Chapter X

The Recovery: Investigation and Return to Flight

For every Shuttle launch, technicians in Marshall's operations support Center watched consoles showing continuous updates of data. For the ill-fated 51–L launch, they were stunned when the screens froze shortly after liftoff. Initially suspecting a telemetry problem rather than a catastrophe, the technicians turned to television screens and saw the vapor cloud caused by the destruction of the external tank. They sat in complete silence hoping to see the orbiter come out of the cloud, but instead they saw contrails of burning, falling debris. Working silently, they began collecting the data necessary for the post-accident investigation.

The weeks after the *Challenger* accident were the most traumatic in the first three decades of the Marshall Space Flight Center. Marshall people felt shock and a deep sense of loss. They had dedicated themselves to the Shuttle program, identified with its accomplishments, embraced the astronauts as colleagues and friends, and so experienced the accident as personal failure. Many wondered if their anguish would ever go away.[1]

Marshall personnel began investigating within moments after the disaster. Serving on task force panels and on laboratory teams, many worked 12-hour days for months. Their dedication paid off as Center employees played the major role in finding the technical cause of the accident and in fixing the problem. This effort, which Marshall people called "the recovery," enabled the Center and the Agency to return the Shuttle to flight within three years.

While Marshall worked on technical matters, however, independent investigations made Marshall the Center of controversy. In the first half of 1986 official groups and congressional committees studied the events and decisions before the accident, and journalists provided running commentary. Although investigations often made useful examinations of technical causes and organizational circumstances and suggested improvements in NASA and the Shuttle program, the process sometimes degenerated into an inquisition. The inquiries, and especially the scapegoating, were agonizing. The months of investigation and preparation for flight showed the ability of Marshall and NASA not only to fix technical flaws, but also to address sensitive questions, accept criticism, overcome organizational weaknesses, and reorient cultural patterns.

Center of Controversy

After the death of three astronauts in the Apollo 204 fire, NASA had used an internal investigation board which largely confined itself to technological issues and ignored organizational and political factors that contributed to the accident. The narrow technical approach reflected the congressional and presidential commitment to the Apollo end-of-decade deadline and NASA Administrator James Webb's ability to protect the space program from outside criticism.

Challenger not only had an internal investigation by NASA technical panels, but also an independent inquiry by a presidential commission. In part this happened because NASA leaders did not protect the Agency. Administrator James Beggs, subject of an investigation by the Justice Department (which was unrelated to his NASA services and which eventually cleared him of all charges), had surrendered authority over NASA. Deputy Administrator William Graham was new to the Agency and deferred the question of the nature of the investigation to the White House. President Ronald Reagan's Chief of Staff, Donald Regan, worried about allegations that the White House had pressured NASA to launch on 28 January to ensure that the first teacher-in-space would fly on the day of President Reagan's State-of-the-Union message. The charges were groundless, but the Reagan administration was in the midst of numerous scandals and Regan wanted a thorough inquiry to avoid any hint of a cover-up. Consequently President Reagan decided to appoint a special investigatory commission.[2]

The commission, established on 3 February and headed by former Secretary of State William P. Rogers, began directing NASA investigation teams by mid-February. Rogers was a lawyer and he later told reporters that he wanted a thorough and accurate investigation in order to avoid the sort of controversy that had followed the Warren Commission. One way of achieving this was to keep the inquiry open. Rogers said that "full disclosure has advantages over indictments. You don't want to punish. You just want to make sure it doesn't happen again."[3]

NASA implemented its contingency plan and established several technical panels to study various scenarios that could have caused the accident. James R. Thompson (called "J.R." by his colleagues), formerly Marshall's Shuttle main engine project manager and later a university research administrator, headed the NASA investigation. Since the disaster occurred during launch, a phase during which Marshall had primary responsibility, Center personnel played key roles on the technical panels. Propulsion engineers gathered in the Huntsville Operations Support Center to check prelaunch and flight records. With this data, teams led by Center Deputy Director Thomas "Jack" Lee, began to identify possible failure modes and isolate causes. Preliminary analysis pointed to anomalies in the right solid rocket booster (SRB). John W. Thomas, manager of the Spacelab Program Office, headed a team that performed tests on the case joint, and James Kingsbury, head of the Center's Science and Engineering labs, led another team that planned design improvements. Other Marshall employees worked on the parts recovery team to help salvage pieces of 51–L from the ocean floor. Several hundred Marshall employees participated in these teams and worked more than 12 hours a day from February until mid-May.[4]

An unclear division of labor between NASA and the presidential commission contributed to problems that Marshall had with the media. NASA Headquarters directed that no one serving on the NASA task force give media interviews and referred questions about the accident and the investigation to the commission. Marshall personnel with expertise on the subject areas, moreover, were working long hours and had little time for talking with the press. The Center's Public Affairs Office handled technical inquiries from 25 news organizations, including most of the major national outlets, which had set up shop at Marshall when attention focused on the solid rocket boosters. The office relayed answers from Marshall experts, but the reporters were not satisfied by the limited access and information. The Center's public information officers believed that the Headquarters' policy left Marshall defenseless and, by depriving the media of news, encouraged an adversarial posture toward Marshall and the entire Agency. Reporters searched for stories by hanging out in the Marshall cafeteria and camping outside the homes of Center officials.[5]

Meanwhile on 10 February in a closed session of the presidential commission, Morton-Thiokol officials described the history of the joints and their original recommendation to delay the launch because of the dangers of cold weather. During a lull in testimony on 11 February, Commissioner Richard Feynman performed a dramatic demonstration with a section of O-ring, a clamp, and a glass of ice water; this showed that a cold, compressed O-ring material only slowly returned to normal shape when the pressure was released. The demonstration showed how temperature could inhibit the sealing of O-rings and helped reporters explain the cold weather thesis and move easily from technical causation to managerial responsibility.

Afterwards, the commission increasingly challenged Marshall officials. Rogers described NASA's decision process as "flawed" because the eleventh-hour teleconference had allowed a launch with a known hazard; he asked the Agency to exclude SRB project officials, Shuttle managers, and Center directors from internal investigation teams.[6] Rogers became very critical, saying Marshall personnel had lacked "common sense" and had "almost covered up" the joint problems. Feynman called the joint design "hopeless" and said that poor communication between engineers and managers at Marshall was symptomatic of "some kind of disease."[7]

After 15 February the national media also began finding fault with NASA and regarded the ban on interviews as an attempt to cover up a scandal. Marshall officials wanted to talk to the media to correct what they believed was an inaccurate interpretation of the launch decision. They decided to keep silent, however, fearing that the commission would regard press interviews as crude attempts to influence proceedings.[8]

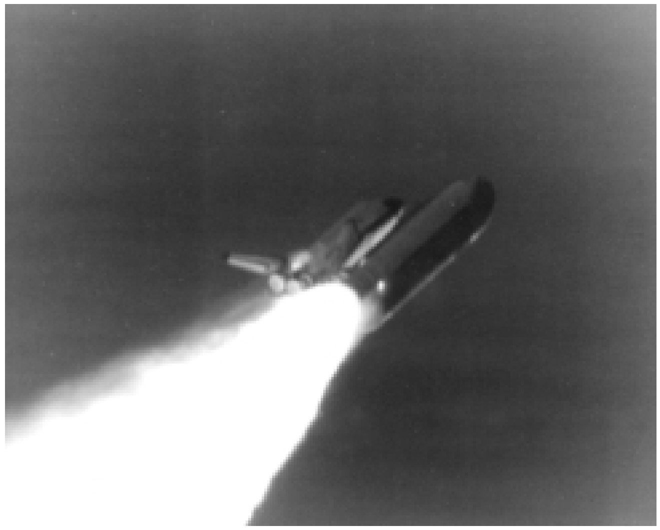
On 26 and 27 February the commission took testimony from Marshall officials involved in the teleconference. Center Director William Lucas said the tone of questioning was "very sharp." Center officials complained of difficulty explaining how they had experienced events and believed the commission did not listen sympathetically. Judson Lovingood, deputy manager of the Shuttle Projects office, said, "we're engineers . . . and that makes me tend to think one way and try to communicate one way. I found it difficult to communicate with some members of the commission. And that's not critical of them. But . . . an engineer does not think like a lawyer might think."[9]

