Chapter IX

The *Challenger* Accident

On the morning of 28 January 1986, the Space Shuttle *Challenger*, mission 51–L, rose into the cold blue sky over the Cape.[1] To exuberant spectators and breathless flight controllers, the launch appeared normal. Within 73 seconds after liftoff, however, the external tank ruptured, its liquid fuel exploded, and *Challenger* broke apart. Stunned spectators saw the explosion and the trails from the spiral flights of the solid rocket boosters, but the vapor cloud obscured how the orbiter shattered into large pieces. The crew cabin remained intact, trailing wires and plummeting to the Atlantic; the six astronauts and one school teacher aboard perished.[2]

Over the next three months, a presidential commission led by former Secretary of State William P. Rogers and a NASA team investigated the accident. Television images of the flight revealed an anomalous flame from a joint between segments of the right-hand solid rocket motor. Photographs showed puffs of black smoke escaping from the joint during the first moments of ignition. Wreckage of the motor recovered from the Atlantic floor demonstrated the failure of the joint and proved that propulsion gases had melted surrounding metals and caused the explosion of the external tank. Propulsion engineers from Morton-Thiokol Incorporated, the Utah company responsible for the solid rocket motors, testified that for years they had been discussing problems with the joints and their O-ring seals, especially in cold weather. The night before the launch they had warned Marshall officials that the anticipated cold weather could freeze the rubber O-rings and trigger disaster, but company executives and Marshall project managers had rejected calls for a launch delay.

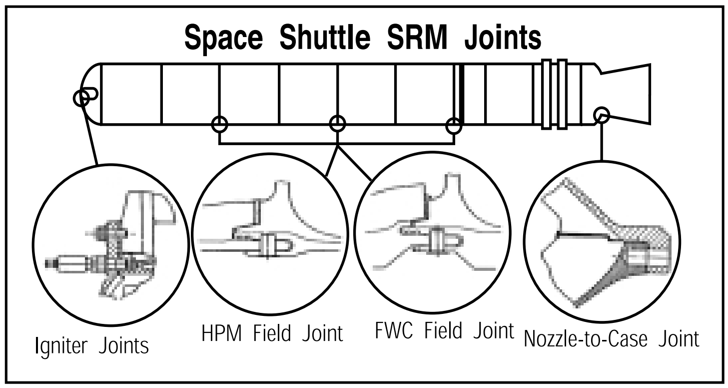
The Rogers Commission concluded that managers at Marshall and Thiokol had known (or should have known) that the case joints were hazardous. They had failed to inform senior officials in the Shuttle program or to act promptly to reduce risks, and thus had failed to prevent a predictable accident. The commission decided that since Marshall officials had prior knowledge of the hazard, the accident primarily resulted from ineffective communications and management at the Center.[3]

The commission's interpretation has dominated discourse about *Challenger*. Journalists and academics have relied on the commission's evidence, and have mainly added analysis to confirm its "bad communication" thesis. "Instant histories" often treated the scenarios in the Rogers Report as quasi-crimes, with journalist-authors reporting dirty deeds in the Shuttle program and telling scabrous stories about NASA officials with "the wrong stuff."[4] Academic studies tried to show why the Rogers scenario occurred, explaining how communications problems could have emerged from the interdependence of Marshall and Thiokol, the lapses in statistical analysis by propulsion engineers, the groupthink of the preflight reviews and last minute teleconference, and authoritarian management patterns at Marshall.[5] Two scholars have also discussed why the interpretation of the presidential commission seemed persuasive to the media and the public while the point of view of Marshall officials did not.[6]

Unfortunately, the commission's interpretation oversimplified complex events. The oversimplifications emerged mainly because the commission and later pundits dismissed the testimony of Marshall engineers and managers and distorted information about hazards in written sources from the Shuttle program prior to the accident. Allowing Marshall engineers and managers to tell their story, based on pre-accident documents and on post-accident testimony and interviews, leads to a more realistic account of the events leading up to the accident than that found in the previous studies. The story of the Marshall engineers and managers was that they had carefully studied the problems of the motor case joints and had concluded that the joints were not hazardous, that they had taken steps to improve the joints, and that they had communicated their conclusions and actions to superior Shuttle officials. Because they believed the joints were not hazardous, they did not predict the accident and could not have prevented it.

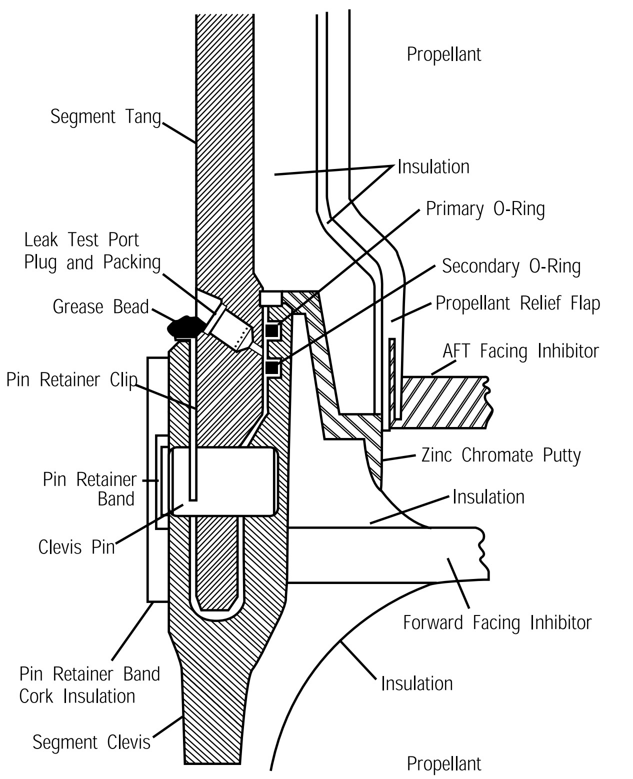
Design and Development

From the beginning of the design and development phase of the Solid Rocket Motor (SRM) project in 1973, Marshall had trouble with Morton-Thiokol and the joints.[7] Several Center engineers worried that the joint and seal designs were deficient and Center managers fretted about the contractor's quality systems. But after improvements, reviews, and many successful tests, senior project managers and engineers decided that the design was successful and the joints were safe to fly.



Space Shuttle solid rocket motor joints.

Because Thiokol would ship the motor by rail between its Utah production site and the Florida launch site the solid rocket motor case was divided into several segments (as shown in illustration of Shuttle SRM joints). This meant that the design required joints and seals to prevent leaks of the high-temperature, high-pressure propulsion gases. Thiokol's engineers used the Titan III–C rocket, considered state of the art for solid motors and very reliable, as their model. The Shuttle motor, however, differed from the Titan because the SRM was larger and intended for refurbishment and reuse. The differences in design showed in the field joints connecting the motor case segments.[8] The Titan had insulation along the interior wall of the steel case to prevent hot gases from penetrating the joint and damaging its rubber seals (see the SRM field cross section and the comparison illustration if Titan III and SRM joints); the SRM used an asbestos-filled putty. The segments had upper and lower parts; Thiokol engineers expected that motor pressure would push together the "tang" (the tongue on the rim of the upper segment) and the inner flange of "clevis" (the groove on the rim of the lower segment) and facilitate sealing. Motor pressure would also push the primary O-ring, a quarter-inch diameter rubber gasket, against the steel case and seal the joint. Thiokol sought redundancy by placing a second O-ring behind the primary O-ring.

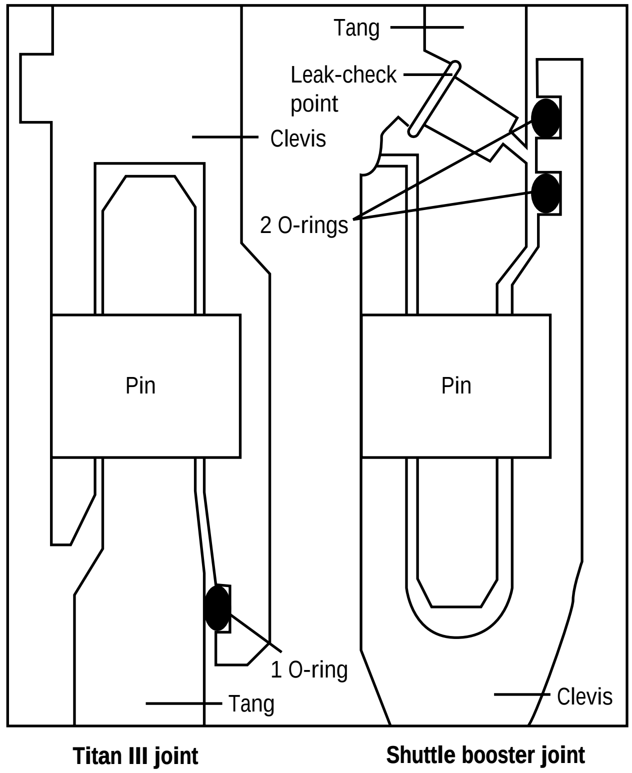


Solid Rocket Motor cross section shows positions of tang, clevis, and O-rings. Putty lines the joint on the side toward the propellant.

Cross section of SRM field joint.

The second O-ring forced another departure from the Titan, requiring that the SRM have a longer tang and a deeper clevis. The longer joint of the SRM was more flexible than the Titan, since the combustion pressure in the SRM was one-third higher than the Titan and its case had a greater diameter. Moreover, the SRM clevis pointed up, rather than down like that of the Titan. Finally, to test the seals after connecting the segments,Thiokol engineers added a leak-check port so that compressed air could be forced into the gap between the O-rings and verify whether the primary O-ring would seal. The leak-check, however, pushed the primary O-ring to the wrong side of its groove.[9]

Thiokol and Marshall evaluated the SRM and its case joints in structural, pressure, and static firing tests beginning in 1976. Because tests of the large solid rocket were more expensive than liquid engines, engineers ran fewer tests.[10] From the beginning of the test program, they showed confidence in their design, perhaps stemming from the success of Titan. They scheduled static firings of the entire motor before completion of subsystem tests such as pressure tests of the joint and case. The first static firing of DM–1 (Development Motor 1) confirmed that the hardware met design requirements, including the integrity

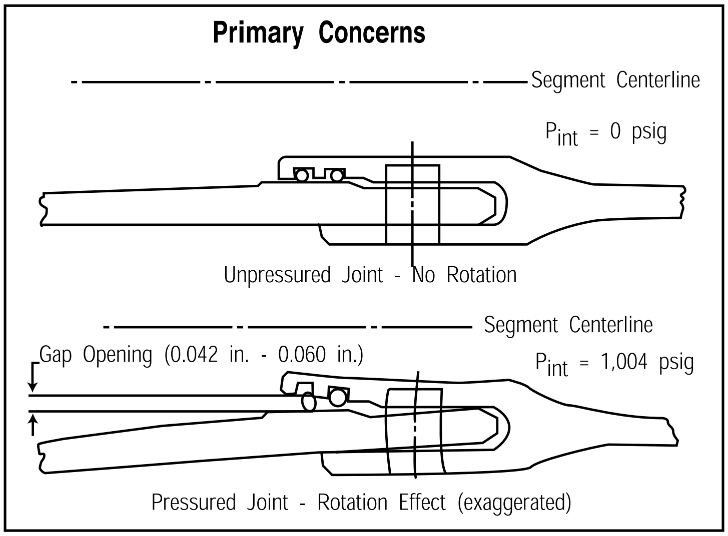


Comparison of Titan III and SRM joints.

of the steel case and the thrust of its motor. Marshall's Weekly Notes reported on DM–1 that "all case joints were intact and showed no evidence of pressure leaking" and that "all test objectives were met."[11]

In a September 1977 hydroburst test, however, the field joints and O-rings performed contrary to expectations. Engineers simulated a launch by filling a motor with fluid under 50 percent more pressure than during ignition. Thiokol had expected pressure to force the tang and the inner flange of the clevis to bend toward each other and squeeze the O-rings tighter. The company's final report of the test concluded that "the burst test was a complete success and met all the design requirements. Failure occurred in the joint seals. The leakage was caused by the clevis spreading and not providing the required O-ring squeeze." The engineers were perplexed and reported that the joint opened more than they predicted.[12]

In Weekly Notes, Marshall's SRM project engineers said the burst test revealed "excessive O-ring leakage." Both the primary and secondary O-rings leaked, and disassembly revealed each had pinches and cuts. "The most logical explanation," the MSFC motor engineer observed, "is joint rotation which allowed both O-rings to lose compression."[13]



Joint rotation of SRM field joint.

