The Trickle-Down Effect:
Policy Decisions, Risky Work, and the *Challenger* Tragedy

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The *Challenger* launch decision often is used in business schools and management training seminars as a classic exemplar of how-not-to-do-it. Depending on how the cause of the decision failure is portrayed, however, the lessons for administrators change. In the months following the *Challenger* disaster, the official investigations and media accounts led many citizens to believe that managerial wrongdoing was behind the launch decision. Locating the cause in managers and their potential for unethical conduct, the preventive strategy seemed clear: strengthen individual ethics. As scholars began to analyze the event, however, many located the cause in the dynamics of the teleconference itself. Although this research is diverse and eludes easy classification into tidy categories, three general themes appeared: poor engineering analysis, communication failure, and (perhaps most prominently) Groupthink. Again, strategies to prevent similar decision failures in other workplaces flowed logically from the causes identified: improving training for engineers, sharpening communication and decision-making skills, or altering group dynamics.

Another body of scholarship looked beyond the teleconference, locating the cause of the disaster in NASA's political, economic, and institutional environment. This research indicated that historic policy decisions made by top agency administrators, responding to environmental threats to the agency and their own power base, changed the culture of the space agency so that production pressures dominated the workplace. The thesis—sometimes explicitly stated, sometimes implied—was that decisions by lower participants, in particular, NASA middle managers, were influenced by an organization culture in which production concerns took priority over safety. These scholars directed attention to environmental contingencies that affected the NASA organization. Locating the cause of the flawed decision in NASA's own distinctive history created the impression that the tragedy was an anomaly—a mistake peculiar to NASA. Also, this research left an empirical gap: it did not show *how* those historic policy decisions and the culture that resulted affected engineering decisions about the Solid Rocket Boosters, the technical cause of the disaster. Not only were specific lessons for managers making daily decisions difficult to identify, but the idea that the organization was uniquely flawed led many to conclude that "it couldn't happen here."

What happened at NASA was no anomaly, but something that could happen in any organization. Drawing on archival data and interviews unused by other analysts, this research revises conventional wisdom about the *Challenger* launch decision in several ways. First, it affirms that prior policy decisions played a pivotal role in the *Challenger* tragedy. Thus, this analysis shifts attention from the launch decision to NASA's larger system of organizational relations and to the past. Second, it reveals how the decisions of top space agency administrators trickled down through the organization, altering both the structure and culture of the organization, affecting official engineering risk assessments made at the bottom of the hierarchy. Third, it affirms that production concerns permeated the culture of the workplace, but challenges conventional understandings by revealing that the culture was governed by three cultural imperatives: production concerns, bureaucratic accountability, and the original technical culture. Fourth, it shows how this complex culture affected all people doing the risky work, managers and engineers alike.

The connection between policy decisions and mistakes in the workplace is an issue relevant to all organizations, but of particular concern where loss of life and/or extensive social harm is a possible outcome. Many organizations that do risky work are devoting resources to identifying the causes of errors and eliminating them: for example, hospitals are concerned with errors in surgery, anesthesiology, medication, and diagnosis; U.S. Forest Service Wildland Firefighters explore decision making by firefighters in a crisis; social work agencies try to eliminate errors in placement and monitoring that result in abuse and death of children; naval aircraft carriers aim to avoid disasters at sea; the U.S. Air Force seeks to eliminate deaths in military training exercises and errors in judgment during combat; the FAA targets decision errors in flawed aircraft production and maintenance, airline cockpit crews, and air traffic control. What all these examples of risky work have in common is that decisions are being made under conditions of uncertainty in complex organizations, where history and political contingency are facts of life. Yet in most of these organizations, error-reducing activities have concentrated upon the decision-making situation and the individuals who participated in it. Much less attention—if any—is paid to the organizational system and its environment, as they contribute to decision errors.

To be effective, strategies for control should target the causes of a problem. The purpose of this discussion is to examine the *Challenger* launch decision in order to draw attention to factors that systematically produce errors in organizations but routinely receive little attention in error-reduction efforts. First, I contrast the conventional wisdom about events at NASA with contradictory information found in primary data sources in order to challenge commonly-held views about the launch decision and prepare readers for the analysis that follows. Second, I analyze the history of decision making at NASA, 1977-1985, and the eve of the *Challenger* launch teleconference. An overview, I lay out the structure of the argument only, omitting details that support my inferences and claims. This discussion will be suggestive, rather than definitive, isolating a few key factors for attention. Interested readers should see the original.[1] Third, I present new information describing the social impact of the *Challenger* disaster on the space agency. These sections lay the groundwork for a discussion of three targets for administrators interested in reducing the possibility of mishap, mistake, and disaster: policy decisions, organization culture, and signals of danger.

Revising the Conventional Wisdom

The Presidential Commission investigating the *Challenger* disaster revealed that the O-ring failure on the Solid Rocket Boosters was preceded by questionable middle management actions and decisions. First, the Commission learned of a midnight hour teleconference on the eve of the *Challenger* launch, in which contractor engineers located at Morton Thiokol in Wasatch, Utah, protested launching *Challenger* in the unprecedented cold temperatures predicted for launch time the next morning. Following a heated discussion, NASA middle managers at Marshall Space Flight Center proceeded with the launch, apparently violating safety rules about passing information up the hierarchy in the process. Second, the Commission discovered that in the years preceding the January 28, 1986 tragedy, NASA repeatedly proceeded with shuttle launches in spite of recurring damage on the O-rings. They were flying with known flaws, accepting more risk each time.

The Commission concluded that the disaster was not simply a technical failure, but an organizational failure of tragic proportion. Based primarily on the Presidential Commission's findings about economic strain, production pressures at the space agency, and repeated safety rule violations by Marshall managers responsible for the Solid Rocket Booster Project, the conventional wisdom conveyed by the media was this: NASA managers at Marshall Space Flight Center, warned that the launch was risky, succumbed to production pressures and violated safety rules in order to stick to the schedule.

The televised hearings of the Presidential Commission and Volume I of the Commission's report were the basis of the media-generated conventional wisdom as well as subsequent research by scholars. However, primary data sources stored at the National Archives showed that many taken-for-granted aspects of the tragedy were more complex than they appeared and, in many cases, completely mistaken. The archival record contained many surprises about the technology. The shuttle had not "exploded," as most media accounts reported. According to engineers, there was a fireball and a structural breakup, but no explosion. More surprising, the technical cause of the failure was not as the conventional wisdom portrayed. The primary O-ring in the aft joint of the right Solid Rocket Booster was badly charred, but the charred material itself helped to seal the joint. Then, 50 seconds into the launch, an unprecedented, unpredicted wind shear violently shook the vehicle, jarring loose the charred material and allowing the hot propulsion gases to penetrate the booster joint. Had it not been for the wind shear, the joint would have remained sealed through the two-minute burn of the boosters, and *Challenger*—barring other technical failures—would have returned.