After they had testified, Marshall officials held a series of press interviews. Defending his people, Lucas said "in my judgment, the process was not flawed," and "given what they say they knew, what they testified they knew, I think it was a sound decision to launch."[10] Managers defended the launch process which allowed decisions to be made by low-level experts. They exonerated the joint's design, argued that they had lacked hard evidence that the cold was a hazard, disputed the claim that cold weather was the technical cause of the O-ring failure, and suggested that assembly errors could have damaged the O-ring and caused the accident.[11]

The Marshall strategy of openness backfired. Media reports interpreted their statements as attempts to discredit the commission and as signs of an arrogant refusal to admit mistakes. Marshall public information officers later complained that the media had twisted information and lamented that Marshall had been "gang-banged by the media."[12] The commission's response was just as critical. One commission member believed that the Marshall managers' defense of the flight readiness review process and their decisions was "totally insensitive." Commissioner Joseph F. Sutter believed Center managers were "pretty defensive." After reading the stories and after the commission requested tapes of the interviews, Marshall officials concluded that talking to the media did more harm than good.[13]

In retrospect, Marshall leaders challenged the wisdom of a public investigation. Bill Sneed said NASA should have tried "to understand what went wrong and tried to make it right, rather than almost put the people on trial." Lucas argued that a public investigation was "clearly a gross error." The commission, he believed, was "totally politically motivated" and "its genesis almost determined its outcome." Its purpose "was never to find out technically what went wrong, but to find out where we could put some blame that would deflect it as far from the [Reagan] administration as possible." Lucas worried that the public inquiry had been "counter-productive entirely" and "could close NASA up." An internal investigation would have discovered as much without the side effect of making people "more inclined to protect their own tail, so to speak, rather than have a purely open situation."[14]

The presidential commission and its NASA investigation teams published a common report on 6 June 1986. The report contained four major conclusions: the SRM (solid rocket motor) joint had a flawed design; NASA's safety and quality systems had been inadequate; the Shuttle flight schedule had been too demanding; and Marshall had poor communications, especially with the Level II Shuttle Program office.[15]



Plume of flame from aft field joint of right SRM of STS 51–L, approximately 60 seconds after ignition.

The accident analysis team, led by Thomas and supported by Marshall personnel, studied flight data and wreckage, performed 300 tests on 20 different joint configurations, and concluded that the O-rings had failed and caused the disaster. In addition, the team concluded that the joint design was flawed and that the weaknesses had not been fully understood before the accident. Only after the accident had ground tests thoroughly checked joint behavior and shown that the design was very sensitive to many factors, including joint rotation, cold temperature, hard O-rings, ice in the O-ring grooves, leak check displacement of the primary O-ring, delay of O-ring pressure actuation by the putty, blow-holes in the putty, misfit of the

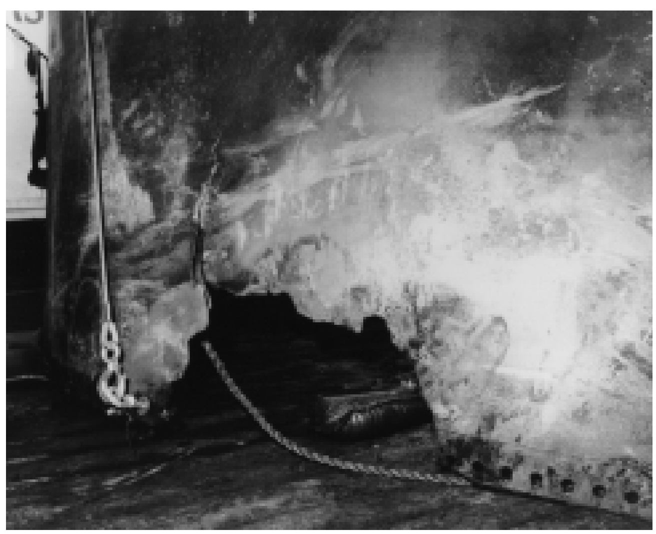


Photo of recovered fragment of aft center segment of right SRM of STS 51–L, showing hole burned through the case wall.

tang and clevis caused by out-of-round and reused segments, excessive compression on the O-ring by the tang and clevis, and structural stress on the joint caused by an external tank strut and launch dynamics. Thomas's team concluded that NASA must "modify the SRM joint to preclude or eliminate the effect of all these factors and/or conditions."[16]

While accepting that post-accident tests had revealed the inadequacies of the design, most Marshall officials observed that they had had confidence in the design before the accident. Keith Coates, former SRM chief engineer, said, "We knew the gap was opening. We knew the O-rings were getting burned. But there'd been some engineering rationale that said, "It won't be a failure of the joint." And I thought justifiably so at the time I was there. And I think that if it hadn't been for the cold weather, which was a whole new environment, then it probably would have continued. We didn't like it, but it wouldn't fail."[17] Lovingood, former deputy director of Shuttle projects, brooded that "we thought we had thoroughly worked that joint problem. And, you know, I just see it as an error in judgment—a terrible error in judgment."[18]

Some Center officials, however, sought to discredit any simplistic cold weather interpretation. They believed that the design was adequate in cold weather if the joint was properly assembled. Kingsbury doubted that temperature alone had caused failure of the O-rings; if conditions had been so severe, he asked, why had the other five field joints sealed?[19]

Instead, Kingsbury and others pointed to misassembly of the fateful joint as a possible technical cause of the accident. The Accident Analysis Team had found that the joint that failed had been one of the most difficult to assemble in the entire Shuttle program because the upper and lower segments were out-of-round. Ovality of the reusable segments was caused by the sagging of the case walls as the segments lay on their side during rail shipment from Thiokol's plant in Utah to Kennedy Space Center. The Thiokol assembly team at KSC had failed to mate the segments for the 51–L aft right joint several times and succeeded only after using a rounding tool to force the upper segment into shape. While the assembly process followed the correct procedures and the mate was within NASA's numerical specifications, the fit was extremely tight with possible metal-to-metal contact of the tang and clevis. The accident analysis team's report observed that the fit could have compressed the O-rings so tightly that they could not slide across the groove and seal the joint. The report noted that the tightest fit of the segments was in the same location as where gases burned through the joint.[20]

This evidence implied that the tight fit alone could have caused a leak and that the accident could have occurred even in warm weather. Obviously if cold did not cause the accident and if launch managers had not known of the assembly problem, then criticism of the launch decision process and the decision to launch in cold weather was misplaced and more scrutiny should have fallen on the assembly process. Kingsbury believed that the Rogers Commission had made conclusions too early in the investigation, put too much emphasis on cold weather as the technical cause of the accident, paid too little attention to assembly factors, and then made unfair accusations against Marshall managers. Chairman Rogers made up his mind, Kingsbury said, he “quit investigating and became prosecutor” and “we were hanging on the cross and bleeding and hoping it would end quickly.”[21]

The official reports of the investigations had different conclusions about the tight fit of the fateful joint. The presidential commission’s report devoted an appendix to the issue, and acknowledged the danger of a metal-to-metal fit. The commission concluded, however, that assembly records and flight experience showed no causal connection between tight joints and O-ring problems either on 51–L or on previous launches. The NASA accident analysis team’s report described the tight fit only as one of many factors that contributed to the leak. The team’s report did not single out any single factor that had caused the joint failure, and instead showed problems in the entire design.[22]

J.R. Thompson, overseer of the day-to-day work of the NASA investigation, faulted the whole design and its sensitivity to many factors. Thompson said that “we were walking right on the edge of a cliff and several of these factors just pushed us over.” He lamented that, “We missed it in the design, and some of the prior flight anomalies just really were not taken seriously. Looking back on it, that joint has several shortcomings and it is quite marginal, so if things are not just right it is very susceptible to a leak. It did leak on some prior successful launches… This was just the first time it propagated to a failure. The conditions were marginal enough that it just fell over the edge.”[23]

Thompson later denied that the joint had been improperly assembled, but observed that cold was not the only factor that had contributed to the accident.

