Chapter VIII

The Space Shuttle: Development of a New Transportation System

In the aftermath of Apollo, Marshall Space Flight Center increased its research activities, conducted space operations, and engaged in entrepreneurial ventures. But Marshall was still primarily a propulsion Center, and its reputation would rise and fall depending on the success of its rocketry. If the Space Shuttle propulsion system did not dominate Marshall's second two decades in the way that Saturn had in the first, it was nonetheless the Center's preeminent concern, source of its greatest post-Apollo triumphs, and its most sobering tragedy.

Of the four major Shuttle components—solid rocket boosters, external tank, main engines, and orbiter—Marshall bore responsibility for all but the orbiter. Each offered new technological challenges that pushed engineers and administrators beyond Saturn. For the first time the Center developed a rocket that relied on solid fuel. For the first time the Center worked on a reusable vehicle system.

Choosing a Configuration

NASA adopted the Space Shuttle as a formal program in 1969, but the origins of its concepts predate the formation of the Agency. Marshall participated in the earliest Shuttle studies, and the Center's struggle to define its role in the Shuttle program was an important part of its post-Apollo transition.

The Shuttle broke with Apollo technology most significantly as a reusable spacecraft, an idea that had appealed to philosophers, scientists, and rocket engineers for decades. Indeed most 19th century speculation about space travel envisioned reusable vehicles, not because of a systematic approach to technological obstacles, but because of assumptions drawn from familiar systems. German and American theorists suggested the possibility of rocket airplanes in the 1930s

and 1940s, and American experimental craft like the X–15 bear more kinship to the Shuttle than to early spacecraft.[1] The Air Force and the Army both pursued studies in the late 1950s that could be considered precursors to the Shuttle. The Army Ballistic Missile Agency in Huntsville, before relinquishing its Development Operations Division to NASA in 1960, contrived various means of recovery for its expendable Redstone and Saturn I rockets including paragliders and parachutes, but none of them were flight tested.[2]

A Shuttle launch.

From the earliest months of its establishment, Marshall began to investigate reusable systems. The first study began in 1961 when the Center's Future Projects Office issued a statement of work calling for winged, reusable launch vehicles including orbital passenger and cargo carriers with easily accessible payload bays in which all stages would be capable of multiple reuse. In December 1963 Boeing, Lockheed, and North American Aviation all conducted studies for Marshall. By December 1963, they concluded that such vehicles were indeed possible.[3] Lockheed and Boeing conducted a follow-on study for the Marshall Future Projects Office in 1964 and 1965 that suggested possible systems criteria for "the design of space launch vehicles similar in operation to today's airplanes."[4]

Hermann Koelle, who headed the Future Projects Office, also pursued studies of high-performance rocket engines. Jerry Thomson remembered Koelle approaching him about engine designs that might surpass the performance of Saturn engines. "Up through the Apollo Program we were only operating about a thousand PSI of chamber pressure, which is what the F–1 ran. But we wanted

to go much higher than that," Thomson recalled. "Some of us, sort of on a side track, went off to get some components built and tested for these engines that were later to become the Space Shuttle main engine."[5]

John McCarty, one of Thomson's colleagues, remembered that "When we put the requirements of the aerospace plane together with propulsion rocket engine technology and requirements, it was clear we needed to start a new approach to an engine. We started two or three projects. We started high-pressure turbopumps—one for hydrogen for the fuel and one for oxygen for the oxidizer. We started some engine system design studies to arrive at what was the right configuration. . . . How would you control it? What are some of the fundamental limits in the engine? . . . That was really the beginning, I think, of the SSME [Space Shuttle main engine]."[6]

At the time of these early studies, NASA was far from settling on a major post-Apollo program. When NASA's planners did discuss future goals, they assumed that an orbiting workshop would be the next major manned program. Houston and Marshall already had Space Station Projects Offices. Officials assumed that "the large manned Space Station seems to be the most probable initial mission" for a reusable launch vehicle. In this context, a "Shuttle" would function as a logistics vehicle in support of a Station rather than an independent system. Furthermore, planners would try to minimize development costs for the logistics vehicle in order to avoid compromising station funding. While NASA expected eventual development of a reusable vehicle, planners acknowledged that concrete designs would have to be deferred.[7] The shadow of a presumed Space Station thus constrained investigations, since NASA was already beginning to realize that the post-Apollo era would offer political and economic limits.[8]

Studies at Marshall, Houston, and the Air Force between 1963 and 1967 helped keep plans for a Shuttle-type vehicle alive. People involved in the mid-1960s Shuttle studies acknowledged that they were working in a highly speculative environment. They had no foolproof way of judging the cost of advanced reusable systems, and few precedents for evaluating technical risk, refurbishment costs, abort capabilities, system size, or performance.[9] Since these factors were interrelated, changes in one area could greatly affect others; for example, as size increased, engine performance and thermal protection would both be affected in very complex ways.[10] Frank Williams of the Marshall Future Projects Office suggested that one set of assumptions could lead to hundreds of millions

of dollars in savings, while slight changes in these assumptions could lead to hundreds of millions of dollars in losses.[11]

Wernher von Braun helped to keep the idea of a Shuttle-type vehicle before the public. His 1952 Collier's articles envisioned a logistics vehicle to supply an orbital space station. In 1965 he called for a reusable earth-to-orbit vehicle that could service space stations in 10 to 15 years, one in which both launch vehicle and spacecraft would be "capable of returning to Earth in a lifting-flight mode." In one of the optimistic projections of Shuttle use characteristic of early planning, he suggested that a system to deliver a 10,000-pound payload and 10 men to orbit could be developed for $1 billion, and that if it could perform 1 mission per week for 50 to 100 missions, it could lower the cost to lift a payload to orbit to only $50 per pound.[12]

The origins of the Shuttle are disparate, but 27 October 1966 might qualify as the point at which NASA began to define a real configuration for development. On this date representatives of the Office of Manned Space Flight (OMSF), Marshall, and the Manned Spacecraft Center (MSC) met in Houston to discuss logistics systems for the post-Apollo era. Max Akridge, one of the Marshall representatives, called the meetings "the beginning of the Space Shuttle as such." Planning for the Shuttle began at each Center, and engineers began to contemplate possible designs.[13]

Competition between NASA Centers would intensify as Agency resources became scarcer, and competition between Houston and Marshall would be an important factor in Shuttle development. Houston's early configuration study was but an indication of the competition that would characterize post-Apollo relations between the Centers. Houston's Shuttle was a fully reusable two-stage vehicle with straight fixed wings that became the basis for early configuration discussions.[14]

As part of the post-Apollo planning process during 1968, NASA began to pull together concepts developed by Agency and defense contractors. George E. Mueller, NASA's Associate Administrator for Manned Space Flight and the Agency's leading Shuttle advocate, began to argue the merits of a Shuttle independent of a space station.[15] In February Mueller called for a fully reusable low-cost transportation system that might eventually be competitive with other forms of transportation. Marshall helped Mueller's office conduct further econometric and engineering studies examining manned spaceflight options, and

among those released midyear was one that offered a cautionary note. It questioned the viability of a fully reusable aircraft-type transportation system before the mid-1980s because of high risks and the necessity for very high annual launch rates over a sustained period of years to amortize high development costs.[16] The very issue of viability showed another difference from Apollo; whereas Apollo's goals were political, Shuttle would always be held to economic criteria. In the fall, NASA directed Marshall and Houston to review their studies on low-cost transportation systems with a view toward reducing costs.[17]

The space program enjoyed a peak of popularity in 1969 as the anticipated Moon landing allowed the nation to divert its attention from the protracted war in Vietnam. Out of the public spotlight, the year saw crucial decisions that would shape the space program for years. In January NASA committed $500,000 to each of four Shuttle feasibility studies and assigned management to field Centers, thus initiating Phase A of Shuttle development.[18] Marshall managed the General Dynamics and Lockheed contracts, Houston monitored McDonnell Douglas, and Langley supervised North American Rockwell. NASA directed each contractor to examine a different design approach and to report their findings at a September appraisal.[19]

On 13 February, President Richard M. Nixon appointed a Space Task Group to give him advice regarding the direction of the space program in the post-Apollo years. Chaired by Vice President Spiro T. Agnew, the task group included NASA Acting Administrator Thomas O. Paine, Secretary of the Air Force Robert C. Seamans, and Lee Dubridge, science adviser to the president, as well as observers from other agencies.[20]

The announcement of the formation of the Space Task Group stimulated planning activity in NASA, for the Agency now had only a few months to influence decisions expected to affect NASA's direction for years. Mueller directed Manned Space planning activities, and in doing so shaped both NASA's commitment to the Shuttle and the role Marshall would play in its development. "The Shuttle business grew out of what I call the Mueller Plan," Huntsville's Bob Marshall recalled. Mueller hired BellComm to aid in planning. "He directed them to plan a program which had in it the Shuttle."[21] Mueller also guarded the Center's interests. Concerned about the traumatic post-Apollo transition in Huntsville, he ensured that the Center received its share of Shuttle development business. The Agency began discussions with the Air Force about possible joint efforts to develop the new vehicle.

Meantime the Centers began jockeying for position. Marshall, in the throes of post-Apollo cutbacks, sensed an opportunity to gain new responsibilities. One of the Houston participants in intercenter meetings noted that "MSFC is really building up to handle the advanced program."[22] Marshall formed an Integrated Launch and Reentry Vehicle (ILRV) task team early in April, two weeks before Mueller did the same at Headquarters, and some speculated that Marshall might win the assignment to manage the Shuttle.[23]

Max Akridge of the Marshall group maintained that the term "Space Shuttle" originated after Mueller's address to the group on 5 May. Akridge recalled Mueller saying that NASA needed "a vehicle that's like a shuttle bus." "I kind of liked the name 'Space Shuttle,'" Akridge recalled, and he directed the Marshall contractors to begin using the term, which soon became common.[24]

Mueller, in one of several actions he initiated to assist Marshall through its post-Apollo reductions, assigned the Center to take the lead in evaluating Shuttle configurations. (Privately, one Houston manager wrote his reaction to the assignment: "MSC losing out."[25]) The baseline characteristics requiring a vehicle that could transport 50,000 pounds to orbit and back and have a payload volume of 10,000 cubic feet eliminated ballistic configurations from consideration, but at least eight options remained open for evaluation in Phase B. Mueller directed that the evaluation be predicated on performance, development risk, cost, and schedule.[26]

In the weeks following the 20 July 1969 Apollo 11 lunar landing, NASA attempted to capitalize on the afterglow of its greatest achievement to gain support for Shuttle and other new starts. Mueller advocated continued development of both Space Station and Shuttle, which would be necessary for Station logistics support; he anticipated that both might be launched by 1975. He also supported development of a space tug that might operate between the Station and other spacecraft, and a nuclear shuttle that could operate between Earth orbit and lunar orbit. The Shuttle, he suggested, could be developed and put into operation for $6 billion, and while NASA's percentage of the Gross National Product might rise slightly during development, it would never reach Apollo-era figures and would decline in the 1980s.[27] NASA was perhaps entitled to a rush of optimism after the Apollo landing.

In September, Vice President Agnew's Space Task Group presented its report, which in effect ratified Mueller's goals for manned space. The report offered

guidelines for space operations, and stressed the importance of "three critical factors" of commonality, reusability, and economy. The panel offered President Nixon three alternative courses. The first two were ambitious and expensive, incorporating a manned mission to Mars. The third was more modest, but still supported both a Space Station and a Shuttle. Nixon selected the third option six months later.[28]

In the months that followed the release of the Space Task Group report, NASA made key decisions regarding Shuttle configuration, means of development, and the division of labor between the Centers. During the early months of the year, the Agency saw its future on the line, and battled effectively to influence the Space Task Group report. Now, in the months following the release of the report, the Centers battled to preserve their stake in post-Apollo work. Marshall was fighting this battle on several fronts, and its success in diversifying into space science and maintaining its traditional role as the NASA Propulsion Center ensured the Center's survival.

Marshall and Houston worked out a joint agreement regarding Shuttle contracting and management in a series of meetings in September and October, and referred their plan to Headquarters. Von Braun and Robert R. Gilruth, Center Director at the Manned Spacecraft Center, agreed that the Shuttle was of such complexity that development of the orbiter and booster should be handled by separate contractors. If separate contractors were to be used for the orbiter and booster, different Centers could manage each contract, and their historic roles made it logical that Houston would manage the orbiter, Marshall the booster. The relationship between the Centers would thus be similar to that under Apollo, although the interfaces between the orbiter and booster would be much more complex than those between the Apollo capsule and the Saturn stages.

By the time Mueller resigned as Associate Administrator for Manned Space Flight in December 1969, a general management approach was in place. Task teams had defined general characteristics of the Shuttle; it would be a two-stage fully reusable craft capable of performing for 100 missions. High-performance hydrogen/oxygen engines with throttle capability would provide the vehicle's power. The Shuttle would take off vertically and land horizontally. The orbiter's cargo bay was to be 60 feet long and 15 feet in diameter.[29] Many questions about Shuttle would remain for definition during Phase B of system design.

NASA knew that to win administration approval the Agency would have to build a coalition in support of the Shuttle. Political considerations thus influenced Shuttle planning throughout to a greater degree than they had in earlier NASA programs. NASA needed support from the Department of Defense both for its congressional clout and as a customer that would provide payloads, so DOD had been involved in Shuttle planning from the beginning. Its demands for cross-range (the ability to maneuver in a horizontal plane during reentry) and minimum cargo bay dimensions became inflexible Shuttle requirements that determined Shuttle size and wing configuration.[30]

The aerospace industry would also play a larger role in developing the Shuttle than it had during Apollo. The decline of the arsenal system owed in part to NASA's need for industry support. Contracting created political constituents for the Agency, but as a consequence NASA relinquished its in-house manufacturing capacity, and lost some ability to measure contractor performance. NASA expected competitive development to promote better use of manpower, earlier completion, and lower prices.[31]

Few aspects of the Shuttle program had as much impact on Marshall as NASA's decision to minimize in-house manufacturing. The Center had used in-house manufacturing of prototypes and subsystems to hone its engineering skills. Mueller sought to reassure von Braun that use of contractors offered economic advantages and earlier completion.[32] Von Braun tried to maintain pockets of in-house strength. He warned Headquarters that Marshall would be "more constrained in influencing the contractor's designs and practices," and find it more difficult to "retain its penetration" of contractors. He warned that costs could rise, schedules would be less exact, and contractors would be compelled to take risky shortcuts to maintain a competitive advantage.[33]

Another departure from Apollo was that concern for costs was paramount. George Low put it succinctly: "I think there is only one objective for the Space Shuttle program, and that is 'to provide a low-cost, economical space transportation system.'"[34] Costs became a prime driver of Shuttle development, influencing schedule, prompting design changes, determining development strategies.[35] Unrelenting emphasis on costs led NASA and its contractors to develop over-optimistic projections of anticipated Shuttle performance and low estimates of development costs that precipitated overruns.[36]

With Mueller's departure, some expected that power would shift back to the Centers.[37] In fact the intercenter Shuttle management agreement gave the Centers leverage against Headquarters. Marshall and the Manned Spacecraft Center would continue to quarrel with one another about control of pieces of the Shuttle program, as they did over control of auxiliary propulsion late in 1969.[38] In disputes with Headquarters over Shuttle management, however, the two Centers were in general agreement, defending the autonomy of the field Centers.[39] But Headquarters was reluctant to grant such latitude on Shuttle.