Joint rotation meant that under pressure the tang and the inner flange of the clevis bent apart and the joint opened (as shown in the joint rotation of the SRM field joint). Rotation occurred because the motor joint was thicker and stiffer than the case walls on either side; as the flexible case wall expanded outward, it spread the tang and clevis and opened the joint. The joint opening during the hydroburst test unseated the O-rings and created a gap too large to seal.[14]

Thiokol denied that the tests revealed design flaws. The test subjected the same hardware with the same O-rings to 20 cycles of pressure and release; only in the final cycles did the rings leak. Consequently, Thiokol engineers believed that with each cycle, the O-ring was pushed into the gap, then released, then pushed in farther, and so on until the rubber condensed, cut, and failed. Rather then interpreting the tests as indications of bad design, Thiokol engineers argued that the joint had withstood many cycles without failure and so test results showed the soundness of the joint. They believed that potential leaks on flight motors could be avoided through careful assembly of the joints and by inserting dozens of shims, which were U-shaped clips, between the outer clevis and the tang. The shims would maintain the centricity of the case and the compression of the O-rings; this would prevent any "gathering" or bunching of the O-ring that could cause a leak.[15]

Some engineers in Marshall's laboratories disagreed with the contractor and believed the joint design was flawed. In September 1977, Glenn Eudy, the Center's chief engineer for the SRM, expressed his doubts to Alex McCool, director of the Structures and Propulsion Lab, and argued that refined assembly methods alone could not fix the problem. “I personally believe,” Eudy wrote, “that our first choice should be to correct the design in a way that eliminates the possibility of O-ring clearance.” He requested that the director of Science and Engineering review the problem. In October, Center engineer Leon Ray argued that shims allowed for error during assembly and hence were “unacceptable.” He advised that the “best option for a long-term fix” was a “redesign of the tang” to prevent joint opening.[16]

By January 1978 Ray and his boss, John Q. Miller, chief of the Structure and Propulsion Lab’s solid rocket motor branch, believed that the joint issue required the “most urgent attention” in order to “prevent hot gas leaks and resulting catastrophic failure.” Alarmed that Thiokol was trying to lower requirements for the joint, they saw “no valid reason for not designing to accepted standards.” Miller and Ray recommended “redesign of clevis joints on all oncoming hardware at the earliest possible effectivity to preclude unacceptable, high risk, O-ring compression values.”[17]

Not only did Thiokol reject the analysis of the Marshall rocket engineers, but so did Center managers. Marshall management accepted the existing design, complemented by shims, mainly because of the continued successes of static motor firings. In the Weekly Notes following the firing of DM–2 in January 1978, McCool wrote that “all major test objectives were met” and “no leaks were observed in the case during the firing and post-test examination revealed no discolorations nor other evidence of leakage.” Robert Lindstrom, Shuttle Projects Office manager at Marshall, wrote that preliminary analysis of DM–2 indicated “no problems which require immediate attention of NASA.”[18]

A Thiokol report on the October firing of DM–3 said “all case joints were intact and showed no evidence of pressure leaking.” The report acknowledged that “the relative movement of the sealing surfaces is much more than indicated,” but this evidence of joint rotation was not presented as anything ominous.[19] In November, Thiokol’s SRB (Solid Rocket Booster) project manager wrote George B. Hardy, Marshall’s project manager, that the static firings “confirmed the capability of the O-rings to prevent leakage under the worst hardware conditions.”[20]

Results from Structural Test Article–1 (STA–1), however, were less optimistic. Hydroburst tests through the summer of 1978 on STA–1 again revealed the dangers of joint rotation. Thiokol's report concluded that "the relative movement between the clevis and the tang at the interior of the case joints was greater than expected. This resulted in some oil (pressurizing fluid) bypassing the O-ring seals at the case joints." The engineers decided that the O-rings unseated as the joint opened. Nevertheless, company engineers dismissed the leaks, arguing that test pressure was higher than flight pressure and "the amount of oil loss on any one occasion or totally was very small and motor case pressurization was never lost or affected by this phenomenon." As on the tests from the previous year, they concluded that the repressurization cycles had caused the failures rather than a faulty design. They acknowledged that imprecise calibration devices prevented accurate measures of the joint opening, but denied that the joint opened so wide as to be unsafe.[21]

STA–1 data led Miller and Ray to call Thiokol's design "completely unacceptable." In January 1979 they wrote another memo to Eudy and Hardy, explaining that joint rotation prevented the design from meeting contractual requirements. The contract specified that seals operate through compression, but the opening of the joint caused the primary O-ring to seal through extrusion. As a sealing mechanism, extrusion used ignition pressure to push the O-ring across the groove of the inner flange of the clevis until it distorted and filled the gap between clevis and tang. This, they said, "violates industry and Government O-ring application practices." In addition, Miller and Ray for the first time questioned whether the secondary O-ring provided redundancy. Although the contract required verification of all seals, tests had proven the secondary O-ring design to have been "unsatisfactory" because the opening of the joint "completely disengaged" the O-ring from its sealing surface.[22]

In February 1979 Ray sought advice from two seal manufacturers. One manufacturer said that the design required the O-ring to seal a gap larger than that covered by their experience. The Parker Seal Company, the contractor for the SRB O-rings, reacted the same way and "expressed surprise that the seal had performed so well." Ray reported that Parker engineers believed that "the O-ring was being asked to perform beyond its intended design and that a different type of seal should be considered."[23] However, Ray and Miller failed to convince Thiokol and Marshall to change their commitment to the existing design. The contractor reported that the static test of DM–4 on 19 February had "no indication of joint leakage" and the case showed "no evidence of structural problems." Thiokol's summary of the development motor firings concluded that after each test "all case joints were intact and showed no evidence of pressure leaking" and measurements revealed "no stresses that indicate design problems or that compromise the structural integrity of the case."[24] In 1979 and 1980 three qualification motors fired successfully and had no leaks.[25]

When in 1980 the Shuttle program underwent its final qualification for flight, the Center and contractor presented their data and conclusions to NASA's Space Shuttle Verification/Certification Propulsion Committee on the motor. During briefings from May to September and in its report, the committee fretted over O-ring leaks, assembly problems, and joint rotation. Members were concerned that the leaks "could grow in magnitude and could impinge on the ET [External Tank] during flight." Moreover the Propulsion Committee pointed out that testing on new assembly configurations "does not appear to exist and sensitivity data on O-ring damage is lacking." For the design to function, assembly procedures had to be perfect; although the O-ring leak check put the secondary O-ring in position to seal, it pushed the primary O-ring in the wrong direction (as evidenced in the illustration comparison of Titan III and SRM joints). Accordingly the panel recommended "an up-to-date rigorous and complete verification package covering safety factor on sealing at ignition," including purposely testing to failure and static firings at temperatures from 40 to 90 degrees F.

NASA did not conduct such a test program before the first Shuttle flight. The booster office at Marshall, the Level II Shuttle Program Office at Johnson Space Center (JSC), and the Level I associate administrator for Space Flight at NASA Headquarters all believed that previous tests showed the primary O-ring was an effective seal and that the secondary O-ring provided redundancy. Marshall and Thiokol offered reassurances that readings about joint rotation were misleading because of faulty measuring devices and that corrections were underway using shims and bigger O-rings. NASA believed that careful assembly procedures would ensure safety and that ongoing tests on a new lightweight motor case fulfilled the Propulsion Committee's intent.[26]

The committee accepted this response, and the flight certification phase of Shuttle development closed when the Agency assigned a "criticality" designation to the field joints and O-ring seals. A criticality rating in the Shuttle critical items list categorized the reliability of important hardware; the designation affected the attention the item received in flight preparations and reviews. Thiokol's November 1980 report for the critical items list, which NASA approved, designated the joint as criticality 1R, meaning that the component had "redundant hardware, total element failure of which would cause loss of life or vehicle." The report justified the redundancy rating by the design's similarity to the successful Titan III–C joints and the solid rocket motor's successes in structural and burst tests and seven static motor firings.

Nonetheless, the criticality report contained a contradiction. It admitted that the "redundancy of the secondary field joint seal cannot be verified after motor case pressure reaches approximately 40 percent of maximum expected operating pressure." At that point, joint rotation created a gap too large for the secondary to seal. The report added that it was "not known if the secondary O-ring would successfully re-seal if the primary O-ring should fail after motor case pressure reaches or exceeds 40 percent of maximum expected operating pressure." In other words, the report classified the seals as redundant despite incomplete data.[27]

Throughout the design and development period of the solid rocket motors, Marshall had sufficient oversight of its contractor to discern technical and managerial problems. For this reason, the presidential commission concluded not only that the joint design was flawed, but that "neither Thiokol nor NASA responded adequately to internal warnings about the faulty seal design," and that neither made "a timely attempt to develop and verify a new seal after the initial design was shown to be deficient." In addition, NASA's internal investigation teams for Development and Production and for Data and Design Analysis, which included many Marshall personnel, faulted the test program. Testing was not realistic; dynamic loads of launch and flight conditions were not adequately simulated; the putty configuration during static firings differed from the launch configuration because after assembly of the test motors, engineers crawled through the bore of the propellant and packed in extra putty to fill voids; tests did not evaluate performance under temperature extremes; subsystem tests did not yield realistic information about putty performance, joint rotation, and O-ring compression and resiliency.[28]

Even so, the 1986 accident investigations tended to read history backwards and to ignore the positive information about the joint. Looking back after *Challenger*, Marshall managers believed that they had studied, tested, reviewed, and verified the joint design. Lindstrom, Marshall's Shuttle Projects manager, Hardy, the SRB project manager, Bill Rice, the SRM project manager, Eudy, the SRM chief engineer, and McCool, the director of the Structures and Propulsion Lab, explained that they had no data showing serious problems. The positive data from all the static firings far outweighed negative data from parts of the pressure tests. Because of positive test data, McCool said, "no one really took it with seriousness, and I say all of us collectively, as serious as we should have." James Kingsbury, the head of Marshall's Science and Engineering Directorate, believed that before 51–L NASA had not fully understood the design. Lack of information "posed a real problem for us safety-wise—obviously one we did not fully resolve. There were some things about the Motor that had never been done before. It was a very big motor. It was being reused. And so there were some complications."[29]

Similarly, Hardy thought that the tests of the solid motors compared unfavorably to the Saturn system of testing. For the Saturn rockets, the Center had conducted many tests and had tested components and subsystems before hardware reached a final design. The solid rocket motor tests, in contrast, had been too few and too mild to return realistic and complete information. To save money in the short-term, Marshall had moved away from testing of subsystems and toward testing of whole systems. Restricting tests to late stages of development, Hardy said, had locked NASA into one joint design and boosted costs in the long-term.[30]

Marshall's engineers in the SRM Branch of the Structures and Propulsion Lab had a different recollection of the design and test phase. Looking back after the accident, they vouched for the openness of communication channels. Believing he had opportunity to present his criticisms, Ray told investigators for the presidential commission that Marshall differed from the military and allowed dissenters to bypass the chain of command and disagree with superiors. "Communication is very good," he said. "I feel at ease in picking up the phone and talking to anybody. It doesn't make any difference who it is. And I have—many times."[31] They had kept arguing that the joints had failed to meet contract requirements and that Thiokol had underestimated the width of the joint opening.

Although the engineers stopped short of recommending that the solid rocket motors not be flown, they recommended during the design and evaluation phase that new hardware built for later Shuttle missions incorporate a redesigned joint. They were unable to convince senior managers and engineers however. Miller, chief of the SRM Branch, recalled that "when you present something, a concern to someone, and nothing is perhaps immediately done, you don't—in the position I was in, you don't push the point and try to back them in a corner." Consequently the engineers pushed for tight requirements in the assembly of the joints. Ben Powers, a propulsion engineer, recollected that "after we had been turned down over and over, I think we just accepted the fact that as the hardware kept being manufactured, you know, that there was not going to be a change in the joint design. So we, I think, accepted that fact that we were not successful in getting that change that we recommended and had to do the best we could with the joint that we had."