If temperature had been the single cause, then NASA could have introduced a launch rule that prohibited cold weather launches. The NASA accident team believed the culprit had been an inadequate design and so had recommended redesign of the joints and seals.[24]

The presidential commission also faulted the Agency and the Center for their "silent safety program" and failure to uphold "the exactingly thorough procedures" of the Apollo Program. The Agency and Center had safety, reliability, and quality assurance offices that were responsible to chief engineers in Washington and Huntsville. Marshall's quality office, the commission charged, had failed to maintain a consistent listing of the change of O-ring criticality from 1 to 1R, to perform statistical analysis of trend data, to attend key reviews, and to report critical problems and launch constraints to officials outside the Center. Without knowledge of hazards, managers could not make informed decisions. The commission attributed these problems to an inadequate number of personnel, lack of independence for the quality office, and unclear communications guidelines.[25]

In commission interviews, Marshall's quality officials described how their work had changed greatly from the Saturn era. In 1965 the Center's Quality Laboratory had 629 people; the lab independently analyzed and tested hardware built by the Center. After abandoning Arsenal practices in the seventies, the contractors oversaw quality, and NASA relied on inspectors from the Air Force or the Defense Logistics Agency. In 1985 Marshall's quality office had only 88 inspectors who tracked problems reported in formal documents, and checked that the Center and contractors were addressing anomalies. Center officials acknowledged some lapses in documenting criticality and launch constraints. Nonetheless, Center Director Lucas said the safety program "wasn't silent. It might not have been as noisy as it should have been" and "probably was not as strong as it should have been because we didn't have the personnel."[26]

Lucas and Wiley Bunn, director of the quality office, agreed that the commission misunderstood quality practices in Marshall's matrix organization. Rather than merely the responsibility of special inspectors, quality and safety were the primary charges of the Center's Science and Engineering Directorate. Lab specialists were studying the joint problem, project officials were reporting it in flight readiness reviews, and both had determined that no hazard existed. However, the quality office lacked resources to duplicate research and therefore it depended on the labs for engineering analysis and accepted their judgment that the joint was safe. Quality officials had no reason to "lay down in front of the truck," Bunn explained, because "the truck wasn't even coming." He regretted that 51–L had resulted from incorrect judgments rather than an inspection or reporting error. "Had the problem with 51–L been a clear quality escape," Bunn said, "in other words the area I'm responsible for had overlooked something that had resulted in the tragedy, it would have been better for NASA, it would have better for this Center, and better for the people involved in the decision to fly."[27]

Bunn also regretted that no one in his office or the labs made statistical correlations of O-ring damage with leak check pressure or temperature.[28] Indeed the presidential commission had ignored how this failure was symptomatic of NASA's antipathy to "numerical risk assessment." Here the Agency's technical engineering practices lagged behind the military and the nuclear industry which had routinely used statistical methods since the 1970s. Developed by Bell Labs and the Air Force, the system sought to help decision-makers by providing a probabilistic statement of risk. This computer-aided technique traced the causes of potential malfunctions back through every subsystem to identify parts most likely to fail.

During the lunar program, however, the Agency had bad experiences with probabilistic risk assessment. When General Electric, using primitive techniques, determined that the chance of a successful landing on the Moon was less than five percent, NASA abandoned the practice. Will Willoughby, the head of the Agency's quality office during Apollo, said "Statistics don't account for anything. They have no place in engineering analysis anywhere." NASA engineers were uncomfortable with probabilistic thinking and argued that meaningful risk numbers could not be assigned to something as complicated and subject to changing stresses as the Space Shuttle. Thus the Agency did not normally require statistical assessments for its hardware.

NASA used a more qualitative approach called "failure mode effects analysis," or FMEA, developed by the Agency and Boeing in the 1960s for the Apollo Program. It emphasized engineering analysis during the design stage rather than risk assessment in the operational stage. Rather than assign probability estimates to parts or systems, failure mode analysis identified worst case problems. Engineers could then design critical parts for reliability. Failure mode analysis worked well during the Apollo Era because NASA had the money to develop several different designs and then could choose the best.[29]

When NASA began using numerical techniques, assessments of the solid rocket boosters became political. In 1982 the J.H. Wiggins Company determined that the boosters were the highest risk on the Shuttle and likely to fail on 1 of 1,000 flights. Challenging this, the Space Shuttle Range Safety Ad Hoc Committee said the study had included data from primitive military solid rockets and that improvements made the Shuttle's boosters likely to fail on 1 of 10,000 flights. In 1983 Teledyne Energy Systems estimated the probability of failure was 1 in 100 flights, but a 1985 study by JSC (Johnson Space Center) put the failure rate at 1 in 100,000 launches, a prediction which was 2,000 times greater than the performance of any previous solid rocket.[30] Presidential commission member Feynman compared informal estimates from NASA engineers and managers and found that the engineers expected failure in 1 of every 200 or 300 launches while the managers expected failure in 1 of every 100,000. Feynman concluded that the manager's "fantastic faith in the machinery" precluded realistic judgments.[31]

Some Marshall veterans attributed the poor judgments to a decline in the technical culture of the Agency. The abandonment of the Arsenal system and the adoption of contracting, the retired German rocket engineers observed, had meant a loss of "dirty hands engineering" at Marshall. Karl Heimburg, who had headed the Test Lab, believed that the in-house design and development of prototypes produced more reliable technology than contracting and ensured that civil servants understood the hardware. Walter Haeussermann, former chief of the Guidance Lab, said that "if the engineer has only to supervise, without going and directing experiments, he is not as familiar with it. Finally, you get a paper manager." A 1988 survey of NASA employees found that less than 4 percent of professional workers spent most of their time at hand-on jobs and 76 percent worked most of the time at office desks.[32]

The presidential commission attributed some of the risky decisions to an "optimistic schedule" for Shuttle launches imposed by NASA and the Reagan administration. The commission found no "smoking gun" that showed that the Reagan administration had applied pressure to any NASA official to launch 51–L on 28 January. However the administration and Agency had maximized total flights in order to minimize the cost per flight and please commercial customers. The Shuttle had flown 9 missions in 1985, and officials had been confident that they could fly 15 in 1986 and 24 in 1990. Consequently they had assumed the Shuttle was "operational" and safe rather than experimental and risky, reduced tests to free up money for flying, accepted problems rather than apply costly fixes, and subordinated reviews of past performance to planning future missions.[33] After the accident, some in the news media acknowledged that they had applied pressure to NASA by criticizing the Agency for missing its schedules.[34]

Marshall personnel were very aware of schedule pressures. The RIFs of the 1970s had made Center personnel sensitive to meeting schedule and budget requirements.[35] Personnel evaluations in the Agency were based in part on schedule criteria and several Shuttle officials at Marshall and other Centers received salary bonuses for staying within time constraints.[36] Marshall engineers used the expression "get under that umbrella" to show desire to finish a task on time.[37] Moreover, when the Center had been the source of delays, such as with development work on the Space Shuttle main engines or launch postponements due to propulsion problems, NASA Administrator Beggs had been critical.[38]