As NASA prepared to initiate Phase B Shuttle studies, it became clear that Mueller's successor, Dale D. Myers, would be aggressive in asserting Headquarters' prerogatives over the Centers. He insisted on the need to "maintain discipline," and stipulated that all changes must be approved at Headquarters.[40] Myers went even further than Mueller in his insistence that contractors be given free rein. He warned Eberhard Rees, who had become Center Director at Marshall when Von Braun accepted a position at Headquarters in January 1970, that "in order to establish the right tenor" the Centers would have to exercise "considerable restraint" in relations with contractors. "We must guard against over-managing and tight control of the contractor's activities," he warned.[41] Three weeks later, he was even more explicit. He told Rees to limit previously approved in-house studies, and informed him that "I hold you responsible to limit the in-house studies to that effort which does not dissipate the contractor or the Center resources and to activities which truly supplement and support the industrial effort."[42]

The concept of a fully reusable Shuttle ran into both technical and fiscal obstacles that forced evaluation of alternatives. A "fly-back" booster would require two piloted stages, one for the orbiter and one for the booster, and would have posed technical difficulties at the point of stage separation and in case of the need for abort. Another critical technical problem involved the challenge of inspecting for reuse large cryogenic tanks that were integral to the Shuttle structure, a problem that led some engineers to champion an expendable external tank.[43]

The problem of controlling costs also forced reconsideration of a fully reusable system. The cost issue became more serious on 7 March when President Nixon retreated from the goals of the Space Task Group. He offered six goals for the space program, of which only the Shuttle survived as a major new start for

NASA. Congressional criticism of the manned space program in general and the Shuttle in particular also forced NASA to reconsider its plans.[44]

Pressed from one side by Air Force requirements to develop a larger and more expensive vehicle than would have been necessary for NASA alone, and from the other by unrelenting pressure to cut costs, NASA had to find a middle way. A fully reusable Shuttle would realize savings over the life of the program, but would be more expensive to develop. By accepting a partially reusable vehicle, NASA might salvage its program by saving development costs, even if it meant that the cost per flight would be higher because of the need to buy expendable parts for each Shuttle flight. Since expendable components were less expensive to develop, their use could save money on the front end of the program by postponing expenses.

NASA thus moved into Phase B Shuttle studies in a very different environment than that immediately following the Apollo 11 moon landing. Headquarters asked Marshall to study the feasibility of a "low cost manned support module which could be transported by the Shuttle."[45] No longer could the Agency rely on the concept of a total manned system linking Shuttle to Station; instead, NASA argued that Shuttle was justified based on reduced payload costs, ironically subordinating the manned space program to unmanned space science.[46]

The plan for Shuttle development became clearer in the spring of 1970 as NASA evaluated Phase B proposals for both the Shuttle and its main engines. The plan for Phase B management represented something of a victory for the Centers, and especially for Marshall Director Rees, who had argued persistently for the "Apollo concept" in which the Centers "were not encumbered with offices and groups to oversee, review, integrate, and coordinate their activities."[47] Headquarters sought to balance management authority between Houston and Marshall, with Houston managing Phase B systems studies, Marshall the main engine studies, and the Centers dividing the Phase A Alternate Space Shuttle Concepts Studies intended to explore alternatives to a fully reusable system.

On 30 April the Agency awarded Phase B Shuttle main engine contracts under Marshall's management to Aerojet, Rocketdyne, and Pratt & Whitney. On 9 May Headquarters announced awards of parallel 11-month Phase B Shuttle contracts to McDonnell Douglas and North American Rockwell to investigate fully reusable concepts employing a two-stage Shuttle with a piloted flyback booster and an orbiter that would carry its payload and fuel internally.[48]

Phase B studies proceeded more slowly than planned, in part because of the constantly shifting fiscal terrain, but largely because of the range of configuration under consideration.

Another important change in emphasis occurred in March. The fully reusable concept began to look untenable. "The OMB [Office of Management and Budget] and the President gave us a budget. And the fully reusable vehicle would not have met that budget," remembered one of Marshall's engineers working on Phase B studies.[49] Discussion of expendable options had become more common with increasing cost pressure. The idea of using an external tank, which apparently originated in the Grumman Phase A study, gained support since it would simplify development of the Orbiter, make the orbiter lighter, and reduce development costs. In a fully reusable system, the orbiter would have carried liquid hydrogen internally. "Because hydrogen is such low density," Marshall's Mike Pessin explained, the orbiter would have required "large hydrogen tanks. It had to protect those hydrogen tanks during reentry, because it was coming back at more of a velocity. It needed the heavyweight, high temperature TPS [thermal protection system]. . . . By going to a drop tank Orbiter, where you had an External Tank, then you ended up bringing the mass fraction of the Orbiter system down, because the Tank no longer had to be protected from the high heating." In March NASA requested all contractors doing definition studies to evaluate use of an external hydrogen tank.[50]

James C. Fletcher became NASA Administrator on 27 April 1971, and soon committed the Agency to the Shuttle. "I don't want to hear any more about a Space Station, not while I am here," he proclaimed.[51] He soon faced budget pressure that made the constraints of previous months seem modest. The Office of Management and Budget announced in May that NASA could not expect any budget increases for the next five years, casting all Shuttle plans in doubt since it would limit funding for the new system to between $5 billion and $6 billion, far below what Paine or Low had anticipated as minimal.[52]

Management of the Shuttle program was another pressing issue when Fletcher took the helm. Houston wanted a Lead Center approach, with the Manned Spacecraft Center responsible for "complete systems engineering, program management and control including financial management," with a Headquarters director "who would review the MSC decisions and concur in these decisions."[53] The Houston plan sought to decrease the authority the Headquarters program office had under Apollo by shifting program and financial management to the Lead

Center.[54] Talk of single-Center management worried people in Huntsville, who feared that Marshall might lose even the propulsion system.[55]

When word leaked out that Myers, the head of the Office of Manned Space Flight, supported the idea of naming Houston Lead Center, the Alabama congressional delegation, led by Huntsville's Senator John Sparkman, requested a meeting with Fletcher. Sparkman dropped his request after receiving assurance that Marshall would get a "sizable portion" of Shuttle work.[56] More than Shuttle work was at stake, however. When Myers sent his organizational plan to Fletcher, he proposed assigning Houston as Lead Center on Shuttle, and assigning Marshall the Research and Applications Module (RAM, the predecessor of Spacelab) and Space Station studies in addition to its Shuttle propulsion.[57]

The Shuttle management plan that Myers announced on 10 June made compromises to minimize Center rivalry. Marshall received responsibility for the booster and the main engines, Kennedy for launch and orbiter implementation. It gave Houston everything it wanted except financial management, which remained in Washington. Christopher Kraft, Houston's deputy director at the time, claimed that leaving financial control in Washington gave Houston technical management but not control. Marshall "got the money for their programs through Headquarters. That was a ploy to satisfy their distrust in the system," Kraft said.[58]

But Headquarters had no intention of relinquishing financial control, particularly when management was seeking to demonstrate its cost-consciousness. As George Low insisted, "We can't let the people at Marshall and Houston solve all their problems by calling up the budget office and saying they were going to let out another contract for $10 or $15 million."[59]

Nor was Marshall satisfied. "That was a very controversial decision, and a decision that I think some people would argue today might not have been a good decision," explained Bill Sneed, who was involved in Shuttle planning as a part of Program Development. "It has been our experience here that it's very difficult for one Center with equal posture to lead and manage another Center. There's a certain amount of competitiveness and parochialism between the Centers that makes it difficult for one Center to be able to objectively lead the other. And perhaps more difficult would be to have one follow the other. That was the real flaw in that arrangement."[60]

Houston's aggressive assumption of its Lead Center responsibilities gave Marshall concern as well. Roy Godfrey, manager of Marshall's Space Shuttle Task Team, attended a meeting of contractors in Houston shortly after the Manned Spacecraft Center became Lead Center, and reported that the contractors received "liberal doses of MSC philosophy from Max Faget and Chris Kraft." When one of the contractors responded to criticism that they were only doing what had been requested in Washington, Kraft told him, "You are in Houston now, not Washington!" Godfrey concluded that "MSC has taken firm hold of Shuttle—they left no doubt in the contractors' minds that they intend to have their way."[61] Two months later, Marshall complained to Headquarters that the Houston Shuttle Program Office was approving its own facility requirements and disapproving Marshall's. Dick Cook, Marshall's Deputy Director for Management, suggested that the facilities issue demonstrated that "no matter how one Center that has been given program management responsibility over other Centers tries, it cannot look at the requirements of another Center in an unbiased manner."[62]

In the summer, as budget pressure increased to the point that the survival of the Shuttle was in question, a configuration breakthrough gave the program new life. The development was so significant that by the end of the year Fletcher could claim that "the cost and complexity of today's Shuttle is one-half of what it was six months ago."[63] The Shuttle orbiter's main engines required both liquid hydrogen and liquid oxygen for fuel. For several months, all four Phase A and B configuration contractors had been looking at designs using an external tank for liquid hydrogen and an internal tank within the orbiter for liquid oxygen. The breakthrough of May 1971 involved putting all of the Shuttle's ascent fuel in external tanks, utilizing one large shell for both liquid hydrogen and liquid oxygen tanks. In addition to lightening the orbiter and allowing for a larger payload bay, the concept allowed the tank to perform the structural function of absorbing the thrust of strap-on boosters.[64] Furthermore, it lowered costs since its development required no new technology. "We went with essentially Apollo technology. We were deliberately not wanting to invest into a high risk technology in the Tank," remembered James Odom, who would later head Marshall's External Tank Program. "That was the way we got the cost down from ten billion down to the five billion. In doing that, we had more expendable hardware. The per launch cost went up, but we got the development cost down to within a range that Congress would support."[65]

Piece by piece NASA had been forced to accept reductions below what it considered necessary to build the Shuttle. From Paine's $10 to $15 billion estimate, Low had accepted a cut to $8.3 billion in the fall of 1970. Fletcher had been able to stave off OMB's goal of $4.7 billion in the protracted battle from May to December 1971. On 5 January 1972, President Nixon approved the Shuttle with a budget of $5.5 billion. Treasury Secretary George Schulz insisted on another cut, and NASA finally had to settle for $5.15 billion.[66]

Nixon approved a Shuttle whose configuration was not yet set. Refinements of the configuration continued until the final decision in March 1972. The expendable external tank concept not only allowed for a more efficient orbiter, but offered new possibilities for booster design. A smaller, lighter orbiter could shoulder more of the burden of attaining orbit; booster separation thus could take place at lower altitude and lower velocity. Budget cutbacks and the external tank thus eliminated the piloted flyback booster from consideration, and forced NASA to examine booster concepts that were simpler and less expensive.

By the fall of 1971, three types of boosters were under consideration: pressure-fed and pump-fed liquid propellant boosters and solid propellant boosters. Marshall had used pump-fed liquid boosters in its Saturn engines. The Center had no peers in their development, testing, and operation. Pressure-fed boosters would have required more technical risk but would have had thicker walls more able to withstand ocean impact, making recovery and refurbishment easier. NASA preferred the lower cost and lower technical risk associated with the pump-fed engine despite recovery disadvantages.[67] So the booster question narrowed to a choice between pump-fed liquids and solids.

No technological issue was as sensitive at Marshall as the debate between liquid and solid rocket engines. With its tradition of conservative engineering and extensive testing, Marshall had always relied on liquid-fueled engines and resisted the use of solids. A liquid system could be tested over and over, "literally thousands of times," according to Marshall's Bill Brown, who had long experience with solids at contractors and Marshall. "The cost of testing large [solid] rocket motors repeatedly is very, very high. . . . They have, I don't know how many, maybe tens of tests rather than hundreds or thousands of tests such as you would have in a liquid system. So, there has to be much more extrapolation of the data" than with a liquid system.[68]

Unlike the Air Force, which had used solid rocket motors, NASA—and Marshall—had experience almost exclusively with liquids. "Solids had never been used in manned space flight before, except the escape rockets on the Apollo and Mercury programs," explained LeRoy Day. "There were people who were not enthusiastic about them. Von Braun was one who didn't think we should go solids."[69]

"The Germans did indeed oppose the solid rocket motors—and not just the Germans. Many of us did," recalled Brown. "The basic problem is that you have your oxidizer and your fuel already mixed. And if you get that started, it is extremely difficult, if not impossible, to stop it from going, unlike the liquid system which mixes the oxidizer and the fuel only at the time you wish to combust them."[70] Ron McIntosh, who spent most of his career at Marshall working on solid rocket motors, explained that "Solid rocket motors are a lot like fireworks or roman candles. Once you light that thing you better be prepared to put up with whatever is going to happen, because you're not going to be able to turn it off."[71]

Recovery of reusable solids posed another problem. According to Day, "There were a lot of skeptics, because the size of the solids is about like a freight train car. . . . It's going to impact the ocean at about 100 miles per hour and . . . the damage would be so severe that it wouldn't be cost effective."[72]

The debate placed Marshall in a precarious position, particularly when Headquarters began to prefer solids. Marshall was opposed to solids, but could not afford to be too persistent for fear of losing the responsibility to manage the booster development. Fletcher had made clear his concern that Marshall would not give solids a fair shake. After a discussion with Headquarters, Rees reflected that "Mr. Myers emphasized again that Marshall Space Flight Center is obviously known as being against solids." Dan Driscoll, preparing to present Marshall's point of view to Headquarters, said that he planned to show that Marshall "understands the advantages of the solids as well as their disadvantages." Rees urged him to convey to Fletcher the Center's "enthusiastic involvement in the configuration of the Shuttle booster with solids."[73]

Aerospace publications perpetuated the widely held conception that Marshall was irrevocably opposed to solids. The *Aerospace Daily* quoted "industry sources" as citing the Center's long history of work with liquids as evidence

that Marshall "is not about to put itself out of business."[74] When a report circulated that "directors of certain NASA Centers" were trying to close off debate by selecting pump-fed liquids before competitors had a chance to make their presentations, one of Marshall's executives wrote cynically in the margin: "We will, of course, get full credit for this."[75]

NASA did not decide to go with solids until March 1972, nine weeks after President Nixon approved the Shuttle. In fact, when Fletcher met with the President in January, he took with him a model of the Shuttle graced by pencil-thin liquid boosters.[76] The decision boiled down to two issues: thrust and cost. The Agency anticipated that liquid engines would be used in a series burn configuration, meaning that a liquid booster stage would separate before the orbiter's main engines would ignite. Solids, on the other hand, could be designed in a parallel burn configuration in which the boosters and main engines could fire at the same time, taking maximum advantage of the high performance main engines during early ascent. Solids also would be $700 million less expensive to develop and have a lower unit cost. Since they could withstand impact better, they offered recovery advantages. And since they were less expensive, loss during recovery could be more easily absorbed.[77] For Fletcher the decision was "a trade-off between future benefits and earlier savings."[78]

Selection of a solid propellant booster completed the configuration of the Shuttle. The nation's next generation space vehicle was to be a delta-winged craft with a 60- by 15-foot payload bay. Its main engines were to be powered by liquid hydrogen and liquid oxygen supplied from an expendable external tank. Two reusable solid rocket boosters mounted on the external tank would help power the Shuttle into orbit.

Selecting Contractors

Marshall would manage three Shuttle projects: the main engines, three of which would be arrayed in each orbiter; the solid rocket boosters, two of which would be attached to the external tank below the orbiter; and the external tank itself. Planning for Shuttle contracts clearly showed NASA's new focus on keeping costs to a minimum.

Shuttle was to be a very different program from Apollo. NASA management had to adjust from a program in which there was ample money to one with very

tight funding constraints. "The Shuttle presented some new challenges for the Agency that we really had not experienced," remembered Sneed of Marshall's Program Development directorate. With Apollo, the technical requirement was fixed, the schedule was fixed, and cost was a variable. "Any time we got into difficulties with the Apollo program, we had the money to 'buy our way out of it,'" Sneed continued.

