Shuttle Inquiry Focuses on Weather, Rubber Seals, and Unheeded Advice

Thiokol engineers warned against launching because of doubts about the performance of seals between segments of the booster rocket at low temperatures

On the evening before the accident that destroyed the space shuttle Challenger on 28 January, several dozen engineers and technicians participated in a highly contentious telephone conversation about the potential impact of low temperatures on the performance of the shuttle's booster rockets. Florida was then in the grip of an extraordinary cold wave, and temperatures on the pad were expected to dip to the low 20's—well below the coldest previous temperature before a launch.

During the conference call, representatives of Morton Thiokol, Inc., the booster's manufacturer, explicitly warned the National Aeronautics and Space Administration (NASA) that rubber gaskets used to seal the joints of the boosters—known in the trade as O-rings—might not work at such low temperatures. Test data suggested the performance of the gaskets might be sharply diminished below 50°F, Thiokol officials said. The company's engineers recommended unanimously that the launch be postponed.

According to five of those who participated in the conversation, NASA officials argued vigorously that Thiokol's data were unduly speculative, and that in any event the presence of two gaskets at each joint ensured that one would hold even if the other failed. Several Thiokol officials recall a senior NASA engineer saying that he was "appalled" by the company's recommendation. A request was made that Thiokol look at the data again.

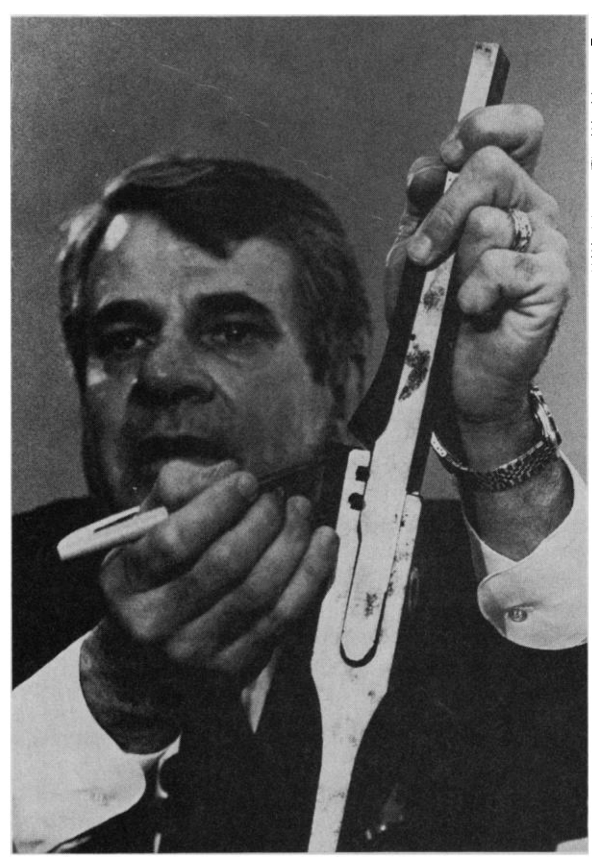
With the telephone button on "mute," Thiokol's engineers caucused and once again unanimously recommended not to launch. But the company's managers, feeling what one Thiokol official characterized as "a lot of pressure from our biggest client," decided to give way and officially endorsed the lift-off. Previously, NASA had demanded that Thiokol present considerable evidence to support a launch, one Thiokol official said. "This time, we were asked to *prove* that *no* launch should occur, and the data were not black and white." Thiokol's solid rocket motor project manager Alan McDonald, the senior company official at the cape, refused to sign the company's formal launch approval.

The next morning, 73 seconds after its launch, the spaceship was consumed in a fiery white and yellow explosion. As *Science* went to press, NASA was still officially uncertain whether a gasket failure was the principal cause. But it had established that a flame breached the side of the booster in the vicinity of a joint before the craft perished.

The strong likelihood that low temperatures and a defective joint combined to lethal effect has prompted NASA to comb its files for all relevant documents, many of which are now in the hands of a special commission appointed by the President. The documents reveal that a potentially serious defect in the joints was identified by the agency in 1983, but a major study of repairs did not get under way for roughly 2 years. Many engineers at Morton Thiokol, as well as a few at NASA, argued that prompt action was needed to develop and implement booster modifications, but senior NASA officials elected to pursue a slower, less expensive research effort, which has not yet produced concrete solutions.