Equally startling were original documents and archival data, unexamined by other researchers, that revealed that much of the conventional wisdom about NASA decision making also was wrong. Some examples:

- In the years preceding the *Challenger* teleconference, NASA repeatedly launched with known flaws in the Solid Rocket Boosters. Memos, written by worried engineers during this period, created the public impression that NASA managers had a history of ignoring engineering concerns. But Morton Thiokol engineers, not NASA managers, initiated official risk assessments and launch recommendations about the Solid Rocket Boosters. All official launch decisions originated with contractor engineers at the bottom of the launch decision chain. For each of the controversial decisions prior to 1986, Thiokol engineers—the very engineers who authored the memos and protested the *Challenger* launch—had repeatedly recommended that NASA managers accept risk and fly.
- On the eve of the launch, the dichotomous view of "good" engineers versus "bad" managers was not borne out. Not all working engineers were opposed to the launch: only the ones who were opposed were called to testify before the Presidential Commission. Moreover, eleven of the fourteen engineers present that night stated that Thiokol's engineering analysis was flawed and unlikely to convince managers.
- Rumor had it that NASA managers needed to launch because of a planned hook-up between the *Challenger* crew and President Reagan, who was making his State of the Union address the evening of the launch. But NASA rules prohibited outside communication with the crew during the first 48 hours in orbit because the crew were too busy, and those rules had never been violated. Moreover, every launch has two launch windows, morning and afternoon. If NASA managers truly believed they were making an unsafe decision but felt an urgent pressure to get the launch off, they could have launched *Challenger* in the afternoon when the temperature was predicted to reach between 40 and 50 degrees, with no political repercussions for the program.
- The image of rule-violating middle managers was unfounded. In the history of decision making on the Solid Rocket Boosters, 1977-1985, and on

the eve of the launch, Marshall middle managers abided by every NASA launch decision rule.

Primary data sources indicated that key aspects of conventional post-tragedy wisdom—and thus many of the facts on which other research was based—were wrong. With all the public scrutiny this event received, how could this be? First, post-tragedy analysts, viewing what happened at NASA retrospectively, saw key incidents and events very differently than the managers and engineers responsible for risk assessments as the problem unfolded. In large part, this was due to retrospection. Starbuck and Milliken point out that when observers who know the results of organizational actions try to make sense of them, they tend to see two kinds of analytic sequences.[2] Seeking to explain the bad result, observers readily identify the incorrect actions, the flawed analyses, that led inexorably to it. In contrast, when the outcome is good, observers invariably identify the wise choices and persistence that were responsible. Second, it was clear that post-tragedy analysts had not grasped key aspects of NASA culture: the rules, procedures, and bureaucratic and technical language that were essential to understanding how engineering decisions were made in the space agency. Culture was even an obstacle to the understanding of the Presidential Commission, which spent three months and enormous resources to investigate the incident. Third, many post-tragedy investigators based their analysis on secondary sources. Most relied extensively on Volume 1 of the Presidential Commission's report, published in June 1986, which was an extensive summary, but a summary nonetheless, of a 5-volume report. Omitted from scrutiny were the other four volumes, the report of the House Committee on Science and Technology, published later, and over 200,000 pages of original materials available at the National Archives.[3]

Using the full documentary record, I reconstructed a chronology of engineering decisions at NASA that explores the meaning of actions to insiders as the Solid Rocket Booster problems unfolded. Despite the acknowledged importance of culture in organizations, ethnographies of decision-making processes as they unfold in natural settings are rare. Occasionally, however, the outcome of a decision is such a public calamity that information becomes available allowing us to reconstruct what happened.[4] As a profession, engineers are particularly attentive to maintaining written records. Perhaps most important in this research were National Archives documents containing engineering post-flight analyses, risk assessments, NASA procedures, and 160 lengthy interview transcripts collected by government investigators working for the Commission. The latter represent a rich untapped resource, as only 40 percent of those interviewed were called before the Commission. These archival data, plus personal interviews, were the basis of an ethnographic account that shows how top policy decisions altered both culture and structure, undermining safety at NASA.

An Incremental Descent into Poor Judgment

In *Man-Made Disasters*, Turner found disasters usually were preceded by "failures of foresight": long incubation periods typified by signals of potential danger that were either ignored or misinterpreted.[5] The infamous teleconference can only be understood as one decision in a long line of decisions that show an incremental descent into poor judgment. From 1977 through 1985, the decision-making history was studded with early warning signs. Anomalies—deviations from design expectations—were found on many missions prior to *Challenger*. But in post-flight analysis, Marshall and Thiokol working engineers responsible for initiating risk assessments of the boosters continually normalized the technical deviation that they found. By "normalized," I mean the remarkable fact that, individual perceptions and concerns notwithstanding, *in all official engineering analyses and launch recommendations prior to the eve of the* Challenger *launch*, Morton Thiokol and NASA engineers analyzed evidence that the design was not performing as predicted and reinterpreted it as acceptable and non-deviant. Based on engineering calculations, tests, and analysis showing that if the primary O-ring failed, a second O-ring would back it up, Marshall and Thiokol working engineers continued to recommend to their superiors that it was safe to fly. Circumstances changed on the eve of the *Challenger* launch. But in the years preceding it, engineering analyses demonstrated that the O-rings operated as a redundant system; therefore, they were an "acceptable risk."

Perhaps most salient and puzzling about the normalization of deviance in official risk assessments was that as missions continued, Marshall and Thiokol working engineers gradually expanded the boundaries of acceptable risk. History and precedent were influential. The critical decision was the first one, when, expecting no damage to the O-rings, in-flight damage occurred and they found it acceptable. This precedent, created early, started the work group on a slippery slope. The engineering analysis and testing that supported this decision were foundational: they resulted in a set of engineering decision rules about how the O-rings operated. Over the years, that first set of decision rules was reinforced by increasingly sophisticated tests and analyses that supported the redundancy of the O-rings. Gradually, in their formal engineering risk assessments, the work group accepted more and more risk. Each of these decisions, taken singly, seemed correct, routine, and, indeed, insignificant and unremarkable, but they had a cumulative directionality, stunning in retrospect.[6]

Presidential Commission member Richard Feynman observed that it was as if they were "playing Russian roulette."[7] Starbuck and Milliken called it an example of "fine-tuning the odds until something breaks."[8] Why, if working engineers were concerned and writing memos, as the historic record indicates they did, did these same engineers repeatedly recommend launching in the years prior to the *Challenger* teleconference?

