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Abstract: This report discusses the role of communication feedback during product development. Three case studies are detailed to identify the reasons why feedback failed and what the consequences of that failure have been. The cases are Three Mile Island, Ford Pinto, and the space shuttle Challenger.

NEGATIVE FEEDBACK COMMUNICATION IN PRODUCT DEVELOPMENT

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NEGATIVE FEEDBACK COMMUNICATION IN PRODUCT DEVELOPMENT

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• Your title can be "Communication Feedbacks in Product Development"

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Executive Summary

This paper will discuss the role of negative feedback communication during product development. Three case studies were studied in detail to identify the reasons why negative feedback communication failed and the consequences of the failure. A common set of failures in negative feedback communication were compiled from the three case studies. Each type of failure was discussed as far as the root cause of the failure, and what possible changes could be made to either eliminate the source of the failure or greatly reduce the risk of failure.

The three case studies were:

Ford Pinto
Space Shuttle Challenger
Three Mile Island

A literature search was done for each case study. Journals, periodicals, magazines and books were consulted for information. Specific root causes as to why the negative feedback communication failed to result in corrective action were identified. The root causes were grouped into three generic failures as a result of round table discussions involving each of the authors. The three major reasons for failure in negative feedback communication that were identified were:

- Psychological Barriers: Compromise of personal ethics. This includes the personality differences in individuals, and the emotions that individuals exhibit.

- Sociological Barriers: The attitudes, beliefs, values and ethics of the upper management (also known as mindset). Corporate ambience and climate are the melting pot of the attitudes, beliefs, values and ethics of management. The importance of goals and objectives also contribute to the mindset of the organization.
- Mechanical Barriers: The organizational structure of the company. This includes the lack of a negative feedback communication channel or no defined responsibility with management.

After identifying the three major root causes of failure in negative feedback communication, the paper discussed recommendations to reduce the risk of the failure or eliminate the cause of the failure.

The single most significant barrier to negative feedback which requires constant self inspection by management is the mindset within the organization. The mindset of the organization can be dictated by the personal ethics, attitudes, beliefs and values of upper management and can have either a positive or negative effect on the organization. Management must always strive to ensure that the organizational mindset has a positive effect.

How could a company knowingly market a dangerous product? How could an organization recognize the potential for disaster, yet proceed as usual? How could an industry, aware of its own hazards, disregard previous warning signs? These are the scenarios which actually occurred with the Ford Pinto, the Space Shuttle Challenger, and Three Mile Island. What went wrong? Our history is full of events such as these which probably could have been prevented.

The common element in these cases is the lack of effective negative feedback communication. The communication cycle, in its simplest form, can be described as a loop, which at any given time includes a sender and a receiver. Negative feedback communication is the receiver's attempt to alert the sender of a potential problem with previously communicated information, and in doing so, affect a positive response. For effective communication, the negative feedback information must induce corrective action.

The purpose of this study was to explore why negative feedback is often unsuccessful at obtaining a remedial response, and to make recommendations based on the understanding of the causes. This study bridges several disciplines, including communications, personal and organizational ethics, and whistle-blowing.

The catastrophic consequences of the Ford Pinto, the Space Shuttle Challenger, and the accident at Three Mile Island were chosen for examination. Each case study includes a definition of the design problem, a description of the events surrounding the problem, and an analysis of the communication between engineering and management. The wide variance of organizational types and products illustrates the universal nature of the problem and allows us to compare and contrast the causes and to arrive at generic recommendations.

Since its introduction in 1970 until the 1976 model year the FORD Pinto had a dangerous tendency to burst into flames when struck from the rear. The following is a brief description of the design that caused this problem and a description of the sequence of events surrounding the Pinto.

FORD Pinto Design Flaws

The design of the Pinto contained several serious problems, mostly relating to the position of the fuel tank. The fuel tank was positioned approximately six inches behind the rear bumper, below the trunk. A major problem with this design was that the fuel tank was located in the 'crush zone'. The crush zone is the portion of the car that is supposed to be crushed on impact, providing a shock absorption effect. The reason for using a crush zone is to reduce the number and severity of serious injuries, such as whiplash, to the passengers of the vehicle. Crushing the fuel tank may cause it to burst from hydraulic pressure. A second major problem with the fuel tank positioning was that the ends of sharp axle bolts were located several inches in front of the fuel tank. In a rear end collision, the fuel tank could easily be shoved forward and be punctured by these bolts. Finally, the fuel filler tube, which was inserted in, yet not attached to the fuel tank, could pull out quite easily if the tank were shoved forward during an impact. This allowed fuel to spill from the tank into other areas of the vehicle. Another indirectly related problem involved its windshield. In July of 1970, the first Pinto prototype was tested to comply with Federal Motor Vehicle Safety Standard #212 - Windshield Retention. The windshield continually failed.

Sequence of Events

FORD wanted to quickly market an automobile that would compete with foreign and domestic subcompacts. Their plan was to have a sporty subcompact weighing less than 2,000 pounds and costing less than $2,000. The appearance, price, and weight were frozen very early in the development cycle. Therefore, the usual give and take between styling and engineering feasibility was disrupted. Additionally, top management pressured the design team to produce this automobile as quickly as possible.

After reviewing the design, several of the engineers voiced their concerns about the vulnerability of the fuel tank in the event of a collision. They suggested that the fuel tank be moved to a safer position, such as straddling the rear axle. This moves the fuel tank out of the crush zone and puts it in a position where it is protected by the chassis (the FORD Capri uses this design). After reviewing the proposed change, top management decided that previously stated design constraints would remain intact.

In 1970, evidence of the seriousness of the problem came from FORD's internal testing. The type of testing that is most important to this case involves backing the vehicle into a fixed wall at various speeds to determine fuel loss if/when the tank is damaged. Crashing into a fixed wall at 30 mph is approximately equivalent to a rear end collision with an impact speed of 45 mph. FORD's testing showed that the Pinto was clearly inferior to all other tested vehicles with respect to fuel tank integrity. In one set of tests, a Capri was modified to have its fuel tank positioned similar to that of the Pinto (in the rear of the car, immediately behind the bumper). When tested, the Capri suffered similar damage to the fuel tank. This clearly demonstrated the danger of positioning the Pinto's fuel tank in the crush zone. Similar tests done (with the fuel tank moved to the 'crush zone') with other makes of automobiles showed the same problem. It should be noted that the standard Capri was able to withstand the most stringent tests with little or no fuel leakage. Unquestionably, FORD was capable of building a car with a fuel tank that would stand up to the rigors of rear end collisions. At the same time, tests involving windshield retention were also failing.