When evaluating the cases for and against the design, the engineers concluded, Center officials showed more trust in the contractor than in laboratory personnel. Center management recognized that Thiokol's engineers had greater expertise in solid rockets than the Center's liquid propulsion specialists and so depended on the contractor's interpretation of the data.[32] Center Director William Lucas recalled that "We did not consider ourselves expert in what Thiokol was doing. In fact we were not, so we relied heavily on Thiokol to bring the expertise of solid rocket propulsion to the program. We were not able to assess the details of what they were doing."[33]

Flight Review and Response

Beginning with early flights, the solid rocket motor experienced recurrent problems with its joint and O-ring seals. Thiokol and Marshall regarded the problems as aggravating but acceptable anomalies; successful flights and ground tests gave the engineers confidence that the joints were not hazardous. They recommended that flights continue, improved motor assembly configurations, and initiated redesign studies in the summer of 1985. After *Challenger*, Marshall's response seemed too little, too late, and the presidential commission faulted NASA's management structure and flight readiness review process, and criticized the Center's judgment and communications.

The primary system of communication and decision-making during the flight phase of the Shuttle program was the flight readiness review. In formal inquiries, contractor and government officials discussed the preparedness of hardware, paperwork, and personnel for the upcoming flight. They also discussed problems and anomalies encountered in the previous flight, solutions that had been implemented or planned, and rationales that confirmed safety and reliability. Marshall reviews proceeded up from the Level IV at the prime contractor, to Level III at the project office, to the Shuttle Projects Office (which Center personnel called "Level 2-and-A-Half"), to the Center director, to the Level II pre-flight readiness review at JSC, and finally to the Level I flight readiness review at Headquarters held two weeks before launch. Officials from all space flight Centers attended the Level I review.

Decisions coming out of the reviews were only as sound as the information going in. Flight would proceed only after the reviews had certified each element safe and reliable. The success of the process depended on an upward flow of information and a downward flow of probing questions. Presentations were most detailed at the low levels, but with each step up the ladder, time constraints due to reports from additional project organizations normally led to increasingly general discussions.

At the Level I review, NASA rules required that project managers discuss problems with criticality 1 hardware that could cause loss of mission or life. In practice, however, the amount of detail varied. Project managers gave meticulous presentations of new problems or problems considered as major. For problems considered minor or routine, project managers often gave brief comments; they frequently proceeded like a pilot reading through items in a preflight check-off sheet and listed such problems as "closed out," meaning verified safe.[34]

Rocket engineers first noted field joint O-ring problems in November 1981 on STS–2, the second Shuttle flight. When they took the recovered motor apart and examined the O-rings, they found one scorched primary O-ring. They interpreted this as a failure of the zinc chromate putty to protect the ring from combustion gases. This impingement erosion of a sealed O-ring, the deepest found on a primary ring in a field joint before 51–L, had resulted from a hole the diameter of a pencil in the putty. Marshall's project office reasoned that the void came during "lay-up" of the putty; high humidity and temperature during joint assembly had made the putty "tacky" and caused gaps. They expected that refrigerating the putty before assembly would eliminate the problem. Marshall notified NASA Headquarters of the flight anomaly but did not report the condition in the Level I flight readiness review before the next mission or in the Center's problem assessment system.[35]

In early 1982 Marshall and Thiokol concerns about the seals led to new studies of putty lay-up and the joints of the new lightweight steel motor case. Tests, especially high-pressure tests of the O-rings, convinced Marshall management that Ray and Miller had been right; joint rotation could prevent the secondary O-ring from sealing. Consequently Marshall reclassified the joint from criticality 1R to criticality 1, meaning no redundancy, and received approval for the change from the Shuttle Level II Office at Houston and Level I at Headquarters. The new critical items report explained that leakage beyond the primary O-ring was "a single point failure due to possibility of loss of sealing at the secondary O-ring because of joint rotation." Failure could result in "loss of mission, vehicle and crew due to metal erosion, burn-through, and probable case burst resulting in fire and deflagration."

Despite reclassification to criticality 1, the criticality report argued for the reliability of the design. Virtually all Marshall and Thiokol engineers believed that the joint was safe and redundant most of the time. The report explained that the joints had no leaks in eight static firings and five flights, the primary O-ring alone provided an effective seal, and the joint was similar to the safe Titan III which had one O-ring. In addition, some tests showed that the secondary O-ring would seal and so the joint often had redundancy. Accordingly some documents continued to designate the seals as Criticality 1R five weeks after the *Challenger* accident. This mislabeling, the presidential commission charged, confused decision-makers and made it "impossible" for them to make informed judgments.[36]

In fact, Marshall and Thiokol engineers were convinced that the joint still had redundant seals. Given the criticality 1 designation, such claims confused the presidential commission. In commission interviews and testimony, the Center's institutional managers, project managers, and chief engineers explained their understanding of joint dynamics during ignition. They expected that combustion gases would almost always seat the primary O-ring. In the rare event that the primary O-ring would not seal, gas would almost instantly flow to the secondary O-ring and seal it; later the joint rotation would widen the gap but the secondary O-ring would flatten enough to seal.[37]

According to Marshall, the joint lacked redundancy only under exceptional circumstances and these necessitated the documentary change. Dr. Judson Lovingood, deputy chief of the Shuttle Projects Office, said assembly errors could be "such that you get a bad stackup, you don't have proper squeeze, etc. on the O-ring so that when you get joint rotation, you will lift the metal surfaces off the [secondary] O-ring." Lawrence Mulloy, project manager for the solid rocket booster after November 1982, described another "worst case" scenario. If the primary O-ring sealed and then failed after joint rotation, he said, the joint could have "a worst case condition wherein the secondary seal would not be in a position to energize." Such a circumstance, Mulloy believed, was very unlikely. Hardy, Mulloy's predecessor as SRB project manager and later deputy directory of Science and Engineering at Marshall, agreed, saying "the occasion for blow-by on the secondary O-ring, in my opinion, would be extremely nil or maybe not even possible."[38] Similarly, propulsion engineers and managers at Thiokol considered the joint to have redundant seals, and the company's paperwork continued to categorize the joint as criticality 1R even after the *Challenger* accident in January 1986.[39]

Other NASA managers accepted the judgment of Marshall and Thiokol even after the criticality change. Glynn Lunney, former manager of the Level II Shuttle Program at JSC, believed "there was redundancy." L. Michael Weeks, the Level I associate administrator for Space Flight (Technical) at Headquarters said that "we felt at the time—all of the people in the program I think—felt that this Solid Rocket Booster was probably one of the least worrisome things we had in the program." Only a few engineers in the Center's Solid Rocket Motors Branch believed that joint rotation could jeopardize the secondary seal.[40]

Even so Marshall and Thiokol began working on a long-term fix on a new lightweight plastic SRB case. To increase the Shuttle's lifting capacity for military payloads, NASA decided to develop a filament-wound case with graphite fiber-epoxy matrix composite casewalls and steel joints. The joints would incorporate a "capture feature," a steel lip on the tang that would fit over the inner flange of the clevis and eliminate joint rotation (fig. 1). Hercules Incorporated proposed the design for the capture feature, which became one of the primary reasons why NASA in May 1982 chose the company to develop the filament wound case as a subcontractor to Morton-Thiokol. Marshall's Ray remembered "there was a lot of opposition" to the capture feature from engineers who "didn't understand" joint rotation, especially from those at Morton-Thiokol. NASA's choice of Hercules not only meant less business for Thiokol, but also indicted the firm's design of the steel case joints. According to Ray, Marshall's engineers debated whether to add the capture feature to the steel motors, but decided to wait for test results from the filament wound case. The first full-scale static firing of the new design occurred in October 1984.[41]

Meanwhile NASA confidently proceeded with Shuttle launches, and successes seemingly justified belief in the technology. After the fourth flight in June 1982, the Agency declared the Shuttle system "operational," meaning that the spacecraft and propulsion system had passed their flight tests. In seven static firings and nine launches, O-ring problems occurred on only four joints.[42]

In early 1983, however, NASA made changes in the solid rocket motor that would exacerbate O-ring problems. The Fuller O'Brien Company, which had manufactured the original asbestos-filled putty, ceased making the product and NASA substituted a putty made by the Randolph Products Company. The Randolph putty, used first on STS–8 in the summer of 1983, proved to be more difficult to pack in the joint during assembly and less able to provide thermal protection during launch.[43]

In addition the Center and its contractor believed that success depended on careful assembly and they sought to improve procedures, including the O-ring leak check. To ensure that the O-rings could hold a seal, the leak check compressed nitrogen in the cavity between the rings much like inflating a tire. The rocket engineers had initially used pressure of 50 pounds per square inch (psi). Since the Randolph putty alone could withstand this low pressure and hide a faulty O-ring, they raised the pressure to 100 psi on STS–9 in November 1983. Still the Randolph putty hampered the tests and produced leak check failures. After a failed check, assembly crews had to destack the solid rocket motors, and reassemble the joint. To minimize this expensive procedure and to verify the O-rings, the engineers decided to raise the leak check pressure to 200 psi for case-to-case joints on STS 41–B in January 1984 and to 200 psi for all joints on STS 51–D (the 16th flight) in April 1985.[44]

Unfortunately the high pressure necessary for a leak check also blew gaps in the putty. These voids, normally about one inch wide, would direct jets of combustion gas to sections of the primary O-ring and produce erosion. Thiokol and Marshall engineers found the gaps after disassembling recovered motors. Nonetheless the joint design created a conundrum; the engineers wanted high-pressure tests to verify O-ring assembly, but verification of the O-rings could create dangerous gaps in the putty, which could jeopardize the O-rings.[45]

Greater leak check pressure led to increased incidence of O-ring anomalies. Before the January 1984 increase in the pressure for case-to-case joints, post-flight inspection had found only one anomaly for nine flights. After the increase, over half the missions had blow-by or erosion on field case joints. The changes were even more dramatic for the nozzle joint. At 50 psi, 12 percent of the flights had anomalies; at 100 psi the rate rose to 56; and at 200 psi anomalies occurred on 88 percent of the flights. Unfortunately the engineers did not fully analyze this pattern, and no one performed an elementary statistical analysis correlating leak check pressure and joint anomalies.[46]

Worries over the O-rings mounted in February 1984 after 41–B, the 10th mission, when primary O-rings eroded in two case-to-case joints and one case-to-nozzle joint. The erosion on one case-to-case joint O-ring was 0.050 inch of the 0.250-inch diameter. Thiokol and Marshall recorded the incidents and conducted studies. On 29 February 1984, Keith Coates, an engineer in the Center's SRB Engineering Office, fretted that Thiokol was overconfident and so had very weak plans to resolve the problem. On 28 February, John Miller of the Center's SRM branch observed that environmental conditions during assembly and leak check were creating voids in the putty. Finding a solution was an "urgent matter," he said, because the putty was a thermal barrier which prevented "burning both O-rings and subsequent catastrophic failure."[47]

Although acknowledging problems on 41–B, Center engineers recommended that flights proceed. In Weekly Notes on 12 March, McCool wrote that in spite of the large number of occurrences, no hot gas had leaked past the damaged O-ring seal.[48] The Center Flight Readiness Review Board for the next mission, STS–13 (41–C), decided to fly based on the following rationale:

"Conservative analysis indicates that the maximum erosion possible on STS–13 is 0.090 inch. Laboratory testing shows the O-ring to maintain joint sealing capability at 3000 psi with a simulated erosion of 0.095 inch. The Board accepted a recommendation to fly STS–13 as is, accepting the possibility of some O-ring erosion."[49]

In other words, Marshall created a new performance criteria, diluting its original standard of no erosion to a new one of "acceptable erosion" with a numerical margin. In a presidential commission interview, SRB manager Mulloy explained "there was a very clear recognition that this was something that we couldn't be proud of. It was working but it wasn't performing to the standards that we set for ourselves." Ironically erosion created false confidence, since erosion meant that the joints were sealing even with weaknesses. It was "an O-ring erosion problem not a joint leak problem," Mulloy explained. "It was not a perceived problem of this design won't work," he said. "It was this design won't work unless we do these things" to improve putty lay-up and O-ring installation. Mulloy remembered that "nobody ever" recommended that flights cease until O-ring erosion could be eliminated.[50]

In March 1984 Marshall and Thiokol presented their rationale for accepting erosion to a Level I flight readiness review at NASA Headquarters. Hans Mark, NASA deputy administrator, and General James Abrahamson, associate administrator for Space Flight, attended the review and agreed with the rationale. In April, however, Mark issued an "Action Item" for May that required Marshall to perform "a formal review of the Solid Rocket Motor case-to-case and case-to-nozzle joint sealing procedures to ensure satisfactory consistent close-outs." This followed Abrahamson's January 1984 request for a Marshall plan to improve the design and manufacture of the solid rocket motors. The Center's project office passed these directives to its contractor.[51]

In May 1984 Thiokol issued a preliminary proposal for improvements and the next month Marshall assured NASA Headquarters that the Center would carefully monitor the situation. But for more than a year, until August 1985, NASA allowed the contractor to proceed without a plan to eliminate erosion. Headquarters dropped pressure after Mark and Abrahamson left the Agency later that spring. Other NASA Headquarters administrators followed the guidance of Marshall and Thiokol and accepted the anomalies. As Mulloy later explained, "we never perceived that we had to make a radical design change."[52] In other words, the engineering consensus that the joints were safe slowed the responses of Marshall and Thiokol.