"Shuttle program management was more difficult than Apollo in that we had a fixed budget, which significantly influenced every major program decision. Since technical requirements were essentially fixed, it meant that schedules had to be delayed to make dollars available on a near-term basis to solve technical problems. This was an acceptable near-term solution but not a good long-term solution since extended schedules required considerably more total dollars for the program—dollars that were not available to NASA. So there was a conflict built into the program from the outset. It required the Shuttle project managers to complete the development program within a set of fixed technical requirements, fixed budget and a fixed schedule—a most formidable and challenging task. This condition forced our project managers to be more frugal in executing the development program, conducting a minimally acceptable test program, minimizing back-up developments for problem areas, and in general introducing greater risks in the decision making process."[79]

With some 60 percent of the operating costs of each Shuttle mission dependent on components under Marshall's responsibility, Rees realized that the Center would have to place new emphasis on monitoring costs. He decided to establish a Centerwide cost estimating group. "I know that MSFC was never too good in this particular area," he acknowledged.

"Our engineers just are not used to design for low cost. When we awarded the contracts for the Saturn stages, we based them on Work Statements which never spelled out unit costs. These contracts were rather spelling out a development program for those stages and incidentally included in the price was the delivery of so and so many stages within a certain time."[80]

The constant threat of recurring reductions-in-force reinforced programmatic demands that Marshall monitor costs carefully. Fletcher made the connection between Shuttle costs and personnel reductions explicit in August 1973 when he insisted that if the Program Office made a decision that increased the cost of the Shuttle, Marshall would have to lose another 150 people.[81]

The impact of costs on Shuttle development affected the negotiation of development contracts, a process already underway during the evolution of the Shuttle configuration. Development of the Shuttle main engine preceded Marshall's other Shuttle programs. An integral part of the orbiter, the main engine was the pacing component of the Shuttle; its development had to proceed in tandem with Houston's work on the orbiter.[82] Thus the main engine moved through Phase B program definition and preliminary design while shuttle configuration studies were still underway. Three aerospace contractors—Aerojet, Pratt & Whitney, and North American Rockwell's Rocketdyne Division—participated in the preliminary design studies. Marshall planned to follow Department of Defense procurement strategy and have a "shoot-out" in which, as Frank Stewart explained, "we'd go up to a few engine-level test firings with two contractors, and then we'd make a final selection." Stewart remembered having set aside $25 million to execute the plan.[83]

Then tightening budgets intervened. Headquarters decided that rather than continue two main engine contracts into Phase C/D development and then have a "shoot-out" to select the better design, NASA would select one contractor at the conclusion of Phase B definition studies. Marshall's program management office worried that "once we choose a company and a configuration, we are locked in," and that "the 'benefits of competition' must be realized at the negotiation table."[84] Nor was the approach necessarily less costly in the long run. Richard L. Brown, who helped evaluate the main engine proposal, claimed "there were economic studies that indicated it would actually be cheaper to run the competition because of its influence on price" and to arrive at "a better definition of cost, and therefore less overrun."[85]

The Center issued its Request for Proposals for Phase C/D in March 1971, and the three companies that had participated in definition studies all responded. On 13 July, Marshall announced selection of Rocketdyne for negotiations leading to a contract worth perhaps $500 million for design, development, and delivery by 1978 of 36 engines, each capable of 100 missions.[86] Pratt & Whitney protested, initiating what one report termed "a savage fight between two giants in the economically depressed aerospace industry."[87] Pratt & Whitney filed charges with the General Accounting Office (GAO), claiming experience superior to that of Rocketdyne, and complaining of the selection as "manifestly illegal, arbitrary and capricious, and based upon unsound, imprudent procurement decisions."[88] Both Alabama senators joined seven colleagues from the Southeast protesting selection of a California company over one from Florida:

"It seems inconceivable that Pratt & Whitney's low risk design based on flightweight hardware testing can be matched by limited boilerplate testing and paper studies of the bidding competition."[89] Rocketdyne, which built Saturn engines for Marshall, claimed better experience in building large liquid-rocket engines.[90]

The protest had several ramifications. In the short term, it delayed work on the main engines, which NASA considered the pacing item for the Shuttle. The GAO allowed Marshall to continue to negotiate with Rocketdyne with the understanding that no definitized contract could be signed until resolution of the protest, which took seven-and-one-half months.[91] The Center issued a series of interim level-of-effort contracts to Rocketdyne pending resolution. On 31 March 1972 GAO ruled in favor of NASA. Rocketdyne worked under a letter contract until completion of the formal contract in August—more than a year after NASA first selected the company for negotiations.[92]

The long-term ramifications of the protest were more serious. With NASA still worried about winning approval of the Shuttle late in 1971, the Agency could ill afford another protest. NASA needed the support of aerospace contractors. Top manned spaceflight and Shuttle administrators met late in November and discussed ways to bolster the depressed aerospace industry. Marshall's Shuttle Program Manager Roy Godfrey reported to Rees:

"George [Low] and his people were very concerned about handling the selection and subcontract awards so we minimized the possibility of a protest. This led to a discussion of dividing up the orbiter and Booster into subcontracts, such as avionics, structures, etc. . . . This way, all the major primes would get enough Shuttle business to support the Shuttle and not protest."[93]

NASA thus adopted a strategy of spreading out Shuttle business among as many aerospace contractors as possible, a pragmatic approach that raised no dissent. Sound politics does not necessarily lead to sound engineering, however. The test of the plan would come as NASA negotiated contracts for other Shuttle components; it would affect in particular the way in which the solid rocket motor (SRM) would be contracted, developed, and assembled.

Negotiations for the solid rocket motor contract were as laden with controversy as the main engine deliberations. The first disagreement was internal, as NASA prepared to request proposals from industry. NASA envisioned the solid rocket

booster (SRB) as a system comprised of a steel case (the SRM), and several other elements such as forward and aft skirts, nose cone, attachment structures, thrust vector control, separation, and recovery devices.[94] Rather than contract the solid rocket booster and require industry to be responsible for the entire system, Fletcher decided to contract only the solid rocket motor and give Marshall integration responsibility.

Fletcher's decision did not have unanimous support at Headquarters. NASA comptroller Bill Lilly proposed making one contractor responsible for the entire system, including design, recovery, and refurbishment. To break bidding into contracts for separate components would double the price of the booster, he argued. Fletcher chose to ignore Lilly's warning, hoping to spread business around and fend off OMB's threat of closing Marshall.[95] When NASA developed a list of 19 internal ground rules before initiating booster procurement, the first guideline gave Marshall the sort of protection it had been seeking since the peak of Apollo: "SRB to be designed in-house with the exception of the SRM."[96]

NASA also made a key decision affecting the configuration before letting the SRM contract. The Program Office in Houston, supported by prime Shuttle contractor Rockwell, decided in April 1973 to eliminate a baseline (minimum) requirement for an abort procedure called thrust termination. Thrust termination would have required a means of shutting down the solid rocket boosters within a specified period of time (which had not yet been determined). It would have been designed to protect against failure of the SRB to ignite before launch, loss of two or three main engines, or burnthrough of the casewall of the sort which caused the *Challenger* disaster.

But thrust termination would have been costly. No abort procedure could be a hundred percent risk-free. Three years earlier, when NASA first considered abort procedures for the Shuttle, Max Faget had commented on one proposal that suggested a 0.999 guaranteed probability of success, "This is going to greatly increase cost if carried to nauseating extreme." Faget argued that system redundancy requirements might be waived "where common sense indicates the risks are low and the cost high." Thrust termination might have added as much as 8,000 pounds to the external tank and increased the orbiter load from two-and-one-half times the force of gravity to three times. Rockwell argued that the concept had too high a system penalty for too little return, and the Program Office believed that the system had sufficient design redundancy.

At meetings in Houston and Washington, Marshall agreed to eliminate thrust termination, but argued for retaining an option to implement it later. Houston considered allowing the option, but Headquarters determined to disallow "scar penalties" (weight allowances held in reserve) that might have made later addition of thrust termination possible, but did allow for SRB separation studies that were never executed. Marshall made one last attempt to revive the thrust termination option in August, but in reality the Headquarters decision ended any possibility of reconsideration.[97]

So when NASA requested proposals for its major booster contract on 13 July 1973, the request involved only the solid rocket motor and lacked provision for thrust termination. Four aerospace companies responded: Aerojet Solid Propulsion Company, Lockheed Propulsion Company, Morton-Thiokol Chemical Corporation, and United Technology Center. The SRM was to include the case, flexible nozzle, ignition system, case liner and insulation, and propellant. Aerojet seemed to have an advantage, since it planned to use a large tract in Florida for assembly and could have constructed one-piece motors for water shipment to Michoud in Louisiana and to Kennedy, whereas the other companies would build segmented boosters for shipment by rail.[98]

After evaluation of proposals by teams involving 289 people representing five NASA Centers, Headquarters, and the three military services, NASA selected Thiokol Chemical Corporation to develop the solid rocket motor. The top three competitors ranked closely on mission suitability criteria; Thiokol won the competition principally on the basis of cost. Thiokol's proposal anticipated the lowest costs for the early years of the program and for development and production, an advantage gained by virtue of lower expenses for facilities and labor.[99] Cost weighed heavily, and indeed Congress had lauded Fletcher's pledge that solid rocket motor procurement "would be accomplished in the manner considered most cost effective."[100]

The selection of Thiokol prompted controversy for two reasons. Critics alleged that Fletcher had pushed business to his home state of Utah, where Thiokol had its headquarters. Fletcher vehemently denied the charge, and others on the Source Evaluation Board defended him. The rationale announced for the selection and the close competition also raised questions, and Lockheed filed a formal protest. Once again NASA feared that its schedule would slip while the Agency sought to defend its decision. Marshall's analysts estimated that the delay would cost $60,000 per day if the dispute was not resolved by 1 February 1974, and

$400,000 per day if it was not settled by 15 March.[101] On 24 June, the General Accounting Office ruled against Lockheed, and two days later NASA awarded the contract to Thiokol.[102]

As a result of the decision to separate the SRM from the rest of the booster, Marshall managed the SRB differently from either the other Shuttle components or other large programs. In addition to the Thiokol contract, Marshall's SRB Program Office managed a contract with United Space Boosters, Incorporated (USBI) for booster assembly in a conventional contractual arrangement. What was unusual was that the Science and Engineering Directorate (S&E) performed as a third prime contractor, and subcontracted other elements of the SRB including the recovery system, booster separation motors, and integrated electronic assembly. The arrangement not only gave Marshall more business than it would have had if all SRB work had been given to a single contractor, but required less money in the early years of development.[103]

The expendable external tank was the third Shuttle component under Marshall's supervision. Rees considered the tank "something very challenging to work on, but also very complex and difficult. I want to go even so far as to state that an optimum drop tank design is one of the key factors for the whole Shuttle Program not only from the viewpoint of performance but also as to economics."[104]

As with all Shuttle components, cost was of primary importance in tank design. James Kingsbury, who headed Marshall's Science and Engineering Directorate during tank development, explained that "the challenge with the Tank was to get it built at minimum cost. There was nothing really challenging technologically in the Tank. . . . The challenge was to drive down the cost."[105] The tank was nonetheless as complex as Rees anticipated. The contractor selected for external tank development would be responsible not only for the liquid hydrogen and liquid oxygen tanks themselves, but for an intertank section, avionics equipment, a thermal protection system, and the assemblies connecting the tank to other Shuttle systems. And the tank would be more than just a container for fuel: it would be the critical structural component of the Shuttle system, the base to which the boosters and orbiters would be attached during ascent.[106] Kingsbury explained that "whereas in the original concept it was a big dumb tank that just kind of carried fuel, it became the structural backbone of the stack."[107]

After the selection of the Shuttle configuration in March 1972, the Center began to devise a strategy for tank development. Since the power systems for the Shuttle were interdependent, and since the tank required less new technology than other Shuttle systems, one school of thought in NASA held that the tank should be the variable element and its development should be deferred until other systems were defined and sized.[108] Rees disagreed, and wanted Marshall's laboratories to start work immediately. "We can initiate immediately all kinds of necessary parametric and trade-off studies, help in clarifying requirements, look into possible tank designs, select best materials, establish tank pressure ranges," he directed.[109] Industry studies confirmed Rees's approach, suggesting that once system weight estimates were set, basic tank design could be frozen and solid rocket motor diameter established.[110]

Selection of the contractor for the external tank went smoothly. In August 1973, NASA named the Denver Division of the Martin Marietta Corporation (MMC) for negotiation of a contract for the design, development, test and evaluation of three ground test tanks and six developmental flight tanks. NASA stipulated that assembly would take place at Marshall's Michoud Assembly Facility in New Orleans.[111]

Developing the Elements

By the time Marshall completed negotiation of contracts for its Shuttle projects, NASA's system for Shuttle program management was in place. NASA established three levels of management. Level I resided in the Office of Manned Space Flight at Headquarters, where the Space Shuttle Program director administered overall planning and allocated resources. Level II resided at Houston's Johnson Space Center, where Robert F. Thompson exercised Lead Center responsibilities as the Space Shuttle Program Manager.[112] Project offices comprised Level III management, and each of Marshall's three Shuttle projects had its own project manager. Marshall also had a Shuttle Projects Office to oversee the three Huntsville projects. Roy Godfrey headed the Marshall projects office during most of the contract negotiation period; in March 1973 Robert Lindstrom took his place. Marshall's Shuttle Projects Office thus had two lines of responsibility: to the Program Office in Houston, and to the Marshall Center director.[113]

Marshall's experience in *Skylab* led the Center to initiate a means to exercise independent engineering judgment on its Shuttle projects through which the Science and Engineering Directorate could make technical decisions unencumbered by managerial responsibilities. Larry Mulloy, who worked on both the external tank and the solid rocket boosters, explained that, "in a project office you're balancing budgets and schedules against technical requirements. And growth in technical requirements leads to growth in budget, leads to growth in schedule. The Project Manager is often under pressure to not grow budget and schedule. His decision process relative to technical matters might be clouded a little bit by those other factors. So they decided to set up a separate Associate Director for Engineering in the Science and Engineering Directorate and have chief engineers who have an autonomy from the project office in terms of technical courses of action."[114]

Each Marshall project had both a project manager and a chief engineer. Project managers were responsible for schedules, budgets, contractor oversight, and contract changes. But the chief engineer had technical authority. Project offices "didn't want the lab making engineering decisions for them," Kingsbury explained, but they "were not staffed with the engineering talent to make those decisions. So they had to depend on the labs."

Thus in addition to their direct lines of authority to the program manager in Houston and the Center Director at Marshall, project managers had to weigh input from Science and Engineering. William Lucas wanted to ensure that "S&E talent will be used as an influential part of the team, not in a second-guessing or trouble-shooting role."[115] As head of Science and Engineering, Kingsbury had the same concern. If the project manager "didn't pay any attention to my engineers, then he was accountable to me," Kingsbury insisted. "If he didn't pay any attention to me there was another guy he would pay attention to, that was his boss and mine. We never had any confrontations."[116]

Their mutual boss was of course the Center Director. The Center Director was technically not part of program management, but NASA recognized his responsibilities by differentiating between "programmatic relationships" and "institutional relationships."[117] Since the Shuttle was the largest program involving Marshall personnel, it would have been inconceivable for the Center Director not to be involved in Shuttle management. This was particularly true of Lucas, who became Center Director in June 1974 when Rocco Petrone returned to Washington as Associate Administrator. Lucas had been involved in

propulsion throughout his career. He had founded the Program Development directorate, and participated in Shuttle planning as its Director and as Deputy Center Director after his appointment in 1971.

Lucas insisted that the project manager and chief engineer on each Marshall project keep him informed. He used the Weekly Notes initiated during von Braun's directorship as a management tool. "It was a technique that encouraged communication," Lucas explained.