Signals of Potential Danger: Information and its Context

Sensemaking is context-dependent.[9] At NASA, having problems was not itself a signal of potential danger. Because of the innovative, uncertain character of the technology, they were working in an organization culture where having problems was expected and taken-for-granted. The shuttle was composed of many component parts, made by different manufacturers, that had to be put together by NASA. Since many parts were purchased "off-the-shelf" and not designed specifically to fit with others, there were bound to be problems in assembly. Also, because the shuttle design was unprecedented, the working engineers had no rules to guide them about how it would operate.[10] Despite engineering lab tests, field tests, and calculations, they could never predict and prepare for all the forces of the environment that the shuttle would experience once it left the launch pad. The sky was the laboratory. They were learning by doing, and post-flight analysis taught them the most important lessons about how the vehicle behaved. Finally, the shuttle was designed to be reusable. They knew that the shuttle would experience in-flight damage that required new analysis and correction before it could be launched again.

Taking this uncertainty and risk into account before missions began, in 1981 NASA created a document titled "The Acceptable Risk Process," in which the agency acknowledged that after they had done everything that could be done, the shuttle would still contain residual risks.[11] The residual risk of each component part had to be analyzed to determine whether or not that part was an acceptable risk prior to each flight. The document articulated, in broad strokes, the directions that the Acceptable Risk Process must take prior to each flight. These decision-making guidelines were reflected in the language appearing in engineering hazard analyses: "acceptable risk;" "acceptable erosion;" "anomalies;" "discrepancies." To outsiders after the disaster, this language looked like rationality gone wild. To insiders, it was normal, every day talk. Record keeping and computerized problem-tracking systems made "blizzards of paperwork" a part of the information context that concealed more than it revealed.[12]

This cultural context contributed to the normalization of deviance because having problems was unremarkable and routine. In addition, when the Solid Rocket Boosters began behaving in unexpected ways, the interpretive work of engineers was influenced by the pattern of information as problems began to occur.[13] What, in retrospect, appeared to be clear signals of potential danger that should have halted shuttle flights were interpreted differently at the time by the engineers responsible for risk assessments. As the problems unfolded, signals were mixed, weak, or routine.

Mixed Signals

A mixed signal was one where a signal of potential danger was followed by signals that all was well, convincing engineers that the problem had been successfully diagnosed, corrected, and thus, that the component was an acceptable risk. When returning flights showed anomalies on the booster joints—a signal of potential danger—engineers analyzed and corrected the problem (a piece of lint on an O-ring was enough to cause damage to an O-ring). Subsequently, a number of flights would return showing no problems—a signal that all was well.

Weak Signals

A weak signal was one that was unclear, or one that, after analysis, seemed such an improbable event that working engineers believed there was little probability of it recurring. To illustrate: A launch in January 1985—a year before *Challenger*—showed the worst O-ring damage prior to that date.[14] Cold temperature was thought to be a factor, because the vehicle was on the launch pad through three consecutive days of 19-20 degree overnight Florida temperatures. Knowing that *Challenger* was affected by the cold, we saw this as a strong signal. In fact, Thiokol engineer Roger Boisjoly, who was present at Kennedy Space Center for post-flight disassembly, observed the damage and was alarmed.[15] However, according to Boisjoly, they had no quantitative data proving that temperature was responsible for the damage they found—many factors had been causing problems—and they believed such a long run of record cold temperatures was unlikely to happen again.[16] Thiokol began some temperature testing but, in the words of Boisjoly, there was "no scramble to get temperature data" because no one expected a recurrence.[17] The vehicle was tested and designed to withstand extremes of heat, not cold. Cold temperature was, to them after analysis, a weak signal—until the eve of the *Challenger* launch.

Routine Signals

Routine signals are those that occur frequently. The frequent event, even when acknowledged to be inherently serious, loses some of its seriousness as similar events occur in sequence and methods of assessing and responding to them stabilize.[18] In mid-1985, O-ring erosion began occurring on every flight. Post-disaster analysts were incredulous that flights continued. However, these anomalies also were determined to be acceptable risks in official engineering risk assessments. For Marshall and Thiokol working engineers assigned to the Solid Rocket Booster Project, multiple instances of erosion indicated not danger, but assurance that they correctly understood the problem. Marshall and Thiokol engineers had instituted a new procedure that guaranteed that the O-rings would be properly positioned. This procedure increased the probability of erosion, but erosion was not viewed as a problem. Better they assure redundancy by getting the rings in proper position than worry about erosion, which was, in fact, occurring exactly as they predicted. What we saw, in retrospect, as signals of potential danger were to them, routine signals showing the joint was operating exactly as they expected.[19]

The Trickle-Down Effect: Policy Decisions and Risk Assessments at NASA

After the disaster, the Presidential Commission and other post-tragedy analysts unanimously concluded that policy decisions had been a contributing cause of the tragedy. Political bargains and goal-setting by agency elites had altered the organization culture so that production concerns dominated the space agency, contributing to NASA's incremental descent into poor judgment. These post-disaster analysts were correct. NASA's relationships with its connected communities—Congress, the White House, contractors—altered the organization culture. Political accountability and thus, production pressures were introduced into the agency. However, these policy decisions resulted in a three-faceted culture comprised of the space agency's original technical culture, bureaucratic accountability, and political accountability. All three contributed to the Solid Rocket Booster work group's repeated decisions to accept risk and fly in launch recommendations prior to the *Challenger* teleconference.

The Original Technical Culture

The standards of engineering excellence that were behind the splendid successes of the Apollo era made up NASA's original technical culture.[20] Integral to that culture was the reliance on and deference to in-house professional technical expertise and experiential knowledge of the technology, known as the "dirty hands" approach.[21] Also, the original technical culture insisted upon scientific positivism.[22] It required that risk assessments be guided by extensive testing, engineering principles, and rigorous quantitative analysis. Hunches, intuition, and observation, so essential to engineering, had a definite place in lab work. But when it came to decisions about whether to proceed with a mission or not, the subjective and intuitive were not allowed: flawless, precise, engineering analysis, based on quantitative methods, grounded in solid engineering data, was required for launch decisions.