The consensus came not only from the success of flights with O-ring anomalies, but also from successful ground tests conducted at Thiokol beginning in the spring of 1984. The company's engineers created a subscale model of an SRM joint, and fired a five-inch solid rocket in three-second burns into a chamber housing a section of O-ring. The model tested various putty and O-ring materials and configurations, and demonstrated O-ring erosion. Although the engineers debated how realistic the subscale tests were, they concluded that erosion primarily occurred because of voids in the putty. In fact, they found that in tests without putty, there was no O-ring damage. Consequently the tests led to continued efforts to improve assembly procedures and to study various putty materials and new puttyless configurations. More importantly, the engineers believed that subscale tests confirmed the safety of the existing design, showing that combustion gas would not melt an O-ring enough to produce a leak.[53]

By fall 1984, Marshall's reports in flight readiness reviews had become routine. A "quick look" bulletin on Mission 41–D dismissed heat distress as "typical of O-ring erosion seen on previous flights." When Lucas asked Mulloy about the problem during the Center flight readiness review for Mission 41–G, the project manager reviewed the problem, concluded that it was "an acceptable situation," and explained that a search for an alternative putty was underway. At the Shuttle Projects Office review for 41–G Mulloy said the "maximum erosion possible" was "less than erosion allowable."[54]

Concerns arose again in late January 1985 after Mission 51–C. The launch was the Shuttle's coldest and O-ring temperature was 53 degrees F. Two primary O-rings in case-to-case field joints had erosion, and primary rings in two field and both nozzle joints had soot blow-by. A form of erosion appeared that differed from previous impingement erosion of a sealed O-ring; blow-by erosion resulted from combustion gases burning an unsealed O-ring and flowing beyond it. Not surprisingly a secondary O-ring in a field joint experienced heat damage for the first time.[55]

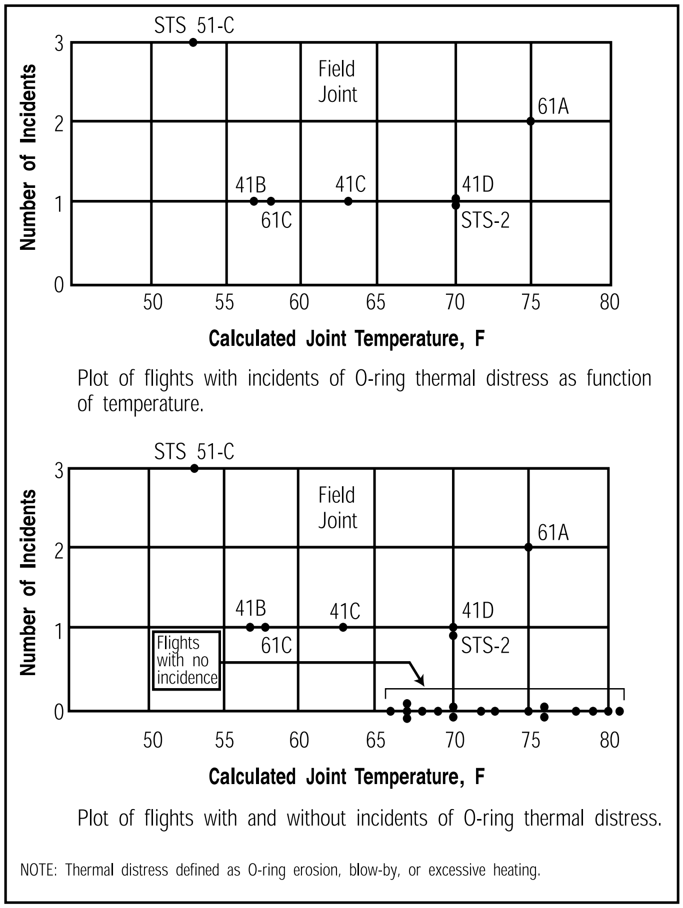
The incidents startled Marshall, and Mulloy sent Thiokol a "certified urgent" request for an erosion briefing at the next flight readiness review.[56] At the 8 February 1985 SRB Board, Thiokol engineers discussed in detail the new types of O-ring damage and for the first time described the effects of temperature on the resiliency of the O-rings. For the joint to seal, the rubber rings had to be resilient because the primary O-ring had to travel rapidly across its groove and both rings had to flatten quickly to fill the opening gap. Low temperature, the contractor observed, made the putty "stiffer and less tacky" and made the O-ring smaller and harder. Thus cold could slow the sealing process and produce an "enhanced probability" of erosion.

Thiokol's engineers admitted that similar events could happen again, but concluded that the joints were "acceptable for flight." Cold was not a concern because Mission 51–C had experienced very rare weather, the "worst case temperature change in Florida history." Even so erosion remained "within the experience data base" and the margin of safety. Consequently the contractor did not request a new launch commit criterion based on temperature for the O-rings. Finally, the engineers decided that damage to the secondary O-ring, rather than revealing flaws in the primary, proved the joint had a redundant seal.[57]

Because Marshall's project office and Thiokol had faith in the seals, they downplayed bad news about 51–C as they went up the levels of flight readiness review. At the Center Shuttle Projects Office Board, the presentation barely mentioned temperature effects and listed as "closed" all motor problems requiring action before the next launch. The meeting's Final Report identified "no SRB failures and anomalies." At the Center board, one sentence covered the 51–C joint incidents. Mulloy's presentation to the Headquarters Level I board ignored temperature issues and briefly explained that thermal distress beyond the primary O-ring was an "acceptable risk because of limited exposure and redundancy." With this positive information, Level I administrators approved Marshall's recommendation to keep flying.[58]

Since the *Challenger* disaster occurred in cold weather, the 51–C reviews in retrospect seemed a lost opportunity to examine temperature effects on O-ring dynamics. But in the SRB review, Marshall had disputed the theory of Thiokol engineers that cold increased the possibility of O-ring failure. Mulloy, recalled Roger Boisjoly, an O-ring expert at Thiokol, had "objected to some of our original statements in our charts that temperature had an effect on the joints." Robert Crippen, an astronaut attending the Level I meeting, said Marshall presented the 51–C "as an anomaly" but failed to explain that the joint was a single point failure; "it wasn't considered that much of a big deal, and it wasn't like we had a major catastrophe awaiting in front of us." Mulloy later told the presidential commission, "I can't get a correlation between O-ring erosion, blow-by [around] an O-ring, and temperature" because anomalies had occurred at warm as well as cold temperatures.[59]

Neither the contractor nor the Center conducted a statistical analysis of existing data. In 1987 Bob Marshall, the manager of MSFC's Shuttle Project Office, regretted that 51–C had not moved motor experts to reinterpret the available data. After 51–C, he said, "we should have been thinking more. . . . The analyses of the tests we were doing just wasn't enough. We weren't finite enough in what we were doing." No one performed a statistical analysis correlating past O-ring performance with either temperature or leak check pressure.[60] Lacking such analysis, both Thiokol and Marshall had been correct about 51–C; the contractor engineers had rightly surmised that low temperature increased the probability of erosion, and Center managers had rightly questioned Thiokol's demonstration of the correlation.



Plots of incidence of O-ring distress as function of temperature.

At the 51–D review Marshall Director Lucas confidently observed that "we are maturing. There are fewer action items than last time, and we are getting better hardware." Even so the four flights after 51–C had O-ring problems with the most extreme occurring on the April 51–B mission. When Thiokol disassembled the segments in late June, the engineers found that the left nozzle joint's primary O-ring had not sealed and had eroded severely and its secondary O-ring had eroded as well. The 51–B findings were doubly troubling because motor engineers had always expected the primary to seal and had never experienced erosion of a secondary.[61]

With their predictions disproven by 51–B, Marshall engineers in July 1985 imposed a formal launch constraint on the motor nozzle joint for all subsequent missions including 51–L. According to NASA requirements, a formal constraint prevented flight until a technological problem was fixed or verified safe. Flights continued, however, because SRB project manager Mulloy filed formal waivers lifting the constraint for each of the six flights through 51–L. NASA required review and approval of each waiver by organizations responsible for project management, engineering, and quality. After the *Challenger* accident, however, several NASA and Thiokol officials claimed ignorance of the formal constraints and waivers. The claims by Thiokol managers are difficult to explain given that the company's records listed Marshall's document number for the launch constraint. Apparently Marshall failed to report the constraint and waivers to Level II Shuttle managers in Houston.[62]

The presidential commission condemned this failure to communicate bad news but found that NASA lacked clear guidelines for reporting problems. In 1983, the Level II Shuttle Office had changed reporting requirements from Level III in order to streamline communications for the Shuttle's "operational" phase. Marshall no longer had to report problems on hardware elements for which it had sole responsibility. Level II only required reports which dealt with interface hardware for which Marshall shared responsibility with Houston. Consequently Marshall only sent one copy of its monthly Open Problems Report to a Level II flight control engineer and a statistical summary to Rockwell, the Shuttle integration contractor. Criticality 1 items, however, were supposed to be reported to Level II.[63]

Moreover, a NASA 51–L investigation team determined that after several Shuttle flights, the Level I flight readiness reviews adopted a built-in bias that limited the flow of information. Since the Shuttle had proven flight worthy and was designated "operational," and the experts in lower levels had already certified flight readiness, the Level I review became increasingly ritualistic. Reviews were often short and key officials failed to attend.[64]

Nonetheless, the commission severely criticized Marshall's reports and response to the clear evidence of technological flaws from 51–B. At the Level I review on 2 July, Marshall did not mention the launch constraint, accepted erosion to the secondary, and presented 51–B O-ring problems as "closed," meaning acceptable for flight. The Center, the commission charged, had lowered standards, neglected to report problems, and failed to implement actions necessary to ensure safety.[65]

The Center's motor officials denied these charges and defended their judgment. Mulloy admitted his failure to inform Level II managers directly of the formal launch constraint, but pointed out that Marshall and Thiokol continued to discuss the joint problems in flight readiness reviews. Motor officials also made a thorough presentation to Headquarters in August.[66] Mulloy explained that he had lifted the launch constraint because motor engineers had again reviewed the problems and found the situation acceptable.[67]

Particularly encouraging were results from a computer model that Thiokol created to evaluate the risks of O-ring erosion. The model, called ORING, used data from flights, static firings, and subscale tests. It predicted that chances were "improbable" that hot gases would burn through a sealed primary O-ring or that hot gases blowing past a primary would melt through the secondary O-ring. The model had limitations as an analysis of the potential danger; it defined the hazard based on evidence from previous missions and tests, none of which had resulted in catastrophic failure, and hence drew the obvious conclusion that there was no proof of a hazard. Nevertheless Thiokol's ORING, first presented to Marshall in April 1985 and updated to include the nozzle joints in July, helped bolster confidence among NASA and contractor officials.[68]