Time pressure affected the mentality and decisions of Center officials. Sneed, assistant director for Policy and Review, recalled that Marshall had been "budgeting to fly" rather than to make long-term improvements. "Because we were flying the thing at the rates we were," he recalled, "most of our attention—our management attention, our engineering attention—was on flying the next vehicle. Maybe more so than looking and saying, 'Well, how did that last one fly?' and 'What is wrong with the last one, and what do we do to make it better, to make it more reliable?'" The Center, Sneed said, "didn't have time to stop and fix and end flight; you had to continue to fly and try to get your fixes laid and incorporated downstream."[39]

The pressures had intensified by late 1985. In December 1985, Jesse Moore, Level I Shuttle manager, set a goal of 20 flights per year by FY 1989 and requested that this objective be the principal item for discussion at the February Management Council Meeting. In the meantime Moore suggested that between flights NASA should only make modifications that were "mandatory for reliability, maintainability, and safety." After Marshall had delayed launch of 61–C because of a troublesome auxiliary power unit in the SRB, Arnold Aldrich, the Level II manager, wrote that the Shuttle program was "proud of calling itself 'operational.' In my view one of the key attributes of an operational program is to be able to safely and consistently launch on time."[40] During the 27 January teleconference, Allan McDonald of Thiokol recalled, Lawrence Mulloy observed that the 53-degree criteria would jeopardize NASA's plans to launch 24 shuttle flights per year by 1990, especially those scheduled from Vandenberg Air Force Base in northern California.[41]

Nevertheless, Marshall officials denied that they had sacrificed safety to meet the schedule. They believed that they had carefully reviewed the joint problems throughout the Shuttle's flight history and that schedule pressures had not affected their decisions. No Center employee who participated in the 51–L teleconference believed that schedule pressure had affected decisions. George Hardy, the highest ranking engineer present, said Science and Engineering was responsible for safety, not for schedule or the flight manifest. Ben Powers said that lab engineers referred to the schedule and money concerns of the program office as "bean counting." Center Director Lucas observed that "there is always schedule pressure," but "I don't know of anybody at Marshall who would deliberately, knowingly, take a chance just for the sake of schedule. We had never done that before. We'd been called down from launches, and I didn't feel any pressure and I didn't think that [for 51–L] there was any pressure."[42]

Finally, the presidential commission attributed the accident to Marshall's "management isolation" and a failure to communicate bad news, especially with the Level II office in Houston. The commission found it "disturbing" that "contrary to the testimony of the Solid Rocket Booster Project Manager [Mulloy], the seriousness of concern was not conveyed."

Aldrich, and Jesse Moore, the Level I manager, said they had not been informed of the launch constraint, the O-ring anomalies on flights late in 1985, the temperature concerns, or the teleconference. They admitted that NASA had confusing communications requirements, but thought the NASA custom was to report concerns about criticality 1 hardware. Aldrich also said he had not known that the Center had ordered steel SRB cases with the capture feature lip in July 1985; the budget channel for Marshall's Shuttle work came through Headquarters rather than the Shuttle Program Office at JSC.[43]

Although the commission report did not explain the communications problems, Commissioner Feynman did in his autobiography. Center rivalry and budget pressures, he reasoned, led NASA managers to think like businessmen who wanted only good news.[44] In any event, the commission recommended that NASA improve its communications requirements, strengthen Shuttle management, and "take energetic steps to eliminate this tendency [to isolation] at Marshall Space Flight Center, whether by changes of personnel, organization, indoctrination or all three."[45]

The notion that Marshall had a closed culture and had tried to hide the O-ring problems was believed throughout the Agency. Given the long-standing rivalry between the Centers, the view was prevalent at Houston. Astronaut Story Musgrave said "the trail goes on and on and on, and it turns out that the trouble is endemic to a major part of the organization." One JSC official said, "Nothing was ever allowed to leave Marshall that would suggest that Marshall was not doing its job. Everything coming out of that Center had to have 'performance' written all over it." Moreover, Marshall's culture was not open enough to detect and solve problems; superiors had been unwilling to hear bad news and subordinates had been unable to make themselves heard. Jack James, an astronaut instructor, said "if you have too closed a shop, you get in-grown and convoluted." Chris Kraft, the former director of JSC, wondered if Marshall had decided to keep problems to itself because the authoritarian management of Administrator Beggs, his Associate Administrator Hans Mark, and Associate Administrator for Space Flight, General James Abrahamson had created "underground decision-making" throughout the Agency. Marshall officials, Kraft speculated, "knew that if they made it [the O-ring problem] visible it would be hell to pay."[46]

Aerospace scholars used long-standing stereotypes to explain Marshall's apparent provincialism. Alex Roland, a space historian at Duke University, said "von Braun set up Huntsville as a feudal state with himself as lord of the manor. He insisted on a high degree of autonomy, and as a result Huntsville was and is highly defensive and combative, almost a bunker-style mentality." John Logsdon, an aerospace policy expert at Georgetown University, thought "there is a certain closed character about Marshall, an unusual arrogance, and at the same time a paranoia, perhaps because it has been a place that the Office of Management and Budget wanted to close."[47]

The presidential commission sought evidence of a cover-up and Marshall's closed culture. Investigators found no evidence of an after-the-fact cover-up and little clear evidence of closed communications within the Center. Investigators never found the anonymous middle manager who penned a vituperative attack on the "feudalistic" management of Director Lucas. Signed "Apocalypse," the letter said Lucas was intolerant of dissent, used a "good old boy" promotion system, and tried to "cover up" O-ring problems. Lucas allegedly had a flawed flight readiness philosophy; "for someone to get up and say that they are not ready is an indictment that they are not doing their job." Problems, the letter said, were "glossed over simply because we were able to come up with a theoretical explanation that no one could disprove," and "if no one can prove the hardware will fail, then we launch." The commission, however, never found Apocalypse.[48]

The theme of bad communications was taken up in a management study by Phillip K. Tompkins. In interviews conducted in January 1990, he asked middle and high ranking Marshall managers, almost none of them from inside the Shuttle organization, about communications under Center Director Lucas. Tompkins believed that subordinates felt intimidated by Lucas; they feared his tendency to "kill the messenger" bringing bad news and so they censored bad news or sugarcoated problems. The result was a "paranoid organization" that could not discuss problems or communicate them to outsiders.[49]

In interviews with commission investigators in 1986, however, Marshall personnel defended the openness of the Center. Engineer after engineer said that Marshall management was open, but insisted on facts to corroborate opinions. Bunn told the commission "if there's one thing that Dr. Lucas really doesn't like, it's for somebody to tell him something that they don't know. He can't stand that. Or somebody to know something and not tell him."[50] In later statements, Marshall personnel and contractors defended Lucas. Bob Marshall, a Center propulsion engineer, said that "the institution takes on the character of the lead manager because his style is emulated in those who work with him" and "we are a disciplined organization. We are also a driven organization." Joe Moquin, president of Teledyne Brown Engineering, said "He was demanding. He demanded the facts and substantiation of the facts. He could be tough on the experts." The president of Rockwell International's Rocketdyne division wrote Lucas that "You have set standards that we must maintain. After all our internal reviews, we always asked the final question, 'Will Dr. Lucas accept our logic?'"[51]

Marshall personnel also denied that their Center had failed to communicate the O-ring situation to the rest of the Agency. Center officials believed they had reported what they knew about the booster joint to "everyone" and Mulloy said he had told the truth during reviews and commission hearings. Kingsbury argued "I don't want to take exception to the commission's report," but "I don't know how they came to the conclusion that we are autonomous. . . . I don't believe we're autonomous or isolated." Lucas later said that the charge of isolation was "probably one of the most hurtful things because it's the furthest from the truth. The readiness reviews were held in the presence of Headquarters and everybody else" and "the weakness in that particular design joint had been recognized by Marshall, by Johnson, by Headquarters, including the Administrator." He believed that "the only thing I know of that was not common knowledge was the description of what occurred the night before, the so-called very hard arguments about whether we're ready to fly or not and apparent fact that the management of Thiokol applied pressure to their engineering people."[52]

The disagreement between the presidential commission and Marshall was essentially a matter of chronology: When did responsible Center officials know that the booster joint was unsafe? The commission's answer, stated baldly, was that the joint had always been hazardous and that Marshall had hard evidence of the danger from the beginning. Rather than admit failure, the Center discretely began repairs, and deliberately glossed over bad news through the launch of 51–L. If Marshall had communicated the bad news, the commission implied, wiser heads in Houston or Headquarters would have stopped flight until the joint was fixed. This assumption that more complete communications would have produced solutions or stopped the launch of 51–L was pure speculation. Would officials without expert understanding have stopped flying a joint verified safe by experts from the contractor and NASA's propulsion Center? No.

