1966 von Braun said the problems were "extremely urgent" and that Marshall would "apply whatever talent is necessary at whatever level, even at the expense of other Center programs." Finally, after the Apollo Command Module fire in January 1967, for which North American Aviation was the responsible contractor, NASA conducted another investigation and directed another project reorganization. The company added more talent to its NASA projects and another team from Marshall facilitated engineering changes and helped improve quality. During this time, Odom recalled, Marshall's Eberhard Rees told the team that "we will work 24 hours a day, 7 days a week, and if that is not sufficient, we will start working nights!" Although in August 1967 Center Director von Braun informed Headquarters that North American had "not yet demonstrated that it fully meets the standards expected of a NASA prime contractor," the first flight stages of the S–II were complete. By summer 1967 the stacking of the first Saturn V vehicles had begun in the assembly building at the Kennedy Space Center.[26]

In addition to working on the Saturn stages, Marshall people also labored over the vehicles' checkout and flight control systems. The checkout systems, which monitored the flight readiness of the vehicle on the launch pad, rested on military missile technology. The Center and its contractors advanced the state-of-the-art by automating more of the process with computers that read information from 5,000 data sensors on the vehicle.[27]

Marshall also helped design and develop the Instrument Unit (IU) that controlled the Saturn during launch. The Center, believing that an instrument unit provided redundancy, resisted efforts by the MSC for a single vehicle control system located in the Apollo spacecraft. Marshall's conservatism paid off when lightning struck AS–507 (Apollo 12) during launch; the spacecraft controls failed but the IU kept operating and NASA used its data to realign the guidance and control system in the command module. Located between the S–IVB and Apollo Service Module, the unit had systems for guidance and control, engine cutoff and stage separation, and data communication. Marshall began design and development as an in-house project, relying on German gyroscope technology, American electronics, and American military guidance systems like the Jupiter and Redstone. IBM became the contractor and manufactured the units at Huntsville's research park. The Center and its contractor improved guidance and control technology by using modular components, lightweight materials, microminature circuitry, and digital programming. When in 1965 the IU for the first Saturn IB launch (AS–201) fell behind schedule, Marshall and Boeing technicians jury-rigged a clean room on a barge, and continued work while chugging down the Tennessee and Mississippi Rivers.[28]

Before any Saturn stages reached Kennedy, Marshall and its contractors tested each one extensively in special facilities. Test stands stood in an irregular pattern around the East and West Test Areas. The largest was the S–IC Stand described earlier. The Static Test Tower had dual positions; it was constructed in 1951 to accommodate Redstones and Jupiters, modified in the 1960s for Saturn IB tests on one side, F–1 engine tests on the other, and reconfigured again in the 1970s for shuttle tests. A water-cooled bucket deflector absorbed the heat and sound of its exhaust. In one early test, however, enough acoustical energy bounced off low clouds to damage a Huntsville shopping mall, necessitating weather constraints on subsequent tests.[29]

Following successful static firing, the Saturn stages moved on to dynamic testing. Marshall engineers subjected each stage to a variety of stresses, such as the vibration induced by engine thrust and the sloshing of LOX fuel experienced during ascent. The Saturn V Dynamic Test Stand, a 360-foot tower topped by a 64-foot derrick, was the tallest structure in North Alabama. Marshall engineers assembled an entire 364-foot Saturn V with its Apollo capsule and enclosed it within the stand. Tests in 1966 and 1967 examined the effects of stress at 800 measuring points on the Saturn configuration.

Tests of the S–IC first stages and S–II second stages occurred not only in Huntsville but also at the Mississippi Test Facility (MTF) that Marshall managed. Built by the Army Corp of Engineers and operated mainly by contractors, the facility had a railway, a barge canal, laboratories, and three huge test stands.[30]

Transporting the huge Saturn stages led Marshall to develop its own ground, sea, and air fleet. Center engineers designed ground transporters; military trucks with aircraft tires carried the stages, which rested on assembly jigs that doubled as transport braces. In 1961 the Center began acquiring a fleet of barges, most of them converted World War II Navy ships, to ferry Saturn stages between Marshall, Michoud, Mississippi Test, and Cape Canaveral. The 3,500-kilometer barge trip from Huntsville to the Cape via the Tennessee and Mississippi Rivers and the Intracoastal Waterway took 10 days.[31] Marshall also used air transportation, contracting for a Boeing B–377 Stratocruiser with a lengthened and enlarged fuselage that could accommodate an S–IV stage. The "Pregnant Guppy," which separated in the middle for loading, carried its first Saturn stage late in 1963. This success and plans for larger stages prompted Marshall to contract for an even larger transport aircraft. The new "Super Guppy," large enough to hold the S–IVB stage, became operational in 1966. Both planes carried not only stages and engines, but other Apollo and *Skylab* cargoes.[32]

Flights and Fixes

More than an engineering development organization, Marshall assisted Kennedy Space Center with launch operations and the MSC with the first part of lunar flights. The Center helped oversee 32 successful Saturn launches, including 9 by Saturn Is, 10 by Saturn IBs, and 13 by Saturn Vs. No Saturn launch was a failure, a remarkable record for technology as complex as the Saturns and a stunning testimonial to the quality of engineering and management of the Center, its contractors, and the whole Apollo team. Their expertise was especially evident after the second Saturn V flight when they rapidly corrected problems to clear the way for human exploration of the Moon.