Interviews with a variety of NASA and Thiokol employees also reveal that in the months before the accident, virtually no one believed that all flights should be suspended until the boosters were modified. Apparently, the sole suggestion that continued booster operations were unduly compromising flight safety was issued last fall by Richard Cook, a 39-year-old budget analyst who was relatively new to the job, and whose concern was considered extreme by his superiors.

The management of the booster problem, as well as the decision to go ahead on the eve



James K.W. Atherton/The Washington Post

Focus of the investigation

Larry Mulloy, manager of booster programs at Marshall Space Flight Center holds part of joint showing two black rubber O-ring gaskets that form seal between interlocking segments of the rocket casing.

of the Challenger's launch, are likely to be scrutinized closely in coming weeks by the commission, the Congress, and the public. Anticipating a lengthy inquiry, NASA has already formally postponed the next three shuttle flights, which were to have ferried some important scientific experiments into outer space (*Science*, 14 February, p. 661–667). Should substantial booster modifications be required, all shuttle operations could be suspended for well over a year.

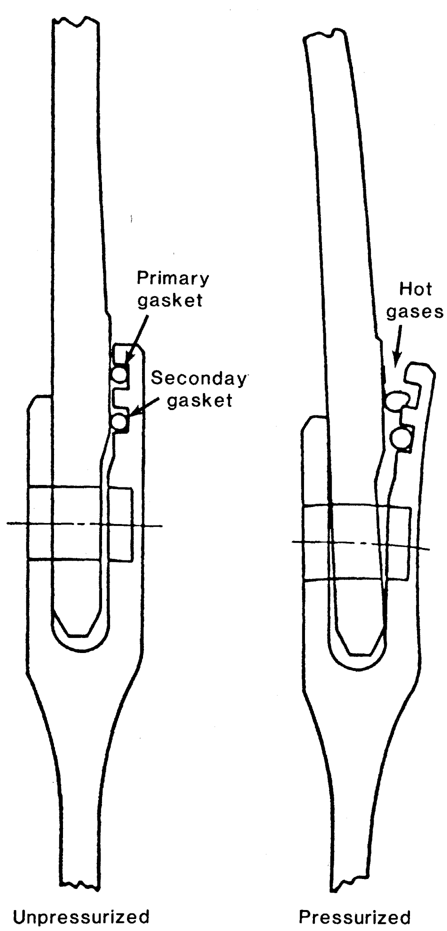
Although the issue first attracted public notice last week, NASA has been aware of problems with the booster joints for some time. Beginning with the second shuttle flight in November 1981, more than 30 seals have been partially eroded by rapid compression on the inside of the boosters. In ten of these seals, hot gases were able to penetrate the primary barrier, a strip of zinc-chromium putty, as well as the secondary barrier, a galvanized rubber gasket, and deposit some soot just ahead of the final barrier, another rubber gasket.

A series of shims, added to narrow the joints early in the shuttle program, proved to have little beneficial effect. By late 1982, the agency had learned that rapid pressurization of the booster segments widened the joints by 0.04 to 0.06 inch approximately 20 seconds after launch (see diagram). This was just enough to prevent the backup gasket from forming an effective seal, potentially eliminating any redundancy for this portion of the flight. Instead of repairing the defect, the agency formally waived the redundancy requirement in a memo dated March 1983 that explicitly listed the danger of "loss of mission, vehicle, and crew due to metal erosion, burnthrough, and probable case burst resulting in fire and deflagration" if just a single gasket failed. It did so because test results and previous flight experience appeared to indicate that such a failure was unlikely.

According to the documents, senior NASA officials next looked at the problem a year later, after partial erosion occurred in several additional seals. But Lawrence Mulloy, the manager of the booster program at NASA's Marshall Space Flight Center in Huntsville, Alabama, concluded that the problem was due to improper seal installation, rather than faulty design, and recommended continuation of shuttle operations. Hans Mark, who was then the agency's deputy administrator, ordered a detailed review of installation practices, but it was still not completed more than a year later.