This original technical culture still existed at NASA during the shuttle program. It was perhaps most visible in NASA's formal pre-launch decision structure known as Flight Readiness Review, where contractor engineers brought forward their engineering analyses and recommendations about risk acceptability. These contractor launch recommendations and the engineering analysis that supported them were challenged in four hierarchical Flight Readiness Review levels in harshly adversarial, public confrontations designed to test engineering risk assessments.[23] But these mandates for excellence integral to the original Apollo technical culture were struggling to survive amidst two other cultural mandates that resulted from policy decisions early in the Space Shuttle Program: political accountability and bureaucratic accountability.[24]

Political Accountability

During the Apollo era, Congress gave NASA a blank check. As the Apollo program neared completion, changes in US domestic and international affairs eroded the consensus for space exploration that had produced both autonomy and money for NASA. NASA barely managed to get the shuttle program endorsed. Top administrators did so by selling the shuttle to Congress as a project that would, to great extent, pay its own way. The space shuttle, they argued, would be like a bus, routinely ferrying people and objects back and forth in space. It could carry commercial satellites, and at the projected launch rate, could produce enough income a year to support the program. Thus, the shuttle would survive as a business, and concerns about cost effectiveness and production pressures were born.[25]

Impression management was the name of the game: after the fourth shuttle flight in 1982, top NASA officials (aided by a ceremonial declaration by President Reagan) declared the program "operational," meaning the developmental or test period was over and henceforth space flight would be "routine and economical." Top administrators continued to establish program goals consistent with the public imagery of an "operational program," even though advised by safety regulators that the shuttle was a developmental, not operational, system. Among those were efforts to accelerate the turn around time between launches in order to increase the launch rate, and later, taking non-astronauts on missions for political purposes. Meeting the schedule became the key to continued funding from Congress. Consequently, for middle managers and engineers assigned to the hardware, performance pressures and political accountability invaded the original technical culture of the workplace.[26]

Bureaucratic Accountability

The agency became bureaupathological. During Apollo, the "dirty hands" approach was maintained, although occasionally contractors were used. After Apollo, as a consequence of international space competition, the multi-component shuttle design, and its complex mission, top agency administrators institutionalized the practice of "contracting out."[27] The expanded NASA/contractor structure required ever more rules to coordinate vehicle assembly, launch and mission. Attention to rules and burgeoning paperwork became integral to organization culture. In addition, the Reagan Administration required greater accountability of all government agencies.

Both these developments affected working engineers in the shuttle program. The entire launch decision process always had been guided by rigid rules for procedural accountability. Policy decisions now joined these rules with rules that governed nearly every aspect of the work process. The "dirty hands" approach was undercut by contracting out: instead of getting their hands dirty, many NASA engineers were assigned responsibility for contractor oversight. They spent much more time doing desk work, filling out forms. For each launch, 60 million components and thousands of count-down activities had to be processed. With the accelerated launch schedule, managers and engineers were working evenings and weekends just to turn around all the paperwork necessary to qualify the vehicle for launch.

The Trickle-Down Effect

Between 1977-1985, the original technical culture, bureaucratic accountability, and political accountability contributed to the normalization of deviance in official launch recommendations as follows:

The original technical culture required that rigorous, scientific, quantitative engineering arguments back up all engineering recommendations. As long as the managers and engineers in the Solid Rocket Booster work group had convincing quantitative data affirming risk acceptability (which they did), they could not interrupt the schedule to do tests necessary to understand *why* it was operating as it was. Policy decisions and impression management at the top eroded the ability of engineers to live up to some of the precepts of the original technical culture. Once the shuttle was declared operational, engineers could not request money for additional developmental testing unless analysis showed a component was an unacceptable risk.

It is important to point out that even though the agency was experiencing economic strain, the schedule was the problem, not money for hardware redesign. The budget was based on an over-optimistic launch rate. Budgeted to launch twelve in 1985, they actually launched nine. The inflated mission model gave them plenty of money for new hardware.[28] But unless data indicated a component was a threat to flight safety, delay was out of the question. Many launches were delayed during this period when data indicated a particular component was not an acceptable risk for an upcoming launch. Marshall and Thiokol engineers in the Solid Rocket Booster work group even delayed launches, one requiring a two-month postponement for a different booster problem. But within the culture, quantitative data were necessary: engineering concerns and intuitions were insufficient reason to interrupt the schedule.

Bureaucratic accountability contributed to the normalization of deviance in official launch recommendations in an ironic way. The sensemaking of managers and working engineers was affected by the fact that they followed all the rules. Interviews showed that the working engineers and managers assigned to shuttle hardware had not lost sight of the inherent riskiness and developmental nature of the technology. Indicating a healthy respect for their innovative design and the mysterious forces of nature it would encounter on a mission, many reported praying before every launch. Many experienced a "gut check," or a nauseatingly tight stomach every time countdown proceeded to its final stages. Macho risk taking was not in the cultural script of these managers and engineers, and in proof of it are the many times they canceled launches prior to *Challenger*.[29] In spite of their concerns about escalating O-ring problems, they reported a belief in their official launch recommendations to accept risk and fly that was based in bureaucratic accountability: if they followed all the rules, all the procedures, then they had done everything they could to reduce residual risk and to assure safety.

The Anatomy of a Mistake

Together, information and its context, a three-faceted organization culture composed of the original technical culture, political accountability, and bureaucratic accountability, and the NASA/contractor organization structure shaped the sensemaking of individual participants, and thus the *Challenger* teleconference outcome. Historic policy decisions changing culture and structure had dramatic impact. Two things are striking: the subtlety of their effect upon the proceedings; and that they affected managers and engineers alike. A few examples, condensed from a lengthy reconstruction, show how all factors combined to create a disaster.[30]

The launch decision was the outcome of a two-hour teleconference between 34 people gathered around tables in three locations: Morton Thiokol in Utah, Kennedy Space Center in Florida, and Marshall Space Flight Center in Alabama. Bear in mind that the participants came to the teleconference with a historic understanding of how the joints worked that was based on a cumulatively developed, science-based, paradigmatic engineering analysis that supported redundancy. The engineering analysis supporting risk acceptability in the past was a critical context for the discussion. Bear in mind also that this decision scenario was unprecedented in three ways:

- the predicted cold temperature was below that of any previous launch;
- although teleconferences were routine at NASA, launch decisions based on formal contractor engineering analysis and presentation always were discussed face-to-face in Flight Readiness Review, held two weeks before a launch;[31]
- Thiokol engineers had never before come forward with a no-launch recommendation.