Before launch Marshall and the Kennedy Space Center worked closely together, coordinating booster design with checkout and launch equipment, stacking the stages, and preparing for launch. During a launch, an elaborate communication system linked Marshall to Kennedy. For human missions, another network linked Huntsville to Mission Control at the MSC in Houston. This communication network relayed telemetry data to the Huntsville Operations Support Center, the Flight Evaluation and Operational Studies Division of the Aero-Astrodynamics Laboratory, and other units which monitored the Saturn stages.[33]

Marshall applied its "building-block" approach to the early Saturn flights, testing launch vehicles stage-by-stage, launching the first stage with dummy upper stages, and adding live upper stages only on later missions. The Block I flights, the first four missions beginning in October 1961, had dummy upper stages and primarily tested large rocket technology and clustered-engines. The missions validated Marshall's cluster concept and showed the Saturn's capability of launching with one engine out; the Center also learned that more baffles were needed to control fuel sloshing. The second and third launches also performed the engineering and atmospheric experiments called "Project Highwater."[34]

In 1964 NASA turned to Block II missions which tested fins on the lower stage and had the first flights of the S–IV upper stage. In January 1964, SA–5 successfully flew with live first and second stages successfully and boosted a heavier payload, albeit ballast sand, than the Soviet space program had. NASA press releases and media coverage described Marshall as closing "the missile gap." Representative headlines shouted "Out-Rocketing the Russians" and "We're No. 1 with Saturn I." Stories portrayed NASA as champion of the free world and the Saturn I as taller than the Statue of Liberty. From an engineering perspective, the Block II missions proved the liquid-hydrogen engines, verified the early versions of the IU, and carried the first Apollo spacecraft. In addition, the missions put in orbit three Project Pegasus satellites which detected micrometeoroid impacts to test spacecraft engineering concepts.[35]

Marshall's next building-blocks were the Saturn IB missions. Beginning in

February 1966 the flights mainly tested the Instrument Unit and the S–IVB stage, which were nearly identical to Saturn V equipment. Especially successful were tests of the S–IVB which examined how liquid-hydrogen acted in orbit and proved that the engine could restart for the upcoming lunar missions. Later missions continued testing the Apollo Command Module. Launch vehicle SA–205 boosted the Apollo 7 capsule and the first crew into orbit in October 1968.[36]

Even as the Saturn I and IB flights were proceeding, NASA and Marshall abandoned the conservative, building-block method of flight testing for the Saturn V. George Mueller, who became NASA's associate administrator for Manned Space Flight in September 1963, argued that stage-by-stage tests were expensive and unnecessary. The test flights increased costs and delayed schedule without added assurance of safety or success. As an alternative Mueller proposed the "all-up" testing he had used as a systems engineer in the Air Force Titan II missile program. An all-up test launched an entire stack of live stages on the first flight. In a teletype of 1 November 1963, Mueller directed NASA Centers to prepare all live stage first flights for the Saturn IB and Saturn V; he further directed that the first Saturn V mission with a crew be the third rather than the seventh flight.[37]

Mueller's decision caused "shock and incredulity" among Marshall's engineers. All the lab chiefs and project managers initially opposed all-up testing, believing that it was an "impossible" and "dangerous idea." They particularly worried about problems from the liquid-hydrogen upper stages. Karl L. Heimburg, director of the Test Laboratory, expressed "immediate and strong opposition" and William A. Mrazek, director of the Structures and Propulsion Laboratory, thought Mueller had lost his mind. Lee James, project manager for the Saturn IB, said that "everybody explained [to Mueller] how complicated, how big this was, how the valves had never been used, how the engines had never been used."[38]

Nevertheless, Marshall quickly accepted the all-up approach. After some thought, Center engineers could neither refute the concept nor offer convincing technical justifications for stage-by-stage tests. Dr. Walter Haeussermann, director of the Guidance and Control Laboratory, and Dr. Ernst D. Geissler, director of the Aeroballistics Laboratory, concluded that the all-up concept could neither be proven right or wrong. Because of Marshall's conservative engineering and ground testing, there was "nothing to worry about."[39]

Von Braun and Rees sided with Mueller. Both initially had some doubts; later Rees said he "personally fought" the idea and von Braun said it "sounded reckless." After listening to the technical arguments, Marshall's director informed his people that all-up was the way to go. Von Braun and Rees decided that stage-by-stage launches would inhibit meeting the end-of-the-decade deadline, mainly because launch facilities would have to be reconfigured for each mission.[40]

First Saturn V launch, 9 November 1967.