Generally, after such failures, a complete engineering analysis of all results determines a necessary course of action. However, in the case of the Pinto, the vehicle which would 'meet the challenge' of foreign competition, the analysis was squelched. The tooling for production had already been completed and the production schedule had been set. Management decided that the Pinto would be certified *at all costs*. Unfortunately, these instructions from FORD management disallowed any substantial structural design changes and refused any consideration of remedies which would increase costs.

In 1971, the Federal government proposed making all new automobiles pass a rear end crash test. This law would have been phased in over two years, with more stringent requirements coming in the second year. The requirements would have been far too stringent for the Pinto to pass.

FORD's reaction to the proposed legislation was twofold. First, they and several other major automobile manufacturers banded together to lobby against the proposed legislation. Second, FORD designated a task force to look into the problems with the Pinto fuel tank and propose some solutions in the event that the legislation passed.

The lobbying efforts were very successful, managing to push off the proposed law by more than four years. When the law did pass, the standards had been substantially reduced.

FORD's task force was able to make a large number of suggestions that would have increased the relative safety of the vehicle. (The prices, where indicated, are per vehicle.)

Move tank and install sheet metal barrier, $9.95.
Put a strong rubber bladder inside fuel tank, $6.00
Use 'tank in a tank' construction, with polyurethane liner, $5.08
Use a nylon shield to protect the fuel tank, $0.44
Smoothing axle to remove sharp protrusions, $2.10
Repositioning spare tire to absorb some of the impact energy, n/a
Add body rails to strengthen rear end, $2.40
Attached tank end of fuel filler pipe, n/a

FORD management decided that no gas tank improvements would be made until they were "required by law". Consequently, no design changes were made to alleviate fuel tank problems. Since there were standards in place concerning windshield safety, FORD was forced to address this problem. The final solution *attempt* involved rechanneling some of the resulting impact energy away from the windshield through the drive shaft to the differential housing and the gas tank. In October of 1971, 5 of 7 windshield crash tests failed. The two successes were reported as indicative of the Pinto's windshield reliability. The Pinto windshield was finally certified. In 1972, Pinto collisions resulting in gas tank explosions could, in part, be directly related to the rechanneling of impact energy to the gas tank.

Simultaneous to the introduction of the Pinto, FORD attempted to justify (to themselves) their position of not modifying the Pinto gas tank design. To do this, FORD pressured the National Highway Traffic Safety Administration to provide a dollar amount for loss of human life and suffering. Taking this information, along with its own, FORD produced a cost/benefit analysis for implementing fuel tank safety features into its cars and light trucks.

Based on the following figures, FORD determined the benefits of adding safety features to the fuel tank to be $49.5 million (based on 180 accidents per year).

Human life, $200,000 x 180 incidents
Serious burn injuries, $67,000 x 180 incidents
Destroyed vehicle, $700 x 180 incidents

Based on a cost of $11 per vehicle, FORD determined the cost of implementing the safety features to be $137 million.

It was thus concluded that it was not cost efficient to add an $11 part to each car to prevent 180 burn deaths and 180 serious burn injuries per year.

In 1973, when problems with the Pinto were becoming apparent through highly publicized court cases, one of the design engineers responsible for the Pinto's windshield testing felt compelled to confront management. Frank Camps began with several letters to management explaining the actions which had taken place during testing. He wrote about known violations of federal law, unethical decisions made by management in suppressing information, and the restrictions put on engineering. Management's only response was a downgrading in the appraisal of his performance.

During 1974, Frank Camps continued on his crusade to inform management by initiating several meetings with the purpose of resolving these problems. In December, he was removed from engineering testing to positions unrelated to any compliance with federal standards.

More meetings and letters followed in 1975 and early 1976. In mid 1976, in the wake of several allegations against some prominent American companies, Henry Ford II issued the "Standards of Corporate Conduct" policy. The policy stated that: concerns about illegal or unethical acts within the company should be brought to the attention of the Office of General Counsel.

An elated Frank Camps responded to this statement with a letter to the Office of General Counsel in June 1976,

> ... I wish to once again voice my views regarding questionable decisions in Federal Motor Vehicle Safety Standards compliance made... (during the early 1970's). I suggest that during the past three years, while endeavoring to bring these irregularities to the attention of upper management, I have been misled and misinformed by my supervisors... I am shocked at the deceit and intimidation used to abort any real attempt to objectively review the facts which are clearly supported by existing corporate records...

During the next six months, several meetings were scheduled and subsequently cancelled. In February 1977, one final letter to the general counsel's office resulted in a promise of action (as far as a meeting was concerned). Nothing followed.

Finally, in 1978, FORD was forced by the federal government to recall the Pinto. FORD began the task of recalling 1.5 million automobiles to make them *less vulnerable* to fuel tank damage. It is interesting to note that FORD did not send out any advance warning that the recall was imminent, citing public relations issues. They felt that their customers would be very angry if parts were not immediately available. Had FORD informed the public immediately instead of waiting for the recall kits to be complete, several deaths might have been prevented. For the 1979 model year, FORD permitted design changes to the Pinto that would allow it to consistently pass the windshield tests.

Analysis of Communications

The initial design review presented to management by engineering brought out several potential hazards, yet management could not effectively disseminate the information. The competitive nature of the automotive industry forced Ford's management into a reactionary mode. In order to maintain and/or increase market share and therefore profits, Ford recognized an urgency to compete with foreign auto makers. They were determined to produce THIS vehicle with the previously stated design criteria. The climate within Ford would not allow compromise; in order to compete, "it had to be done this way".

All test results reported by engineering were absolutely conclusive in demonstrating the serious nature of the problems with Pinto gas tank. Ford's management clearly received all test information and was aware that repositioning the gas tank would make the vehicle safer. However, management's perception was that the fuel tank problems were not significant. They had become very narrow minded in their quest to compete and were not receptive to negative input. The acknowledgement of the possible existence of design flaws would have destroyed the mindset.

Ford had set up a system for providing solutions to potential design problems. However, management had predetermined that the design was final and therefore began to prepare for production. Consequently, the usual analysis of test results was forgone. Management overruled the engineers' concerns and continued with the production schedule. Their decision to continue was based primarily on their desire to produce the vehicle as quickly and cheaply as possible. Redesign would require retooling, thus increasing costs and delaying production.

In the case of the fuel tank, Ford's management decided to proceed with the original design. Their reasoning was that federal standards for fuel systems did not exist. However, there were standards for windshield retention which Ford could not ignore. Management chose to address this problem by selective reporting to the government. Again, they were driven by the cost and time factors.