The response of the Marshall engineers and managers was that the joint was always "safe" in the sense that they lacked convincing contrary evidence. Successful launches had confirmed its reliability, and so the Center had little bad news to report and much good news to believe in. Even so the Center had continued studies, introduced short-term improvements, and begun long-term redesign. Although the Center had no excuse for not always communicating all the information and minority views, Marshall officials had typically described the strengths and weaknesses of the joint and their rationale for believing in its safety. When had they known the joint was unsafe? After 51–L.

When the commission published its report on 6 June, Center workers naturally had mixed feelings. John Q. Miller said "I personally have not seen any indications that there has been any lapse in concerns over safety here" and "we thought the necessary precautions had been taken." Feeling betrayed, one engineer, an 18-year NASA veteran, said "we were working overtime to give Mr. Rogers everything he wanted," but the commission criticized the Center unfairly and "nobody in NASA has stood up to defend us." Dr. Lucas said he viewed the report "as an assessment of a mistake that was made, or mistakes, perhaps, and it's going to enable us to fix problems and move on with the program as it should be" and he promised that "not one single word will be taken lightly."[53]

Scarcely had the Center absorbed the commission report, when Congress held its own hearings. The hearings before the House Committee of Science and Technology and Senate Space subcommittee mainly duplicated the anachronisms of the commission and assumed that decision-makers had known the joint was unreliable before 51–L. The main congressional contribution was in making second-guessing and scapegoating explicit. Congress complained that the commission report should have named names. Representative James H. Scheurer (D–NY), wanted to "find out what NASA officials knew and when they knew it." Senator Donald Riegle (D–MI) said "every single person that didn't behave and function properly has got to be identified and some kind of disciplinary action has to be taken." They wanted irresponsible civil servants held accountable and removed from the chain of command; this would ensure that in the future NASA officials would follow procedures. The most challenging questions were directed at Marshall officials. Senator Ernest Hollings (D–SC) blamed "Lucas policy" for creating "a cancer at Marshall" and said "that fellow [Mulloy] either misled or lied" to the commission.[54]

Faced with such comments, NASA officials said if they knew then what they knew now they would have stopped flight, but they did not doubt the joint then. Mulloy explained that 51–L happened because "I wasn't smart enough, the people who advised me weren't smart enough, the contractor wasn't smart enough . . . the people who review my activities weren't smart enough. . . . No one was smart enough to realize what was necessary." After the accident, he said, "knowing that something has failed, one might be able to recognize better what might have precluded it." Some Headquarters officials, including the Level I Deputy Director L. Michael Weeks, acknowledged that they had known of the O-ring problems from the August 1985 briefing. Dr. James Fletcher, who again became NASA Administrator in June 1986, told Congress that "Headquarters was at least as much to blame as other parts of the organization. I don't think all the responsibility should reside at the Marshall Space Flight Center."[55]

Other NASA veterans questioned putting the blame only on Marshall. Kraft said, "You have to fault the Johnson Space Center just as much as the Marshall Space Flight Center. They knew the goddamn thing was bad. It was written up in their files over and over again. That came out in the Rogers' Commission explanation. I don't know why the whole system allowed that to continue to fly. They are all to blame. Every goddamn one of them are to blame."[56]

The pressures helped several Marshall officials decide to leave the Agency. By the end of 1986, Hardy, Mulloy, Reinartz, Kingsbury, and Lucas had retired. Kingsbury said of his long-time friend and boss that Lucas had received a "bum rap" for 51–L. Instead Lucas should have gotten credit for initiatives that had diversified Marshall. "Before Lucas we had just been a propulsion Center. We built rockets. But under his direction we have branched out into Spacelab, the Space Telescope, a major role in the Space Station—all the things that have made Marshall a more viable, more important part of the American space program." Lucas, Dr. Ernst Stuhlinger recognized, had "directed more space accomplishments than almost any other NASA director." Kraft, a rival and ally from Houston, recognized the constraints on Marshall and NASA, writing Lucas that "those of us in the forefront of NASA, particularly the Center directors in the manned space flight programs, have an insight into the management of NASA over the last 10 years which no one else has even an inkling of. Maybe someday, when all the present trauma passes, we will be able . . . to tell the real history of the situation. At any rate, you and I know what had to be endured and the accomplishments that were brought about in spite of these inadequacies."[57]

In summary, the conclusions of the presidential commission were a mix of fact and fallacy. On the positive side, they revealed real problems about technology, resources, schedule, and communications and helped NASA find solutions. Revelation of the problems, and NASA's promise to fix them, removed suspicions and allowed the Agency to win the congressional support necessary to return the Shuttle program to flight. On the negative side, the commission engaged in scapegoating that put unfair blame on a few individuals. While this may have satiated the psychological needs of the nation and the political needs of powerful people inside and outside the Agency, scapegoating led to widespread misunderstanding of the accident, the Space Shuttle, and the process of development of high technology by complex organizations. Scapegoating also damaged the reputation of Marshall and NASA and left a legacy of bitterness and perceived injustice among many Center veterans. Only time would tell whether such sentiment would actually close the culture that the investigations had sought to open.

Recovery and Redesign

The recovery from the disaster and preparations for a return to flight began almost immediately after 51–L. The Center and the Agency reorganized Shuttle management, improved communications, and revitalized safety and quality programs. Bolstered with extra appropriations, Marshall redesigned and tested the SRM joints and improved other Shuttle hardware. The recovery culminated in the launch of STS–26 in September 1988.

As the 51–L investigation progressed, NASA administrators recognized that the Shuttle flights would be delayed for a considerable time. With the overall goal of a "conservative return to operations," NASA began studies of problems in the Shuttle program and in the Agency as a whole.[58] Organizational studies conducted by committees led by astronaut Robert Crippen and former Apollo manager Sam Phillips complemented the recommendations of the presidential commission and the House Committee. By the fall of 1986, the implementation of the recommendations was well underway.

NASA's organizational changes sought to open communication and centralize direction by copying parts of the Apollo Program. Dale Myers, a former Apollo manager who returned to the Agency as deputy administrator, said the reforms would "reduce the trend toward parochialism that tended to grow at the Centers under the pre-*Challenger* accident management style." The reforms strengthened the Management Council and established an independent quality and safety office. Headquarters devoted more full-time personnel to the Shuttle program; a deputy director for Shuttle operations, a new official, would work from the Cape; he would have a small staff at each Center, manage the flight readiness reviews, and direct the launch decision process.

Many of the reforms helped Headquarters and the Centers exchange information. The reforms increased the authority and access of the JSC Level II office. A Level II deputy director managed the day-to-day Shuttle program and directly supervised the manager of the Shuttle projects office at Marshall; both officials would be responsible to Headquarters rather than to any Center director. In addition, the Level II office was brought into the budget process of Marshall and all other space flight Centers; Marshall's director would still submit requests for Shuttle funding to the Headquarters program director, but the Level II manager would offer an assessment. The Level II office also penetrated deeper into the Shuttle organization by strengthening its engineering integration office and by using astronauts as liaisons with technical teams at the Marshall Center. Bob Marshall, the new manager of Center's Shuttle projects office, said that the new structure would "assure that in our discussions and in the problems that we have to address that we have not left someone out or bypassed them."[59]

In addition to a new Shuttle projects manager, the Marshall Center had personnel changes in several offices including the SRB project manager, director of Science and Engineering, and Center director. Marshall's new director was J.R. Thompson, who had worked at the Center from 1963 to 1983. Thompson had managed development of the Space Shuttle main engines; "I've blown up more engines," he said, "than most of those guys have seen." After leaving NASA in 1983, he went to the Princeton Plasma Physics Laboratory before returning to direct the technical aspects of the 51–L investigation for the presidential commission.