Moreover, engineers working on the solid rocket motor concluded that the 51–B problems had resulted from a faulty leak check procedure. They believed that leak check pressure on 51–B had been too low; putty in the joint had withstood 100 psi and thereby had masked a faulty primary O-ring. The engineers decided that increasing the pressure to 200 psi would prevent recurrence of the problem. The Thiokol report also took solace from how the primary O-ring erosion had been "within historical levels" and the damage on the secondary had been "within the demonstrated sealing capability of eroded O-rings." The company concluded that "this anomaly is not considered a launch constraint." As Mulloy told the commission in 1986, the motor experts had reviewed and responded to the situation and "it was not just a matter of nothing was done."[69]

Two years later, however, during a retrospective interview, Mulloy questioned the engineering evaluation of 51–B. "I truly believe that if there was a fatal error made . . . among a lot of people in engineering judgment, it was accepting that kind of condition where you've completely destroyed a primary O-ring and accepted damage to the second and concluded that that was an acceptable thing to fly with." He added that "there's something drastically wrong when something that you think isn't supposed to get any damage at all sustains that kind of damage, and you conclude it's okay."[70]

After the *Challenger* accident, space flight veterans also doubted NASA's decision to keep flying. In 1991, Chris Kraft, former director of JSC, said that "The creed of manned spaceflight is you never fly with a known problem. Never. Get that word never. So . . . when the main ring is burned and the back-up ring is scorched in a joint and you don't stop the goddamn thing right there and fix it, regardless of whether it be a band-aid fix or any other kind of fix, you have made a cardinal sin. You many times fly with unknown unknowns, but you do not fly with known unknowns."[71]

Concerns about erosion on 51–B led the Center to seek a permanent solution. In July Marshall asked Thiokol to go beyond improving assembly procedures and begin studying new hardware designs. The contractor established an O-ring Task Force whose goal, according to Mulloy's Weekly Notes, was finding "a longer term, a design solution to the O-ring erosion" and to joint rotation. By the end of August the task force had proposed 63 possible joint modifications, including 43 for the field joints. The proposals included a capture feature lip similar to the filament wound case. Indeed in July Marshall ordered from the Ladish Company 72 steel case segments with the capture feature.[72]

Meanwhile Thiokol continued to verify the safety of the existing design. In early June 1985 the contractor performed bench tests to evaluate the effects of temperature and joint rotation on the performance of the secondary O-rings. Thiokol reported to Marshall on 9 August that "at 100 degrees F the O-ring maintained contact [with the metal sealing surface]. At 75 degrees F the O-ring lost contact for 2.4 seconds. At 50 degrees F the O-ring did not re-establish contact in ten minutes at which time the test was terminated." The tests also indicated that joint rotation made the secondary O-ring more likely to fail late in the ignition phase. The company report reassured Marshall, however, that it had "no reason to suspect that the primary seal would ever fail."[73]

NASA Headquarters knew about Marshall's O-ring worries. The Propulsion Division at Headquarters had held monthly reviews on the motor joints since

51–C in March 1984. In July 1985 a Headquarters' engineer visited Huntsville for a briefing on 51–B and reported that Marshall was concerned about the putty and joint rotation. The Center was working on solutions, but he recommended a briefing to Level I. Moreover Headquarters budget officials, using information from the Propulsion Division, had discussed how motor problems and solutions could impact the Agency's FY 1987 budget.[74]

In a briefing at NASA Headquarters on 19 August 1985 Marshall and Thiokol finally responded to the April 1984 action item and presented their engineering evaluation and redesign plan. The experts observed that only 5 of 111 primary O-rings in field joints and 12 of 47 primary O-rings in nozzle joints eroded. O-ring erosion resulted from blow-holes in the putty, increased frequency of voids, and heat damage resulted from defective putty, higher leak check pressure, and greater engine pressure. Nonetheless, Thiokol argued that data from static firings, Shuttle flights, subscale tests, and the ORING computer model verified the safety of the design. Erosion could be no worse than 51–B; even "worst-on-worst case predicted erosion" was "within [the] demonstrated sealing capacity of [an] eroded O-ring."

The review rated the field joint as the "highest concern" and described the criticality change from 1R to 1. Erosion could damage the primary seal and joint rotation could cause the secondary O-ring to fail. The experts believed that "the primary O-ring in the field joint should not erode through but if it leaks due to erosion or lack of sealing the secondary seal may not seal the motor." They warned that "the lack of a good secondary seal in the field joint is most critical and ways to reduce joint rotation should be incorporated as soon as possible to reduce criticality." Nozzle joints were of less concern because of the greater rigidity of the case and because 51–B proved that its secondary O-rings would seal even if eroded.

The motor engineers and managers also presented plans for improving the joints. Marshall and Thiokol planned to introduce short-term changes for the field joint; they would qualify an alternate putty source, use thicker shims to ensure O-ring compression, and replace the 0.280-inch-thick O-rings with thicker 0.292-inch rings that would provide an extra safety margin, add insulation strips in the joint to prevent hot gas circulation, and insert a third O-ring. NASA would introduce long-term changes in 27 months, including the capture feature already proven on the filament wound case; this would reduce joint rotation and ensure redundancy. The review concluded that leak checks and careful assembly made it "safe to continue flying [the] existing design." Nevertheless NASA's reconfiguration and redesign efforts needed "to continue at an accelerated pace to eliminate SRM seal erosion."[75]

Marshall's presentations to Agency officials during July and August would become controversial after the *Challenger* accident. Several top Agency officials said Marshall had not brought problems to the surface and Center managers said they had. Both were right. Marshall had failed to discuss O-ring resiliency at the August briefing, and evidently told Thiokol to delete from the conclusion a sentence that said "data obtained on resiliency of the O-rings indicate that lower temperatures aggravate this [sealing] problem." Center managers continued to deny that temperature was a factor because erosion had occurred at cool and warm temperatures. Moreover Mulloy pointed out that in the reviews "the effect of temperature never came across [from Thiokol to Marshall] as the overwhelming and most important concern on that joint." Temperature excepted, the August presentation was thorough and the presidential commission concluded that "the O-ring erosion history presented to Level I at NASA Headquarters in August 1985 was sufficiently detailed to require corrective action prior to the next flight."[76]

As the work of Thiokol's O-ring task force proceeded in the summer and fall, members became frustrated by a lack of support from corporate management. Thiokol O-ring expert Boisjoly explained to engineering management in July that joint rotation could yield a "catastrophe of the highest order—loss of human life." He protested that the problem required "immediate action" but that support was "essentially nonexistent at this time." The task force had only 5 full-time engineers out of the 2,500 employed at Thiokol. On 1 October Robert Ebeling, manager of the group, signaled "HELP! The seal task force is constantly being delayed by every possible means" and "this is a red flag." He thought "MSFC is correct in stating that we do not know how to run a development program." On the same day another project engineer complained that the group was "hog-tied by paperwork every time we try to accomplish anything" and requested "authority to bypass some of the paperwork jungle." A few days later Boisjoly wrote that Morton-Thiokol's "business as usual attitude" prevented progress and that "even NASA perceives that the team is being blocked in its engineering efforts." He believed that "the basic problem boils down to the fact that ALL MTI [Morton-Thiokol Inc.] problems have # 1 priority and that upper management apparently feels that the SRM program is ours for sure and the customer be damned."[77] These bureaucratic obstacles slowed purchase of equipment and manufacture of test hardware, and thus delayed tests.[78] As an example of inertia at Thiokol, Boisjoly noted in his log on 13 January 1986 that O-ring resiliency tests requested in September 1985 were now scheduled for January 1986.[79]

Throughout the fall, Marshall motor engineers maintained close contact with their Thiokol counterparts. They had teleconferences every week and face-to-face reviews every few weeks, and the Center regularly sent experts to Utah to monitor the contractor's work. Although these contacts mainly discussed technical problems, Marshall technical personnel were aware of the organizational and financial obstacles faced by the O-ring task force and of the delays in procurement and testing. Officials from Marshall's Solid Rocket Motor Branch and SRB Chief Engineer's Office offered to help the task force get more authority and resources.[80]

In late August, after years of argument between Marshall and Thiokol about whether joint performance was within design specifications, the Center convinced the company to accept a "referee test"; Marshall hoped that an independent expert would settle the controversy and pave the way for a redesign. In early September, Kingsbury wrote to Mulloy that the task force efforts "do not appear to carry the priority that I attach to this situation. I consider the O-ring problem on the SRM to require priority attention of both Morton-Thiokol/Wasatch and MSFC." The Center's project office tried to speed problem-solving by allowing Thiokol to make the first public description of the joint problems to the Society of Automotive Engineers on 7 October.[81] Even so, Marshall's efforts did little to accelerate the progress of Thiokol's O-ring task force.

A primary reason for the slow progress was Thiokol's incentive-award fee contract. After 51–L, congressional investigators found that the contract offered the corporation no incentives to spend money to fix problems believed unlikely to cause mission failure.[82] Based on this information, a sociologist concluded that, "The incentive fee, rewarding cost savings and timely delivery, could total as much as 14 percent of the value of the contract; the award fee, rewarding the contractor's safety record, could total a maximum of 1 percent. No provisions existed for performance penalties or flight anomaly penalties. Absent a major mission failure, which entailed a large penalty after the fact, the fee system reinforced speed and economy rather than caution."

Not only did Thiokol have disincentives to fix problems that would cause flight delays, but Marshall had little means to sanction the firm's pace. In fact NASA imposed no penalties on Thiokol for the anomalies and at the time of 51–L the Agency was contemplating awarding the company a near maximum incentive fee of 75 million dollars.[83]

After the accident, Thiokol task force members explained how the contract, corporate policy, and government regulations created obstacles. Because preparations for upcoming missions had higher priority than redesign activity, work on flight hardware came before work on test hardware. The company paid the costs of the redesign activities without additional money from Marshall. To get the extra money necessary to speed progress for the O-ring task force, Thiokol would have had to submit an engineering change request and thus acknowledge the failure of its design. Consequently, the task force had responsibility without authority or resources.[84]

Looking back on the fall of 1985, Marshall motor officials maintained that they had no information that indicated urgency. Jim Smith believed Thiokol was "working the problem in a timely manner." He and other Marshall officials claimed that no Thiokol engineer had communicated serious concerns about safety or bureaucratic obstacles. No Marshall official saw the memos drafted by O-ring task force members that expressed alarms about the delays to Thiokol management. Smith said that if the task force had informed him of the need for flight delays or for extra resources, he would have presented and defended their position to Marshall management.

Lawrence Wear, manager of the SRM, said the consensus was that the problem was "troublesome" and "contrary to design." But at the time "there was no discussion and no revelation on anybody's part that what we're doing here is flying something that is in an absolutely unsafe condition and you ought to stand down until you get it fixed." Leslie F. "Frank" Adams, deputy SRB manager, said the communications from Thiokol were "not in the context of a safety of flight kind of concern." Stanley Reinartz, manager of the Shuttle Projects Office, believed the contractor's position after August 1985 was that the motor was "completely safe and reliable for launching while these concerns about O-rings were being worked on in a parallel fashion."[85]

Marshall's confidence in the joints was evident in many ways. In comparison to the Saturn POGO problem or Space Shuttle main engine development, the Center devoted minimal attention and resources to the SRM joints. Jerry Peoples observed in a presidential commission interview that the Marshall Center task force was organized at a "low level." When briefed on the O-rings, he said, Marshall project and institutional managers would "politely listen to our presentation, but seemed to give no response or heed no warning as to what we were saying and seemed to . . . be in certain times bored with what we were saying."[86]

Moreover Marshall and Thiokol continued Shuttle flights while delaying by several months the static firing of Qualification Motor–5 which would test the filament wound case and the capture feature. In the Weekly Notes, Mulloy said delay was needed to prepare for modifications that could "alleviate the joint O-ring erosion experienced." Eventually Marshall scheduled the firing for 13 February 1986. The Center informed Level I officials at Headquarters of the progress in a November briefing.[87]

Marshall and Thiokol's confidence in the joint also showed in flight readiness reviews in the fall and winter. Thiokol continued to verify that the case joints were not hazardous. In the Level I review in late September on mission 51–I Marshall dismissed two cases of O-ring nozzle erosion as being "within experience base." Mission 51–J had no damage and the Shuttle Project review on 15 October said its O-ring performance was "nominal." Mission 61–A had nozzle erosion and blow-by past the primary O-ring on two field joints which Mulloy described to Level I on 18 November as "within previously accepted experience." Flight 61–B had primary O-ring erosion of both nozzle joints and blow-by past one, but he informed Headquarters on 11 December there had been "No 61–B Flight Anomalies." Similarly mission 61–C had nozzle joint erosion and blow-by and field joint erosion; nevertheless at the Level I review on 15 January 1986, the meeting which certified *Challenger* 51–L for flight, Mulloy's presentation listed "No 61–C Flight Anomalies" and "No Major Problems or Issues."[88]

The presidential commission concluded that by late 1985 Marshall's flight readiness reviews only discussed problems that were "outside the database" and dismissed O-ring problems as routine and hence insignificant.[89] Mulloy later admitted that "since the risk of O-ring erosion was accepted and indeed expected, it was no longer considered an anomaly to be resolved before the next flight."[90]

Acceptance of the anomalies helped lead to formal "closure" of the O-ring problems in Marshall's Problem Assessment System. In this system, engineers with an open problem would write monthly reports and conduct flight-by-flight reviews until they implemented a correction. Then they would report their solution to a review board and the board would "close out" the problem and no longer require reports or reviews in the system.