Even so, many of Marshall's engineers felt uncomfortable with the policy and sometimes expressed doubts about all-up testing. James recalled that "I don't think anybody at Marshall believed it would work. I don't think anybody believed we would never have a failure in the Saturn program."[41]

Obviously the preparations for the all-up, first launch of the Saturn V booster AS–501 were very tense for Marshall and indeed the entire agency. The fact that checkout, prelaunch tests, and preparations took three weeks rather than one week only added anxiety. Consequently on 9 November 1967 everyone waited nervously. As the F–1 engines spitted flame and the Saturn V lifted off, von Braun could not contain his excitement and shouted, "Go, baby, go!" And after a flawless three-stage flight, he turned to Arthur Rudolph, the Saturn V project manager, and said that "he never would have believed it possible." Rudolph was just as surprised and even more pleased. The flight came on his 60th birthday, and he said the Saturn was "the best birthday candle" ever. The success made the whole Marshall team euphoric.[42]

Unfortunately, on 4 April 1968 the second Saturn V, booster SA–502, had many troubles that required emergency responses from Marshall. Each stage had problems. The S–IC first stage had severe vibrations from 125 to 135 seconds into the burn. Two of the five J–2 engines on the S–II second stage shut off prematurely and the stage required a new trajectory and longer burn. Once in orbit, the S–IVB third stage failed to reignite. If these problems had occurred on a lunar mission, NASA would have scrubbed it.[43] Unless Marshall could develop quick fixes, the agency could miss the end-of-decade deadline.

Marshall immediately assembled teams of experts from the Center and contractors. Following the discipline of "automatic responsibility," each lab checked flight and test data to investigate whether its specialty was involved. The Center worked primarily with Rocketdyne, the engine contractor, but the stage contractors also participated actively. To get independent perspectives, Marshall brought in consultants from the Air Force and academe and had other contractors investigate separately.

The experts determined that the S–IC had experienced the "pogo effect."[44] Pogo was longitudinal oscillation like the motion of a pogo stick in which the vehicle lengthened and shortened several times a second. The natural frequency of the stage structure of four cycles per second was very close to the operational frequency of the propulsion system (the fluid vibrations in the fuel lines and the hydraulic actions of the engines) of five cycles per second. As propellants drained, the structure's frequency increased until at 110 seconds into the flight it coincided with that of the propulsion system. The coupling of the frequencies amplified the up-and-down oscillations and caused tremors through the entire vehicle.

Pogo oscillations affected most large liquid-fuel rockets, but were not always severe. For example the Saturn I had no serious pogo problems. Even so Marshall had anticipated potential trouble and installed flight vibration detectors on the Saturn V. After AS–502 the Center's propulsion experts lacked proof that the S–IC's oscillations were dangerous. Nonetheless they worried that severe pogo could destabilize the propulsion systems, damage the command and lunar modules, or threaten the astronauts.

Two weeks after the flight and after identifying the pogo problem, Marshall formed a working group of about 125 engineers and 400 technicians from the Center, Rocketdyne, Boeing, and several other contractors. At Marshall, the Propulsion and Vehicle Engineering Lab performed the primary studies. Since the oscillations could not be duplicated on the ground, they relied on the Astrionics Lab and Computation Lab to create computer models of the phenomenon based on flight data and previous tests. The working group used a formal logic tree to assist their deliberations and identified several criteria to evaluate possible solutions; the optimal solution would prevent recurrence of pogo, would not adversely affect other systems, would be easily retrofitted, would not delay the Apollo schedule, and could be tested on the ground. Because of costs in development time and money, the team ruled out several proposals to change the vehicle structure or stiffen the fuel lines.

By 2 May, the team had decided to reduce the frequency of the propulsion system. Rocket engineers had already proven this approach; the Titan II had used a similar fix for the pogo effect, and in 1965 Marshall had applied that lesson to the S–IC fuel lines. Consequently the working group decided to test two alternative redesigns of the LOX intake system and divided tasks among the team. Marshall's Test Lab ran 9 of the 14 major types of tests which evaluated components, alternative LOX feed and pump subsystems, and the impact on the F–1 engines and S–IC stage. By July, static firings with the redesigns had produced data that the labs incorporated into computer models of flights; the tests and flight simulations verified that either design could suppress the oscillations.