The cost/benefit analysis performed by Ford shows their awareness of the problem and exemplifies their single-minded drive for profits. Interestingly, they did not consider the potential loss of sales due to public disdain for the basis of their decision.

Frank Camps unsuccessfully attempted to make Ford management acknowledge and take responsibility for previous decisions regarding windshield standards. Undoubtedly, Ford was in a precarious situation. Taking responsibility meant admitting fraud to the Federal Government. Not only would their already suffering reputation be tarnished further, but there undoubtedly would have been action taken by the government.

Frank Camps was unable to receive any action from Ford management even by following the procedures set forth in the "Standards of Corporate Conduct" policy. Apparently, the policy was merely a public relations ploy. Providing policies of this nature give both consumer and the employee the impression that the company is not concerned solely with profits.

Conclusion

In the case of the Ford Pinto, channels existed for effective communication to top management, and all essential internal communication did take place. This is an example of an organization which became driven by profits to the exclusion of ethical considerations. The question remains: What, if anything, could have altered this sequence of events?

First, and foremost, would have been Ford's genuine commitment to public safety, as well as profits. Ford had a system in place which would have worked if management had used it. In this situation, the engineers' design concerns were overruled by management's dollar concerns.

What about the responsibilities of the design engineers?

There are many avenues that the engineers could and perhaps should have taken.

- Notifying the government.
- Professional Engineering Organizations.
- Community Organizations/Newspaper.

Since that time, the government has implemented safety standards requiring safer design of fuel tanks. However, as shown in Ford's handling of the federal windshield standards, this "obstacle" can be overcome. There is also the possibility of more regulated enforcement of vehicle safety standards. Yet, this may not remedy the problem either.

The following case study will discuss the design problem and sequence of events relating to the Space Shuttle Challenger Disaster that occurred on January 28, 1986.

The Design Problem

The Space Shuttle's Solid Rocket Booster (SRB), produced by Morton Thiokol, had a major design problem in the field joint. A field joint is a location in the SRB where sections of the SRB are joined together. The joints have a tang which fits into a Y-shaped clevis (See Figure 1). The joints are sealed by two rubber O-rings which are installed during the assembly of the SRB.

Zinc chromate putty is used as a thermal barrier to prevent direct contact of combustion gas with the O-rings. The O-rings themselves were designed to actuate and seal the gap between the tang and clevis when the putty is displaced during the ignition transient. If the O-rings do not actuate and seal during the ignition transient, then the rocket's combustion gases will blow-by the O-rings and damage or destroy the seal.

The joint sealing performance is sensitive to the following factors:

1) Damage to joints/seals as they are assembled
2) Tang/clevis gap opening due to motor pressure
3) Static O-ring compression
4) Joint temperature
5) Putty performance

Because of the low temperature of the field joint at launch, the O-rings resiliency was seriously degraded, causing the O-rings not to actuate and seal during the ignition transient. As a consequence, hot gases escaped past the O-rings and leaked out the aft field joint. This combustion gas leak penetrated the External Tank and initiated the structural breakup and destruction of the Space Shuttle Challenger during STS Mission 51-L.

Sequence of Events

The inherent unreliable design of the solid rocket boosters field joint were known to the Marshall Space Center engineers in 1977. For three years, engineers in Marshall's Solid Rocket Booster Project wrote memoranda to the Project Manager, George Hardy, strongly suggesting that the current Thiokol field joint design was unacceptable. One memo written in 1978 by Marshall's Chief of the Solid Rocket Motor branch indicated that the design was so hazardous that it could produce "hot gas leaks and resulting catastrophic failure".

These memos were not forwarded to Morton Thiokol. The alarming concerns of knowledgeable Marshall engineers did not result in a redesign of the Solid Rocket Booster field joint before flights began. In September 1980, the Shuttle Verification and Certification Committee recommended that the SRB field joints be accepted for flight.

A change in the reporting requirements was initiated by Glynn Lundey, Level II (See Figure 5) manager in 1983. This changed the organizational structure in that all flight safety problems, trend problems, and close out actions were no longer reported to Level II unless the problem was associated with hardware and was not flight critical. This requirement was substantially reduced to include only problems relating to common hardware problems or physical interface elements.

After a few flights took place in the early 1980's there was sufficient evidence from the recovered SRB's that the primary O-ring in the aft field joint of the right hand SRB had been badly eroded by the hot combustion gases. The Marshall and Thiokol engineers thought they had the situation in hand. They felt that the erosion of the O-ring occurred in the first 200 or 300 millisecond ignition transient, and after that, the O-rings would seat in their grooves and the pressure seal would be complete. The engineers at Thiokol considered this an "acceptable risk".

In an effort to justify not stopping the shuttle flights, the Marshall and Thiokol engineers stated that it was safe to continue flying the existing design as long as all joints were leak checked with 200 psig (pounds per square inch gas) stabilization pressure, were free of contamination, and met O-ring squeeze requirements. However, the effects of raising the test pressure made the O-ring distress worse on subsequent flights. Over half of the subsequent flights experienced O-ring erosion or actual blow-by of hot gases. The term blow-by means that during the ignition transient, the hot gases would blow by the field joint sealing putty. The higher pressure leak test was actually creating "blow holes" in the sealing putty, which gave the super hot ignition gases a clear route to the O-rings. Marshall engineers, after realizing that the test was making the field joint integrity worse, told Thiokol that they were concerned about the effects of the test procedure. Thiokol's progress in analyzing the test procedure was slow, causing Marshall engineers to write internal memos complaining about Thiokol's slow progress.

By the summer of 1985, the Marshall and Thiokol engineers realized that they were risking disaster by allowing shuttle flights to continue despite the chronic O-ring erosion. At Thiokol, a field joint redesign task force was assembled by Thiokol's Vice President of Engineering, Robert Lund on August 20, 1985. Their charter was to fix the joint rotation and the O-ring damage problem. Joint rotation is caused by the sudden expansion of the solid rocket booster during the ignition transient at the beginning of the liftoff. Thiokol went slowly on the project so as not to make the problem public and jeopardize their position in the contract-renewal negotiations scheduled for the fall of 1985.

The Thiokol task force and Marshall could not agree about the nature and scope of the problem. This situation did not lend itself to allowing Marshall and Thiokol to reach a mutually acceptable redesign. Thiokol and Marshall exchanged memos, but there appeared to be a stronger than normal degree of organizational inertia at Thiokol. Marshall's engineers grew increasingly impatient with Thiokol's foot dragging. Marshall Director of Science and Engineering, James Kingsbury wrote to Lawrence Mulloy, Manager of the SRB project at the Marshall Space Flight Center, complaining about Thiokol's progress. The memo in effect stated that the redesign effort of the O-ring seal problem on the Solid Rocket Booster needed priority attention of both Thiokol and Marshall. There is no record that Kingsbury communicated this sense of alarm outside the Marshall organization.