"People in the laboratories could introduce these notes. They were read and annotated and sent back. . . . They did not supplant any other thing in terms of communication, any of the more formal things. It was an information exchange, to help the top management understand other views."

"In top management, it is pretty easy to get isolated. You are totally dependent upon what other people tell, you can't be everywhere. It gave you a little better feel for what the disagreements were. . . . I always read the notes; even if I had to leave off something else, I would do that."[118]

Lucas used the Weekly Notes as both a means of gathering information and as a means of communication. In marginal comments he responded to the remarks of his managers, often promulgating policy in the process. His comments thus often set the tone for Marshall's response to problems, often highlighting, for example, deficiencies with contractor management.

Lucas's long experience in engineering and administration prepared him to direct both technical and managerial aspects of Marshall's Shuttle projects. "His technical participation in Shuttle development was as significant as any engineer at the Center," according to Bob Marshall. "His participation in Shuttle was more from a chief engineer role than the senior manager."[119] His role in guiding Marshall's participation in Shuttle development also grew as a result of changes at Headquarters. Over time Level I management became more active; a 1979 internal NASA report concluded that the Associate Administrator for the Shuttle program had become the de facto program director, and demanded more direct participation by Center Directors.[120]

With its management structure in place, Marshall began to move its Shuttle projects into development. The Space Shuttle main engine (SSME), the first of Marshall's projects to begin development, was "the real challenge in Shuttle,"

according to Kingsbury. "It was an unproven technology. Nobody had ever had a rocket engine that operated at the pressures and temperatures of that engine."[121] The engine had to develop 470,000 pounds of thrust for eight and one-half critical minutes of each flight, and although this was less thrust than Saturn engines, those had not been reusable. It was to be lighter and more efficient than previous spaceflight engines, requiring the use of new materials and welding techniques. Operation would generate very high temperatures, so an efficient cooling system utilizing the engine's own hydrogen fuel had to be employed or the engines could melt down. The engines had to withstand reentry and still be reliable enough to make 55 flights without overhaul.[122] "The SSME was by far the most challenging and difficult of all the Shuttle elements," according to Bob Marshall. "Nearly every engine test run contributed a 'first' time test for a fix of a failure in the previous test."[123]

Since the main engine was the pacing development project in the Shuttle program, there was great concern throughout the Agency when the project began to encounter problems. By mid-1974, the main engine project was in trouble, experiencing delays in construction of facilities and in development of critical components, management problems at the contractor, schedule slippage, and substantial cost overruns. Fletcher warned in May that Rocketdyne's projected cost increases were "unacceptable and pose serious threats to the Space Shuttle Program."[124] An internal company report a month later acknowledged that several things were going wrong, including "technical, schedule and cost problems in the Honeywell controller, delays and overruns in the construction of the facilities at Santa Susana, serious material shortage and vendor delivery problems."[125]

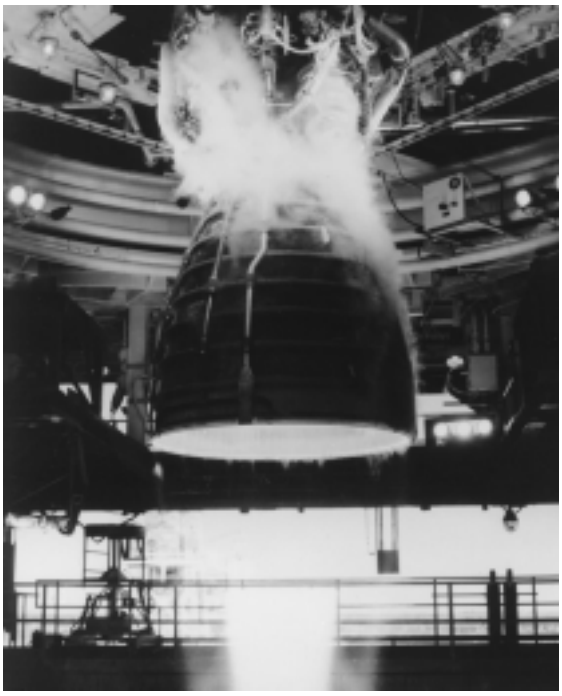
Some of Rocketdyne's problems derived from its management of subcontractors for the main engine controller and facilities at Santa Susana. The controller was an electronic computer meant to monitor the functions of the engine such as pressure, temperature, and flow, and then to translate these readings to direct a predetermined sequence of events. Honeywell's controller experienced design and fabrication problems related to the power supply and line noise in the interconnect circuits. For a time these problems were so troubling that Fletcher expressed "serious doubts about the capability of Minneapolis-Honeywell to develop the engine controller for reasonable cost under Rocketdyne management."[126] Rocketdyne even considered development of an alternate backup system, but by the summer of 1975, Marshall was confident that remaining difficulties could be solved.[127]

The Santa Susana facility issue was perhaps more troubling, since it raised questions about Rocketdyne's management of its main engine responsibilities. Rocketdyne operated a test area at Santa Susana in the mountains north of the San Fernando Valley near Los Angeles. Bovee and Crail, another subcontractor, had responsibility for constructing test positions at the cluster of Santa Susana test sites designated COCA–1 through COCA–4. Rocketdyne's schedule had already slipped by the beginning of 1974 when the company requested an additional $2.7 million to complete construction. For the next several months, things only got worse. Marshall, hoping to keep main engine development on track, requested an accelerated construction schedule. Instead, the schedule slipped again and again, and NASA cited Rocketdyne for "failure to perform." Rocketdyne and Bovee and Crail agreed to work 10-hour days and 6-day weeks in order to finish the facilities by an "absolutely necessary" deadline of 15 December.[128]

Cost overruns plagued facilities construction, controller development, and labor expenses. Fletcher called the increases in wages and fringe benefits resulting from a new labor agreement "staggering," and warned that "the funding level for the Space Shuttle Budget is essentially fixed and will not accommodate inflationary growth of this projected magnitude."[129] A Rockwell internal review of Rocketdyne acknowledged poor morale and criticized a $70.3 million cost overrun, a six-month slip in schedule, and excessive overtime. The report observed that "working relationships between Rocketdyne and NASA at all working levels have deteriorated," and judged that both Rocketdyne and the government had underestimated the complexity of the project.[130]

Marshall responded aggressively to Rocketdyne's problems, and increasingly focused on the company's management as their source. As soon as the Santa Susana cost and schedule problems surfaced, the Center formed a "Facilities Tiger Team."[131] In May, two Marshall reviews cited management shortcomings. One said that while there had been improvements in scheduling, "good control is not yet evident."[132] The other, from Program Development, made recommendations, the first two of which were to "get the company integrated" and "make the VPs accountable and measure their performance against hard criteria."[133] When Rocketdyne mislabeled equipment, Lucas considered it symptomatic, an indication that "discipline is still lacking in the Rocketdyne organization."[134] Rockwell complained that Marshall was "so concerned over the Honeywell situation that it appears to have 'taken over' technical management of the controller program."[135]

Rocketdyne made changes, naming a new program manager for its main engine program, bringing in other new people, and conducting program reviews.[136] By the end of summer, improvement was apparent. The new program manager seemed "keenly aware of the need for good morale and a team spirit."[137] Facilities problems continued, but engine development was now moving along, and Marshall's main engine Project Manager J. R. Thompson told Lucas that "we probably understand and have better control over the engine powerhead in terms of cautious, safe operation than we have over the facilities."[138] By late October, Marshall's assessment of the Rocketdyne operation was even more positive. "Tests now occur when planned" noted one comment, and morale among test personnel, where there had been so many problems with facilities, was "now one of the highest at Rocketdyne." Problems remained, for the cost overrun continued to grow and Marshall still expected improvement in management, but the engine program had passed through a difficult early shakedown.[139]



Space Shuttle main engine test in Mississippi.

In March 1975, Rocketdyne completed the first main engine a month ahead of schedule. The engine was intended for testing, not flight. Rocketdyne shipped it to the National Space Technology Laboratories (NSTL) in Bay St. Louis, Mississippi, a facility operated by Marshall and used to supplement tests conducted at the COCA site at Santa Susana.[140]

Cost considerations forced Marshall to apply a different approach to testing Shuttle than had been used in Apollo. First, during Apollo more money was available during the design phase. "The heritage of the Germans was

conservatism always," Marshall engineer Robert Schwinghamer explained, "and if there was any question or any doubt on the Saturn, you just overdesigned it." Shuttle had less money for robust designs.[141] Second, component testing on Shuttle was more limited than in the Apollo Program, where Marshall applied extensive independent component testing before assembling and testing the whole engine. "We didn't have that luxury on the Shuttle," according to Schwinghamer. "We just never really had enough money to go into a components test program on the Shuttle. And so, I think some of the problems that we had with the Engines in the early days had to do with wringing out the bugs. . . . That did give us some problems."[142]

Test activity at both the California and Mississippi sites was intense. "We worked harder on that program than on any program that I have ever been associated with," according to Jerry Thomson, the chief engineer on the main engines. "It was a 60-hour a week job. . . . We were running tests late into the night, and worrying about getting everything fixed that we failed, and we were trying to make schedule. . . . None of the Apollo activities ever had the challenge and the difficulties that we had with the SSME."[143]

The first major technological challenge involved a rotor instability problem that caused vibration, limited the speed of the turbopump, and caused bearing failures. In March 1976 turbine end bearings failed as a result of high temperatures and violent rotor instability known as subsynchronous whirl. "The rotor was orbiting within its bearing supports," according to J. R. Thompson, who later remembered this as "one of the more elusive problems we had." A joint NASA-Rocketdyne team used mathematical models, consultation with universities and industry as well as laboratory tests to derive design changes. These adjustments eliminated the whirl problem.[144]

Four explosions associated with testing high-pressure oxidizer turbopumps occurred before the first Shuttle flight. Rocketdyne's project engineer described liquid oxygen explosions as "nightmarish events in rocket development programs." Not only did they take equipment out of commission and thereby disrupt schedules, but the explosions often destroyed equipment, leaving no evidence of the cause of the failure. At least two of the fires resulted from failure to keep liquid oxygen separate from the hydrogen-enriched steam that drives the turbine, the "overriding design concern" with the turbine pump. Design changes included modifications to shaft seals and turbine end bearings.[145]

Ron Tepool remembered the first time an engine blew up at the Mississippi test area. The accident took place at the time of a main engine quarterly review in Huntsville, so J. R. Thompson and a "planeload" of Marshall executives went to inspect the damage. "About two in the morning, J. R. wanted to see the engine. So, we went up to the test stand, just he and I. And he stalked this thing. He just walked around it, looking. It was just ashes basically. And he said, 'We ain't never going to do this again.' I told him then that in the F–1 program, we blew up about 15 engines or something like that. I told him this was just the first of many. He didn't believe that, but he believes it now."[146]

Tepool was right. As time went on Thompson became more sanguine about engine tests, and Ron Bledsoe remembered that "J. R. always indicated that whenever we had a failure, it was an opportunity."[147] John McCarty explained that "we always used to say that an engineer didn't learn anything until we had a failure. There's a lot of truth to that, because if you're just operating and everything's performing as predicted, all you know is that it's performing as predicted. It could mean your prediction is perfect or could mean that your prediction is off."[148]

Failures were to be expected in a high-risk developmental project, but they were nonetheless costly. On 4 February 1976, an oxygen flowmeter failed at the COCA–1A Test Site at Santa Susana. Parts broke loose and hit a liquid oxygen discharge valve, causing an explosion and igniting a fire that lasted 20 minutes. The machinery under test and the test stand suffered significant damage, and Marshall had to divert $1.2 million from the Mississippi facility to make repairs.[149] Four months later a fuel subsystem test at the neighboring COCA–1B site resulted in another major fire.[150] Fires, lack of resources, and the expense of operating two main engine testing facilities finally forced NASA to phase out component testing at the COCA site by September 1977, although other areas at Santa Susana would be used for main engine testing. "They just couldn't afford to keep both Mississippi and COCA open, so they closed COCA down," according to McCarty. "We couldn't get a reliable enough test frequency out of it."[151] New NASA Administrator Robert Frosch rationalized that "the best and truest test bed for all major components . . . is the engine itself."[152]

The Mississippi facility was just as susceptible to test accidents. Tests involving the liquid oxygen pump system resulted in three fires at the National Space Technology Laboratory in 1977 and 1978.[153] Each incident delayed development.

With each failure, said Herman Thomason, "there's an investigation. Put a freeze on and go in and do a complete investigation and find out what happened. You've got to report all the way up to the Administrator. And everybody takes a rap on the knuckles and go fix that. You go test for another week and something else goes wrong, and you've got to go through it all again."[154]

Fortunately Headquarters gave strong backing to Marshall's main engine team. Chief engineer Jerry Thomson recalled that "When J. R. Thompson and I were blowing up the engines every few months and wondering how soon would we be dismissed, John Yardley was giving us encouragement, 'You guys will get it fixed. Just keep trying.'"[155]

Main engine development proceeded more slowly than planned, but NASA still hoped to launch a first manned Shuttle flight before the end of the decade. The engine performed well for several months of successful tests, including one at 100-percent power, before the July 1978 Bay St. Louis fire.

With the main engines operating at higher temperatures and pressures than any previous engine, turbine blade problems became a recurring challenge. The first instances of blade failure occurred in two separate tests late in 1977. In the second and more serious accident, debris from a shattered blade caused the pump to seize up causing loss of the engine. Engineers attributed both accidents to blade fatigue and insufficient damping of the blades. In 1978, as J. R. Thompson remembered, "We really started getting cranked up and running the engine." More fatigue-related problems developed in the main injector and main oxidizer valve. Early in 1979 cracks in the blade platforms and the blades themselves threatened to delay again the oft-postponed first Shuttle launch. But Thompson insisted that in the late phase of development, "the failures predominantly are those associated with fatigue which one would expect in this development program of extended life."[156]

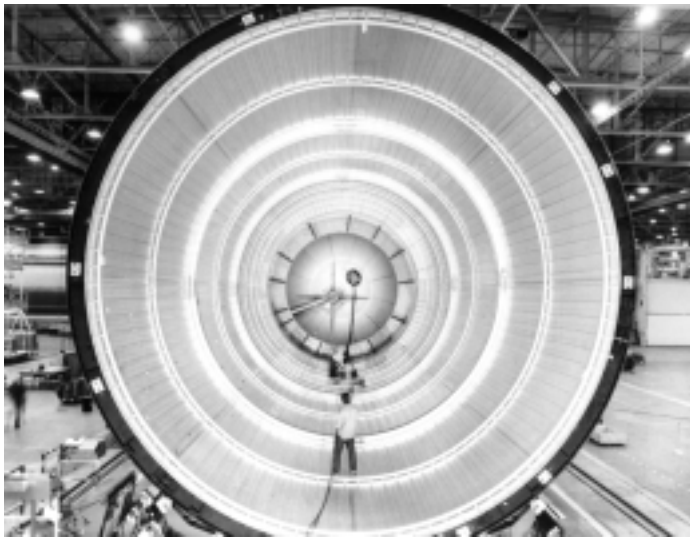
Unlike the main engine, the external tank did not require major technological breakthroughs. Mulloy explained that "The ET [External Tank] was state of the art. There was no technological challenge in the building of the External Tank. The only challenge was building it to sustain the very large loads that it has to carry, and the thermal environment that it is exposed to during ascent within a weight bogie that was assigned as some 75,000 pounds."[157]

The relative simplicity of the tank ironically prompted the tank to go through more design changes than any other Shuttle element. Kingsbury explained that when there was a structural problem with one Shuttle element, engineers studied possible design trade-offs: "Which does it cost the least to modify, that element or the Tank? And more often than not, like 95 percent of the time, the answer came back that the Tank was easiest to modify. So the Tank went through design change and design change—hundreds of them."[158]

Marshall's Shuttle elements entered development during a period of national economic instability that affected all contractors. Like the main engine, the external tank project ran into cost problems immediately. After its selection for negotiation of the external tank contract, Martin Marietta presented cost projections to Marshall that exceeded the company's original proposal by $8 million over the life of the contract. Martin Marietta blamed inflation for the increases, but also explained that the aerospace industry had declined less in New Orleans than expected, making local hiring difficult. Marshall speculated about underbidding, worried about the unreliability of using Martin Marietta figures for planning purposes, and suggested issuing only a short-term contract to guard against future overruns.[159] Fletcher sent a stern letter to Martin Marietta, as he had done two months earlier to Rockwell about main engine cost growth, regarding "alarming increases in the external tank work," warning that the Shuttle budget "will not accommodate a cost growth of this magnitude."[160] In spite of disagreements over costs, by January 1975 Marshall and Martin Marietta agreed on terms for a $152,565,000 cost-plus-award-fee contract for design, development, and test of the external tank.[161]

That the external tank was the only expendable Shuttle element made its development different from other Shuttle projects. As Project Manager James Odom explained, "One of the unique things about the Tank project was that it was a production program, which was new to NASA." Other NASA programs might involve production of perhaps twenty or thirty units at most, but "we had tooled up to build 400 tanks over the next twenty years."[162] Porter Bridwell, who headed Odom's Project Engineering Group, remembered that "we had a Production Readiness Review. We went back to the Army, went to industry, and patterned [the production plan] after what they had done with respect to assuring that when you do start into production, you have the tooling, automation systems, and software on line and ready to go."[163]

Marshall also used an unusual approach in designing for production. "I did something that's a bit unique in a production program," said Odom. "Typically, you will design an article and you will build what you call a prototype. . . . In my case, I wanted to make sure the Tanks I qualified were built on the same tooling that I was going to build the flight Tanks on. I took the risk and put a $200 or $300 million investment into tooling up front that normally gets invested later in a program."[164] Mike Pessin, who assisted Odom, said that "we took the risk of going ahead with production tooling from scratch. The tools that we're building the Tanks on today, in most cases, are the same tools that we built the very first test items, with modifications that you walking by would never notice."[165]



Workers in the liquid hydrogen tank, part of external tank, in May 1977.