Concern about the cold temperature arose earlier in the day. The influence of political accountability appeared immediately. When a Marshall manager telephoned contractor engineers at Morton Thiokol in Utah to see if they had any concerns about the predicted cold temperature, Thiokol engineers chose a time for the teleconference to begin. The engineers were used to working in a deadline-oriented culture deeply concerned about costs. If they could make a decision before 12:30 am EST, when the ground crew at Kennedy Space Center in Florida would begin putting fuel into the External Tank, they could avoid the costly de-tanking if the decision was "No-Go." NASA always de-tanked in the event a launch was canceled, but de-tanking was an expensive, time-consuming operation. So Thiokol engineers established an 8:15 p.m. EST starting time. As a consequence, the engineers had to hurry to put together the engineering charts containing their risk assessments. They divided up the work, taking responsibility for creating different charts according to specialization. Some people were putting together the final recommendation chart without seeing the data analysis charts the other engineers were creating. Unprepared at 8:15 p.m., they took the extra time necessary to finish the charts, but the full group did not examine and discuss all the charts prior to faxing them to people in the other two locations. Political accountability took its toll.

As it turned out, the engineering charts contained inconsistencies that did not live up to the standards of NASA's original technical culture.[32] The original technical culture required quantitative, scientific data for every engineering launch recommendation. However, patterns of information undermined the credibility of their engineering position. The charts contained mixed, weak, and routine signals. Thiokol's launch recommendation chart stated "Do not launch unless the temperature is equal to or greater than 53 degrees." They chose the 53 degree limit because that was the temperature of the coldest launch, which had suffered the most O-ring damage. However, data on some of the Thiokol charts contradicted the 53 degree limit they proposed.

One chart indicated that the O-rings would be redundant at 30 degrees; another indicated the second worst damage occurred at 75 degrees—the warmest launch. Thus, Thiokol's charts contained mixed signals that undermined the correlation between cold temperature and damage. Also, Thiokol engineers, hurrying to meet the teleconference deadline, had included some charts used in previous engineering presentations, *where the same data had been used to recommend launches.* To people in other locations, those charts were routine signals, because they had been seen before. Finally, the 53 degree limit was not based on quantitative data, but qualitative data: observations made in post-flight analysis of that particular mission. Within the positivistic norms of the original technical culture, the engineering analysis overall was a weak signal, insufficient to overturn the pre-existing, science-based engineering analysis that had supported redundancy and launch recommendations in all the previous years.

We see political accountability operating again, in the angry voices of Marshall managers who challenged Thiokol's data analysis and conclusions, intimidating the engineers. Infamously, Marshall's Larry Mulloy said hotly, "When do you want me to launch, Thiokol, next April?" Marshall managers would be the ones who would have to carry forward the launch recommendation and defend the engineering analysis behind it to top administrators in a system where schedule was important. Marshall managers frequently had delayed launches for safety reasons, but this time it appeared they would be in the position of arguing for delay with an engineering analysis that was, within the original technical culture, not only flawed, but based on observational data that were unacceptable for launch decisions. Moreover, political accountability was at work in another way: a 53 degree launch limit, if imposed for this launch, would stand as a new decision criterion for all launches—an awesome complication in a system required to meet a tight schedule. Under these circumstances, a tight engineering argument seemed particularly essential.

The effects of hierarchy and organization structure on the discussion were equally devastating. In three locations, people could not see each other, so words and inflections were all important. Midway in the teleconference, the people assembled at Morton Thiokol in Utah held an off-line caucus. In it, a senior

Thiokol administrator who knew little about the technology took charge, repeating the challenges of the Marshall managers. Without any new data to support their arguments, the engineers could not build a stronger data analysis. Four administrators in Utah reversed the original engineering recommendation, going back on-line and announcing that Thiokol had re-examined their data, reversed the decision, and recommended launch. When Marshall managers asked, "Does anybody have anything more to say?" no one spoke up. Ironically—and fatally—people at Marshall and Kennedy did not know that the Thiokol engineers still objected. Moreover, Thiokol engineers did not know that during the caucus, people at the other two locations believed the launch was going to be canceled. They also were unaware that the top Marshall administrator, participating in Alabama, was making a list of people to call in order to stop the launch.

Bureaucratic accountability also played a critical role in the outcome. In an unprecedented situation, all participants invoked the usual rules about how decisions are made. These rules were designed to assure safety. They included adversarial challenges to engineering analyses and charts to assure no flaws, insistence on scientific, quantitative evidence, hierarchical procedures, and norms about the roles of managers and engineers in engineering disagreements. In conditions of uncertainty, people revert to habits and routines. Weick, in research on firefighting fatalities, observed that those who died failed to drop their heavy tools at critical moments when doing so might have allowed them to escape an out-of-control wildland fire.[33] He pointed out that dropping tools is difficult because not only are firefighters trained that always having them in hand enhances safety, but also the tools are part of a firefighter's identity.

The rules and procedures of formal launch decision making and the original technical culture were the tools that assured managers and engineers in the Solid Rocket Booster work group that they had done everything possible to assure mission safety. In a decision-making crisis unprecedented in three ways, no one thought to do it a different way. This was a "no-launch" recommendation. Yet managers and engineers alike abided by all the usual rules and norms in an unprecedented situation where (hindsight shows) the usual rules were inappropriate. Adversarial challenges to engineering risk assessments were normative in Flight Readiness Review as a strategy to assure the rigor of engineering analyses. However, in a situation of uncertainty, perhaps a cooperative, democratic, sleeves-rolled-up, "what can we make of all this" decision-making session would have produced a different outcome than the adversarial legalism usually employed. Further, people in other locations had potentially useful information and opinions that they did not enter into the conversation because they were subordinates: rules and norms about who was empowered to speak inhibited them from talking on the teleconference.