At Thiokol, engineer Roger Boisjoly and his colleagues were concerned and frustrated over the slow pace of getting support for fixing the O-ring seal problem. Roger Boisjoly was on the Thiokol seal task force. He wrote status reports to upper management complaining about the lack of support and the fact that the redesign was not given top priority. Thiokol and NASA had irrefutable evidence that the O-ring problem was potentially catastrophic. After the 51-B mission in April of 1985, investigators found that a nozzle joint primary O-ring had been badly eroded and blown by and that there was serious erosion on the secondary O-ring.

Bob Ebeling, another Thiokol seal task force engineer was just as concerned as Boisjoly. Ebeling wrote a message to Allen McDonald, Thiokol's Director of the Solid Rocket Motor Project, that started with the word 'HELP'. The message reiterated Boisjoly's concern about lack of personnel and support. Thiokol's aerospace division did not perceive the redesign effort with the same sense of urgency as the seal task force engineers.

The problem of the O-ring erosion was stumbled upon by NASA auditor Richard Cook, in the summer of 1985. Cook discovered that orders were being placed for a special solid rocket booster that had a capture feature. This capture feature was designed to grip the inner clevis face and prevent joint rotation. The order was placed in July of 1985 for seventy-two SRB's with the new "capture feature". Among the Marshall engineers, the capture feature was known as the "big fix", since it was intended to fix the chronic O-ring erosion problem once and for all. Richard Cook sent several urgent memoranda to his superiors, warning of the "catastrophic" results of field joint failure and calling for an immediate halt to shuttle flights. There are no records that the warnings were acted upon in Marshall or at NASA headquarters.

Thiokol was successful in getting NASA to affect a formal 'closure' of the O-ring problem since a safe redesign was supposedly in progress. Thiokol had requested a closure of the problem because tests were in progress that would lead to a safe redesign. The request worked, as the problem was closed out of the Marshall's monthly Problem Reports five days before the Challenger accident.

On Tuesday, January 14, 1986, Kennedy Space Center Director Richard Smith convened the Launch Readiness Review meeting at Cape Canaveral. Members included contractors for the shuttle program and over 100 representatives of NASA. Lockheed, the principle contractor and NASA officials presented the status of the space craft. Included was a review of plans for emergency landing. The Johnson Space Flight Center in Houston, which has overall responsibility for the Space Shuttle program approved of the launch. A poll of top NASA officials gave approval and Smith signed a "launch readiness certificate".

On Wednesday, January 15, 1986, a video teleconference linking NASA Space-Flight centers reviewed all systems beginning at the engineering level for the space craft through the in-flight responsibilities of the Johnson and Marshall centers. The conclusion of all the participants was "Go for Launch".

On Thursday, January 23, 1986, countdown began for a Sunday morning launch, January 26th at 9:36 AM.

On Saturday, January 25, 1986, overcast skies, rainstorms and a gloomy forecast caused postponement of the launch until Monday, January 27th.

On Monday, January 27, 1986, thirty knot crosswinds and problems with a bolt on the shuttle hatch developed. Launch Director Gene Thomas called off the launch. A cold front moved in overnight. The External Tanks were fueled and the lift off was set for Tuesday, which marked the seventh delay in the flight schedule. Flight 51-L was one month behind in the aggressive launch schedule.

When the cold weather moved in on Cape Canaveral on the night of January 27, 1986 the unusual weather alarmed Allen McDonald. McDonald immediately setup a teleconference meeting with the Thiokol engineers and upper management, NASA Marshall Space Flight Center engineers and upper management, and Kennedy Space Flight Center upper management.

The Thiokol engineers had gathered detailed charts of engineering data to try to convince NASA (Marshall Space Flight Center) that the temperature effects on O-ring performance may cause serious problems. The engineers from Thiokol presented a convincing argument that the combined problems of field joint rotation and delayed O-ring seating due to the cold temperatures would lead to serious problems in the field joints (See Figure 2).

The delayed O-ring seating would allow blow-by of the primary O-ring and the secondary O-ring probably would not seal in time. This data was based on a launch temperature of 26 degrees Fahrenheit. Robert Lund, Vice President of Engineering at Thiokol recommended that the launch should be delayed until the ambient temperature rose high enough to warm the O-ring seals to at least 53 Degrees Fahrenheit (See Figure 3 for written launch recommendations). This was the same temperature as the previous coldest O-ring temperature at launch (Flight 51-C one year before).

The reaction from NASA was swift and heated. Larry Mulloy, manager of the SRB Project at the Marshall Space Flight Center challenged Thiokol's data and their logic.

Roger Boisjoly continued to argue that the data was valid because the most O-ring damage was done on the previous coldest shuttle flight. Now the temperature was 30 degrees Fahrenheit cooler and the damage to the O-rings would be worse than before. Joe Kilminster, Vice President of the Space Booster Group at Morton Thiokol sided with the engineers.

George Hardy, Marshall's Deputy Director for Science and Engineering was 'appalled' at Kilminster's recommendation to delay the launch. Stan Reinartz, manager of Shuttle Projects at the Marshall Space Flight Center also questioned Thiokol's logic. Morton Thiokol was now put in the position of having to prove that there would be a problem with the launch at a cold temperature.

Joe Kilminster asked for a five minute caucus to resolve the discussion between the Thiokol management and engineers. During the caucus, Jerald Mason, Senior Vice President at Thiokol indicated that a management decision was required. Now Boisjoly and Arnold Thompson, Supervisor of the Rocket Motor Cases Division at Thiokol, realized that they were out of the decision making caucus. The upper management at Thiokol would not listen to Boisjoly and Mason's arguments. At one point, Jerald Mason said to Robert Lund, "Take off your engineering hat and put on your management hat".

After thirty minutes of discussion, Joe Kilminster went back on the teleconference and read the new recommendation "Morton Thiokol recommends STS-51L launch proceed on 28 January, 1986". George Hardy recommended that Thiokol should put their launch recommendation in writing and telefax it to both Kennedy Flight Center and Marshall Space Flight Center before launch time. The telefax was sent out twenty minutes later signed by Joe C. Kilminster, Vice President, Space Booster Programs at Morton Thiokol (See Figure 4).

This decision was not discussed with Arnold Aldrich, NASA Mission Management Team Leader because the decision made at Morton Thiokol was a level III decision. Since the concern was 'closed' at level III, it was not raised to level II management (See Figure 5 for management structure).