In a production program, Odom insisted "you have to go in and really look at the plant layout." Michoud's proximity to the Gulf of Mexico gave access for barge transportation of the 154-foot-long, 28-foot-diameter Shuttle tanks to the Kennedy Space Center. The assembly facility spread over 833 acres, and Odom remembered that "we had one building that was literally forty-two acres under just one roof." Expecting to produce 24 tanks a year initially, Martin Marietta assembled a work force of 4,300.[166]

While assembly would take place at Michoud, approximately 70 percent of the funds committed to the external tank went to subcontractors scattered around the country, most of whom supplied materials to Martin Marietta. Odom believed

that one of Martin Marietta's strengths was its ability to manage subcontractors. "We would go and visit each subcontractor before we would sign a contract with him: get to know the management, get to know their capabilities, . . . what their financial posture was. We knew every one of those contractors literally on a first name basis almost before we signed a contract."[167] Trucks carrying oversize loads streamed into New Orleans from Dallas, San Diego, Baltimore and other cities around the country, and by the spring of 1976, Michoud was operating at near capacity.[168]

Although the external tank may not have required the cutting-edge technology necessary in the development of other Shuttle elements, the project nonetheless presented formidable engineering challenges. Two requirements in particular, weight and insulation, demanded constant attention throughout development, and further modification after the first Shuttle flight.

Weight was the most significant design issue affecting the external tank. The Houston program office lowered the control weight requirement from 78,000 pounds to 75,000 pounds in 1974.[169] Marshall and Martin Marietta experimented with lighter materials, but found that they were not suited for use with cyrogenic fuels. Marshall reduced weight by using an aluminum alloy with exterior foam insulation and reducing NASA's mandatory manned flight safety factor for the tank.[170] Nevertheless design changes mandated as a result of alterations in other elements forced the weight of the tank to creep up again. By mid-1980, less than a year before the first Shuttle flight, the tank had edged back up to 76,365 pounds.[171]

Another trying design challenge on the external tank was insulation. "In the case of the tank," Odom explained, "you are looking at a tank at the top that's got about a million and a quarter pounds of liquid oxygen at about minus 297 degrees. The whole bottom two-thirds of the Tank is liquid hydrogen. It's much less dense—it only has about a quarter of a million pounds—but it's three times the volume at minus 423 [degrees]."[172] Without proper insulation, ice could form on the tank that might shear off and damage the orbiter tiles during flight. The tank surface and every line and bracket on the outside of the tank had to be insulated to keep the exterior temperature above 32 degrees. Furthermore, insulation had to be as light as possible; but in the initial tank design, insulation contributed to the weight problem. "At the time that we built the first six flight Tanks," remembered Bridwell, "we had a superlight ablator which we put on

the sub-strata Tank. Then we sprayed an inch of foam all over the Tank."[173] Paint then covered the foam insulation. "Just imagine how much paint it takes to fill a third of an acre," said Odom. "That insulation really soaks up a lot of paint."[174] The paint proved unnecessary, and its later elimination reduced weight significantly.

Complicating external tank engineering concerns was the fact that Marshall harbored doubts about Martin Marietta's management of the project. Early in the project, Marshall worried about the ability of the company's Denver division to supervise operations in New Orleans, and urged Martin Marietta to establish a separate Michoud division.[175] The company delayed, and management issues soon became a point of contention. In a performance review early in 1977 Marshall criticized the company's failure to give effective direction.[176]

A tooling incident at Michoud in June brought matters to a head. The dome spray system used to apply insulation to the tank malfunctioned, causing the carriage drive assembly to fall 80 feet to the floor. The company blamed the accident on a software error and mechanical problems, but Marshall claimed Martin Marietta "completely overlooked the lack of management discipline required to preclude this type of incident from occurring." Top Marshall project and engineering managers gave Martin "a pretty rough going over.'"[177] Lucas concluded that "we need to be firm with Martin in our requirement for better management discipline in the daily operation of the activity at Michoud."[178]

Odom and Lindstrom worked with Martin Marietta to improve what Marshall considered weaknesses in Michoud's workforce and supervisory management, using Rocketdyne as an example of strong project management. Martin restructured, running its Michoud operations as if they were a separate division as Marshall had long wanted. Lindstrom reported early in 1978 that Martin had agreed to establish a project manager and had developed an organizational plan that was "perhaps better" than the one he had proposed.[179]

But Marshall's concerns about Martin's management did not go away. From time to time incidents revived old worries, most seriously when the Center learned that the contractor had designed forward orbiter struts below the required factor of safety. "What else has MMC failed to do that we haven't caught yet?" Lucas wondered.[180]

Marshall ran an extensive test program on the external tank, with tests conducted at Michoud, the National Space Technology Laboratories at Bay St. Louis, Mississippi, and in Huntsville. Tests at Michoud and Marshall examined the tank's structural integrity, its ability to withstand cyrogenic temperatures, and its thermal protection system; those at the NSTL checked the Shuttle main propulsion system by integrating the tank and the Shuttle main engines. Where possible, the Center modified existing test stands; the pneumatic test facility at Michoud, which checked for leaks, was the only new structure built for testing the tank.[181]

Tests conducted in Huntsville revived memories of the 1960s, when Saturn rockets fired on the giant test stands at Marshall shook the city. The Center modified some of the Saturn test stands for external tank tests, changing platforms, instrumentation, and the control system. The Test Laboratory also planned to use modified Saturn test stands for mated vertical ground vibration tests (MVGVT) in which all elements of the Shuttle would be assembled for the first time. The Center used barges along the Mississippi, Ohio, and Tennessee Rivers to transport the tank from New Orleans to Huntsville, just as it had done during Apollo.[182]

The technology of testing, however, was entirely new. "We instrumented these test articles probably heavier than any other test article I've ever seen," according to test manager Chuck Verschoore. "On the intertank alone, we had close to 2,000 measurements, . . . on the hydrogen tank we had 4,000, and on the LOX tank, we had another 2,000. . . . Old technology would have taken us forever to monitor all that."[183]

Before testing the assembled external tank, Marshall separately tested the liquid hydrogen and oxygen tanks and the intertank structure. The Center ran four major tests: structural and vibration tests on the LOX tank, and structural tests on the intertank and the hydrogen tank. The test lab contrived a unique way to simulate G-forces for liquid oxygen tank tests. "LOX and water are about the same density, but we get three Gs on the Tank which means it's three times heavier," explained Jack Nichols. "So we mixed up driller's mud and hauled it [from] Mississippi. . . and filled that thing with driller's mud. We had trucks running day and night. But that simulated the pressure from the propellant at maximum G level."[184]

Verschoore and Garland Johnston remember one test that had them both "sweating blood." "This big old LOX tank had 100,000 gallons of fluid in it," according to Verschoore. "One of the conditions we had to test was in the pitch condition just before burnout, and it was 13 degrees [of inclination]. So, we had that whole Tank full of water at 13 degrees . . . floating on airbags because we had to decouple it from any solid structure. . . . And the airbags were not positioned exactly right."[185] Garland Johnston, the test engineer, continued the story:

External tank loaded aboard NASA barge Orion at MSFC in August 1981.

"No one can imagine 1,400,000 pounds sitting on 33 airbags. It's a huge thing. And we have the thing sitting out there, and we try to raise it on the airbags, and she starts walking north like it's going go right out through the north side of [Building] 4619. And there wouldn't have been anything we could have done to stop it if it did. So, you do an emergency dump, and you slam it down, and you start sweating blood. So, that's what we did for seven days. We measured; we calculated; we raised; we did everything we could think of. And finally, just finally, I found on the airbag set on the southeast corner, I don't recall now how it was overlooked by quality, but somebody had mismeasured. [It] was 7/10 of an inch off."[186]

Marshall and Martin Marietta conducted tests on tank components throughout 1977, culminating with a test of the entire tank on 21 December. Successful completion of the sequence meant that the external tank was ready for Shuttle systems tests at Marshall in the spring of 1978.

The final Shuttle element under Marshall's umbrella was the solid rocket booster. Unlike the main engines, Marshall remained within technological frontiers in the development of the boosters; instead, the goal was to apply state-of-the-art solid booster knowledge to ensure reliability. Unlike the expendable external tank, the booster was a reusable element, and as such posed different development issues. The booster had to be designed not only for performance, but for what project manager George Hardy called the "four R's": recovery, retrieval, refurbishment, and reuse.[187]

Reusability influenced the in-house design approach used on the boosters. Engineers considered cost analyses for individual components to determine design characteristics and replacement frequency. "We would put that into our models and decide how strongly we need to make this part in order to keep the attrition rate at the right level," explained Clyde Nevins. "It was a very unique design approach. Usually, you design something not to fail at all. And here we were designing it to fail a certain percentage of the time, because that was the cheapest way to design the hardware."[188]

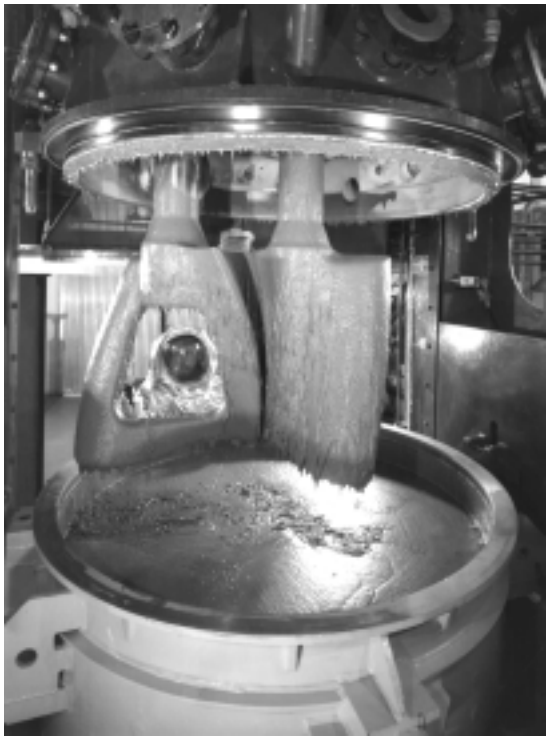
Preparations for the SRB recovery system began long before Thiokol won the solid rocket motor contract. Marshall conducted impact studies dropping a 77-percent scale model from heights of up to 40 feet in California's Long Beach harbor in February 1973.[189] Later in the year, the Center used another scale model to test a parachute recovery system in drops on the Tennessee River south of the Center.[190] From these tests evolved a recovery system comprised of pilot and drogue parachutes to ensure descent stability, and three main ribbon chutes, the largest of their type ever used in flight operations. The pilot and drogue chutes nestled in the booster nosecone, the three main chutes in the frustum immediately behind.[191]

Although the Thiokol solid rocket motor was its heart, the booster was much more complex than indicated in labels like "giant firecracker" or "Roman candle." Subassemblies had to be integrated with the solid rocket motor to build a booster. The thrust vector control system, commanded by a sophisticated guidance system external to the booster, steered the booster by directing its nozzle. The booster incorporated subsystems for instrumentation, separation from the external tank, range safety, and recovery. Its aft skirt, which housed the thrust vector control system, also served as a platform for four points at which the booster was attached to the rest of the Shuttle. Similarly, the forward

skirt provided hardware for connection to the external tank, as well as housing most booster avionics. A large flexible bearing swiveled the nozzle, which penetrated into the motor case.

Contracts for these subsystems spread Shuttle business around the country. McDonnell Douglas, the most active subcontractor, held responsibility for the forward and aft skirts, the frustum and nosecap, and the systems tunnel that housed cables for electrical connections.[192] Marshall began systems integration in-house, and contracted it to United Space Boosters, Incorporated, late in 1976.

Like other Shuttle elements, the SRB recorded historic "firsts." Not only was it the first solid rocket booster designed for human space flight, but it was the biggest gimballed solid ever built. Bigger than any other solid in use, it carried 1.1 million pounds of fuel, or three times the fuel of the Titan III. Thiokol ignited the solid rocket motor for the first time on 18 July 1977 on its Utah proving grounds, 2 miles from the closest building and 24 miles from Brigham City, the nearest town.[193]



Mixing SRM propellant at Thiokol near Brigham City, Utah, in 1980.

The successful first test of the solid rocket motor was particularly welcome. Marshall's Shuttle projects, and indeed the entire program, were entering a crucial phase. Marshall's projects were all maturing, and were about to enter a period of intense testing. Unfortunately, at a time when ample resources were essential to execute a rigorous testing program and complete development of all three elements, pressure again began to mount from several quarters. The

Carter administration was even more frugal in its approach to space than its predecessors. President Jimmy Carter was a supporter of space science, but had questions about the value of an expensive manned space program, and asked Frosch, his new NASA Administrator, to evaluate the Shuttle program to determine whether it ought to continue. Vice President Walter Mondale had been a vociferous critic of NASA as a senator, and put people who shared his views in the Office of Management and Budget where they could challenge NASA's budget.[194]

Static firing of the solid rocket motor in northern Utah in February 1979.