As the erosion problem persisted, engineers including Paul Herr, the solid rocket motor program manager in the propulsion division of NASA's Office of Space Flight, began to list "O-ring charring" on monthly summaries of significant booster cost and schedule "issues/concerns," circulated widely through the agency. But apparently little action was taken until a near disaster during a launch on 29 April 1985. As NASA later discovered, hot gases or flames from the boosters attached to the Challenger that morning were able to penetrate the putty and blow past the first gasket on one joint, and in one area to erode up to 80 percent of the second gasket within a few seconds after launch. Fortunately, no burnthrough occurred, but the incident left a strong impression on the agency's senior management.

"It got me very very very concerned," says Irving Davids, who was then the acting chief of the shuttle propulsion office. "Previously, we'd only seen discoloration" of the second gasket, he says. Michael Weeks, a deputy associate administrator for technical matters at NASA headquarters, remembers that "this was when a vigorous effort [to find a solution] began." Thiokol conducted the first comprehensive tests of gasket performance at different temperatures (50°, 75°, and 100°F), and a more aggressive effort was made to detect improper assembly. (Ironically, the effort, which consisted of pumping air into the joint at higher pressures to check for leaks, was suspected only a few months later of contributing to the erosion problem because it moved the gaskets away from the gap in which they were supposed to "seat.")



Leaky joints?

Where segments of the solid-fuel booster rockets fit together, a seal is provided by two "O" shaped rubber gaskets. Moments after ignition, pressure in the booster causes the joints to open up, as shown in exaggerated form in the diagram on the right. If the gaskets fail to seat properly in the gap, hot gases could escape throught the joint.

Davids, along with William Hamby, a deputy director for shuttle program integration, visited the Marshall Space Flight Center in July to assess the problems firsthand. During the visit, they requested information about the backup gasket problem first identified in 1983, and discussed the possibility of replacing the putty because it is highly vulnerable to extremes of temperature and moisture. (It has not yet been replaced.)

Differences of opinion about the pace of the investigation quickly surfaced. In early July, Mulloy told headquarters in briefing charts that he considered the matter "closed," because a "conservative analysis" indicated that the gaskets would keep working even after considerable erosion. Some engineers in the shuttle propulsion office strongly disagreed, but one of them, Russell Bardos, urged in a memo that "we proceed very cautiously." The immediate emphasis, he said, should be "to assure what we now have will perform adequately." Long-term steps such as changes in design and procedures, he added, will be expensive.

Morton Thiokol, in contrast, argued in a comprehensive August report to NASA that "the lack of a good secondary seal in the field joint is most critical and ways to reduce joint rotation [or widening] should be incorporated as soon as possible to reduce criticality." It proposed a detailed plan of study and testing, embracing more than 43 potential joint and seal modifications. But none of the changes could be implemented any sooner than May 1986, it said, and some could take more than 2 years.

No one argued that shuttle operations should be brought to a halt in the meantime. The poor performance of the gaskets was identified in numerous agency documents as a "budget threat," not a safety hazard. "It was not disturbing for reasons of safety, because [the gasket] did what we wanted it to," Mulloy said recently. "It was disturbing only because we were looking for ways to increase the margin." As Thiokol also noted at the time, "analysis of existing data indicates that it is safe to continue flying [the] existing design so long as all joints are leak checked . . . are free of contamination . . . and meet O-ring squeeze requirements." Even Paul Herr, who had been pressing for nodifications to the joints since 1984, told *cience* that "I was convinced that yes, it's dequate, that we were in good shape—but only so long as there were no adverse launch onditions, such as severe bending, unusual old, or sloppy workmanship."

The tragedy is that at least one and possi-ly all three of these factors may have played role in the disaster. Last November, work-rs at the launch site employed by the ockheed Corporation damaged a segment f one of the boosters destined for the 28 anuary launch, requiring its replacement. An internal agency review concluded that vorker inexperience, lack of motivation, and aulty equipment were to blame. Subse-quently, a similar segment on the other ooster was replaced, at the last moment efore the Challenger was transported to the ad, in an effort to ensure thrust equilibrium luring launch. According to sources at NASA and a member of the White House ommission, the errant plume erupted from he side of the booster in the vicinity of a ole drilled in this segment to test for leaks mmediately after its installation. At the time *Science* went to press, NASA was said to be investigating the possibility that workers carelessly forgot to plug this hole, thereby allowing flames which penetrated the first gasket to breach the booster wall.