On Tuesday, January 28, 1986, the launch temperature was 29 Degrees Fahrenheit. The contract specified a range of 40 to 90 Degrees Fahrenheit, where the temperature of the booster rockets were designed to perform. The crews searched for ice and other potentially damaging debris before launch.

At 4:00 AM in the morning, the Ice Team was inspecting the launch pad of the Challenger. The Ice Team was performing the inspections at the launch pad because the temperature was in the low twenties for approximately eleven hours. The Ice Team reported icicles and ice forming in the water trays beneath the vehicle. Rockwell International, the prime contractor for the orbiter, was alerted to the ice problem by the Ice Team. Rockwell studied the situation and indicated that they could not recommend a launch because of all the ice at the launch pad. Rockwell was concerned about the effects of ice on the shuttle and they wanted to make sure NASA understood that it was not safe to launch. This concern was not communicated to Arnold Aldrich or Jesse Moore, Associate Administrator for NASA. Rockwell made no phone calls or attempts to express their concerns after the 9:00 AM Mission Management Team meeting. Rockwell also did not clearly communicate the concern about the effects of ice on the orbiter at the 9:00 AM meeting prior to the launch.

At 11:38 AM, Challenger lifted off.

Elapsed Time Into Flight:	Event:
0.7 seconds	Smoke escaped field joint from right hand SRB
0.7-2.5 seconds	Eight puffs of smoke escaped field joint
2.5-58 seconds	Glassy oxides sealed burned joint
59 seconds	Glassy oxides crumbled due to high altitude windshear on shuttle
59.2 seconds	Flame escaped field joint
59-73 seconds	Flame burned through external fuel tank
73 seconds	External fuel tank exploded, orbiter and seven human beings are destroyed

Analysis of Communications

There were a number of types of communication failures that prevented effective negative feedback communication in the operation of the Space Shuttle Challenger. A discussion of each of the types of communication breakdowns will be presented.

Management Isolation

Early in the design stages of the SRB, Marshall engineers had serious concerns about the integrity of the design. The engineers wrote many internal memos about the concerns, but they were not forwarded to Morton Thiokol, Inc. The management structure at the Marshall Space Flight Center had a tendency toward management isolation, which effectively prevented negative feedback communication from being sent up the management chain of command. Marshall had a management and climate problem that prevented effective negative feedback communication.

Lack of Negative Feedback Communication Channel

When the change was made in the reporting requirements by Glynn Lundey in 1983, this change effectively cut off all negative feedback communication channels to upper management at NASA. As a result of the restructuring, all flight safety problems, trend problems, and close out actions were no longer reported to Level II Management. Level II and Level I Management were then kept in the dark as far as recurring problems were concerned on the space shuttle program. In addition to the communication channels being cut off, safety and quality engineers were laid off or relocated to cut costs in the shuttle program. Since safety and quality engineers are the people who would be analyzing the flight problems and performing trend analysis, this negative feedback communication source was eliminated. Wiley Bunn, director of Reliability and Quality Assurance at Marshall indicated to the Rogers Commission(6) that had there been people available to do trend analysis, the data on the O-ring erosion problem would have "jumped off the page at you".

Engineering Credibility Problem

The new test method that was used to leak check the field joints to 200 psig, which was initiated by the Marshall and Thiokol Engineers, communicated a false sense of security in the integrity of the field joint to upper management. After a few of the subsequent flights indicated that the O-ring erosion problem was getting worse because of the increased leak check test pressure, the engineers at Thiokol found it difficult to communicate the concern about the worsening O-ring problem to upper management because of the lost credibility of the engineers.

Political Pressure Prevented Problem Correction

The management climate at Thiokol did not allow the seal task force to address the problem in a timely manner. Roger Boisjoly wrote status reports to upper management complaining about the lack of support and the fact that the redesign of the field joint was not given number one priority. Upper management was concerned that allowing the problem with the O-rings to go public would jeopardize the companies position in the contract renewal negotiations that were about to begin. Because of political pressure from upper management, the engineers at Thiokol were not allowed to complete the negative feedback communication loop by implementing a fix to the field joint in the SRB's.

Poor Listening

The urgent memorandum sent by Richard Cook to Marshall and NASA headquarters was not acted upon. This is an example of poor listening on the part of management at NASA. The memoranda was never acknowledged that it had been received, let alone acted upon.

Organizational Ambience

Organizational ambience can strongly influence negative feedback communication. The following discussion illustrates various authors' analyses of the organizational ambience of NASA.

Kenneth Kovach and Barry Render(3), both professors at George Mason University did a study on NASA managers to determine their management profile. Through a series of tests, they characterized NASA management style by a tendency not to reverse decisions and not to heed the advice of people outside their management group. The profile was based on a series of tests taken from 1978 to 1982. NASA had a management style that "Lets program objectives override good judgement". The authors tested with the following instruments: Learning Style Inventory, Androgyny, Management of Motives Index, Work Motivation Inventory and Fundamental Interpersonal Response Orientation, Form B. Five-hundred-thirty-seven mid- to upper-level management personnel were tested. The test indicated the following characteristics:

1. Strong tendencies to collect and evaluate information by thinking and sensing rather than intuition and feeling.

2. Strong masculine decision making characteristics making them unlikely to change their minds.

3. Adequately fulfilled lower-level needs but unsatisfied ego status and self actualization needs (making them unlikely to capitulate in the face of outside intervention).

4. Strong desires to control others and be a part of this homogeneous work group.

The decision to launch Challenger in the face of precautionary warnings was consistent with the management style of the group responsible for the decision according to Kovach and Render.

Senator John Glenn was quoted as saying that in his view the "can do" attitude of NASA gave over to "an arrogant 'can't fail' attitude". Charles Burch(1) has reflected on the "can't fail" attitude and says NASA suffered from a dangerous imperative having made unrealistic promises in order to win congressional support.

In a study by Howard Schwartz, a Ph.D. in organizational behavior, from Cornell University(2), studied the psychodynamics of the disaster. He stated that the vital organizational processes tended to become ritualized. "Rather than solutions to problems, they become excuses for avoiding problems".

During the Presidents Commission investigation, Level III SRB project manager, Mr. Mulloy, stated that he still believed his judgement was correct in not passing the information regarding the O-rings to Level II. Mr. Schwartz(2) explained it his way, "taking responsibility for positive action is a way of linking 'I did it' with the 'NASA did it' which represents perfection". The attitude that NASA "can't fail" existed even with the problem of the O-rings being openly discussed. The concerns of Thiokol did not register as important to NASA management.

Objectives and Goals

The function of objectives and goals to an organization will influence feedback of negative communication, as indicated in the following discussion.