Conformity to all three cultural imperatives permeated the teleconference proceedings. As Starbuck and Milliken put it, "People acting on the basis of habits and obedience are not reflecting on the assumptions underlying their actions."[34] If anyone could be argued to be deviant that night, it was the two

Thiokol engineers, Arnie Thompson and Roger Boisjoly, who continued to argue vigorously for safety based on observational data—a position that they were aware violated the mandates of the original technical culture, political accountability, and bureaucratic accountability. Although a quantitative argument always was required for a "go" launch decision, engineering concern and hunches should have been enough to stop a launch. But retrospection also shows a great irony: had they dropped their tools and done it differently, they might have discovered that they did have the data to put together an engineering analysis that was a sufficiently strong signal to delay the launch.[35]

Impact: The Post-Disaster Period

Whenever organizations have tragedies that cost lives, post-disaster activities seem to follow patterns that have near ritualistic qualities: a public investigation; flaws and errors leading to the tragedy are identified; a set of recommendations to prevent similar incidents is made, followed by a period of implementation, change, and high-attention to problems. The public is quieted and business-as-usual resumes. NASA followed this pattern.

Initially, there was shock and grief. Grieving personnel automatically began to act in their organization roles, trying to figure out what had happened: saving and backing up console data; examining telemetry data; beginning a fault tree analysis to find the cause of the technical failure. At the same time, the agency was bombarded by questions from devastated astronaut families, Congress, the White House, the press, and an angry public seeking an explanation. Significantly, top NASA officials had not created a plan about how to handle the social consequences if mission and crew were lost, and chaos reigned. The Presidential Commission was formed and an official investigation was conducted. The Commission's investigation created a huge extra workload, as relevant personnel were interviewed, documents pre-dating the disaster were retrieved, photocopied, listed, and turned over, and NASA's own internal accident investigation got underway.

Typical of other cases when organizational failures cost lives, the workload dramatically increased at a time when people needed to grieve. NASA and Thiokol were torn by internal conflict, finger-pointing, and official and unofficial attempts to save face. Teleconference participants blamed each other, lodging responsibility for the disaster in the failure of other individuals on that fateful night. They grappled with the loss of their astronaut colleagues and their own possible contribution to their demise. Not knowing the answer themselves, they struggled to answer the questions of family and friends about why the astronauts had died. Most difficult were those of other astronauts and their own children, who had been watching the "Teacher in Space" mission in classrooms. In retrospect, the official investigators, the public, and NASA personnel saw clearly the signals of danger that had looked so different to insiders as the problem unfolded. Teleconference participants focused on the past, identifying turning points where they should have acted differently, passionately wishing they had said or done other than they had. They feared for themselves, their jobs, the agency, and the future. While they had understood all along that failure was always possible, the awareness that they had followed all the usual rules and procedures and still lost *Challenger* generated deep doubts about the organization, its mission and capabilities, and their own competencies. People dealt with their grief in different ways. Some have never resolved it. Unable to move forward, they still focus on the past, working it through again and again.

Then the post-disaster ritual entered a different phase: the report of the official investigation and a series of recommendations that targeted the causes the Commission identified. In common with most post-disaster rituals, the investigation following *Challenger* focused attention on the physical cause of the accident and the individuals responsible for the flawed decision: middle-level managers at Marshall Space Flight Center. Having identified the causes of the disaster, the strategy for control was fairly simple: fix the technology, replace the responsible individuals, and tighten up decision rules. In terms of individual accountability, middle managers were, of course, responsible. But their isolation in the spotlight deflected attention from the responsibility of top decision makers who made political bargains, established goals, allocated resources, and made other key decisions that altered both the structure and culture of the agency, converting it from an R&D organization to a business complete with allegiance to hierarchical relations, production cycles, and schedule pressures. It was top NASA administrators who elected to take civilians on shuttle missions, not the technical people who attended the teleconference. The emphasis on individual middle managers also obscured from the public the truly experimental nature of the technology, its unpredictability under even the best of circumstances, and the logical possibility of another failure. The final phase of the post-disaster ritual was completed when the Commission's recommendations were implemented, convincing the public that the disaster was an anomaly that would not recur. Spaceflight resumed.

The Connection Between Cause and Control

The *Challenger* disaster cannot be accounted for by reductionist explanations that direct attention only toward individual actors, nor theories that focus solely on communication failure or the social psychological dynamics of the teleconference itself. Several scholarly accounts published in the years since the disaster have concluded that Janis's theory of Groupthink—perhaps the leading theory of group dynamics and decision making—was responsible for the launch decision.[36] But many of the elements of Groupthink were missing, and those that were present have explanations that go beyond the assembled group to cultural and structural sources.[37] It was, as sociologist Robert K. Merton has so famously written, "the unanticipated consequences of purposive social action."[38] To a great extent, group dynamics during the teleconference—and the outcome

—were shaped by decision makers not present at the teleconference who made historic political bargains that caused political accountability and bureaucratic accountability to become institutionalized and taken-for-granted in the workplace, having a profound impact on the proceedings.

Mistakes are indigenous, systematic, normal by-products of the work process,[39] and thus could happen in any organization, large or small, even one pursuing its tasks and goals under optimal conditions. The possibility of error and mistake are exacerbated by the complexity of risky work: the more complex the technology, the more complex the organization, the greater the possibility of the kind of "failures of foresight" that Turner identified.[40] When environmental contingency, politics, and structures of power are added to this formula, risky work becomes even more risky. We can never eliminate the possibility of error and mistake in organizations. For this reason, some kinds of risky work are too costly to society to undertake.[41] For others, however, learning from failures as well as successes can reduce the possibility that failures will occur.[42] Errors and failures come in many varieties, so the lessons will vary from one to another. Keep in mind that the *Challenger* disaster was an organizational-technical system error, the former feeding into the latter, so there are many lessons.[43] Here we focus only on three strategic targets that flow from this discussion: policy decisions, organization culture, and the sending and receiving of signals.

Target Elite Decisions

Safety goals routinely get subverted as administrators respond to environmental forces, both to further the survival of the organization and their own interests. *Top administrators must take responsibility for mistake, failure, and safety by remaining alert to how their decisions in response to environmental contingencies affect people at the bottom of the hierarchy who do risky work.* The obstacles to achieving this goal are great, making it perhaps the most difficult strategy to employ.[44] First, accidents and errors in risky work tend to get blamed on the proximate cause—human error by operators (nurses, firefighters, case workers, technicians, anesthesiologists, assemblyline workers)—rather than the administrators who determine the conditions in which they work. Second, policy decisions have deferred results, so that by the time a failure occurs, responsible administrators have left the organization or are in other positions in it, so are not publicly associated with the harmful outcome. Third, the "politics of blame" protects the powerful when organizations have bad outcomes.[45] The *Challenger* case explicitly shows the relationship between goal-setting, negotiations, and bargains with external competitors, suppliers, regulators, and customers. One obvious lesson is the importance of policy that brings goals and the resources necessary to meet them into alignment. When this is not the case, the organization is in a condition of strain, with the people responsible for the hands-on work caught in the squeeze, increasing risk and the possibility of mishap, mistake, and disaster.