To restore Marshall's reputation and recover the Shuttle program, Thompson recognized that improved technical analysis and communications were necessary. He believed "they've done it better at Marshall than anybody else had been able to—but that's still not near good enough." In reference to the commission's charge that Marshall had been isolated and closed, Thompson said, "When I was there, I was not aware of it. If you go back through the twenty years I was there and that was true, then I was part of the problem. But in the spirit of accepting the commission report, I'm going to assume there's probably some substance there and we're going to fix it. . . . We will open up that communication."[60]

Thompson later recalled that when he became director in 1986, NASA had lost some of the "internal tensions between Centers and within a Center" that he had remembered from the early 1980s. During Shuttle design, development, and testing, experts from within Marshall and across the Agency had quarreled about technical issues. The conflicts, which often seemed like wasteful infighting to outsiders, were actually sources of strength which had deepened thought and improved technology. When the Shuttle became "operational," however, Thompson believed that all of NASA "got too comfortable" with the Shuttle and stopped looking for problems and arguments. Headquarters had imposed the goal of making the Shuttle pay for itself and so ground tests were reduced and criticism muted. One of Thompson's goals as Center director was to cultivate openness and allow free discussion of problems.[61]

His candor showed in a reply to Aaron Cohen, the director of JSC. Cohen had forwarded a memo from John Young, chief of the astronaut office, that had criticized Marshall's solid rocket tests. Thompson reassured Cohen with a technical explanation, and then, in a hand-written note, he said, "I appreciate John's assessment on this and other items. We'll keep him informed of our progress and where we're wrong. JR."[62]

Thompson improved the Center's internal and external communications. He made impromptu visits to Center work sites, ended the executive luncheons on the ninth floor of Marshall's Headquarters building and ate in the cafeteria, initiated more employee socials and old-timers gatherings, improved media access, facilitated exchanges and meetings with other Centers, and encouraged Marshall employees to take temporary assignments at Headquarters. To open decision-making, Thompson created a Marshall Management Council and expanded attendance at meetings. The Center fostered participative management, offered monetary rewards for suggestions, and established quality control circles called NASA Employee Teams.[63]

Alex McCool, who became director of Marshall's quality office, said Thompson wanted to make "a cultural change" at the Center by trying "to keep us talking together, working closer together, communicating." McCool explained that "Prior to *Challenger*, we had a kind of 'kill the messenger' syndrome. In other words, [if] somebody brings bad news, man, shoot him. We had that. The Agency had that, particularly at this Center" and "if you'd bring bad news, first thing you know all the bosses would jump on you. And there you are on the defense."[64] Accordingly the Center's management training program sought to teach openness. In one such program in April 1987, middle managers, after hearing a Thompson speech, offered anonymous comments on what they had learned: "survey results at MSFC indicates worst Center in NASA for communications; separate technical differences from personal relationships; taking a position is not as important as surfacing all sides; be prepared to defend and support positions with both the pros and cons; don't allow ourselves to become 'comfortable' in our technical and managerial jobs to the point that 'feedback' data is either ignored, overlooked, or not evaluated."[65]

The Center director tried to be the model of a participative leader. He began meetings by asking the question, "What are the problems?" Robert Schwinghamer, director of the Materials Lab, said that Thompson ran meetings much like von Braun and both men created a climate in which people said what they thought and "nobody feels like he's inhibited anymore."[66]

The new Center Director reorganized Marshall to improve rocketry engineering and management. On the laboratory side of the Center, he sought to bring propulsion specialists together. He divided the old Office of the Associate Director for Engineering into offices for Space Systems and Propulsion Systems, and gathered rocket engineers from several laboratories into a new Propulsion Laboratory. On the project side, the Shuttle Projects Office reorganized for the recovery and for later return to flight. Two offices merged to form the Space Shuttle Main Engine Office which began developing an alternate turbopump and testing the main engine. The SRB Project Office created a Systems Management and Integration Office to handle project control and contractor management.[67]

Center and Agency programs in flight safety and technical quality also restructured in the post-*Challenger* reforms. People throughout the Agency recognized that safety functions had to be strengthened. McCool said that after 51–L the Agency developed "an obsession" to "do the job right." Everyone recognized that "we can't have another *Challenger*. The nation can't stand it. I'm saying… we probably wouldn't have NASA with another *Challenger*." McCool kept a billiard ball on his desk to remind him that he was "behind the eight ball" and had to do a good job.[68] As part of the reforms, NASA opened a confidential hotline for reporting safety problems, trained engineers in quality control, increased use of statistical risk and trend analysis, and standardized procedures for tracking significant problems. The Shuttle program developed a computerized database to support trend analysis and problem reporting. NASA moved away from cost-plus-incentive-fee and cost-plus-fixed-fee contracts that subordinated quality standards to cost and schedule requirements, seeking to enhance safety and quality by using cost-plus-award-fee contracts with specific quality requirements and incentives, and putting quality experts on Award Fee Boards.[69]

The Center established a new Safety, Reliability, and Quality Assurance Office to consolidate the old Marshall Safety Office, the Reliability and Quality

Assurance Office, and part of the Systems Analysis and Integration Laboratory. The office gained greater capacity to make independent judgments by employing more civil servants with expertise in quality, hiring a support contractor, separating from the Science and Engineering Directorate, and reporting directly to the Center Director and the new associate administrator for Quality at NASA Headquarters. The office employed an astronaut as liaison to facilitate communication with the astronaut office at Johnson Space Center.[70]

Two oversight panels, one of NASA personnel and another from the National Research Council (NRC), studied the Agency's quality control programs and proposed improvements. The independent panels worried that NASA still had not corrected some flaws in the quality organization that had contributed to the accident. They worried that NASA performed hazard analysis after-the-fact rather than as part of the design process, implemented quantitative risk assessment too slowly, and clogged communications between flight managers and organizations responsible for inspection, tests, and repair. They fretted that NASA's matrix organization could jeopardize the independence of quality engineers and that the proliferation of Shuttle boards and committees could lead to "collective irresponsibility." This complicated, multilayered organization, the National Research Council worried, could "lead individuals to defer to the anonymity of the process and not focus closely enough on their individual responsibilities in the decision chain." Nonetheless, both committees decided the quality and safety systems were sound and represented progress over pre-*Challenger* days.[71]

During the reorganization, the Shuttle program reviewed the safety of all Shuttle flight hardware, software, and ground support equipment. The work was painstaking and Marshall people met the challenge with a spirit of self-sacrifice. Many Center employees delayed retirement to help. Many more worked 60- or 70-hour weeks for the 32-month recovery effort. Special teams implemented the recommendations of the presidential commission. System design reviews identified problems for redesign and improvement. As if the Shuttle was flying for the first time, new design certification reviews verified that all hardware met contract requirements, passed qualification tests, and had proper documentation. The Shuttle Projects Office reviewed the external tank, Space Shuttle main engines, and the solid rocket boosters. With the assistance of Level I and Level II, the office also reevaluated all failure mode and effects analyses, critical items lists, and hazard analyses. New rules for the critical items lists substantially increased the number of items designated as criticality 1 or single point failures. Rather than just designating a subsystem like a turbopump, the new rules included several parts of the pump. Bob Marshall, manager of the Shuttle Projects Office, said "I agree with the new ground rules because it has put more potential failure modes under more controlled approach and review."[72]