Kovach and Render(3) in their citation stated "one of the most frequent and serious charges has been that NASA managers were so committed to reaching programs objectives, they ignored many safety warnings from individuals, both within and outside the agency".

NASA had a goal of launching 14 flights in 1987, and 24 launches by 1988. NASA's objectives could be classed as, "The game NASA is playing is the maximum tonnage per year at the minimum cost available" quoted Paul Cloutier(4), a professor of space physics.

The contribution that goals made is quite evident in most of the research on the Challenger disaster. Howard Schwartz(2) is quoted as saying, "The schedule NASA set out to meet was, after all, self imposed. At this stage it seems incredible that an organization like NASA with its clear history of successful management, could lock itself into a schedule that it had no chance of meeting".

In an article dated July 21, 1986 an issue of Aviation Week and Space Technology stated that the NASA agency had a "group think" mentality and a management style that "Lets program objectives override good judgement".

Organizational Structure

The organizational structure of a company has a direct impact on the effectiveness of negative feedback communication. The following section discusses the organizational structure of NASA and the impact it had on hindering negative feedback communication.

The organizational structure for the NASA shuttle program was set up with four levels:

Level IV was the contractors for the shuttle elements. This level was responsible for both design and production.

Level III was responsible for the development, testing and delivery of the hardware.

Level II was responsible for the shuttle programs base line and requirements.

Level I was responsible for policy-budget and was the top level for technical matters.

A very important change in the organizational structure was made in 1983, one that changed the decision making process. A reorganization shifted the responsibility for monitoring flight safety from the chief engineer in Washington, DC to the field. What this reorganization did according to safety engineers who talked to Mark Topscott(4) was to "close off an independent channel with authority to make things happen at the top".

Prior to 1983, Level III was to report all problems, trends, and problem closeout actions to Level II unless the problem was associated with hardware and was not flight critical. According to the Roger's Commission(6) this requirement was substantially reduced to include only problems which dealt with common hardware items or physical interface elements. This change in reporting requirements was initiated by Glynn Lundey, Manager of the National Space Transportation System(Level II Manager in 1983). The change was to stream line the system, however, the revision eliminated reporting on flight safety problems, flight schedule problems and problem trends to Level II. Level II lost all insight into safety, operational and flight schedule issues resulting from Level III (See Figure 5 from previous section for Shuttle Program Management Structure).

Readiness reviews for both launch and flight of a Shuttle mission are conducted at ascending levels that begin with the contractors.

The objections of the Morton Thiokol staff about the effects of cold temperatures on the O-rings performance on the SRB's and the concerns of Thiokol and Marshall engineers of the joint seals was not passed up the communication chain to Level II or Level I.

The organizational structure where problems, action items, anomalies and weather were reviewed was the Level I flight readiness review, a fully planned step by step activity designed to certify the readiness of the Shuttle assembly. This review began about two weeks before the launch. The Level I directives established a Mission Management Team to assume responsibility for the launch beginning 48 hours before the launch (See Figure 6). The structured Mission Management team is called L-1. L-1 meets 24 hours prior to launch. The agenda includes any open work, any anomalies, and weather. The concerns of the Level IV contractors regarding O-ring and seal erosion and the objections to launch voiced by Thiokol engineers were not communicated up to Levels I or II Management. The O-rings had been designated "criticality 1" of the SRB. This meant a failure would cause a loss of life or vehicle if the component failed. This constraint, though waived, had been regularly waived by SRB project manager at Marshall, Lawrence Mulloy, Level III Manager. It is note worthy that Moore, Level I nor Aldrich, Level II nor Thomas, Level II, were aware of the six previous waivers prior to the Challenger launch. The only major concern of the L-1 Team was the approaching cold front.

Mr. Aldrich, the Level II program official, summarized three areas of breakdown in the communications. First, the teleconference and Thiokol's concerns were not passed up to Level II. Second, the communication between NASA headquarters and the Marshall Organization was not routed through Level II Management. The O-ring concerns had not gone through his office from either direction. This was against the documented reporting channels according to Mr. Aldrich(6). He had not been on the line of reporting for that activity. The third breakdown according to Aldrich was that the budget for the work on the new configuration of the joints was not routed through him. Had the budget gone through his office, he would have seen the concern for the O-ring safety and other concerns.

Analysis of Changes Made

A discussion of solutions that have already been implemented and suggested solutions for the types of communication problems that existed during the Space Shuttle Program leading up to the Challenger accident are discussed below.

Management Isolation

Horizontal communication breakdown occurred between the Marshall Space Flight Center and Morton Thiokol regarding the concern about the integrity of the SRB design. Communication channels must be open between divisions or companies to facilitate information sharing, problem solving and problem correction coordination.

Since the Challenger accident, management changes in the Marshall Space Flight Center have facilitated a much more open atmosphere in bringing out problems and communicating them to other contractors. Morton Thiokol engineers and Marshall Space Flight Center engineers worked together to redesign and test the changes in the field joint design on the SRB's. The combined effort allowed the engineers to design a reliable and safe field joint for use on the SRB's. This redesign effort proved to be successful, as evidenced by the recent Discovery flight.

Lack of Negative Feedback Communication Channel

Because of the lack of a negative feedback communication channel, Level II and Level I Management was unaware of the serious problems that existed with O-rings on many of the flights. Reducing the number of the Quality Assurance and Safety engineers removed an important source of negative feedback communication.

Since the Challenger accident, safety and quality control have been emphasized in every step of the shuttle launch. Problem close outs are now inspected by both NASA quality experts and contractors. This new procedure is mandatory during the preflight preparation. Another new procedure requires that there be no open problems at the time of the launch.

Reliability analysis is now mandatory on the SRB's. Engineers are required to examine the recovered SRB nozzles and field joints for possible problems. X-ray and ultrasonic analysis will be performed to find the smallest defects in the SRB's(10).

Engineering Credibility Problem

Loss of credibility was not the only problem. Once the engineers realized that the new test was causing more problems than it was solving, they had an uphill battle trying to convince management of the severe O-ring problem. The engineers tried to convince management of the problem but they failed. The engineers were also afraid to go outside the chain of command for fear of retaliation by Morton Thiokol. These fears proved true, as Allen McDonald and Roger Boisjoly were reassigned and had their responsibilities reduced after testifying to the Presidential Commission investigating the accident.

"The code of ethics of engineers says if you are overruled by a matter of safety by management, you shall go to the proper authority." This statement was made by Dan Pletta, professor emeritus at Virginia Polytechnic Institute and State University(9).