Although Morton-Thiokol was working on the problems and Marshall still had a launch constraint on the nozzle joint, Kingsbury, Marshall director of Science and Engineering, requested that the firm reduce its open items, including O-ring items. Hence on 12 December 1985 Thiokol's project manager requested that monthly problem reports on the O-rings be discontinued because a task force was working on a correction and regular reports were proceeding through group's reports and flight readiness reviews. Consequently on 23 January 1986 a Marshall problem report stated that the problem was "closed" because Thiokol had filed a plan to improve the seals.[91] A close-out of an open problem perplexed the presidential commission. To commissioner Robert W. Rummel the closure signified that "somebody doesn't want to be bothered with flight-by-flight reviews, but you're going to continue to work on it after it's closed out." MSFC's SRB project managers said the closure was "in error" and that they had not approved it.[92]

At the same time as the closure, Morton-Thiokol's contract was coming up for renewal, and NASA asked aerospace contractors for preliminary proposals for a second source for the solid rocket motors. This was not done out of specific dissatisfaction with Morton-Thiokol's performance, and indeed Marshall believed the firm was improving. Mulloy noted in October 1985 that the average number of problems per flight set was decreasing. Instead the initiative resulted from lobbying by Thiokol's competitors for a piece of NASA's solid rocket market and from desires by Congress to ensure a steady supply of motors for the Shuttle's military payloads.[93]

NASA's bidding rules for the second source threatened Morton-Thiokol. The rules, announced on 26 December 1985, assumed the motor joints were operational and so the government would not give "qualification funds" for rocket redesign to the competitors. Consequently each firm would have to invest as much as $100 million in production facilities, test equipment, and prototypes without any guarantee of a contract. However, since NASA required no redesign, the Agency could encourage competition by publishing Thiokol's blueprints and asking competitors for lower bids. NASA was also stimulating competition by proposing a "split buy" rather than a "shoot out." Thus even if Morton-Thiokol would retain considerable motor business, the firm would face competition. NASA's initiative, which the presidential commission overlooked, threatened Morton-Thiokol's monopoly and so corporate managers had incentive to please their customer during negotiations in January 1986.[94]

Meanwhile, Thiokol's task force continued work. After the accident, Robert Ebeling, manager of the SRM task force, told the commission that he had discussed with team members the possibility that "we shouldn't ship any more motors until we got it fixed." Regardless of these discussions, formal presentations by the task force to Thiokol management and Marshall officials in mid-January described its activities and long-term schedules without any expression that the existing joint was too hazardous to fly.[95]

The central theme in the history of O-ring erosion before 51–L was that officials at Marshall and Morton-Thiokol had confidence that the joints were not hazardous. Based on static firings, flight data, and laboratory tests, they concluded that the primary O-rings provided effective seals, that thermal damage was limited and acceptable, and that the secondary O-ring normally offered redundancy. "Neither Thiokol nor the Marshall Level III project managers," concluded the presidential commission, "believed that the O-ring blow-by and erosion risk was critical" and both thought that "there was ample margin to fly with O-ring erosion."[96]

Confidence in the joint affected communications. Because their overall evaluation of the joints was positive, officials sometimes failed to communicate contradictory information. Marshall, the presidential commission observed, minimized problems in flight readiness reviews and failed to report the launch constraint and waivers, the controversy about temperature and O-ring resiliency, and the O-ring anomalies of later flights.[97] This silence, however, evolved from confidence that the joint was not hazardous rather than from some conspiracy to cover up problems.

Unfortunately the certitude rested on weak engineering analysis. Presidential commission member Richard P. Feynman, a physicist and Nobel prize winner, drove this point home after the fact. He observed that although the Center and its contractor used tests, analyses, and computer models, the standards of project officials showed "gradually decreasing strictness." They assumed, Feynmen said, that risk was decreasing after several successful missions and so they lowered their standards. The standard became the success of the previous flight rather than the danger of erosion and blow-by. Thus a successful flight with erosion was proof of the reliability of the O-rings and justification for another launch, rather than a warning of a potential catastrophe and a sign to stop and fix the problem.[98]

Once decision-makers at Marshall and Thiokol accepted the problems, they failed to facilitate deeper analysis. Project engineers failed their managers, neglecting to perform even elementary statistical analysis of the relationships between O-ring anomalies and such factors as temperature and leak check pressure.[99] Had they done so, they may have understood the risk better than they did, and that flying the Shuttle was, in Feynman's words, like playing Russian roulette.[100]

The Teleconference and Launch

On the evening of 27 January 1986 before the scheduled launch of 51–L the next morning, Center and contractor project managers and engineers held an impromptu flight readiness review over the telephone. Thiokol engineers argued that cold temperatures, projected to be the coldest recorded in Florida, would aggravate the O-ring problem. Neither Thiokol nor Marshall managers accepted their arguments that the cold was hazardous, and the managers decided to launch 51–L.

Earlier in the day, high crosswinds at the Kennedy Space Center (KSC) forced NASA to postpone Flight 51–L for the fourth time. Launch managers, tired from lots of work and little sleep, rescheduled launch for the next morning. Even so the weather forecast predicted an overnight low of 18 degrees F, and early in the afternoon Marshall asked Morton-Thiokol to consider the possible effects of cold. At the plant in Wasatch, Utah, Thiokol's SRM engineers decided that the temperatures were far below previous experience and could make the O-rings too stiff and hard to seal the joints. While the engineers prepared a presentation, their managers arranged a teleconference with Marshall personnel. The teleconference, which connected Wasatch, Huntsville, and Cape Kennedy, began at 5:45 P.M. Eastern time. Because of hissing phone lines and missing officials, however, participants decided to postpone. In the interim, Marshall's Stanley Reinartz, the Shuttle Projects manager, informed Center Director Lucas of the impending discussions.[101]

After Thiokol had faxed hand-written charts, the teleconference began at 8:45 P.M. Eastern time. Thiokol participants included motor engineers and project managers and the vice presidents for engineering and space motor programs. Also attending in Utah were the senior vice president for Wasatch operations and the vice president and general manager for space programs; no Marshall official in Alabama or Florida knew of their presence or their participation in the engineering discussions. The senior participant in Huntsville was George Hardy, the deputy director for Science and Engineering, who had support from several project officials and laboratory engineers. Reinartz and SRB project manager Mulloy participated from KSC. As usual for a Level III review, no Houston or Headquarters officials were present.[102]

The Thiokol engineers wanted to show that cold temperature could stop the O-rings from sealing. They observed that cold temperature would thicken the grease surrounding rings, and stiffen and harden the O-rings; these factors would slow the movement of the primary O-ring across its groove and reduce the probability of a reliable seal. Sealing with a cold O-ring, the contractor reasoned, "would be likened to trying to shove a brick into a crack versus a sponge." If hot gases blew past the primary O-ring after the joint had opened, the probability of the secondary O-ring sealing would decrease.[103]

The engineers also presented a history of erosion in field case joints. They pointed out that the previous coldest launch, 51–C in January 1985, had occurred at 53 degrees, and that the predicted launch-time temperature of 29 degrees was far outside Shuttle experience. Moreover 51–C had eroded O-rings and its blow-by deposits of charred grease and O-ring rubber had been jet black, which was an ominous sign that the primary O-ring had nearly failed. Some of Thiokol's evidence, however, appeared contradictory. It showed that four static motors fired between 47 degrees and 52 degrees had no blow-by and that the October 1985 flight of 61–A had blow-by at 75 degrees. The Thiokol engineers dismissed this contrary evidence, rationalizing that the vertical static-fired motors had had a putty packing method unavailable for the horizontal 51–L motors, and that the blow-by deposits of the 61–A flight were less dark and more innocuous than 51–C. In conclusion, Thiokol argued that NASA should stay within the experience of 51–C. Air temperature should be at least 53 degrees at launch time (see page 359, plots of incidence of O-ring distress as a function of temperature).[104]

Marshall officials immediately questioned Thiokol's ideas. Hardy said that he was "appalled" by the contractor's reasoning. Reinartz observed that the recommendation violated the Shuttle requirement that the motor operate between 40 and 90 degrees. Mulloy noted that NASA had no launch commit criteria for the joint's temperature and that the eve of a launch was a bad time to invent a new one. He asked, "My God, Thiokol, when do you want me to launch, next April?"[105]

Marshall's institutional and project managers doubted that cold increased risk over previous flights. Test data showed, they believed, that the O-rings would have to be colder than the expected temperature before resiliency and reliability declined significantly. Moreover, motor pressure was so great and increased so rapidly that combustion would almost instantly force even a cold primary O-ring into place. Even if the primary was too cold to seal, gas would blow past quickly, before the joint opened, and seal the secondary. "We were counting," Mulloy said later, "on the secondary O-ring to be the sealing O-ring under the worst case conditions."[106]

Most importantly, however, the Center's managers saw no causal connection between temperature and O-ring damage and believed that 61–A proved their case. During the teleconference Mulloy, the project manager, and Hardy, the senior Marshall engineer, criticized Thiokol's proofs. Hardy told the presidential commission that the temperature data were not conclusive because blow-by had occurred at 75 degrees. He added that "I do not believe that temperature in and of itself induces the blow-by, and I think that is kind of obvious because we have occasions for blow-by at all temperatures."[107] Thiokol admitted that that they lacked a statistical analysis to verify the relationship. O-ring expert Boisjoly remembered, "I was asked to quantify my concerns, and I said I couldn't, I couldn't quantify it, I had no data to quantify it, but I did say I knew that it was away from goodness in the current data base."[108]

Despite Thiokol's failure to demonstrate the causal connection, it existed and was easily quantifiable. Thiokol's charts did not juxtapose temperature and O-ring damage in elementary two variable plots. If done, this would have shown that in the 24 flights before 51–L, 20 missions had temperatures of 66 degrees or above and of these only 3 had problems in field joint O-rings. In contrast, all four flights with temperatures below 63 degrees had problems in field joint O-rings. Moreover the predicted temperature at launch time was 29 degrees, 3.6 standard deviations below the average launch temperature of 68.4 degrees. With this information, the engineers would have known that the launch would be far outside Shuttle experience and very risky.[109]

Given the history of success and the confidence in the joint, Thiokol's engineers needed hard, quantitative information and not to believe what they had been believing so long in order to persuade top corporate and NASA officials to postpone. Boisjoly later observed that Marshall engineers, following the lead of Center Director Lucas, would only make decisions based on a "complete, fully documented, verifiable set of data."[110] Unfortunately Thiokol's data were inconclusive. After the accident, NASA investigators concluded that "the developed engineering knowledge base, and the interpretation of available engineering data, were inadequate to support the STS 51–L launch decision process." The presidential commission believed that "a careful analysis of the flight history of O-ring performance would have revealed the correlation of O-ring damage and low temperature. Neither NASA nor Thiokol carried out such an analysis; consequently they were unprepared to properly evaluate the risks of launching the 51–L mission in conditions more extreme than they had encountered before."[111]