Although the external tank and Space Shuttle main engines had not caused the 51–L accident, the Center performed reviews and introduced improvements. Marshall and Martin Marietta made few modifications to the external tank, but changed test and checkout procedures. They improved the tank's lightning grounding system and studied proposals for its use with an unmanned Shuttle.[73] For the Space Shuttle main engine, Marshall and Rockwell International's Rocketdyne division enhanced safety and reliability by increasing performance margins and durability. They modified the vibration damper system for the turbine blades in the turbopumps, strengthened the main combustion chamber, redesigned a temperature sensor, ensured redundancy in the hydraulic actuators, improved the electronic engine controller, and added latches to hold open the fuel disconnect valves between the main engines and the external tank. Performance rules became more conservative with power levels of 104 percent during a normal launch; the previous norm of 109 percent power would be used only during emergencies and tests would be run at 113 percent. Ground tests became very rigorous and included tests with built-in flaws and margin tests to destruction to determine weak links. Static firings totaled more than 83 hours, the equivalent of 50 Shuttle missions. Although most of the firings occurred at NASA's Stennis Space Center in Mississippi and at Rocketdyne's Santa Susana Field Laboratory in California, some took place in Huntsville, where Marshall's Saturn SI–C test stand, rechristened as the Technology Test-Bed, became a site for main engine tests.[74]

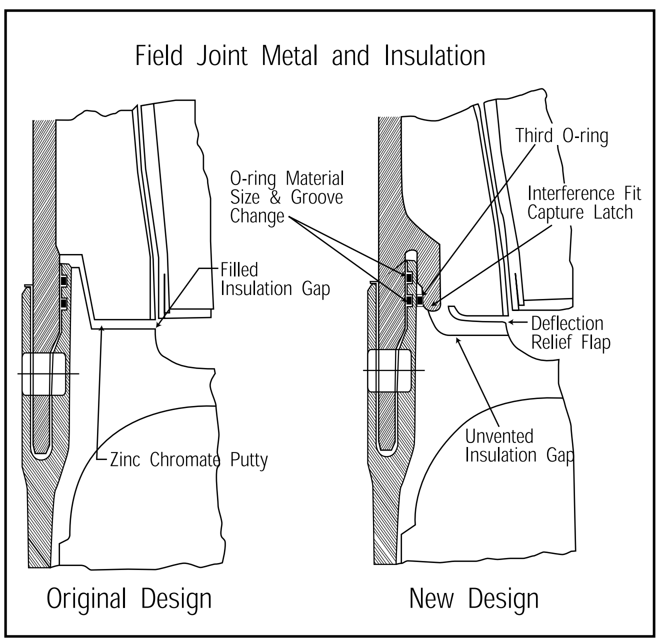
The solid rocket motors, of course, underwent the greatest modification, and the Marshall members of the SRM redesign team deserve the greatest credit for the successful return to flight. Particularly important were personnel from the Structures and Propulsion Lab. Not only did Marshall personnel determine the technical cause of the accident and analyze the weaknesses in the motor joints, but the Center also conceived the solution.

Marshall, in response to presidential and congressional directives and technical imperatives, adopted an unusual organization for booster redesign. To prevent the redesign teams from becoming isolated, a problem that the presidential commission had believed contributed to the accident, Marshall sought openness through an elaborate system of cross-checks which gave overlapping responsibility to numerous organizations. The Center, according to SRB Project Manager Gerald Smith, “probably violated every management rule that you would ever have the occasion to violate in trying to do the program.” Marshall’s SRB accident investigation team under John Thomas and its SRB redesign team under Kingsbury merged in April under Thomas. To generate the best ideas, Thomas’s team in Huntsville worked separately from a Morton-Thiokol team in Utah; the teams met regularly to compare ideas and select the best designs. The Marshall team included about 100 Center specialists and engineers from other NASA Centers, and another 200 experts from Martin Marietta, Lockheed, Wyle Labs, Teledyne Brown, United Space Boosters Incorporated, Rockwell International, McDonnell Douglas Technical Services, and Morton-Thiokol in Huntsville. The entire redesign process came under scrutiny of experts from Headquarters, JSC Shuttle program and astronaut offices, other NASA Centers (Langley, Lewis, and KSC), the solid rocket industry, the Jet Propulsion Laboratory, the Air Force Rocket Propulsion Lab, the Army Missile Command, and the National Research Council (NRC). Also maintaining surveillance were officials from congressional committees, the General Accounting Office, and the Federal Bureau of Investigation. Public interest in the program was intense, and the redesign team responded to more than 2,300 letters offering criticism and advice.[75]

The most important oversight came from a National Research Council panel for SRM redesign. The NRC panel, which had been formed at the suggestion of the Rogers Commission, monitored the entire redesign effort and participated in nearly 100 meetings, technical interchanges, reviews, conferences, and site visits. The panel drafted reports with criticisms and recommendations about all aspects of the redesign, and pressed NASA to conduct a thorough test program. Oversight by the NRC played a determining role in the success of the redesign.[76]

Managing a program with so many overlapping responsibilities and so much political interest was very difficult. Many people also felt depressed, Smith observed, because they felt responsible for 51–L, and “were absolutely devastated from the accident.” Marshall’s solution was the “open door policy.” Thomas and other managers of the redesign team, Smith said, “made it very clear at meetings that if anyone had a concern or issue, let's raise it. Do not, do not hold back. If you've got a problem, let's say it. If you don't like a decision, let's hear it, let's talk about it." Solving technical problems required that people communicate bad news and that they know they were "not going to get punished for it."[77]

In order to expedite the recovery, NASA renegotiated its contract with Morton-Thiokol. After the accident, the company had been willing to accept a $10 million penalty for failure of its hardware, but had refused to sign a document admitting legal liability. Consequently, NASA and Morton-Thiokol negotiated a deal that would avoid litigation and return the Shuttle to flight as quickly as possible. The company accepted a $10 million reduction of its incentive fee and admitted no legal liability. It would perform at no profit approximately $505 million worth of work to redesign the field joint, reconfigure existing hardware, and replace motor hardware lost with 51–L.[78] Congressmen questioned this agreement, which seemingly rewarded Morton-Thiokol for its deficiencies. But NASA had few choices given the pre-existing contract and pressures to return to flight quickly.[79]



Comparison of original and redesigned SRM case field joints.

Throughout the redesign period, NASA quality experts remained troubled with Thiokol's organization. A June 1986 review of the firm's management by Air Force and Marshall inspectors rated all functions as "satisfactory," except for Safety and Engineering, which rated "marginal." Even though Marshall established a resident quality office in Utah, troubles continued. A March 1987 Marshall review concluded that Thiokol quality and manufacturing personnel paid "an inordinate amount of attention to schedule." In August the Marshall Center resident manager for quality worried that the firm's quality program was "in a mode of complete capitulation to schedule pressure" and told Thiokol management that "quality and safety will not be compromised blindly to meet a 'schedule.'" Marshall ordered the firm to give quality managers more authority, track information more carefully, and surface bad news more readily. A JSC quality inspector complained that the Thiokol attitude was "just tell me what you want me to do and I'll do it" and attributed the company's lack of initiative to "NASA's constant criticism and overmanagement."[80]

Marshall imposed strict requirements for the redesigned motor joints and changed the design from a dynamic seal activated by ignition pressure to a quasi-static seal that was not pressure dependent. The technical requirement specified that the seals be redundant, verifiable, and perfect; the redesign would tolerate no blow-by or erosion.[81]

By August 1986, Thomas, as leader of the redesign team, announced the new concepts. The case-to-case field joints had several improvements that added redundancy and safety margin (see the illustrated comparison of original and redesigned SRM case field joints). The engineers deleted putty from the design and protected the joint from hot gases with insulation formed into a rubber J-seal, a flap inside the case that closed with motor pressure. The steel capture feature lip reduced joint deflection, created an extremely tight fit between tang and clevis, and maintained contact between the O-rings and sealing surfaces. By changing only tang segments, NASA saved money by using its clevis segment inventory. The capture feature also housed a third O-ring and a silicon filler to protect the primary O-ring. The combination of the J-seal, capture feature, and third O-ring prevented combustion gases from reaching the primary O-ring.