The new environment had an immediate impact at Marshall. The impending test series meant that the Center's support requirements were expanding as budget pressures became more confining. At a Center performance review in June 1977, Headquarters informed Marshall that its next budget submissions would have to "contain very explicit descriptions of the program requirements" in order to meet new Carter zero-based budget requirements. Headquarters acknowledged related pressures on the Huntsville Center: increasing schedule pressure, lack of sufficient travel funds, reductions in support contractors, and an increasing skill mix imbalance in civil service personnel as a result of reductions-in-force.[195]

To make matters worse, Marshall had begun to experience problems in administration of its SRB contracts, and the constraints enumerated at the Center review compounded them. Cost, schedule, and processing problems hindered the McDonnell Douglas structures fabrication contract. Marshall worried that it had insufficient penetration to monitor the contractor's corrective action. Marshall implemented daily reviews, assigned more personnel, and insisted that "MDAC [McDonald Douglas Astronautics Company] must resolve hardware processing problems [and] MDAC must provide MSFC some visibility into these resolutions."[196]

Even more troubling were problems with the Thiokol solid rocket motor contract. During the summer and early fall, seven material handling incidents took place; none of them caused serious damage, but as Hardy reported, "the trend is disturbing."[197] Incidents continued. By the next summer, Marshall conducted its own investigation and demanded a Thiokol review of 26 incidents over an 18-month period. Thiokol blamed insufficient training, schedule pressure, and human error; but Hardy suggested that lack of adequate management attention was behind all incidents. Lucas agreed, and questioned whether Thiokol had "strong management determination" to improve.[198] Thiokol and Marshall both took corrective action. Marshall initiated a three-shift quality assurance program at the contract site.[199] Nonetheless Lindstrom, head of Marshall's Projects Office, told Thiokol of his concern that "the conditions and circumstances contributing to these incidents may exist with SRM manufacturing and quality control operations."[200]

An incident in December 1978 caused an estimated $750,000 damage to a segment in one of the development motors, and triggered an investigation.[201] Although Marshall and Thiokol agreed on the findings and recommendations of the investigating team, they disagreed on an essential point. John Potate, the Center's acting deputy director, explained that Thiokol blamed "equipment design as primary cause of problem with procedural inadequacy as a contributor. Our report just reverses these two conclusions."[202] Marshall gave precedence to managerial shortcomings, Thiokol to material deficiencies.

Thiokol began a training program and instituted stricter controls. Still, improvement was slow, and the Center worried eight months later that "negligent events …continue to plague the program." Marshall considered using "severe penalties" in award fee evaluation to pressure Thiokol management.[203]

Marshall's management of all three major Shuttle element contractors bore similarities. Since Marshall often blamed problems on weak management, the contractors' project managers sometimes became reluctant to report problems. Despite formal lines of communication, information often did not flow as intended, and problems took too long to surface. Marshall's William P. Raney summarized the problem:

"In principle, there was a hierarchical responsibility to MSFC, which was supposed to make sure it fit and worked together. In practice, there were lateral responsibilities for exchanging information, specifications, and jointly working

out technical solutions. There was a heavy dependence on documentation to make that work, rather than hands-on contact. However, none of the contractors had any authority to force adequate communication or experience, and MSFC didn't force it."[204]

Houston's Kraft described Marshall's approach as "a hands-off management, an arms-length management of their contractors." In Kraft's view, Marshall "wanted to let the contractor do his thing and then hit them in the head to do it right if they screwed up. And they expected them to screw up."[205]

Once a problem surfaced, Marshall took aggressive action with its three major Shuttle contractors—on-site visits in which high-level managers gave the contractor "a pretty rough 'going over,'" with demands for changes in personnel or organization, or threats to impose award fee penalties. Several factors contributed to the approach. Constant budget reductions and reductions-in-force had eroded Marshall's ability to monitor contractors. Unlike Apollo, where Marshall had skills that often exceeded those of the contractor and ample personnel for effective oversight, in the Shuttle Program the Center had to rely on post-facto action, which was often forceful but less involved.

"MSFC worked to the limit of their manpower to see that the various elements were coming along satisfactorily," Raney said, but manpower was indeed limited. Budget constraints also reduced testing, decreased travel funds and manpower for on-site inspections, and forced revisions in schedules. Rather than working side-by-side with contractors, Marshall had little choice but to rely on quality assurance teams, which worked as inspectors rather than co-workers or on-site evaluators. And the number of people involved in quality and reliability work fell by 71 percent from the mid-seventies to the mid-eighties, more than twice the rate of decline of the rest of NASA's workforce.[206] Contractors resisted penetration, so Marshall had to be firm to keep abreast of problems.

Marshall's relations with its contractors underscored a communications problem that plagued the program throughout the Agency. As Raney observed, "For a combination of semi-political reasons, the bad news was kept from coming forward. Contractors didn't want to admit trouble; Centers didn't want Headquarters to know they hadn't lived up to their promises; and Headquarters staffs didn't want to risk the program funding with bad news."[207]

Marshall's management of contractors also reflected broader trends characteristic of NASA management in general. Kraft argued that similarly high-pressure methods under James Beggs, Hans Mark, and James Abrahamson drove NASA Centers to create "an underground decision-making process" that ran counter to the Agency's traditions and prevented open discussion.[208]

High-pressure management was not always characteristic of Marshall contract management. Marshall regularly worked cooperatively with contractors to derive creative solutions. Plasma arc welding (an improvement introduced for use on the external tank and discussed below) was one such case. As Schwinghamer explained, "We brought the contractor in with us and we developed that thing together. And when it was finished, there was no NIH [not invented here] factor—it wasn't invented here. We had done that together. And [Martin Marietta] felt very comfortable with that."[209]

Ultimately technical problems required technical solutions. Chief Engineer Bob Marshall argued that the Center emphasized technical solutions over managerial ones. "It is true that if you have a technical problem, management is to blame because they are responsible programmatically and technically," he explained. But "these problems were strictly technical and could not be resolved without correct technical analysis and action."[210]

One advantage that Marshall did have in monitoring the work of its contractors was its vast test complex on the southern sector of the Center. And early in 1978, attention of all of NASA—indeed of the nation—shifted to Huntsville and Marshall's test stands. For the first time all Shuttle elements would be assembled and Americans would get a first look at the new Space Transportation System. NASA's purpose was to run the mated vertical ground vibration tests (MVGVT) in which the vehicle would be subjected to different types of stress to determine its structural integrity.

March 1978 was a festive month in Huntsville as residents turned out to celebrate the arrival of Shuttle components. The orbiter *Enterprise* garnered the most attention. It arrived at the Redstone Arsenal atop a Boeing 747 on 13 March. After "demating" the orbiter from the aircraft, technicians towed it at a walking pace along the road that bisects the Center and past the Headquarters building as Marshall employees watched. Over the weekend Huntsville residents turned out in "throngs" to view the *Enterprise*. One small boy asked his father, "Is this the same one that's on Star Trek?"[211]

Technicians modified the Dynamic Test Stand used a dozen years earlier for Saturn V tests in preparation for the vibration tests. For the first phase, which began in May, they used air bags and cables to suspend the *Enterprise* and the external tank from a truss structure high in the 360-foot-high test stand, simulating the configuration of the Shuttle after separation of the boosters and before separation of the tank. The vibration tests did not involve physically shaking the Shuttle; rather, the test laboratory used amplifiers similar to those used on home stereo sets to generate vibrations through shaker rods attached to the vehicle. The first phase went well, slowed only when the dome on the LOX tank buckled while it was being filled with fluid early in the test sequence. The test team repressurized the tank and it returned to its original shape.[212]

Shuttle Enterprise *rolls past MSFC office complex, March 1978.*

On 11 October, Marshall completed the first assembly of the entire Space Shuttle, with the orbiter and tank now attached to two solid rocket boosters in launch configuration. The Center modified the test stand, and now the Shuttle stood with its boosters resting on a cylinder-piston platform with bearings on top that gave the vehicle freedom of motion. In the first tests on these hydrodynamic stands, the boosters were filled with inert propellant, bringing the weight of the Shuttle to over four million pounds. Later, in the final phase of vibration tests, the Center measured the system with boosters empty as they would be just before separation, reducing system weight to 1.5 million pounds.

The Center completed the MVGVT tests on 23 February 1979. Results from the tests prompted some modifications, including strengthening of brackets at the forward section of the boosters. Eugene Cagle, director of the Test Laboratory,

reported that "from a structural dynamics standpoint, we are confident that the Space Shuttle will perform as expected."[213]

The tests at Marshall verified only the structural integrity of the Shuttle, and tests continued concurrently on other Shuttle elements. NASA Associate Administrator John Yardley told Congress in September 1978 that "the only significant Shuttle problems [are] with the main engine and the vehicle's weight." Yardley thought that the main engine could be ready within a year, and that the weight problems would not impact the program until after the early flights.[214]

Shuttle Enterprise *suspended at Marshall's Dynamic Test Stand, July 1978.*

The biggest threat to the Shuttle in the weeks following the Marshall tests was budgetary rather than technical. In May 1979, NASA predicted that the Shuttle might have a cost overrun of $600 million over the course of four years.[215] The announcement touched off a barrage of criticism, precipitated further schedule delays, and put the already fiscally constrained Shuttle program in jeopardy. NASA "is in deep trouble," said one commentator. Congress worried that "serious mismanagement" of the Shuttle program was threatening defense plans dependent on the Shuttle.[216] NASA Administrator Frosch defended NASA program management, arguing that the Agency had done well operating under stringent limitations.[217] But three months later, a NASA panel blamed the cost overruns and schedule slips on insufficient funds, unrealistic schedules, and inadequate long-range planning.[218]

The final preparations for the first Shuttle launch also encountered technical problems. As Houston worked to repair the ceramic tiles comprising the Shuttle thermal protection system, Marshall worried about cracks in the SRB propellant, external tank shrinkage (1.5 inches when loading cyrogenic hydrogen), and

uprating the main engines to achieve greater thrust and payload capacity.[219] Damage to the O-rings used to join segments of the solid rocket motor appeared for the first time, but tests on intentionally damaged O-rings seemed to demonstrate their effectiveness.[220] None of the difficulties threatened the mission, and in the last months people focused more on orbiter tiles than on any problems associated with Marshall's elements.

So despite budgetary threats, schedule slippage, and nagging technological difficulties, NASA moved toward the first manned orbital flight of the Shuttle. In December 1979, the main propulsion system successfully fired for 9 minutes and 10 seconds, longer than would be required to lift the Shuttle into orbit.[221] Two months later the solid rocket motor completed a series of seven test firings begun in July 1977, and Marshall deemed the tests "highly successful."[222] By early 1980, J. R. Thompson could compare main engine testing favorably with that of the J–2 in the 1960s: the main engine had undergone nearly three times as much operating time, had a comparable success rate, and would soon surpass the J–2 in numbers of tests.[223]

In November 1980, personnel at Kennedy Space Center began stacking and integrating the first Shuttle in the Center's Vehicle Assembly Building (VAB), preparing for a launch the following spring. On 3 November, they attached the external tank to the solid rocket boosters. Three weeks later, they conducted the "rollover" of the orbiter *Columbia*, moving the vehicle into the VAB for mating with the tank and boosters.[224] On 29 December, workers moved the entire Shuttle assembly along a three and one-half mile route from the VAB to launch pad 39A. In February 1981 the

Complete Space Shuttle mated for first time in the Marshall Center's Dynamic Test Stand, 6 October 1978.

Center ran flight readiness firing tests on the flight hardware, briefly running the main engines and gimballing their nozzles, concluding that "all MSFC hardware performed as designed."[225]

First Flight and Post-Flight Development

On 12 April 1981, the Shuttle embarked from Kennedy Space Center on its maiden flight, a trip of two days. Marshall engineers monitored the anxious early minutes of flight, during which the Shuttle propulsion system would face its test. "Any time you build a big vehicle like this," Odom said recalling his feelings at the time of launch, "and you put it together for the first time, especially with a man on board, you really worry, 'Have I really tested everything that that vehicle is going to see in that first flight?'"[226] Relief spread through the Cape and the communications center in Huntsville as the boosters shut down after 2 minutes, and jettisoned 12 seconds later. At 520 seconds the main engines shut down on schedule, and 30 seconds later the external tank jettisoned. Less than 10 minutes after liftoff, Huntsville's elements had accomplished their part of the mission. Former Center Director Rees leaned against a console at Marshall and reflected how much this day would have meant to Wernher von Braun. Deputy Center Director Jack Lee told reporters with a smile, "We were on the high side of performance."[227]

The Shuttle returned to Earth two days later, landing on a long runway at Edwards Air Force Base in California. After a week of analyzing data, Lindstrom, Marshall's Shuttle Projects Manager, declared the performance of the Center's elements "flawless."[228]

Marshall had ample reason for pride in the performance of its Shuttle elements, but a satisfying first mission did not mean its development task was complete. Even before the first flight Marshall had begun to plan design changes, and each successive flight exposed new targets for fine tuning. "After we started to fly, there were development efforts to improve performance and increase life," according to J. Wayne Littles. "A lot of our effort after we started flying was keeping the vehicle flying: getting each set of hardware to fly a mission; reviewing it and making sure it was ready to fly; reviewing the data of each flight [and] making sure there were no anomalies . . . and get[ting] rid of latent defects that caused us to change parts out more frequently than we would like to."[229] And after a measured analysis of the first flight, it was clear that some components needed immediate attention.

Space Mission Operations Control Center.

Recovery efforts after the first Shuttle flights demonstrated, Mulloy admitted, that NASA was "far from reaching the operational goal of a recoverable, reusable booster that could rapidly be refurbished and put back into line." Indeed the recovery system qualification program included the first flights since the elements were so large that there was no other way to test them, and the damage sustained far exceeded expectations.[230]

The boosters sustained too much damage upon ocean impact to achieve the quick turnaround necessary to support the planned 24 flight-per-year schedule, let alone the long-term goal of 48 flights per year. Clyde Nevins, who headed an investigation of the recovery system, said that "After the first launch we had excessive damage on the aft skirts. It just tore the heck out of the aft skirt inside—the stiffener rings on the outside, inside the cone, on the back end on the aft skirt. Very severe damage in there. It just wasn't like we predicted at all."[231]

The damage occurred when "it hit the water tail first, nozzle end first at about 88 feet per second, which is 60 miles an hour," Herman Thomason related. "It drove itself into the water, . . . the water was like a hydraulic ram. It comes up inside and you had compression taking place inside where the fuel had burned out." Impact damaged the aft skirt and the thrust vector control system. Compression forced salt water into parts of the rocket not designed to withstand its effects. Then, according to Thomason, "that thing comes back out of the water . . . and it slaps down on its side. And you get all these slap down loads, and even if the thing was five inches thick across, that's not going to be able to take those kinds of loads."[232]

Nevins's investigation showed that the reinforcement rings used in test models had differed slightly from those used on the booster. "So we ended up having to go in and put up a lot of reinforcement. And we also put in some light density foam, which smoothed out the internal contours of the ring. . . . The foam would get damaged, but it was sacrificial."[233]

On the fourth flight, explosive bolts attaching parachutes to the boosters fired prematurely, and the boosters could not be recovered. After locating the boosters on the ocean floor, searchers had to abandon plans to survey them.[234] NASA made improvements to strengthen the boosters. By the 11th flight, Marshall was putting "big gobs of spray foam" on the skirt, and using deflectors called "cow catchers" to keep water away from sensitive components.[235] Along with changes to the parachute recovery system, these changes improved the condition of recovered boosters.[236]

All of Marshall's Shuttle elements continued development after the Shuttle's maiden flight. Jerry Thomson said of work on the main engines, "We had to make design changes to improve the life of the Engine and improve the reliability. So we made some design changes even after we had made the first flight."[237] The types of changes included "basic changes in internal components, like improvement in blades to improve blade life in turbines, and making improvements in bearings."[238]

Limits on the life of components proved to be one of the most persistent challenges in main engine development. Bearings, turbopumps, and turbine blades were the sources of greatest concern. Bearing failure was a problem in the main engine from the early days of the program. The engines ran at about 30,000 rpm, generating heat that always threatened the integrity of the bearings. "The bearings are cooled with liquid hydrogen," explained Jud Lovingood, main engine project manager in the 1980s, and because temperatures are so high, "when you're trying to cool them the [liquid] hydrogen changes to a gas [and] it doesn't cool as much. You end up with bearings overheating and that weakens them. It also changes clearance because of the expansion you get. . . . NASA has just gradually improved them over the years . . . but they still have life limits."[239]