During the teleconference Thiokol and Marshall were distracted by comparison of dissimilar data. They equally weighted static tests and Shuttle flights although each had different forms of putty packing. They pooled erosion data for the two case-to-case and case-to-nozzle joints, thereby confusing different causal systems, since case joints were sensitive to temperature, but not to leak check pressure, and nozzle joints were sensitive to leak check pressure but not to temperature. Without distinguishing between fundamental sources of O-ring damage, Thiokol's rationale seemed insubstantial. Ultimately the teleconference focused on only two data points, 51–C and 61–A, and the contradictory evidence caused debate to dwindle after more than an hour.[112]

As participants sought a conclusion, Allan McDonald, Thiokol's SRM project director, observed from the Cape that the leak check shoved the primary O-ring on the wrong side of its groove and put the secondary in a position to seal. Although he later said he had intended to show dangers for the primary, most participants, including Thiokol management, understood that he believed the secondary would provide redundancy. Hardy then remarked that the data did not prove the O-rings were hazardous, but said he would not overrule his contractor's recommendation to hold the launch. After Reinartz requested a response, Joe Kilminster, Thiokol's vice president for booster programs, took Utah off the line for a five-minute caucus to reassess.[113]

The Utah caucus lasted for 30 minutes and initially two engineers from the O-ring task force repeated their warnings. When they realized that Thiokol's upper management was not listening, the engineers stopped talking and the others stayed silent. Kilminster and Robert K. Lund, vice president for engineering, hesitated to overrule the engineers. Jerald E. Mason, vice president for Wasatch operations then told Lund, "Take off your engineering hat and put on your management hat." Mason later explained that "we didn't have enough data to quantify the effect of the cold" and so "it became a matter of judgment rather than a matter of data." Lund agreed that no correlation existed between temperature and risk and the four Thiokol vice presidents in Utah recognized that they could not prove that 51–L was more dangerous than previous launches.[114]

When the teleconference resumed at 11:00 P.M., Kilminster said that the data were inconclusive and therefore the company recommended that the launch proceed. The rationale was the same as previous launches: despite the problems of joint rotation and cold temperature, the primary O-ring could withstand three times the erosion of 51–C and the secondary O-ring provided redundancy. Level III manager Reinartz asked for dissenting comments, and, hearing none, ended the teleconference.[115]

At the time, two Marshall participants believed the teleconference was unusual. In Huntsville, William Riehl, a materials engineer, wrote in his notes that "Mulloy is now NASA-wide deadman for SRB/SRM" and "did you ever expect to see MSFC want to fly when MTI-Wasatch didn't?" At the Cape, Cecil Houston, Marshall's resident manager, told Jack Buchanan, his Thiokol counterpart, that "he was surprised because MSFC was usually more conservative than the contractor and in this instance, the roles were reversed."[116]

In testimony to the presidential commission, Thiokol officials complained that Marshall had pressured them to launch and had reversed the normal roles of contractor and government during a flight readiness review. McDonald said that normally "the contractor always had to get up and prove that his hardware was ready to fly. In this case, we had to prove it wasn't, and that is a big difference. I felt that was pressure." Boisjoly affirmed that "this was a meeting where the determination was to launch, and it was up to us to prove beyond a shadow of a doubt that it was not safe to do so. This is in total reverse to what the position is in a preflight conversation." Lund said he and the other Thiokol managers changed their recommendation because "we had to prove to them that we weren't ready, and so we got ourselves in the thought process that we were trying to find some way to prove to them it wouldn't work, and we were unable to do that. We couldn't prove absolutely that that motor wouldn't work."[117]

The presidential investigators largely accepted Thiokol's explanation. Commissioner David C. Acheson, an attorney, argued the company should have backed its engineers and ordered NASA to launch only under specific conditions. But the commission's final report stated that "Thiokol management reversed its position and recommended the launch of 51–L, at the urging of Marshall and contrary to the views of its engineers in order to accommodate a major customer."[118]

Throughout the hearings, the Marshall managers tried to refute these charges. Reinartz thought Marshall had conducted the teleconference "in a thorough and professional manner and in the NASA tradition of full and open participation." The discussions, he said, were "deliberate and intense" but "not highly heated or emotional." Marshall managers denied that their questions and challenges constituted "pressure." They needed hard data to overturn a rationale that had been in place since the second Shuttle launch and to request a delay from Level I and Level II. After discussion, both the contractor and the Center concluded, Mulloy said, "there was no significant difference in risk from previous launches. We'd be taking essentially the same risk on January 28 that we have been ever since we first saw O-ring erosion." Marshall's top managers and engineers challenged Thiokol's arguments, but never asked the firm to retract its original recommendation, and Hardy had stated that he would not launch without the contractor's concurrence.[119]

Mulloy believed that Marshall had maintained the traditional government-contractor roles in flight reviews and had never asked the firm to prove the O-ring would fail. But even if the Center had done so, the goal remained flight safety. Both NASA and Thiokol had wanted safety; the firm had an incentive fee contract that rewarded them for success and penalized them for a launch failure. If anyone had abandoned NASA traditions, the Marshall officials argued, it had been Thiokol. The firm had not informed the Center that Thiokol's top managers had been present in Utah or that these managers had recommended the cold launch over the objections of the motor engineers. Moreover Thiokol's dissenters remained silent when Reinartz asked for comments.[120] Center Director Lucas told the commission "the responsibility rests with Thiokol, but I'm not trying to shake the responsibility of the Marshall Space Flight Center. Thiokol reports to us. But I do rely upon the contractor, the prime contractor, to recommend launch" and "I don't recall that we have ever . . . knowingly overridden a go/no-go decision by a contractor."[121]

At least two Marshall engineers also opposed a cold weather launch. Before the teleconference, Keith Coates, a former chief engineer for the solid rocket motor, had expressed concerns about the cold to project officials. Ben Powers, a motor engineer, informed his boss, John McCarty, deputy director of the propulsion lab, and Jim Smith, the SRB chief engineer, that "I support the contractor 100 percent on this thing. I don't think we should launch. It's too cold." But no objections went over the wire.[122]

The presidential commission decided the flight review had "a serious flaw" because it stifled the expression of "most of the Thiokol engineers and at least some of the Marshall engineers."[123] Center engineers who participated offered mixed evidence. Frank Adams believed that the same sort of "questioning that went on" during the teleconference was "the same as any I have sat in thousands of times over the years that I've been here." Lawrence Wear said "it is an open world at Marshall" and "in our system, you are free to say whatever you wish, to recommend whatever you wish. But you've got to be able to stand the heat, so to speak, based on what you have said."[124]

Some engineers said they had been reluctant to bypass the chain of command and inform Hardy of their concerns. Although Hardy had consulted with his senior advisors and said at one point, "for God's sake, don't let me make a dumb mistake," he did not poll all his engineers and was unaware of divergent views. Coates did not "lay down on the tracks," he later explained, because he lacked formal responsibility. McCarty did not forward Power's objections to Hardy, and later said he did not "really believe I had a decision as to whether . . . the temperature concerns were valid or not" and that Powers could have spoken for himself. Powers said "you don't override your chain of command. My boss was there; I made my position known to him; he did not choose to pursue it. At that point it's up to him; he doesn't have to give me any reasons; he doesn't work for me; it's his prerogative." Wear admitted that at Marshall "everyone does not feel free to go around and babble opinions all the time to higher management." The definite statements from Center officials could have intimidated dissenters; he acknowledged that "when the boss had spoken, they might quiet down."[125]

Mulloy, in testimony to a Senate committee, best summarized the circumstances. "We at NASA," he said, "got into a group-think about this problem. We saw it, we recognized it, we tested it, and we concluded it was an acceptable risk. . . . When we started down that road we were on the road to an accident."[126] Indeed the teleconference was a classic case of "groupthink," a form of decision-making in which group cohesion overrides serious examination of alternatives. Top level Marshall and Thiokol officials, believing the joint was safe, rationalized bad news from experts, and refused to consider contingency plans. Recognizing consensus among superiors, some subordinate engineers exercised self-censorship. Consequently participants in the teleconference failed to communicate and find useful ways to analyze the risks of cold temperature.[127] Two personnel experts, who conducted management seminars at NASA from 1978 to 1982, argued that groupthink was not unique to Marshall and was inherent in NASA culture. They believed that internal career ladders, homogeneous professional backgrounds, masculine management styles, political pressures to downplay problems, and over-confidence resulting from a history of success had produced a quest for harmony that was often dysfunctional.[128]

At 11:30, SRB project manager Mulloy and Shuttle projects manager Reinartz of Marshall telephoned Level II Manager Arnold Aldrich of JSC. They discussed the effects of cold weather, especially ice on the launch pad and the status of the booster recovery ships, and agreed that the launch should proceed. The Marshall officials did not mention the teleconference or discuss O-rings. At 5:00 A.M. on January 28, Reinartz met with Lucas, and Kingsbury, chief of the Center's Science and Engineering, informing them of Thiokol's concerns about the O-rings, the firm's initial recommendation to delay, and the final decision to launch.[129]

The presidential commission criticized these exchanges in some of its strongest language, finding that "Marshall Space Flight Center project managers, because of a tendency at Marshall to management isolation, failed to provide full and timely information bearing on the safety of flight 51–L to other vital elements of Shuttle program management" and they "felt more accountable to their Center management than to the Shuttle program organization."[130] Commissioner Donald J. Kutyna, a major general in the Air Force, said going outside the "reporting chain" to describe the O-ring concerns to Lucas rather than Aldrich was like reporting a fire to the mayor rather than the fire chief.[131]

Marshall's project managers, of course, never thought the O-rings were hazardous. Reinartz told the commission that they did not report the teleconference or Thiokol's concerns because the question had been "successfully resolved," the experts had decided that the launch was safe, and the final decision "did not violate any launch commit criteria." Agreeing that Marshall had not violated any "formal documentation," Aldrich wished he had been informed anyway. In hindsight Reinartz acceded the wisdom of notifying Level II, but he doubted that this would have stopped the launch of 51–L since both Thiokol and Marshall had agreed to proceed. Mulloy said "it was clearly a Level III issue that had been resolved," and "it did not occur to me to inform anyone else then nor do I consider that it was required to do so today."[132]

The project managers' responses, however, did not explain why they notified Lucas rather than Aldrich. Cecil Houston, Marshall's resident manager at the Cape, believed that Center rivalry affected their decision. Reinartz and Mulloy, he told commission investigators, "didn't want to mention" the matter to a JSC official. "There is between Centers a certain amount of 'them' and 'us,' you know. It's not overt and we don't make a big deal out of it, but they [MSFC's project managers] do feel like some things are not necessarily their [JSC's] business." The discussion should have been reported to Aldrich, Houston thought, and "we had always done it before."[133]

Between 7:00 and 9:00 the next morning, the ice crew at the Cape inspected the icicle-draped Launch Pad 39B and measured temperature. They recorded a temperature of eight degrees near the aft joint of the right solid rocket motor. They did not report this finding because it fell outside their directives. At 9:00, the NASA mission management team, which included the Level I, II, and III managers, discussed the ice and decided conditions were safe. No one discussed the O-rings. In Huntsville that morning, Powers told a fellow motor engineer of his fear for *Challenger's* astronauts, worrying that "these guys don't have more than a fifty-fifty chance." At 11:38, the boosters fired, helping to lift mission 51–L off the pad. In little more than a minute, the aft field joint on the right motor failed and destroyed *Challenger*.[134]

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1 NASA initially designated each Shuttle mission by sequential numbers. After 1983, each flight had two numbers and a letter; the first number referred to the fiscal year, the second the launch site (1 for Kennedy), and the letter designated the sequence of the flight in the fiscal year.

2 *Presidential Commission on the Space Shuttle Challenger Accident: Report to the President*, Washington, DC: US GPO, 6 June 1986, Vol. I, pp. 19–21, 31, 40, hereinafter, PC Vol., page; Dennis E. Powell, "The Challenger Deaths: What Really Happened?" *Huntsville Times*, 13 November 1986.