Based on this information, the working group unanimously decided on 15 July that helium-charged accumulators in the LOX lines best met their criteria for a pogo fix. The solution took advantage of two preexisting parts of the S–IC. Helium gas was already on board to pressurize the fuel tanks, and the LOX ducts had a bulge called "a prevalve cavity" about 90 inches above the pump to detain oxidizer until ignition. The pogo fix would inject unpressurized helium in the cavity, and the redesign involved little more than adding a new helium line. The helium, which would not condense at the low LOX temperature, acted as a shock absorber to cushion the bottom of the LOX column. Ground tests confirmed that the helium accumulator reduced the operating frequency of the propulsion system from five cycles per second to two cycles. Later tests led the working group to conclude that an accumulator on the center engine could promote oscillations, so in the fall they decided to install the change only on the four outboard engines.[45]

While the pogo working group investigated the first stage, about a dozen engineers and 150 technicians from Marshall and Rocketdyne studied the problems with the J–2 engines on the second and third stages. Leading the way were experts from the Engine and Power Branch of the Center's Propulsion and

Vehicle Engineering Lab who gained clues from telemetry data from the Number 2 engine on the S–II stage. Temperature sensors inside the vehicle initially showed cold, evidence of a liquid hydrogen leak from the lines leading to the engine's igniter. Later the sensors read hot, signifying that the line had ruptured and the fuel burned inside the booster until another detector shut off the engine by closing a fuel valve. Unfortunately a mistake in electrical wiring had sent the shut-down signal from bad engine Number 2 to good engine Number 3 and turned off that engine as well. Exhibiting the same readings as the Number 2 engine, the J–2 engine on the S–IVB also had a rupture in the igniter line that prevented its restart.

In ground tests at Marshall the engineers subjected the igniter lines to greater pressure and vibrations than in flight conditions, but could not duplicate the failure. They then turned to vacuum tests of eight lines and found that all eight lines failed. They concluded that in ground tests the cold liquid hydrogen (minus 400 degrees Fahrenheit) had liquefied moisture in the air around a bellows section of the line; the ice then dampened the line's vibrations. In the rarefied upper atmosphere, there was no moisture to freeze and absorb the stress. Consequently fuel flow in the line caused vibrations of 15,000 cycles per second and led to ruptures. The engineers fixed the problem by eliminating the bellows section, reducing the diameter of the igniter line, and making the line more flexible by adding five bends. To be safe, they redesigned the LOX lines, even though these had experienced no problems. The engineers then performed vacuum tests and by the end of May had certified the reliability of the new configuration.[46]

The AS–502 investigations were so conclusive and solutions so reliable that the Marshall team convinced NASA that another test flight of the Saturn V was not needed. NASA decided to proceed with plans for a crew on the third Saturn V launch. On 21 December 1968, SA–503 (Apollo 8) sent people into orbit around the Moon for the first time.[47]

Of course the ultimate mission of the Apollo program was SA–506 (Apollo 11) which landed men on the Moon in July 1969. Norman Mailer observed lift-off from the observation site for the press located several miles away from the launch tower and lyrically described the sensations. He noted the eerie silence of watching the Saturn V rise before the sound reached his position; initially the liftoff, Mailer said, seemed "more of a miracle than a mechanical phenomenon, as if all of the huge Saturn itself had begun silently to levitate." The engine's bright blaze initially coursed along the ground in "brilliant yellow bloomings of flame," and after the Saturn rose above the launch tower, its "fire was white as a torch and as long as the rocket itself." When the sound reached Mailer, he heard "the thunderous murmur of Niagaras of flame roaring conceivably louder than the loudest thunders he had ever heard and the earth began to shake and would not stop." As the Saturn rose "like a ball of fire, like a new sun mounting the sky, a flame elevating itself," Mailer reflected that humans "now had something with which to speak to God."[48]

Celebration in downtown Huntsville of Apollo 11 landing.

Neil Armstrong's first footstep on the Moon completed Kennedy's challenge and accomplished an ancient human dream. Von Braun remarked that the lunar landing was the "culmination of many years of hard work, hopes and dreams." It was "as significant as when aquatic life first crawled on land" and "assured mankind of immortality." In a celebration in downtown Huntsville, crowds thronged around Marshall's engineers and managers, buoying them in a delirious outburst of happiness and hometown pride.

During the hoopla surrounding the mission, the media and public paid more attention to the Apollo 11 crew than to the Center responsible for the Saturn V booster. At a prelaunch news conference on 15 July, NASA officials fielded questions from the press about the upcoming flight. Lee James, Saturn program manager, represented Marshall, but the press did not ask him one question. The media, James reasoned, already believed that the Saturn V was "old stuff."[49]

For the Saturn V launches, the Center continued in its crucial, behind-the-scenes role. Marshall's engineers managed vehicle preparations, analyzed flight data, and corrected problems. As an example of this, the rocket engineers noticed a very small pogo effect that occurred on the S–II stage on the Apollo 8, 9, and 13 launch vehicles. Although the problem never endangered a mission, the experts took no chances and used computer simulations and static tests to isolate the phenomenon in the interaction of the center engine and the crossbeam on which the engine rested. Marshall added accumulators in center engine's LOX line and shut the engine down 90 seconds before the others, before vibrations in the propulsion and structural systems synchronized.[50]

Rees reiterated the Center's careful approach to space flight in a flight readiness review after Apollo 11. He encouraged his team to remain vigilant, saying, "this was the best launch vehicle we have ever had, but we should not be complacent over the success of this launch. We started calling these problems failures, then anomalies, now deviations. We should go into these deviations in detail and find out the causes. Then we should take corrective action where required."[51] This careful philosophy helped create the tremendous technical successes of the Saturn vehicles.