Decisions to change organization structure should not be undertaken without research evaluating the effect on safety. Changes that make the system more complex

—as many do—also create new ways an organization can fail.[46] Efforts to downsize, which in theory should enhance safety by reducing system complexity, may enhance safety in the long run. But in the short run, the organization may encounter "liabilities of newness"[47] that create new possibilities for error. Altering the structure of an organization can also alter the culture, in both visible and imperceptible ways. When structure is in transition, risk of error and mistake increases as cultures combine and clash, old ways of doing things conflict with new, the institutional memory is lost as files are thrown out and people are discharged or moved, technological changes are introduced. Observers trained in field methods—organization theorists, anthropologists, sociologists—could act as consultants both in planning and implementing change.

Top administrators must remain in touch with the hazards of their own workplace. Administrators in offices removed from the hands-on risky work are easily beguiled by the myth of infallibility. After the *Challenger* disaster, media reports charged that a "can-do" attitude at NASA contributed to the technical failure. That "can-do" attitude was not equally distributed throughout the organization, however. Working engineers at NASA remained keenly aware of risks and the developmental, experimental character of shuttle technology, but three policy decisions, in particular, indicated that NASA top administrators had lost touch with, minimized, or ignored the failure possibilities of the shuttle: extensive cuts to NASA's internal safety regulatory system after the shuttle was declared operational;[48] taking civilians on missions, as part of their attempt to convince Congress and commercial satellite customers that shuttle flight was routine and safe; and the absence of a plan about what to do in the event of a disaster.

Plan for the worst-case scenario. Because a failure has not happened does not mean that one can not happen. If a post-disaster plan is not in place, top administrators should develop one and set aside resources for enacting a strategy to effectively counteract the social harm of a technical failure. Lee Clarke's research on the Exxon *Valdez* oil spill and other failures shows that most disaster plans are not based in reality, but "fantasy documents," underestimating harm and backed by insufficient resources to control a disaster situation.[49] A plan should encompass both the physical consequences of error and human recovery of affected people. Administrators should also consider how employees can best be helped to move on. One possibility would be to make counseling available to help co-workers deal with the deep emotions experienced when organizations are responsible for social harm. Not only is it humane to do so, but in the long run properly coming to grips with individual feelings may help assure future safety. Implementing the plan deserves equal attention. Even the best of plans can fail because organizations seldom devote the same attention to developing an implementation strategy.[50]

Target Culture

Don't make assumptions about organization culture. Although aspects of culture—certain norms, values, and beliefs in an organization that are shared—may be obvious, typically cultures have great variation and diversity.[51] In the *Challenger* incident, the organization culture was much more complicated and its effects on decision making more subtle and hard to detect that even insiders realized. As members of an organization, we are sensitive to certain aspects of the culture, resisting it, but others become taken-for-granted, so that we unquestioningly follow its dictates without realizing exactly what the culture is, how it is operating on us, or how we both use and contribute to it. Research could provide some insights into culture that might prevent future "failures of foresight."

Rules—and whether to obey them or not—are part of an organization's culture. Organizations create rules to assure safety. But in practice, the rules themselves may create additional risks. *In order to assure effective systems of rules, research should examine both rule following and rule violating behavior in normal work situations.* Organizations would benefit from learning how extensive rule violations are, which ones are violated, and why. People violate rules for numerous reasons.[52] A rule may be complex, so is violated out of lack of understanding; a rule may be recent, so people are unaware of it; a rule may be vague or unclear, so is violated because people don't see that it applies to the situation they face; a rule may be perceived as irrelevant to the task at hand, or in fact an obstacle to accomplishing it, so the rule is ignored; a rule may conflict with norms about how best to get the work done. A particularly challenging administrative problem that we can extract from the *Challenger* tragedy is how to instill a rule-following mentality that will assure coordination and control in a crisis, and at the same time teach people to "drop their tools:" to recognize the situation for which no rules exist and for which the existing rules do not apply.

Cultural assumptions about diversity exist in the workplace. Workgroups, teams, and organizations can be a diverse social composite: sex, race, ethnicity, social class. Also important, members often differ in experience. Kanter identified problems that result from skewed distributions in organizations.[53] *To mitigate risk, research could also explore the effects of diversity on safety.* For example, how do contingent workers and core workers relate to one another, and what can be done to develop reliable working relationships? What are the effects of age, race, gender, or experience differences on decision making? Does diversity affect deployment of personnel and job assignments, so that some are underutilized as resources? Do all employees get the same quality feedback on their performance?

Target Signals

Weick stresses the importance of sensemaking in organizations, pointing out that information and how it is interpreted is critical to safety.[54] The social organization of information and its context affected the interpretation of both written and oral exchange about risk at NASA. In organizations where most people are buried in paperwork, signals conveyed in written form can easily be lost, ignored, or misinterpreted. Technical language creates standard ways of communicating that neutralize language as a means of communicating risk and danger. *In decision making, all participants should be alert to the categories of mixed, weak, routine, and strong signals and how they influence others' interpretation of a situation, and therefore, how those others respond.* A challenge for organizations is to design systems that maximize clarity of signals and to train individuals to do the same in written and oral communication about risky work.

Minimizing missing signals is another challenge. In face-to-face discussions, not only words and actions, but inflection, gestures, and body language affect how others make sense of what is happening. Face-to-face communication in an important decision-making situation has obvious advantages over written communication, e-mail, or teleconferences, but still is no guarantee. Professional or organizational status can silence subordinates. *Extra effort must go into assuring that all relevant information gets entered into the conversation.* Significant in the eve-of-launch decision were the many missing signals: Thiokol engineers did not know support existed for their view in other locations; information important to the engineering discussion did not get brought up, and so forth. There is nothing so deadly in a crisis as the sound of silence. It is prosaic but worth repeating to acknowledge that subordinates, newcomers, and others who feel marginal or powerless in an organization often have useful information or opinions that they don't express. Democratic practices and respectful practices empower people to speak. However, some kinds of information will still be hard to pass on in settings where people are trained that suppressing individuality to the collective well-being and following the commands of a leader are central to safety. More difficult still is passing on information contradicting what appears to be the leader's strategy or the group consensus. This is the equivalent of two engineers continuing to argue "don't launch" when all around them appear to want to go.