3 See PC I, espec. p. 148.

4 Malcolm McConnell, *Challenger: A Major Malfunction, A True Story of Politics, Greed, and the Wrong Stuff* (Garden City, New York: Doubleday, 1987); Joseph Trento, *Prescription for Disaster* (New York: Crown, 1987).

5 Diane Vaughn, "Autonomy, Interdependence, and Social Control: NASA and the Space Shuttle Challenger," *Administrative Science Quarterly* 35 (June 1990); Frederick F. Lighthall, "Launching the Space Shuttle Challenger: Disciplinary Deficiencies in the Analysis of Engineering Data," *IEEE Transactions on Engineering Management* (February 1991); Gregory Moorhead, Richard J. Ference, and Chris P. Neck, "Groupthink Decision Fiascoes Continue: Space Shuttle Challenger and a Revised Groupthink Framework," *Human Relations* 44 (June 1991); Phillip K. Tompkins, *Organizational Communication Imperatives: Lessons of the Space Program* (Los Angeles: Roxbury Publishing, 1993).

6 Thomas F. Gieryn and Anne E. Figert, "Ingredients for a Theory of Science in Society: O-Rings, Ice Water, C-Clamp, Richard Feynman, and the Press" in Susan E. Cozzens and Thomas F. Gieryn, eds., *Theories of Science in Society* (Bloomington: University of Indiana Press, 1990).

7 The Morton Salt Company purchased Thiokol Incorporated in 1982, thus creating Morton-Thiokol.

8 SRB segments had joints of two types, factory and field. The Thiokol plant near Brigham City, Utah connected factory joints, and contractors at the Kennedy Space Center connected four field joints. The field joints in turn were of two types, one which connected case segments and one which connected case and nozzle segments.

9 PC I, pp. 120–22; Trudy E. Bell and Karl Esch, "The Fatal Flaw in Flight 51–L," *IEEE Spectrum* (February 1987), pp. 40–42.

10 William Brown, MSFC, OHI by Jessie Whalen, 15 August 1989, pp. 23–24.

11 Lindstrom, "SRB DM–1 Status," and Marshall, "SRM DM–1 Static Firing Test," 25 July 1977, Weekly Notes, MSFC Center Archives.

12 Thiokol, "Case Burst Test Report," 21 December 1977, TWR–11664, Sections 2.0, 4.2, 4.3.4, MSFC Documentation Repository.

13 Lindstrom, "SRM Case," Weekly Notes, 3 October 1977; Marshall, "SRM Case Hydroburst," Weekly Notes, 11 October 1977, quote; McCool, "SRM Case—SRM Hydrostatic Burst Test Vehicle," Weekly Notes, 17 October 1977, MSFC Archives; PC I, pp. 122–23.

14 Thiokol, "Analytical Evaluation of the SRM Tang/Clevis Joint Behavior," 6 October 1978, TWR–12019, MSFC Documentation Repository; PC I, pp. 122–23; Lawrence Mulloy Testimony, 10–11 February 1986, PC IV, pp. 286–87, 354–55

15 PC I, pp. 122–23; Bell and Esch, p. 40; Howard McIntosh, Manager Steel Case and Refurbishment for SRM, MTI, PC I by Patrick Maley, 4 April 1986, Wasatch, Utah, pp. 7–13: Arnold Thompson, MTI, PCI by Robert C. Thompson, 4 April 1986, MSFC, pp. 11–21.

16 Eudy cited in PC I, pp. 123–24; Leon Ray, "SRM Clevis Joint Leakage Study," 21 October 1977, PC I, p. 233.

17 J. Q. Miller and L. Ray to G. Eudy, "Statement of Position on SRM Clevis Joint O-ring Acceptance Criteria and Clevis Joint Shim Requirements," 9 January 1978, PC I, pp. 234–34.

18 McCool, "DM–2 SS SRM Static Firing" and Lindstrom, "SRB DM–2 Static Test," Weekly Notes, 23 January 1978, MSFC Archives; Thiokol, "DM–2 Flash Report," TWR–11704; Thiokol, "Test Report SS SRM DM Static Firing Test," Vol. III, DM–2, TWR–12348, MSFC Documentation Repository.

19 Thiokol, "Test Report, DM–3," TWR–12348, Vol. IV, pp. 108, 103.

20 Cited in Bell and Esch, p. 40.

21 Thiokol, "SRB Structural Test, STA–1 Motor Case, Final Test Report," 2 November 1978, TWR–12051, Sections 2.0, 4.6, 5.0; McIntosh PCI, 4 April 1986, pp. 22–39; Thompson PCI, 4 April 1986, pp. 2–11; Maurice Parker, MTI, PC I by E. Thomas Almon, 14 May 1986, MSFC, pp. 6–27.

22 J. Q. Miller and L. Ray to G. Eudy, "Evaluation of SRM Clevis Joint Behavior," 19 January 1979, PC I, p. 236.

23 L. Ray, "Visit to Precision Rubber Products Corporation and Parker Seal Company," 6 February 1979, PC I, p. 238.

24 Thiokol, "DM–4 Flash Report," p. 3, TWR–12168; Thiokol, "Test Report, DM–4," p. 124, TWR–12348, Vol. V.; Thiokol, "DM Test Report: Introduction and Summary," pp. 36–37, TWR-12348, Vol. I, MSFC Documentation Repository.

25 Thiokol, "QM–1 Flash Report," TWR–12359, MSFC Documentation Repository; "First SRM Qualification Test 'Quite Satisfactory,'" *Marshall Star*, 20 June 1979; "Second SRM Qualification Test Passed," *Marshall Star*, 3 October 1979.

26 Space Shuttle Verification/Certification Propulsion Committee, 5th Meeting, 10 July 1980, pp. C.7.21–22; Robert F. Thompson and John F. Yardley, "Space Shuttle Program Office Response to Propulsion Committee," 10 August 1980, pp. 58–60, Rogers' Commission Records, National Archives, Washington, DC (hereinafter RCR); PC I, pp. 124–25; Bell and Esch, p. 42.

27 Maurice Parker, Thiokol, "SRB Critical Items List," 24 November 1980, PC I, pp. 239–40; PC I, p. 125.

28 PC I, p. 148; J. Sutter and T. J. Lee, "NASA Development and Production Team Report," Appendix K, PC II, pp. K–30–31; STS 51–L Data and Design Analysis Task Force, "Preliminary Lessons Learned Report," April 1986, pp. D.1, D.4–9, 51–L Investigation Documents, Box 5, JSC History Office.

29 Glenn Eudy, Presidential Commission Interview (hereinafter PCI) by Ray Molesworth, 26 March 86, pp. 1–19, RCR; Glenn Eudy, OHI by Jesse Emerson, 30 January 1990, pp. 2–4; MSI SSHP; James Kingsbury, OHI by Jessie Whalen, 17 November 1988, pp. 5–6, MSI SSHP; Alex McCool, PCI by Emily Trapnell, 27 March 1986, pp. 1–25, quoted p. 28, RCR; Bob Lindstrom, OHI by Jessie Whalen, 26 June 1986, pp. 8–9; George Hardy, PCI by Robert C. Thompson and E. Thomas Almon, 3 April 1986, pp. 15–16; Bill Rice, PCI by Ray Molesworth, 26 March 1986, MSFC, pp. 10–12; Fred Uptagraff, PCI by Robert C. Thompson and E. Thomas Almon, 1 April 1986, pp. 1–3, 6–20, 33, RCR.

30 George Hardy, OHI by Jessie Emerson, 1 March 1990, MSI SSHP, pp. 3–4.

31 William Leon Ray, PCI by Emily Trapnell and Bob Thompson, 25 March 1986, pp. 50–51.

32 John Q. Miller, PCI by Ray Molesworth, 27 March 1986, pp. 24–26, 29–31, 34–36, quoted p. 35; William Leon Ray, PCI by Emily Trapnell and Bob Thompson, 25 March 1986, pp. 10, 48–42; Ben Powers, PCI by Ray Molesworth, 25 March 1986, pp. 8–9, 19, 38–39, quoted p. 35, RCR.

33 William Lucas, Oral History Interview by Andrew J. Dunar and Stephen P.Waring (hereinafter OHI by AJD and SPW), UAH, 27 October 1992, p. 41.

34 PC I, pp. 82–83. For examples of the process, see W. Lucas, "MSFC FRR Board for MSFC Elements for Mission 61–C," 3 December 1985, 61–C folder, MSFC Archives; "Flight Readiness Review Treatment of O-ring Problems," PC II, Appendix H.

35 MSFC SRB Office to Paul Wetzel, NASA HQ, "STS–2 SRM O-ring-Effected Condition," 9 December 1981, STS–2 folder; James A. Abrahamson, HQ Asst. Admin. for Space Flight, "STS–3 FRR Minutes," 10 March 1983, STS–3 folder, MSFC Archives; PC I, p. 125.

36 Maurice Parker, Thiokol, "SRB Critical Items List," 17 December 1982; MSFC, "SRB and RSCD System CIL Change Notice No. 23," 21 January 1983; Glynn Lunney, Shuttle Program Manager, "SRB CIL Requirements for SRM Case Joint Assemblies," 2 March 1983; L. Michael Weeks, NASA HQ, "SRB CIL Requirements," 28 March 1983 all in PC I, pp. 241–44; PC I, pp. 126–27, 159.

37 Larry Mulloy and George Hardy testimony, 26 February 1986, PC V, pp. 834–38; William Lucas testimony, 27 February 1986, PC V, pp. 1036–37; William P. Horton, PCI by Ray

Molesworth, 27 March 1986, pp. 20, 22–23; Robert E. Lindstrom, PCI by P. J. Maley, 5 May 1986, p. 5, RCR.

38 Judson A. Lovingood testimony, 26 February 1986, PC V, pp. 925–26; Mulloy and Hardy testimony, 26 February 1986, PC V, pp. 834, 838, 880.

39 MTI, "SRM Redundant Seals: Summary of FMEA/CIA and Certification Rationale," TWR–15538, March 1986, PCR; Robert K. Lund, MTI, PCI by Pat Maley, 1 April 1986, p. 14; Wesley L. Hankins, PCI by Pat Maley, 2 April 1986, pp. 9–11; Roger Boisjoly, PCI by John Molesworth, 2 April 1986, pp. 33–34; Howard McIntosh, MTI, PCI by Pat Maley, 4 April 1986, pp. 60–62, 71; Joe Kilminster, PCI by E. Thomas Almon, 4 April 1986, pp. 26–29.

40 PC I, pp. 126–28, 159; Ben Powers, PCI by Ray Molesworth and Emily Trapnell, 12 March 1986, pp. 36–40, RCR.

41 "Filament Cases Proposed for Solid Rocket Motor," *Marshall Star*, 10 March 1982; "SRB Modification Contract Awarded by Marshall," *Marshall Star*, 19 May 1982; MSFC Structures Engineering Branch, "Structural Test and Instrumentation Requirements for the Space Shuttle FWC SRB," December 1982, MSI Space Shuttle History Project, hereinafter, SSHP; Ray quoted in William J. Broad, "NASA had Solution to Key Flaw in Rocket when Shuttle Exploded," *New York Times*, 22 August 1986.

42 PC I, pp. 5, 128.

43 "SRB Stacking Begins on STS–6 Vehicle," *Marshall Star*, 6 October 1982; "STS–6 Vehicle Moves to Pad," *Marshall Star*, 1 December 1982; Budd McLaughlin, "Prober: Faulty Rocket Joint, Other Factors, Exploded Challenger," *Huntsville News*, 9 April 1986; PC I, p. 125; William H. Starbuck and Frances J. Milliken, "Challenger: Fine-tuning the Odds until Something Breaks," *Journal of Management Studies* 25 (July 1988), pp. 325–26, 337. In April 1983 on STS–6 NASA began using a lightweight steel booster case with thinner case walls and began filling the booster with a more powerful fuel.

44 PC Staff, "Leak Check," 1986, RCR, PC 102597, Reel 46, National Archives; PC I, pp. 133–34.

45 PC Staff, "Leak Check," RCR; PC I, pp. 133–34; Bell and Esch, pp. 42–43.

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