The Lunar Roving Vehicle

Marshall took its expertise in transportation in new directions by developing the LRV for the later Moon landings. The vehicle was the first human spacecraft built by the Center and was a harbinger of Marshall's diversification beyond its rocketry specialty. The lunar rover helped the Apollo astronauts explore the lunar surface and gather geological samples.

Von Braun and other engineers had proposed concepts for lunar cars from the 1950s.[52] Most Center planning for lunar vehicles, however, followed NASA's LOR decision of June 1962. In agreeing to the LOR mode, von Braun had proposed that Marshall build an Apollo Logistics Support System, a combined lunar taxi and shelter.[53] Immediately after this decision, Marshall initiated studies of lunar surface vehicles. For the next six years, the Center and contractors designed and developed various full-scale and subscale prototypes, investigating wheel design, drive systems, steering mechanisms, crew cabins and human factors problems, and navigation simulators.[54]

While Marshall engineers investigated designs, NASA clarified organizational assignments for the lunar missions. The division of labor between the Centers needed clarification because Marshall was entering Houston's domain in human space flight. Agreements of the Management Council of the Office of Manned Space Flight, which included the Center directors and Headquarters administrators, culminated in the August 1966 meeting at Lake Logan in North Carolina. There the Management Council assigned the MSC responsibility for lunar science, including planning for lunar traverses, lunar geology experiments, and biological and biomedical experiments. George Mueller said this gave MSC authority for the "overall management and direction" of the Apollo explorations and equipment. Marshall became responsible for what von Braun termed "devices of an engineering rather than a scientific nature." These included lunar vehicles like various types of surface rovers, a one-man flyer, or a remote controlled scientific surveyor.[55] Houston consented to Marshall's role in lunar engineering because of demands imposed by work on the Apollo spacecraft. As Joseph Loftus recalled, MSC had "an awful lot on our plate."[56]

Despite this division of labor, NASA as late as 1968 hesitated in its choice of a lunar transportation system. The choice of technologies was still open in November 1968 when Marshall requested proposals from aerospace companies to study a dual-mode rover that could carry one astronaut and undertake geological missions under remote control from Earth. But agency officials worried that the dual-mode vehicle would be too expensive and complicated.[57]

Houston's opposition delayed the decision on a lunar vehicle. The MSC stalled because of technical concerns rather than organizational jealousy of Marshall. MSC engineers, especially George Low, feared that a lunar vehicle would reduce lunar module (LM) fuel needed for safe landings; without surplus fuel as insurance, the LM could not hover and move to a suitable landing site. MSC's complaint, LRV Project Manager Sonny Morea remembered, was a "safety objection."[58]

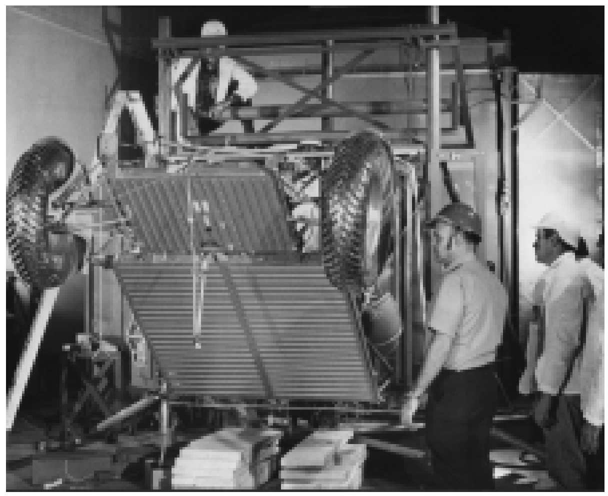
NASA finally made a vehicle decision in late May 1969 by rejecting the flyer, and choosing a surface vehicle. By then the agency was confident that a landing could be done safely. Moreover a piloted Moon car would cost less than a remote-controlled unit and could do more science than a flyer. Indeed advocates of the LRV, especially the Marshall Center and George Mueller, overcame resistance by arguing for its scientific payoffs. On 27 May 1969, NASA authorized Marshall to develop the LRV.[59]

With the rover the Center faced imposing schedule constraints and technical challenges. The vehicle had to be ready by April 1971, making for a design and development schedule much shorter than the four-and-one-half to six years for other Apollo spacecraft and life support equipment. Marshall moved quickly, issuing requests for proposals on the same day as the first lunar landing in July 1969. Later in the month LRV work moved from Program Development to an LRV Project Office managed by Morea, who had previously supervised the F–1 engine program. The creation of a project office occurred before the normal initial steps of Program Development's phased project planning had been completed. In late October the Center chose Boeing as the prime contractor even though the company's bid of $19 million was far below Program Development's estimated cost of more than $30 million. Another unusual feature of the Boeing contract was how it sought to hasten the project and, in Morea's words, "cut out the bureaucracy." It specified performance requirements rather than any predetermined design and made the company responsible for systems integration; the company could authorize some hardware changes without formal NASA approval.[60]