In addition, a second leak check port added above the primary O-ring ensured it was in sealing position. Custom shims between the outer surfaces of the tang and clevis maintained proper compression on the O-rings. External heaters maintained joint temperature at 75 degrees; rubber and cork sealed the heater bands to the case and kept rain out of the joints. Longer pins that joined the segments and a reconfigured retainer band increased the margin of safety.[82]

Joint Environment Simulator test at Morton-Thiokol, November 1986.

The redesign team also improved other parts of the solid rocket motors (SRMs). They reworked the case-to-nozzle joints on much the same principle as the case-to-case joints; they deleted putty, used radial bolts to join the metal of the case and nozzle more tightly, modified and bond the insulation, incorporated a third O-ring, and inserted an additional leak check port. Moreover, modifications improved the factory joints, nozzle, propellant contours, and ignition system. The team also redesigned ground support equipment at KSC to minimize case distortion during handling, improved the measurement of segment diameters to facilitate stacking, minimize risk of O-ring damage during assembly, and enhance leak tests.[83]

Although experts from NASA, the solid rocket industry, and the National Research Council questioned the complexities of the design, they gave preliminary approval.[84] Marshall and Morton-Thiokol then began tests to verify their ideas. The test program for redesign was much more thorough and realistic than the original test program and this rigor was the key to the successful return to flight. The tests proceeded in a hierarchy from tests of components to subsystems to full-scale motors. Laboratory and component tests verified the properties of the joint parts. Subscale tests simulated gas dynamics and thermal conditions for components and subsystems. Hydraulic tests of full-scale segments tested the new joint and seal configuration.

Unlike the original test program, both the Center and its contractor built simulators to study joint behavior and test designs. Marshall's Transient Pressure Test Article (TPTA), built in 1987, used a short SRM stack with two field joints, a nozzle joint, 400 pounds of fuel, a motor, and an igniter. During the two-second firing, the simulator added one million pounds of weight to simulate the rest of the solid rocket booster and applied stress from three struts to duplicate the loads from the external tank. This recreated the dynamic loads on the joint during ignition and allowed engineers to gather information from 1,500 data channels. Morton-Thiokol operated a similar apparatus called a Joint Environment Simulator. Motor engineers conducted 16 simulator tests under different temperatures and with intentionally flawed configurations. The introduction of deliberate flaws was also a departure from the original test program.[85]

The recovery also had five full-scale, full-duration static firings, including two development motor tests and two qualification motor tests. Because of problems simulating flight conditions in static tests of solid motors, the National Research Council initially questioned whether the firings verified the design. After the second firing, John Young, JSC special assistant for Engineering, Operations, and Safety complained that “the motors were fired with dubious conditions which MSFC maintained would not have been allowed in the flight motors. This attitude, which accepts uncertain conditions, cannot be tolerated if we wish to be successful in space flight with humans.” He argued that allowing phenomena that were “not fully understood and where we are not convinced beyond any doubt that the seal in its application will stop the flow, we could be back in the STS 51–L mode.” Gerald Smith, SRB project manager, recalled that Marshall tried to duplicate flight situations by testing with intentional flaws. Introducing deliberate flaws was also controversial, however, because many worried that a failure would delay the program. They developed confidence in their designs by first testing with flaws in simulators. After such tests the Center used a production verification motor to test the flight configuration in August 1988. Royce Mitchell, SRM project manager, said “the hardware and data show that the booster is ready to fly. We demonstrated that the motor is fail-safe.”[86]

Indeed the tests made Marshall very confident in the redesign. Gerald Smith said that “the testing we’ve conducted has been unprecedented and our understanding of the system is thorough. We’ve established the testing standard for the entire solid rocket industry. NASA’s solid rocket booster program, I feel, is the yardstick against which future programs will be measured.” As early as January 1987, J.R. Thompson told Congress that the tests showed “that the insulation does not leak hot gas even if not bonded, and that gapping is so small that any candidate O-ring material, even the old fluorocarbon material, can remain sealed with a 200 percent factor even with two of the three O-rings missing."[87] To ensure proper assembly of the first redesigned flight motor, Thompson dispatched a Marshall team headed by John Thomas to Kennedy Space Center to direct the process.[88]

Firing room celebration after launch of STS–26.

During the test program, NASA reformed its launch rules and procedures. Crippen, a former astronaut and the first NASA deputy director for Shuttle operations, wanted to eliminate ambiguities in launch criteria and "make sure we had clean lines of responsibility and authority." The Agency reviewed all Launch Commit Criteria and established a clear one for temperature. J.R. Thompson suggested that ambient temperature should not fall below 40 degrees at any time during the 24 hours prior to launch; "the specific temperature," he said, "is not magic, but near the spirit." The Level I Flight Readiness Review now required discussion of launch constraints and waivers. A Launch-Minus-Two-Day Review formally verified any changes after the Level I review. For the first time project managers from the contractors joined the Mission Management Team and had authority to stop the countdown without permission of a field Center. A Space Shuttle Management Council, composed of the associate administrator for space flight and the directors of Johnson, Kennedy, Marshall, and the National Space Technology Laboratories, became senior launch advisors. In early summer 1988 a launch simulation checked the new system. In addition, safety and budget concerns led NASA to constrict the Shuttle's flight schedule, which would escalate over several years to a maximum of 16 Shuttle flights per year, 8 fewer than pre-*Challenger* goals.[89]

On 29 September 1988, 32 months and $2.4 billion after 51–L, the recovery came to a close with the final countdown for STS–26. During that conclusive interval, "the biggest change," according to Lovingood, "was people were frightened, including me" and he was too afraid to watch the launch. Most members of the redesign team, however, were confident and were eager for the flight. Employees in Huntsville locked their eyes on the television and some dressed in "green for Go!" Dr. Wayne Littles, head of Marshall's Science and Engineering, watched the launch from the Huntsville Operations Support Center and said, "for the first two minutes [of ascent] you could hear a pin drop."

At the Cape when the solid rocket boosters ignited and *Discovery* lifted off the pad, even staid project managers shouted "Go!" and released months of tension. Cary Rutland, manager for booster assembly, said "I hollered when it lifted off, and I hollered when the solids separated" from the Shuttle. Gerald Smith gushed "this was probably the most exciting day of my life. It was unbelievable. When the solids ignited, I was probably holding my breath. When they separated, I think I yelled 'War Eagle.' I'm not sure." The launch was flawless and in the post-launch press conference, J.R. Thompson said "one good launch doesn't make a space program, but it's a damn good start." He then pulled out a foot-long Jamaican cigar and said, "I'm going to get me a cigar, light my pipe, and get a little glass of bourbon."


Pallet-Mounted Instrument Pointing System, first used on Spacelab 2.

In the flush of success, some engineers became philosophical. Garry Lyles, chief of liquid propulsion at Marshall, observed that the Center would probably not get much credit for the successful launch even though they received most of the blame when *Challenger* failed. "We do a lot of patting each other on the back," he said, "We have a very professional organization. Whether anyone outside pats us on the back, it really doesn't matter."[90] Thompson derived lessons from 51–L and the recovery, believing that space exploration required that everything be "perfect" and without that, "we're gonna end up back on the beach."[91] Because of the improvements in technology and Center culture, Marshall people believed they and the Shuttle were stronger than before the accident. The successes of the post-*Challenger* Shuttle flights gave supporting evidence for their assessment.[92]

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