Roger Boisjoly and Allan McDonald could have gone outside the company, notified the general council in the government, notified a professional engineering organization, or notified the newspaper about what was going on at Morton Thiokol. Their overriding concerns about job security kept them from pursuing these other 'courses' of action. Engineers who are aware of unethical behavior on the part of management must exhibit professional behavior and social responsibility to seek all possible courses of action to correct the problem.

Political Pressure Prevented Problem Correction

The management climate at Morton Thiokol did not allow the engineers to solve the O-ring problem in a timely manner. Morton Thiokol attempted to prevent the problem from going public by attacking the O-ring problem very low key.

Since the Challenger accident, Chairman and CEO Charles Locke of Morton Thiokol has made management changes to improve communication, decision-making and responsibility(11).

The number of quality insurance inspectors has doubled, and the company now promotes a more 'open' discussion of disagreements between engineers and management to resolve problems. The management that is now in place is more open to negative feedback communication from any employee who has a concern.

Poor Listening

NASA was guilty of poor listening, as they were more concerned with maintaining the flight schedule than listen to someone complain about the problems with the O-rings in the SRB's.

Changes in the management structure and preflight procedures at NASA have made it easier for anyone with a concern about a shuttle flight to ask questions during mission readiness reviews. Under a new set of ground rules at the conferences, officials from NASA, the Defense Department and the major contractors can break in with a question at anytime.

Organizational Ambience

Organizational ambience can strongly influence the ability to communicate problems up the management chain of command. In order to resolve any kind of problem, peers and upper management must provide an atmosphere of openness and concern for any problems that need attention.

Changes in the management structure at NASA were made so that the shuttle program could return safely to flight status(12). Rear Admiral Richard Truly returned to NASA as associate administrator for Space Operations. Truly's efforts in promoting an atmosphere of safety at NASA helped change the organization ambience of NASA.

Objectives and Goals

The objectives and goals of an organization can adversely affect negative feedback communication.

Changes made by NASA have made the flight schedules more conservative with an emphasis on planning and precautions.

NASA has implemented changes that include more checks and balances in the pre and postflight operation of the shuttle program. There is now a clear 'take your time' atmosphere at NASA according to Al Harley, ground operations manager for NASA's Kennedy Space Center(13).

NASA has also increased the number of launch commit criteria from 2000 to 2500, with an emphasis on safety.

Organizational Structure

The organizational structure of a company can strongly influence the ability to promote effective negative feedback communication.

Among the many organizational changes made by NASA, the most important ones were in the shuttle launch decision process. For the first time in the shuttle launch decision process, the team is now represented by a mixture of NASA managers and top-level representatives of shuttle processing and hardware element contractors. Previously, contractors functioned primarily as observers during the terminal part of the count.

Changes in the management structure at NASA have now re-emphasized 'safety first'. A more conservative approach is being taken by NASA in the preparation of the hardware for each flight, which includes rigid documentation for each task accomplished. NASA now researches all waivers prior to liftoff to identify the relative importance and criticality of the waiver.

Changes at Morton Thiokol have also been implemented to promote safety. All of the Morton Thiokol managers who overruled the engineers objections to the launch have either retired or have been reassigned. Morton Thiokol has promoted safety by doubling the number of quality assurance inspectors in the Solid Rocket Booster Division.

The events preceding the March 1979 incident at Three Mile Island (TMI) exemplify the lack of effective negative feedback communication that can occur between and within organizations.

The Design Problem

The pressurizer is a steel tank about 40 feet tall that regulates the pressure in the main cooling system of a nuclear power plant. It is the most elevated point in the cooling system, and while every other part of the cooling system is filled with water, the pressurizer is topped with a bubble of steam that acts to absorb transient shocks on the cooling system. At the bottom of the pressurizer are heaters that can make the steam bubble expand and thus increase the cooling system pressure. At the top are water sprays that are used to cool the pressurizer water causing it to contract thus lowering the cooling system pressure.

The plant operators can control and monitor the pressure inside the cooling system and reactor vessel by knowing the water level inside the pressurizer. (See Figure 1.)

1 The weakness in the B&W design is in the pipe connecting the pressurizer to the rest of the cooling system. Because of a design change during the layout of the hardware, the pipe dips, creating a U-shaped loop and inducing a vapor lock almost like a sink drain trap.

Although a vapor lock would not affect the operation of the pressurizer under normal operating conditions, it does have ill effects under certain conditions. If, for example, the pilot operated relief valve (PORV) on top of the pressurizer was to fail open, the steam bubble would escape, the water level inside the pressurizer would rise to a higher equilibrium state, and the pressure in the reactor vessel would decrease allowing the water covering the nuclear fuel to turn to steam, causing the fuel to overheat and possibly melt. Overheating may lead to reactor meltdown and release of radioactivity to the environment.

2 Because of the vapor lock in the "U-shaped" loop, the water level inside the reactor would not be correctly communicated to the plant operators who use the water level in the pressurizer to indicate water level and pressure in the reactor.

The pilot operated relief valve (PORV) is located on top of the pressurizer, above the space normally occupied by the steam bubble. This relief valve is designed to open automatically when the system pressure begins approaching the upper limits of safety. In theory, if the pressure in the coolant system rises very abruptly, the valve will open, some of the steam will rush out (shrinking the bubble), water will move up in the pressurizer from the primary coolant loop, and the system pressure will go down. When the system pressure is back to normal, the PORV closes automatically, having returned the system to a safer pressure. Due to an
3 extremely poor operating history of the PORV's to stick open, B&W installed a block valve between the PORV and the pressurizer, which can be closed by plant operators to stop the leak and/or allow maintenance on the PORV.

The emergency cooling system prevents a meltdown when all other systems have failed to cool the nuclear reactor core. It consists of high-pressure injection pumps driving water into the reactor vessel directly. The emergency cooling system is controlled by the plant safe shutdown computer.

Sequence of Events

On September 24, 1977, the PORV valves lifted at Davis-Besse Nuclear Station in Toledo, Ohio. In response to an increase in the pressurizer water level, the plant operator tripped the nuclear reactor and took note that the water level in steam generator number two had dropped below a readable level. As the water and pressure levels continued to drop in the steam generator and reactor, the safe shutdown computer automatically turned on the emergency cooling system. However, since the plant's operator was overly concerned about the increasing water level in the pressurizer, he turned the emergency cooling system off.

Immediately alarms sounded and six operators gathered to try to make sense out of the
4 incoming signals. At that time, the gauges and indication lights were spread out over the room, so that it was impossible for one person to visualize the entire system. Fortunately, a single operator noticed the essential signal "Containment Pressure HI" and decided to investigate. Two of the three meters indicated that containment pressure was normal, but the third

indicated a problem. The operator acted on a hunch and closed the PORV block valves. In less than twenty minutes the reactor was stabilized.