The lunar module also affected vehicle design. MSC had authority over the LM and wanted to stabilize its design. Accordingly Houston refused to change the LM to accommodate the rover. In effect then Marshall was a contractor working for another Center and had to adjust to MSC's requirements; Morea lamented that Marshall "always seemed to get the short end of the string." The lunar car could not exceed a weight limit of 400 pounds but had to carry over 1,000 pounds of astronauts, equipment, and rocks. This meant that the LRV had to be built of light alloys and would collapse under a person's weight in Earth gravity. In addition, the vehicle had to fit in an LM storage bay about the size of a station wagon's, 66 inches wide, 60 inches high, and 49 inches deep.[61]

The lunar environment also shaped the rover. As Henry Kudish, Boeing's LRV project manager in Huntsville, observed, the vehicle was not a "lunar jeep" but rather "a very complex spacecraft." The vehicle had to operate in a vacuum and in temperature extremes of plus or minus 250 degrees Fahrenheit. It had to serve astronauts in cumbersome life support suits. The roving vehicle needed a navigation system to cope with the Moon's low sun angle and its effects on depth perception, lack of a magnetic north pole, and short horizon. It needed strength and stability to traverse rocks, crevasses, and steep slopes. Clinging lunar dust necessitated that everything be carefully sealed.[62]

Marshall and its contractors cooperatively designed and developed the LRV. As prime contractor Boeing used its expertise in aircraft structures to construct the folding aluminum chassis and to integrate the subsystems. GM and its Delco Electronics Division, Boeing's major subcontractors, drew from automotive experience to develop the wire mesh wheels with titanium chevrons as tread, torsion bar suspension, single stick control and all-wheel steering system, and harmonic drive assemblies. Other contractors built the silver-zinc batteries and communications system.[63]



Deployment testing of lunar roving vehicle in March 1971.

Other Centers, especially Houston, also helped. Marshall, MSC, and Kennedy established several intercenter panels to resolve problems on scientist-astronaut participation, crew systems and training, operational constraints, LM/LRV interface, prelaunch checkout, and communications with mission control. Astronauts from Houston helped with the crew station and suggested assists for getting in and out of the vehicle and upright seatbelts for sure visibility.[64]

Marshall, however, stamped its trademark on the LRV. The Center contributed to the vehicle's conservative engineering of several redundant systems, including two batteries which could individually power the vehicle, two independent steering systems on front and rear, a control stick that could be used from either seat, and separately powered wheels, each of which could be set to free-wheel should its drive assembly fail.[65]

Conservative engineering also showed in the number of rovers NASA purchased. The agency bought four one-sixth gravity flight models and seven test and training units. With enough funding for seven models, Marshall could require extensive tests. The test units included a rubber-wheeled Earth gravity trainer, a qualification unit for testing and troubleshooting during missions, a vibration test article, two one-sixth weight units used in deployment tests, a static mock-up for crew station reviews, and a test article known as "the glob" which Grumman used in early work with the lunar module. Marshall flew one test vehicle on parabolic flights in a KC–135 "Vomit Comet" allowing astronauts in space suits to investigate entry and exit in low gravity. So luxurious was rover's funding that NASA even wasted one flight model; when the Agency canceled an Apollo LRV mission, the LRV parts became spares.[66]

Most importantly the trademark of Marshall's arsenal system showed on the LRV. Marshall people worked on the project in functional teams organized in the Saturn system of matrix management.[67] The most significant contributions came from the Astrionics and Astronautics labs. The Engineering Division of the Astronautics Lab designed and developed a manual method to deploy the rover from the LM. Although designed as a backup to an automatic system, it became the sole deployment procedure. By pulling on two mylar tapes the astronauts unfolded the LRV from the storage bay and lowered it rear first to the lunar surface.[68]

NASA wanted a navigation system so that astronauts could travel widely to predetermined points and return safely to the lunar module. Engineers in the Astrionics Lab's Guidance and Control Division conceived the system because project managers feared that a disoriented navigation contractor had gotten lost with a costly, complicated mechanism. Center technicians constructed it mainly from components already available.

A team from the Sensors Branch developed a dead reckoning system. A processor used elementary trigonometry to make calculations based on a known starting point and measurements of vehicle attitude, direction, speed, and distance traveled. A console displayed distance traveled and distance from the LM, and heading and bearing to the LM. Three gyroscopes determined Lunar North, and a sun shadow compass, added by suggestion of MSC, checked the original heading and guarded against gyro drift.