Greater than expected damage to pumps and turbine blades came from dynamic stress, cavitation erosion (caused when cavities of gas developed and collapsed in liquid fuels), and high temperatures. Using technology unavailable

when main engine development began, Marshall worked with NASA's Lewis Research Center, Rocketdyne, and contractors at Aerojet and Pratt & Whitney. A combination of approaches including powerhead redesign, thermal coatings on the blades, computer modeling to study fluid mechanics, and new metal alloys enabled the Center to gradually extend the life of the main engine.[240]

Anticipated increases in payload demands dictated a need for increased main engine performance, and even before first flight NASA determined to improve engine performance to 109-percent of rated power.[241] The 109-percent rating was "what we originally started calling emergency power level," Bob Marshall explained, and "ultimately it grew to be full power level, FPL."[242] The Center's goal was "to get more performance out of the fuels and higher performance out of the engine," Herman Thomason recalled. Better performance was "a function of temperature and pressure."[243]

The challenges involved in increasing power rating were enormous; power increase of merely four percent would nearly double cavitation erosion, for example.[244] Thus Marshall's efforts to bolster the main engine rating had to overcome persistent obstacles. The most serious accident occurred on 7 April 1982 at NSTL. As the test team pushed the engine to the 109-percent level, vibration forces inside the main oxidizer pump increased to 38 times the force of gravity, causing an explosion that ripped the pump apart. "There were pieces scattered all over," according to Lovingood.[245] Development continued in the months that followed, and by the time of the *Challenger* accident, "we were within one test of qualifying the Engine and within about two weeks of starting the Main Propulsion Test of three engines running at 109%," according to Bob Marshall. The *Challenger* tragedy forced the Center to reconsider the 109-percent rating and look for other ways to improve performance.[246]

No Shuttle element underwent more changes after the Shuttle's first flight than the external tank. Design changes in other elements had increased the weight of the tank, limiting potential Shuttle payloads. In the summer of 1980, 10 months before the Shuttle's maiden flight, Marshall initiated a plan to lighten the tank. Martin Marietta had already produced six flight tanks, and the redesigned lightweight tank would not be used until those earlier models were expended. The two-year redesign program trimmed 7,000 pounds from the 71,000-pound tank used on the first Shuttle flight.[247]

Not painting the tank produced the most visible change. "That saved a couple thousand pounds of weight," explained Odom. "The first time we rolled out one that was that brown color, . . . a lot of people just said that just doesn't look like NASA hardware, it's not pretty. It was pretty to me, because it was economical."[248] After the first six flights, the Center learned that it could eliminate the superlight ablator that coated the tank before application of the foam insulator. "The significant change from a processing standpoint is that it reduced the cost of the Tank significantly," according to Bridwell.[249]

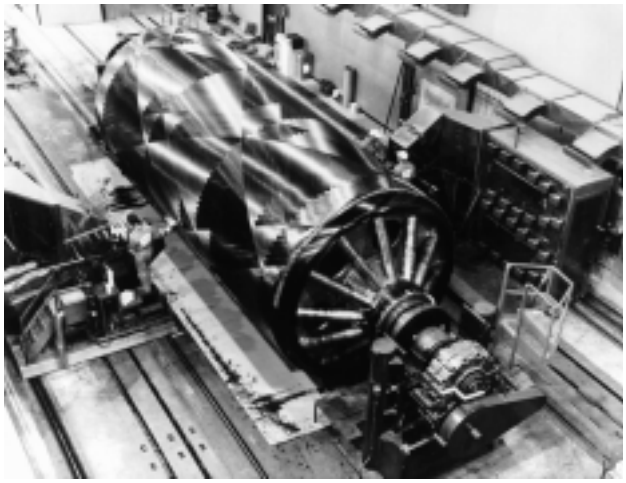
Marshall also introduced structural changes. The Center modified support structures, altered production techniques, and changed materials. Dome caps, previously milled on one side, now had metal shaved from both sides.[250] Nichols explained two other methods used to trim weight: "You start off with an inch-and-a-half thick plate and you machine it down and you leave little stiffeners in it. We took those out. There's a huge ring frame that takes the kick load from the Solid Rocket Motor and also from the orbiter. By going back and sculpturing it, rather than making it uniform all the way around, we took some weight out."[251]

Production of the tank became easier and less costly in 1984 after engineers at Marshall adopted new welding technology.[252] As Kingsbury explained, "The welding of aluminum, historically, has been a reasonably difficult process because aluminum oxidizes very quickly. You really can't have unoxidized aluminum in our atmosphere. It oxidizes too fast. And that oxide becomes a problem when you weld it."[253] Marshall engineers developed a process called plasma arc welding that minimized weld defects. "There are about five miles of weld on the Tank, and any defect that you might find has to be repaired," according to Bridwell. "Once again, that is labor intensity, and if you eliminate that, the cost of the tank goes down."[254] That savings accrued is clear from a comparison with Apollo; according to Schwinghamer, when engineers welded the same alloy on the Saturn V, "about every six feet or so we would get defects in the welding. And the X-ray would show a flaw. We would have to go in and grind the flaw out and reweld."[255]

Redesign of the external tank alone was insufficient to meet Shuttle payload requirements. The Department of Defense planned to launch a satellite in polar orbit from Vandenburg Air Force Base in California. Such a mission required payload lifting capability beyond that of the first flight configuration. Beginning

in 1976, NASA conducted systems engineering studies with a view toward improving Shuttle performance. These studies identified three candidates for modifications to achieve increased capacity, all of which would have affected Marshall's Shuttle elements: increase the thrust of the main engines from a rating of 109 percent to 115 percent; attach a liquid boost module comprised of four propellant tanks to the external tank; or develop a lighter solid rocket booster by replacing the steel casing with a filament wound case.[256]

In the early 1980s NASA rejected the augmented thrust rating for the main engines and the boost module after conducting cost, technical, and schedule analyses on all three options. The Agency decided that the filament wound case for the SRB had the shortest development schedule, least cost, and least technical risk.[257] Most other solid-fueled missile systems except the Titan already employed such cases, so the technology was not new.[258] Marshall planned to use plastic reinforced with graphite fiber, winding it into a cylinder that would reduce the weight of an empty booster by one-third, from 98,000 pounds to 65,000 pounds, and increase the Shuttle's payload capacity by 4,600 pounds. The plan would also simplify booster assembly, replacing 8 of the 11 steel cases with 4 filament cases.[259]



Manufacture of the SRM filament wound case.

By 1985, development of the filament wound case was proceeding well, and NASA was using the program to improve the joints between booster segments. Following the *Challenger* accident, however, the Agency decided to eliminate the filament wound case project.[260]

The booster project faced another challenge from erosion of the nozzle. "We were seeing some very bad, greater than predicted erosion of the motor nozzle insulation, which is a carbon phonolic about three inches thick that is on the

inside of the metal part of the nozzle," explained Mulloy, Marshall's project manager for the booster. The insulation was designed to ablate while the motor burned, but the amount of erosion was unpredictable. Marshall instituted design changes. As McIntosh described it, the Center "made a few changes in the configuration of propellant and grain a little bit and changed the size of the nozzle throat and increased the exit cone length."[261]

NASA's Shuttle problems in the early 1980s were not all technological. The cost decisions of the early 1970s now began to catch up to the Agency. The decision to abandon a fully reusable Shuttle a decade earlier had traded savings in development for larger costs for expendable elements later. In 1982, NASA reduced by nearly 200 the number of Shuttle flights projected over the next decade. Inflation drove costs higher, refurbishment time was longer than planned, all elements needed more additional development work than expected, and each mission required extensive post-flight analysis.

Soon it became apparent that even NASA's reduced projections were too optimistic. In 1983 a National Research Council panel told Congress that NASA's goal of increasing to 24 launches in 1988, 30 in 1990, and 40 in 1992 was unattainable because "major pieces" of the Shuttle would not be available. To have enough solid rocket boosters to achieve even 18 launches in 1990 seemed "marginal." "Because of very strict budgetary constraints in the program," the report continued, "NASA has had to concentrate on near term needs, and its capacity to deal with the longer term requirements was inevitably curtailed."[262]

NASA's rosy expectations for the Shuttle found critics even within the Agency. Noel W. Hinners, director of Goddard Space Flight Center, wondered about projections for reuse, commercialization, and costs. He argued that NASA was too optimistic in its expectations for reusing Shuttle components before encountering "structural integrity problems," and cautioned against expecting "routine" operations in a high-risk venture. "The Orbiter is a subsidized operation," he warned. "I see no way anyone can make a profit at this point without the government being accused (validly in my mind) of a giveaway of its R&D investment."[263] Instead of the early visions of orbiting payloads for as little as $100 a pound, by 1983 the cost was over $5,000 a pound.[264] Criticism of NASA for failing to make the Shuttle commercially viable continued, however, and the Agency even considered relinquishing management of the Shuttle to a private concern before abandoning the idea in 1985.[265]

Shuttle development had faced formidable limitations from the beginning. Cost pressures influenced every step from configuration planning through development and flight. In comparison to Apollo, NASA's only previous program of comparable scope, Marshall worked with less money, fewer people, and reduced skills.

The Center had to learn a new way of doing business. Marshall, without the arsenal system, had to rely on contractors and reduce its testing. And unlike Apollo, the Shuttle was a program of ongoing development in which major improvements continued even after operations began; even as evaluators certified components for flight, engineers were working on improvements.

These new approaches raised new problems, for Marshall and NASA were stretched to the limit of their manpower, skills, and resources. Within the environment of financial and political pressures, the Center and the Agency could no longer afford the conservative engineering approaches of the Apollo years, and had to accept risks that never confronted an earlier generation of rocket engineers.

If the Shuttle fell short of expectations, it may have been because expectations were unrealistic. NASA made extravagant claims for the Shuttle while seeking congressional approval, promising frequent flights, low cost to orbit, rapid refurbishment, and decreasing costs as expendable components entered mass production. The Shuttle was to be a space truck; it would soon pay for itself by providing routine operations. But as Schwinghamer insisted, "it's never going to be like driving a truck. And I guess some people kind of forgot that somewhere in the middle of this thing. But it is a fine-tuned machine. It's a wonderful machine. It's an engineering triumph in terms of efficiency, performance, and in every respect."

Schwinghamer expressed a common sentiment at the Center when he said that "in the context of the limitations imposed, that's an elegant design. That's the finest machine in existence today."[266]

1 Max Akridge, "Space Shuttle History," 8 January 1970, p. 2, Box 0375, Shuttle Series—MSFC Documents, JSC History Office.
2 Akridge, pp. 3–4.
3 H.H. Koelle to Ewald Diemer, 8 February 1963, and Minutes, Meeting of Government Agency Representatives at NASA Marshall Space Flight Center, 24 January 1963, Box 005–13, Shuttle Chronological Series, JSC History Office; "Marshall Studies Advanced Large Vehicles," *Aviation Week and Space Technology* (2 December 1963), 33–34; Akridge, p. 5.
4 Aero-Space Division of the Boeing Company, "System Criteria for Launch Vehicle Systems," May 1965, Box 005–21, Shuttle Chronological Series, JSC History Office.
5 Jerry Thomson, OHI by Jessie Whalen/MSI, 16 March 1989, Huntsville, Alabama, p. 2.
6 John P. McCarty, OHI by Sarah McKinley/MSI, 29 March 1990, Huntsville, Alabama, pp. 2–3.
7 Minutes, Meeting of Government Agency Representatives at NASA Marshall Space Flight Center, 24 January 1963; John F. Guilmartin, Jr., and John Walker Mauer, Management Analysis Office, JSC, "A Shuttle Chronology, 1964–1973," Volume I, December 1988, p. I–4.
8 Guilmartin and Mauer, Volume I, pp. I–2 to I–5; J.H. Brown and D.S. Edgecombe, "The Relevance of Launch Vehicle Recovery and Reuse to NASA OSSA Launch Vehicle and Propulsion Programs," Report Number BMI–NLVP–TM–67–3, Battelle Memorial Institute, 24 February 1967, Box 005–31, Shuttle Chronological Series, JSC History Office; Akridge, pp. 16–21.
9 M.V. Ames, Chairman, Ad Hoc Subpanel on Reusable Launch Vehicle Technology, "Comments on Economic Aspects of Reusability Requested by SSRT Panel," 30 January 1967, Box 005–31, Shuttle Chronological Series, JSC History Office.
10 Loftus, et. al., "The Evolution of the Space Shuttle Design," p. 3.
11 Cited in Brown and Edgecombe, "The Relevance of Launch Vehicle Recovery and Reuse to NASA OSSA Launch Vehicle and Propulsion Programs."
12 Cited in Charles D. LaFond, "Von Braun Urges Reusable Transport," *Missiles and Rockets* (8 November 1965), 16.
13 Akridge, pp. 25–26.
14 Guilmartin and Mauer, Volume I, pp. I–12 to I–14; Jesse C. Phillips to Thomas Grubbs, undated but catalogued under 31 December 1967, Box 005–34, Shuttle Chronological Series, JSC History Office.
15 Akridge, p. 36.
16 NASA, Office of Manned Space Flight, "MSF Vehicle Studies, 1 July 1968, cited in Guilmartin and Mauer, Volume I, pp. I–85 to I–87.
17 Mueller to Charles Donlan, 23 September 1968; and Douglas Lord to Frank Williams, MSFC, and John Hodge and Maxime Faget, MSC, 14 October 1968, Box 005–35, Shuttle Chronological Series, JSC History Office.
18 The contracts developed from a statement of work written largely at MSFC and issued in May 1968, and an RFP (Request for Proposals) developed jointly by MSFC and MSC in October 1968. Guilmartin and Mauer, Volume I, pp. II–1 to II–2.

19 The ILRV (Integrated Launch and Re-entry Vehicle) studies assigned each contractor specific approaches for examination. General Dynamics (MSFC) was to compare flyback and expendable lower stage configurations. Lockheed (MSFC) was to study the stage-and-one-half configuration, in which a strap-on stage would drop off before the stage itself would be fully expended. McDonnell Douglas (Langley) was to analyze several specific design configurations. North American Rockwell (MSC) was to examine configurations with expendable lower stages and a reusable spacecraft. Akridge, pp. 48–53.

20 Observers included U. Alexis Johnson, under secretary of state for political affairs; Glenn T. Seaborg, chairman of the Atomic Energy Commission; and Robert P. Mayo, director of the Bureau of the Budget. Guilmartin and Mauer, Volume I, p. II–11.

21 Bob Marshall, OHI by Jessie Whalen and Sarah McKinley/MSI, 22 April 1988, Huntsville, Alabama, p. 4.

22 Andre J. Meyer, 7 March 1969, cited in Guilmartin and Mauer, Volume I, p. II–12.

23 Meyer, 21 April 1969, cited in Guilmartin and Mauer, Volume I, p. II–30.

24 Max Akridge, OHI by Jessie Whalen/MSI, 1 August 1988, Huntsville, Alabama, p. 10; Akridge, "Space Shuttle History," p. 65. Akridge acknowledged that Mueller had used the term in his address to the British Interplanetary Society nine months earlier. But at the time of the task group meeting in May, the vehicle was still known as the IRLV.

25 Andre J. Meyer, handwritten notes, cited in Guilmartin and Mauer, Volume II, p. III–18.

26 Mueller to von Braun, 22 July 1969, Box 005–45, Shuttle Chronological Series, JSC History Office. Guilmartin and Mauer, Volume I, p. II–154.