A related hypothesis is that an unusually low temperature of 38°F on the launch pad at the time of launch made the first gasket so stiff that it failed to seat properly and seal the joint. According to several Thiokol officials, no reliable data are available on the perfor-mance of the gaskets in the boosters below 51°F, the ambient temperature on the pad at the coldest previous launch, in January 1985. One gasket was badly eroded during that launch, and a backup was charred. Much less erosion occurred on a flight in October, when the ambient temperature was 84°. According to one engineer, "What little information we had in [the 45° to 50°] region indicated that the resiliency of those [gaskets] was going to hell in a handbasket, that they would essentially lie dormant at such temperatures, like a sleeping bear, with no power to think. The trend was pretty clear."

NASA's Larry Mulloy has stated publicly that the decision to launch was ultimately based on an "analysis" showing that "should we compromise the primary ring, the sec-ondary would seat as it has done in the past, even under those temperature conditions." He declined repeated requests from *Science* for amplification. Budget analyst Richard Cook, who has now moved to the Treasury Department, points out the incongruity of such a decision, given that the agency had earlier declared that the gasket system could not be considered fully redundant.

Perhaps the greatest irony is that some potential solutions to the joint problem, including a new putty, a larger gasket, and a seal stiffener, were to be tested at Morton Thiokol on 13 February. The test, which will cost $15 million, has now been post-poned until the accident investigation is completed. NASA's Michael Weeks says that this experiment should probably have been performed earlier. "We should have made more effort earlier, of course," he says, adding that hindsight makes this an easy judgment. ■ R. JEFFREY SMITH

Education Makes Comeback at NSF

After being abolished when Reagan came to office, the education directorate now has a steady budget and is gaining credibility among its critics and within the foundation

PRESIDENT Reagan's proposed budget for next year gives the National Sci-ence Foundation's science education program $89 million, a $2-million increase over the current year. Considering the pre-vailing pressures for deficit reduction and the ups and downs of the program in recent years, science education seems at least to be back from the fiscal depths to which it sank in the early 1980's.

The Reagan Administration abolished NSF's science education directorate upon taking office in 1981. But the decision was reversed in October 1983, following a wave of public concern about the state of Ameri-can schools. Although federal funding for improvement of science and math education has not increased spectacularly in the 3 years since NSF's role in science education was restored, the current view among NSF watchers is that the directorate has now won acceptance by its critics in the Administra-tion—and perhaps inside the foundation as well.

The major initiative by the Directorate for Science and Engineering Education since its rebirth has been in precollege education. A total of $47.7 million is in the new budget for precollege activities. Of that, $22.7 mil-lion would go to materials development and research and $25 million to teacher enhance-ment, the same as for the current year.

Revival of the precollege program has proceeded with some delay and financial backing and filling. The directorate's top job of NSF assistant director for science and engineering education went unfilled for about 8 months until the appointment of Bassam Z. Shakhashiri, who assumed the post in mid-1984. A University of Wiscon-sin chemistry professor with substantial ex-perience in science education, Shakhashiri was faced with rebuilding the directorate staff and developing a new strategy for science and engineering education for the foundation.

During the period when the directorate was gearing up, Congress appropriated more money for precollege activities than the NSF spent. Some $31.5 million re-mained unexpended at the end of fiscal year 1984, and these funds were carried over to the next fiscal year. With the $82 million appropriated for the education directorate in fiscal year 1985, a total of $113 million appeared to be available. Early last year, however, with pressures building on all par-ties to restrain expenditures, discussions be-tween the Office of Management and Bud-get and foundation officials led to a decision to defer spending of the $31.5 million to the 1986 fiscal year. Although the bookkeeping is confusing, the education directorate end-ed up with a budget of only $87 million for 1986. The "deferred" money was actually absorbed by the NSF research directorates and lost to the education program.

The shift was made with the direct agree-ment of the congressional committees in-volved, although the House Appropriations Committee noted in its report that it was going along reluctantly. Interested outsiders tended to see the episode as illustrating the fragility of the directorate's political base,