Marshall worried that lunar soil might inhibit performance of the roving vehicle. Slippage on loose soil in the lunar vacuum could affect navigation and limit range. After considerable research, the Center decided to rely on odometer readings of the third fastest turning wheel to determine distance and speed.[69] In 1969 the Geotechnical Research Division in the Space Sciences Laboratory formed a Soil Mechanics Investigation Team that studied lunar soil samples, astronaut observations, photographs, and film. Marshall even conducted soil penetration and load bearing experiments on KC–135 flights. The research concluded that soil would not hamper a rover.[70]

The Center's technicians built the navigation system and performed tests in 1970 first in fields surrounding the Center and later in the lunar-like desert near Flagstaff, Arizona. Marshall's navigators imitated a rover by using a jeep with masked windows, a television camera on the hood, and the navigation system. The jeep driver found his way using a TV monitor, a map, navigation readouts, and a radio. A station wagon followed the jeep; the wagon's driver could see ahead but its passengers could not. Imitating mission control, the passengers used TV pictures and the navigation display and communicated advice to the LRV driver in the jeep. In this way the navigators tested both their mechanism and remote control methods. They found their way within two-percent error even on 19-mile trips.[71] The system was imprecise but cheap and simple, and team leader Peter Broussard said "we were being pragmatists" who just wanted to get the astronauts in sight of the LM. He recalled the "fun" of working a whole subsystem and seeing it from conception to operation, and remembered that nearly all the engineers who worked on the LRV said "that's the best project I ever worked on."[72]

In spite of Marshall's arsenal system, the rover contract fell behind schedule and went over budget. At one point the project was two months behind targets to meet the April 1971 deadline. Delays came partly because NASA was slow to select power, speed, and range requirements and partly because during vibration tests Boeing/GM found shorts in the electronic controls and broken gears in the harmonic drives.

NASA insisted that schedules be kept. Marshall Director Rees warned Boeing that "this project is simply too sensitive to allow further opportunity for embarrassment in either the technical or the cost area." Rocco Petrone, NASA's director of the lunar landing program, warned in January 1971 that he could only delay the summer launch of Apollo 15, the first rover mission, one month. If the vehicle was not ready after that, Petrone said, Apollo 15 would leave without it.[73]

Boeing made changes to catch up. It moved work from Huntsville to Kent, Washington, to get more skilled workers and to be closer to test equipment. The company conducted qualification testing and concurrently manufactured the first flight vehicle. But Boeing got back on schedule mainly by using more workers and paying them overtime. Most contract overruns went to pay overtime for skilled labor. As John Winch, Boeing LRV project executive said, "when we encountered problems something had to give. In this case it was cost." With the extra expenses, the company delivered the first flight roving vehicle in March 1971, three weeks ahead of the delivery order. The final cost of the project was $38.1 million, close to Marshall's projections but more than double Boeing's bid.[74]

Not surprisingly, critics blasted NASA for rover overruns. Columnist Jack Anderson charged that the agency had "goofed on the design" and compounded problems with a "head-in-the-clouds attitude toward Boeing's expenditures." He claimed that the cost of the project was $10 million more than the 1972 federal auto safety budget.[75] Much of the criticism rested on the assumption that the vehicle was merely an electric car.

But as a NASA official pointed out, the LRV followed "spacecraft rules, not automobile rules." H. Dale Grubb, NASA assistant administrator for Legislative Affairs, told one inquisitive senator that the vehicle was "in line with the cost of other equipment of similar novelty and complexity which NASA has developed and produced in the space program." And the lunar rover followed a 17-month schedule (and only 13 months from the contract award) that was far shorter than the 52 months for the Command Module, 62 months for the LM, 60 months for the astronaut suits, and 70 months for their portable life support systems. Given this rushed schedule and the gross overruns of later NASA projects, rover development seemed remarkably successful. Marshall project manager Morea believed that "unless we went into a mode of a crisis, a national emergency, we would not know how to do a program like that today. We could not do it today."[76]

Marshall assisted Houston on the LRV missions through the Huntsville Operations Support Center (HOSC) located in the Computation Laboratory. Marshall had used the HOSC to monitor earlier Saturn launches. On the LRV flights, however, Marshall extended its operations role and 45 vehicle specialists provided around-the-clock engineering advice to Mission Control in Houston. Center and contractor personnel checked vehicle performance, ensured proper operations, and responded to problems. To simulate any problems the astronauts might encounter, the Center also maintained an LRV qualification unit in a hangar.[77]

With the Center's help, the Apollo 15, 16, and 17 missions of 1971 and 1972 successfully used LRVs. On Apollo 15 the astronauts had some difficulty deploying the LRV, and on the first excursion an electrical short immobilized the front steering, allowing rear steering only. The next day, however, the front steering worked. Astronaut David Scott told Mission Control that "you know what I bet you did. . . . You let some of those Marshall Space Flight Center guys come up here and fix it."[78]