27 U.S., Congress, Senate, Committee on Aeronautical and Space Sciences, *Future NASA Space Programs*, hearing, 91st Cong, 1st sess, 5 August 1969, pp. 41–43.

28 Space Task Group, *The Post-Apollo Space Program: Directions for the Future*, Report to the President, September 1969; McDougall, p. 421.

29 L.E. Day and B.G. Noblitt, "Logistics Transportation for Space Station Support," Presented at the IEEE EASCON Session of Earth Orbiting Manned Space Station, Washington, DC, 29 October 1969, 10s Apollo: Space Shuttle Task Team, NASA folder, MSFC History Archives; Space Shuttle Phase B Request for Proposal (RFP), 20 February 1970, cited in Guilmartin and Mauer, Volume II, pp. III–103 to III–108.

30 Richard P. Hallion, "The Path to the Space Shuttle: The Evolution of Lifting Reentry Technology," (Air Force Flight Test Center, 1983), 56–57; George M. Low to Dale Myers, 27 January 1970, 10s Apollo: Space Shuttle 1970 folder, MSFC History Archives; Joseph J. Trento, *Prescription for Disaster* (New York: Crown Publishers, Inc., 1987), pp. 100–01.

31 To make his case for competition, Mueller relied on Richard L. Brown, "A Study of the Use of Competition in the Space Shuttle Program," August 1969, 10s Apollo: Space Shuttle Task Team, NASA folder, MSFC History Archives.

32 Mueller to von Braun, 25 September 1969, 10s Apollo: Space Shuttle Task Team, NASA folder, MSFC History Archives.

33 Von Braun to Charles W. Mathews, Acting Associate Administrator, NASA, 30 December 1969, 10s Apollo: Space Shuttle Task Team, NASA folder, MSFC History Archives.

34 Low to Dale Myers, 27 January 1970, 10s Apollo: Space Shuttle 1970 folder, MSFC History Archives. The requirement had been spelled out in the Space Task Group report.

35 See for example John M. Logsdon, "The Space Shuttle Program: A Policy Failure?" *Science* 232 (30 May 1986), 1099.

36 Humboldt C. Mandell, Jr., "Management and Budget Lessons: The Space Shuttle Program," National Aeronautics and Space Administration Special Publication–6101, Autumn 1989, p. 44.

37 Andre Meyer of MSC, in a personal handwritten note, wrote: "With Mueller leaving direction will return to the Center." Andre J. Meyer, handwritten notes, 3 November 1969, cited in Guilmartin and Mauer, Volume II, p. III–63.

38 The centers finally agreed that each would administer two of four parallel contracts, with MSFC chairing the Source Evaluation Board. Gilruth to Von Braun, 16 January 1970, 10s Apollo: Space Shuttle 1970 folder, MSFC History Archives.

39 Rees to Myers, 17 February 1970; Rees to Myers, 2 April 1970, 10s Apollo: Space Shuttle 1970 folder, MSFC History Archives.

40 Myers to Rees, 17 June 1970, 10s Apollo: Space Shuttle 1970 folder, MSFC History Archives.

41 Myers to Rees, 28 May 1970, 10s Apollo: Space Shuttle 1970 folder, MSFC History Archives.

42 Myers to Rees, 17 June 1970.

43 Guilmartin and Mauer, Volume III, p. IV–2.

44 Guilmartin and Mauer, Volume III, pp. IV–7 to IV–8.

45 Myers to Rees, 1 April and 22 April 1970, 10s Space Shuttle 1970 folder, MSFC History Archives.

46 Andre J. Meyer, 16 March 1970, cited in Guilmartin and Mauer, Volume III, p. IV–26.

47 Rees to Myers, 17 February 1970, 10s Space Shuttle 1970 folder, MSFC History Archives. Myers acknowledged that "the organizational arrangement presented by MSFC reflects the concept of the Management Plan." Myers to Gilruth, 13 March 1970, cited in Guilmartin and Mauer, Volume III, p. IV–17.

48 Rees to Myers, 3 June 1970, and Lucas to Cook, 9 June 1970, Shuttle Phase A Studies—Lucas Notes folder; David Baker, "Evolution of the Space Shuttle," pp. 204–212; Hallion, pp. 57–58; Guilmartin and Mauer, Volume III, pp. IV–2 to IV–5, IV–70 to IV–71. Marshall had responsibility for the McDonnell Douglas contract, Houston the Rockwell contract. The backup partially reusable Phase A contracts went out in June. Marshall had responsibility for a Lockheed study of an expendable tank orbiter and a Chrysler study of a single-stage reusable orbiter. Houston would manage a Grumman/Boeing study of a stage-and-a-half vehicle with expendable tanks, strap-on boosters and a reusable orbiter.

49 Mike Pessin, OHI by Jessie Whalen and Sarah McKinley/MSI, 18 December 1987, Huntsville, Alabama, p. 13.

50 Guilmartin and Mauer, Volume IV, pp. V–7 to V–8, V–41; Mike Pessin, OHI by Jessie Whalen and Sarah McKinley/MSI, 18 December 1987, Huntsville, Alabama, pp. 12, 13.

51 Cited in Howard E. McCurdy, *The Space Station Decision: Incremental Politics and Technological Change* (Baltimore: The Johns Hopkins University Press, 1990), p. 29.

52 Logsdon, "The Space Shuttle Program: A Policy Failure?", p. 1101.
53 Christopher C. Kraft, Jr., Deputy Director, MSC, memorandum for the Record, 8 April 1971, Shuttle Management/Lead Center folder, Box 1, Shuttle Series—Mauer Source Files, JSC History Office.
54 "NASA Space Shuttle Program Management: Manned Spacecraft Center's Recommended Plan," 21 April 1971 Shuttle Management/Lead Center folder, Box 1, Shuttle Series—Mauer Source Files, JSC History Office.
55 Jack Hartsfield, "MSFC Fighting to Keep Shuttle," *Huntsville Times*, 21 January 1971.
56 Dale Grubb, Assistant Administrator for Legislative Affairs, to Fletcher, 14 May 1971, Shuttle Management/Lead Center folder, Box 1, Shuttle Series—Mauer Source Files, JSC History Office. *Huntsville Times*, 9 June 1971.
57 Myers to Fletcher, 20 May 1971, Shuttle Management/Lead Center folder, Box 1, Shuttle Series—Mauer Source Files, JSC History Office. Myers to OMSF Center Directors, 10 June 1971 cited in Guilmartin and Mauer, Volume III, pp. V–56 to V–57. By the time Myers announced the lead center decision on 10 June, Marshall's grip on the space station had slipped, apparently without knowledge of Center management. Regarding station, Myers had originally recommended that "MSFC would be designated 'lead Center' at the end of the present Phase B studies." When he made the lead Center announcement, Myers promised Marshall only responsibility for "any further space station studies at the end of the current Phase B studies."
58 Christopher C. Kraft, Oral History Interview by Andrew J. Dunar and Stephen P. Waring (hereinafter OHI by AJD and SPW), 28 June 1991, Webster, Texas, pp. 15–16.
59 Low, quoted by Willis Shapley, cited in Trento, p. 112.
60 Bill Sneed, OHI by Jessie Whalen/MSI, 8 April 1988, Huntsville, Alabama, p. 3.
61 Godfrey to Rees, Lucas, and Murphy, 24 June 1971, 10s Space Shuttle 1971 folder, MSFC History Archives.
62 R.W. Cook, draft of Rees to Myers, 7 September 1971, DM01 files, Shuttle 1973 folder; Cook to Harry Gorman, 20 August 1971, DM01 files, Shuttle 1973 folder, MSFC History Archives.
63 Fletcher, memo to Jonathan Rose, Special Assistant to the President, 22 November 1971, NASA Headquarters History Office.
64 Guilmartin and Mauer, Volume IV, p. V–14.
65 James B. Odom, OHI by Jessie Whalen/MSI, 9 February 1988, pp. 6–7.
66 McCurdy, p. 31; Logsdon, "The Space Shuttle Program: A Policy Failure?", p. 1104; Trento, pp. 112–13.
67 "Space Shuttle System Definition Evolution," pp. 4–5.
68 William Brown, OHI, p. 24.
69 LeRoy Day, OHI by Sarah McKinley/MSI, 7 June 1990, Huntsville, Alabama, p. 3.
70 William Brown, OHI by Jessie Emerson/MSI, 15 August 1989, Huntsville, Alabama, p. 23.
71 Ron McIntosh, OHI by Jessie Emerson/MSI, 8 August 1990, Huntsville, Alabama, p. 2.
72 LeRoy Day, OHI, pp. 1–2.

73 Dan Driscoll to Rees, 27 January 1972; Rees to Driscoll, 31 January 1972, Space Shuttle 1972 folder, MSFC History Archives.
74 "Shuttle Booster," *Aerospace Daily* (24 January 1972), 53.
75 MSFC Public Affairs Memo, 24 February 1972, reporting on "Problems Loom in NASA on Shuttle Booster Selection," 23 February 1972, p. 298, Space Shuttle 1972 folder, MSFC History Archives.
76 McCurdy, pp. 30–31.
77 "Space Shuttle System Definition Evolution," pp. 5–7; NASA Special Release, "Space Shuttle Evolution," 1 August 1972, Shuttle History folder, NASA Headquarters History Office.
78 Fletcher to Caspar W. Weinberger, Deputy Director, OMB, 6 March 1972, Shuttle History folder, NASA Headquarters History Office; "Space Shuttle Evolution."
79 Sneed, OHI, pp. 5–6; Sneed to Mike Wright, 5 January 1993, MSFC History Office.
80 Rees, memo to Dick Cook, 7 November 1972, Space Shuttle 1972 folder, MSFC History Archives. Rees estimated that the external tank and the solid rocket boosters would consume 60 percent of the operation costs of each flight.
81 Roy E. Godfrey to Petrone, 8 August 1973, Space Shuttle—Solid Rocket Booster 1973 folder, MSFC History Archives.
82 "NR's Rocketdyne Picked for Shuttle Main Engine," *Space Business Daily*, 57 (14 July 1971), 52.
83 Frank Stewart, OHI by Jessie Whalen/MSI, 4 February 1988, p. 10–11.
84 Myers to Low, 22 October 1970, Shuttle Booster Stage folder, NASA Headquarters History Office; W.D. Brown to Colonel Mohlere, 16 October 1970, 10s Space Shuttle folder, MSFC History Archives.
85 Richard L. Brown, OHI by Jessie Whalen/MSI, 27 June 1988, Huntsville, Alabama, p. 12.
86 "Space Shuttle Engine Negotiations," NASA Release No. 71–131, 13 July 1971, Shuttle Propulsion System 1971 folder, NASA Headquarters History Office.
87 Arthur Hill, "Contract to Develop Shuttle Engine Sparks Savage Fight," *Houston Chronicle*, 29 August 1971.
88 "NASA Charged with Improper Conduct in Shuttle Engine Award," *Space Business Daily*, 57 (6 August 1971), 169; "P&W Files Formal Protest on Shuttle Engine Award," *Space Business Daily*, 57 (19 August 1971), 230.
89 Edward J. Gurney, et. al. to Fletcher, 14 July 1971, Space Shuttle Main Engine Working File, 1971, Mr. Cook, Tab 6, MSFC History Archives.
90 "NR Challenges P&W Engine Experience Claim," *Space Daily* (3 November 1971), pp. 16–17.
91 R.W. Cook, Deputy Director , Management, MSFC to J.T. Shepherd, 19 August 1971, Space Shuttle Main Engine Working File, 1971, Mr. Cook, Tab 6, MSFC History Archives.
92 MSFC, "Chronology: MSFC Space Shuttle Program: Development, Assembly and Testing Major Events (1969–April 1981)," MHR–15, December 1988, pp. 15–21; "GAO Rejects P&W Protest on Shuttle Main Engine," *Space Business Daily* (1 April 1972), 175.

93 Godfrey, memo to Rees, 1 December 1971, Space Shuttle Main Engine 1970–1971 folder, MSFC History Archives. Godfrey describes a meeting held on 29 November. Among those in attendance were Low, Myers, Headquarters Shuttle manager Charles Donlan, and Houston's Shuttle Program manager Robert Thompson.

94 "Proposals Asked for Shuttle Solid Rocket Motors," MSFC Release No. 73–133, 18 July 1973, Shuttle Booster 1972–1973 folder, NASA Headquarters History Office.

95 Trento, pp. 114–15. See also Lucas to Petrone, 2 July 1973, Solid Rocket Motor (SRM) folder, MSFC History Archives.

96 "Groundrules and Assumptions," 25 May 1973, Solid Rocket Booster (SRB) 1974 folder, MSFC History Archives.

97 Robert F. Thompson, "Elimination of SRB Thrust Termination Requirement," Control Board Directive—Level II, 27 April 1973; H. Thomason, "SRB Thrust Termination" Briefing Charts, 27 April 1973; H. Thomason, "Thrust Termination" Briefing Charts, 3 May 1973; Godfrey to Petrone, 8 August 1973; Godfrey to Robert F. Thompson, 8 August 1973; Godfrey to Petrone, 15 August 1973; Thompson to Lindstrom, 18 September 1973; Space Shuttle—SRB 1973 folder, MSFC History Archives. Maxime Faget to M. Silveira, 2 February 1970, Box 005–63, Shuttle Program Chronological Files, JSC History Office. Estimates for the weight penalty of adding thrust termination varied widely; figures cited ranged from 2,400 pounds to 8,000 pounds. Godfrey maintained that Rockwell's principle motive was to prevent "the serious weight penalty with early separation," and that Marshall had fought a "clean, hard decision," only to be blocked by the Headquarters decision. Godfrey to Petrone, 15 August 1973.

98 "Proposals Asked for Shuttle Solid Rocket Motors," MSFC Release No. 73–133, 18 July 1973. "NASA Needs Firecracker," *Washington Post*, 14 October 1973.

99 James C. Fletcher, "Selection of Contractor for Space Shuttle Program Solid Rocket Motors," 12 December 1973, Space Shuttle-SRB 1973 folder, MSFC History Archives. Lockheed, UTC and Thiokol were the top three firms, with Lockheed leading in technical areas and trailing in management, Thiokol leading in management and trailing in technical areas, and UTC falling between the others in both areas. NASA considered these results "essentially a stand-off," leading to Thiokol's selection on the basis of cost.

100 NASA Headquarters TWX to MSFC, 6 November 1973, Shuttle (General) 1973 folder, MSFC History Archives. Headquarters quoted a report from the Subcommittee on HUD, Space Science and Veterans.

101 Richard C. McCurdy, letter to the editor, *New York Times*, 3 January 1987; Godfrey to Petrone, 23 January 1974, Solid Rocket Booster (SRB) 1974 folder, MSFC History Archives.

102 The GAO found NASA's evaluation process fair and reasonable, although it did cite a major error in evaluating costs that would have reduced the difference between the Lockheed and Thiokol proposals from $122 million to $54 million. "GAO Report Clearly Leaves SRM Decision Up to NASA, *Defense/Space Daily*, 26 June 1974, p. 316. NASA, Press Release, 26 June 1974, Solid Rocket Booster (SRB) 1974 folder, MSFC History Archives.

103 George Hardy, OHI by Jessie Emerson/MSI, 1 March 1990, Huntsville, Alabama, pp. 2–3. Subcontracts under S&E management included McDonnell Douglas "for structural, MMC for the recovery system, UTC Chemical Systems Division for booster separation motors, Bendix for integrated electronic assembly, and Moog and Sunstrand for the thrust vector control system." Emerson notes.

104 Rees to Jim Murphy, 30 March 1972, Space Shuttle 1972 folder, MSFC History Archives.

105 James Kingsbury, OHI by Jessie Whalen/MSI, 17 November 1988, Huntsville, Alabama, p. 9.

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