Beware the slippery slope. From 1977-1985, Thiokol and NASA working engineers gradually expanded the bounds of risk acceptability in official risk assessments. Although some engineers expressed concern informally, in official decision-making venues they recommended that the boosters were an acceptable flight risk. The long incubation period that Turner identified as typical in man-made disasters existed at NASA. Hypothetically, a long incubation period would provide more opportunities to intervene. The normalization of deviance in official launch decisions during the years prior to the *Challenger* launch raises an important issue. Sensitivity to risk is essential in organizations that deal with hazards. Yet collective blindness is also possible in an organization where change is introduced gradually, routinization is necessary to accomplish tasks, problems are numerous, and systems are complex. Patterns of information and the wider problem context may obscure gradual change, indicated by signals of potential danger that emerge incrementally. The challenge for administrators is how to develop the kind of common frame of reference necessary for a "collective mind" and "heedful interrelating" in risky decision settings,[55] and still encourage the fresh perspective, the deviant view, the "stranger's eyes" that will be sensitive to gradually developing patterns that normalize signals of potential danger, leading to failures of foresight, mistake, and disaster.

Notes

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4. See, e.g., G. Allison, *The Essence of Decision: Explaining the Cuban Missile Crisis* (Boston, MA: Little, Brown, 1971).
5. B. Turner, *Man-Made Disasters* (London: Wykeham, 1978).
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7. Presidential Commission, *Report*, op. cit., vol. 1, p. 148. See also R.P. Feynman, "Personal Observations on Reliability of Shuttle," in Presidential Commission, *Report*, op. cit., vol. 2, Appendix F.
8. W.H. Starbuck and F.J. Milliken, "*Challenger*: Fine-Tuning the Odds until Something Breaks," *Journal of Management Studies*, 25 (1988): 319-340.
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10. B. Wynne, "Unruly Technology: Practical Rules, Impractical Discourses, and Public Understanding," *Social Studies of Science*, 18 (1988): 147-167.
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12. For illuminating general discussions, see M.S. Feldman, *Order Without Design: Information Production and Policy Making* (Stanford, CA: Stanford University Press, 1989); and A.L. Stinchcombe, *Information and Organizations* (Berkeley, CA: University of California Press, 1990).
13. Vaughan, op. cit., pp. 243-264.
14. Ibid., pp. 154-163.
15. Presidential Commission, *Report* , op. cit., vol. 1, p. 135.
16. Although after the disaster Boisjoly strongly objected to NASA middle managers' failure to pass information about problems on this mission up the hierarchy, contradictory to the conventional wisdom, Boisjoly's own Project Manager A. McDonald participated in this decision, and both McDonald and Boisjoly agreed that the temperature data were inconclusive, which was the reason Marshall and Thiokol Project Managers did not carry it forward. Vaughan, op. cit., pp. 157-161.
17. Roger M. Boisjoly, personal interview by author, February 8, 1990.
18. Emerson, op. cit., p. 433.
19. Vaughan, op. cit., pp. 246-247.
20. H.E. McCurdy, *Inside NASA: High Technology and Organizational Change in the U.S. Space Program* (Baltimore, MD: John Hopkins University Press, 1993); P. Tompkins, *Organizational Communication Imperatives: Lessons of the Space Program* (Los Angeles, CA: Roxbury, 1993);W.A. McDougall, *And the Heavens and the Earth: A Political History of the Space Age* (New York, NY: Basic Books, 1985).

21. M. Wright, Office of Space History, Marshall Space Flight Center, Huntsville, Alabama, personal interview by author, June 2, 1992; Tompkins, op. cit.
22. Vaughan, op. cit., pp. 89, 91, 202, 208, 221.
23. Vaughan, op. cit., pp. 82-84, 90-95.
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25. A. Roland, "The Shuttle: Triumph or Turkey?" *Discover* (November 1985), pp. 29-49; Vaughan, op. cit., pp. 17-28, 209-227.
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27. Romzek and Dubnick, op. cit.; Tompkins, op. cit..
28. Vaughan, op. cit., p. 235.
29. P. Humphlett, "Shuttle Launch Delays," Science Policy Research Division, Congressional Research Service, Library of Congress, Washington, D.C., February 25, 1986, reproduced in Vaughan, op. cit., p. 51-52.
30. Vaughan, op. cit., pp. 278-386.
31. Two weeks earlier, at the Flight Readiness Review for *Challenger*, the Thiokol engineers had presented a risk assessment that recommended the boosters were safe to fly.
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34. Starbuck and Milliken, "*Challenger*: Fine-Tuning the Odds," op. cit., p. 324.
35. Vaughan, op. cit., pp. 382-383.
36. I.L. Janis, *Groupthink* (Boston, MA: Houghton Mifflin, 1982). See, for example, J.K. Esser and J. S. Lindoerfer, "Groupthink and the Space Shuttle Challenger Accident: Toward a Quantitative Case Analysis," *Journal of Behavioral Decision Making*, 2 (1989): 167-177; A. W. Kruglanski, "Freeze-think and the Challenger," *Psychology Today* (August 1986), pp. 48-49.
37. For example, the antecedent conditions that Janis posits were not present. In fact, the constraints on collective thinking that Janis suggests should be present, were present, scripted in the proceedings by organizational rules and norms. Teleconference participants were not an "inner circle" consisting of a cohesive small group of decision makers who liked each other and valued membership in the group. Instead, 34 people were present; not all knew each other; and several had not even participated in launch decisions before. Physically, the group was insulated from others in the organization, but NASA's matrix system functioned to bring in experts not normally assigned to the Solid Rocket Booster Project, specifically to interject alternative views and information. The discussion did not lack norms requiring methodical procedures for decision making. It was guided by norms and rules of the organization about how technical discussions must be conducted. Readers interested in pursuing this issue should see D. Vaughan, op. cit., Chapters 8 and 9, and the detailed discussion of groupthink at p. 525, n41.
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44. For detailed discussion, see Sagan, op. cit.; C.B. Perrow, "The Limits of Safety: The Enhancement of a Theory of Accidents," *Journal of Contingencies and Crisis Management*, 2 (December 1994): 212-220.
45. S.D. Sagan, *The Limits of Safety*.
46. Perrow, op. cit.; Sagan, op. cit.; Vaughan, op.cit.
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