The success of the vehicle muted most criticism. The Apollo astronauts explored more territory and collected more geological samples with the LRV than ever before. On the three pre-rover missions, Apollo 11, 12, and 14, astronauts collected 215 pounds of samples and walked 10 miles in 36 hours. On Apollo 14, Alan Shepard and Edgar Mitchell tried to climb Cone Crater but had to give up after they got tired, disoriented, and began running out of time and air. But on a riding mission the astronauts could range farther, faster, safer. On Apollo 15 alone the astronauts traveled nearly four times farther than the three previous missions combined and collected 170 pounds. On all the LRV trips, NASA collected 635 pounds of samples, and traversed 134 miles in 122 hours.[79] Marshall's navigation system kept on track; the average position error at the end of a traverse was less than 200 meters on Apollo 15 and zero on Apollo 16 and 17.[80]

The rover won considerable praise from the astronauts. Scott said that the vehicle was "about as optimum as you can build." Gene Cernan and Jack Schmitt of Apollo 17 noted that they had "three good spacecraft," the CM, LM, and LRV, and believed "that thing couldn't perform better." They felt it was "a super performing vehicle. If you take a couple more batteries up there, that thing would just keep going."[81]

Meanings and Memories

In narrow terms, Marshall's work in the Apollo program offered many lessons and legacies. The Center contributed to technological progress, such as making advances in materials, metal bonding, and welding inspection, that proved useful in many areas. Marshall's engineering organization showed the value of comprehensive testing and multidisciplinary work teams that integrated specialists in design, manufacturing, testing, and inspection. The project management system successfully combined the efforts of dozens of businesses and government organizations. Marshall created rockets and rovers that allowed humans to explore space and the Moon.

In later years, Marshall's Saturn V cast a long shadow. In the 1980s, an era in which NASA's dreams of a space station were limited by the 25-ton capacity of the Space Shuttle, some longed for the 124-ton capacity of a Saturn V. Some aerospace companies and agency planners even sought blueprints of the Saturn V and its engines to gain inspiration for the next generation of rockets.[82]

In a wider sense, however, the Saturn V became something more than a powerful rocket. As decades passed, Americans reinvented the meaning of the Apollo Program and transformed it into a symbol of excellence. Why, they asked, could Americans not perform the way they had done during Apollo? In this context the Saturn V became a symbol of excellence in American society and government. In an era in which America seemed divided, anniversaries of the first landing on the Moon sometimes expressed nostalgia for the national commitment and unity of the Apollo Program in the 1960s. Looking back after 20 years, a Boeing engineer thought that the Saturn project was "the biggest single example I can think of getting the government-industrial complex together on a goal that had an established end and a monumental technical task before it."[83] That the Saturn V could become such a symbol in American culture was perhaps the most fitting tribute to the Marshall Center.

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1 Statistics from R. Bilstein, *Stages to Saturn: A Technological History of the Apollo/Saturn Launch Vehicles* (Washington, DC: National Aeronautics and Space Administration Special Publication–4206, 1980), pp. 288, 354–55; Diana Woodin, "Saturn-Apollo: Boeing Engineers Reminisce about Early Days," *Huntsville Times* (16 July 1989), 1C.

2 The stand is an example of von Braun's engineering conservatism and his attempts to plan beyond current projects. Had Nova been built, this stand could have accommodated tests on its engines.

3 *Birmingham News*, 28 June 1969; William Lucas, OHI by SPW, 4 April 1994, pp. 34–35.

4 Loyd S. Swenson, James H. Grimwood, and Charles C. Alexander, *This New Ocean: A History of Project Mercury*, (Washington, DC: National Aeronautics and Space Administration Special Publication–4201, 1966), p. 172 ff., Kuettner quoted, p. 181.

5 *Ibid.*, pp. 185–87.

6 *Ibid.*, chap. X, espec. pp. 293–97.

7 *Ibid.*, pp. 323–24, 328–30, 332–65.

8 J. P. Kuettner, “Marshall–STG Management for Apollo, etc.,” 14 July 1961, MSC/STG and MSFC folder, MSFC Archives.

9 E. Rees, routing-slip notes, 3 July 1961, MSC/STG and MSFC folder, MSFC Archives.

10 See James Kauffman, “NASA’s PR Campaign on Behalf of Manned Space Flight, 1961–63,” Public Relations Review 17 (Spring 1991), pp. 57–68; for coverage of MR–3, *New York Times* (May 5–10, 1961); *Huntsville Times* (May 5–10, 1961).

11 Roger Bilstein’s *Stages to Saturn: A Technological History of the Apollo/Saturn Launch Vehicles* (Washington, DC: National Aeronautics and Space Administration Special Publication–4206, 1980) is the best history of Marshall’s role in Saturn development. Many of the Marshall records used by Bilstein have subsequently been lost. Consequently this chapter relies heavily on his research.

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