B&W, the design/engineering company for the Davis Besse plant, was curious enough about the incident that they sent an engineer to the plant for a couple of days afterward to look into the details. When the B&W engineer arrived he met with twenty people from the NRC to field their questions.

5 After returning from Davis Besse, the B&W engineer gave a presentation on the incident to senior management at B&W. At the time, B&W had sold eight nuclear power plants in the United States, and the topic of discussion was pertinent to all of them.

The conversation during the meeting focussed on the PORV valve that was designed to bleed off a little steam, then close. From a design standpoint this was very demanding, since the valve must open at 2,200 psi, then reclose when the pressure drops to 1800 psi. As mentioned
6 earlier, the PORV valves had a history of failing. Ironically, this time the valve stuck due to a missing part.

During the meeting, the chief analyst for the emergency cooling system pointed out that the operators overrode the safety computer, and turned off the emergency cooling system at least
7 15 minutes before it was discovered that the block valve needed to be closed. If the plant had been running at greater than 9 percent power, those 15 minutes would have lead to possible fuel damage or meltdown.

Less than a month after the first incident at Davis-Besse, there was a second, and while this event was not as serious as the first, once again the plant operators overrode the plant safety computer and cut-off the emergency cooling system. Back at B&W engineering offices, the design engineer of the emergency cooling system was concerned and realized that clear
8 instructions had to be relayed to the operators. He decided to try and create some kind of forum to get the issue out in the open. Trying not to sound like an alarmist, he wrote the following in a memo:

> Two recent events at the Davis Besse Plant have pointed out that perhaps we are not giving our customers enough guidance on the operation of the high-pressure emergency cooling system...

He also pointed out that most accidents require continuous operation of the emergency cooling system. He then suggested guidelines and asked for opinions. A copy was sent to his boss, his boss's boss, the manager of training, and several personnel in customer services.
9 Of the seven letters mailed out, only one response was received. It stated that reactor pressure and water level would tend in the same direction in the event of a "loss-of-coolant accident". Exactly the opposite had just occurred, twice at Davis Besse and once at the B&W designed SMUD reactor near Sacramento.

On November 29th, during an investigation into the third unplanned event at Davis Besse in 60 days, NRC inspector Creswell reviewed the recording of the pressurizer water level during the event and noticed that the level dropped off scale.

The significance of the event was discussed in a heated conversation between Davis Besse engineers and the NRC inspector. When Creswell returned to the NRC office in Chicago, he was reprimanded because of the way he had handled the issue at the plant. The chief
10 inspector who reprimanded Creswell based his judgement on Creswell's temperament of communication, rather than on the substance of the communication.

Creswell proceeded to compare the pressurizer level plots from the prior two events with the November 29th plot and found that they were all the same and indicate that right in the middle of a loss-of-coolant accident, the plant operators turned off the emergency cooling. Creswell
11 took the matter up with his boss, who told Creswell that he was "out of line" and that if there was a problem "the guys in Bethesda (NRC headquarters) would have picked it up".

But Creswell had already verified that NRC headquarters had not yet received documentation on any of the three events. The issue was resolved by issuing a memo from the NRC region office to the operators at Davis Besse, which stated the following:

> Prior to securing HPI (emergency cooling), insure that a leak does not exist in the pressurizer such as a safety or electronic relief valve is stuck open.

This was a simple directive, but the possibility that this information was essential to the operators of the seven other B&W plants or to NRC headquarters was overlooked.

In mid-October 1977, a systems analyst at Tennessee Valley Authority (TVA), while reviewing blueprints of the B&W nuclear reactors being built in Alabama, realized that sometime during the design phase of the reactor, the elevation of the pressurizer was lowered in relation to the reactor vessel. Because of the layout of the hardware, the pipe connecting the pressurizer and the reactor vessel took a dip, creating a U-shaped loop. The presence of the loop would cause water level in the pressurizer to rise in the event of a PORV valve opening; whereas, in a correctly designed system, the water level in the pressurizer would drop while the PORV valve was open.

For example, if one of the PORV valves on top of the pressurizer stuck open, the reactor would lose pressure and if the core was hot enough, the water would flash to steam. The steam could not escape through the PORV valve because of the vapor lock in the main loop due to the dip in the pipe connecting the pressurizer and reactor. The trapped steam would then push the water level higher in the pressurizer misleading the operators (who are unaware of the design error) into shutting down the emergency cooling system in order to avoid filling the pressurizer with water (for fear of losing all control over the pressure in the reactor).

This design error was common to all eight operating B&W plants and appeared so obvious that the system analyst thought no one should have missed it; however, the scenario had already happened three times.

The responsibility of the Advisory Committee on Reactor Safeguards (ACRS) is to review the license application for every new reactor and report directly to Congress if they do not like what they see. In December 1977, the ACRS was considering the construction permit for a new B&W plant for Portland General Electric Company. The systems analyst from TVA had a friend in ACRS so he attempted to get the attention of the ACRS through an informal handwritten note to his friend that outlined his concerns:

> For one thing, there is that "U" in the pipe that connects the pressurizer to the main coolant loop. This "loop seal" could trap steam in the core, and this could trick the operators into thinking the system is full of water when it is not.

12 The TVA analyst discussed his concerns with his friend at ACRS who agreed that this was an unreviewed safety item and agreed to deliver the message to the NRC at the review meeting for Portland General Electric Company's license application. At the meeting the NRC was busy and the handwritten note was overlooked.

The TVA analyst also sent a formal report to the B&W engineering headquarters in Lynchburg, Virginia, which read:

> A full pressurizer may convince the operator to trip the HPI pump (emergency cooling system) and watch for a subsequent loss of level. Although this response appears desirable, a full pressurizer may not always be a good indication of high water level in the reactor coolant system...
>
> The loop-seal configuration of the pressurizer surge line allows the pressurizer to remain filled as the reactor coolant system water level drops.

In response to this information, the B&W chief engineer of the emergency cooling section issued a blunt memo to his superiors:

> This memo addresses a serious concern within ECCS Analysis about the potential for operator action to terminate high-pressure injection following the initial stage of a loss-of-coolant accident. ...Concern here rose out of the recent incidents at Davis Besse. During the incidents, the operators terminated high pressure injection due to an apparent system recovery indicated by high level within the pressurizer...
>
> I believe it is fortunate that Davis Besse was at an extremely low power level and extremely low burnup. If this event occurred in a reactor at full power with other than insignificant burnup, it is quite possible, perhaps probable, that core uncovery and possible fuel damage would have resulted.

After a struggle with the people in customer service, the chief engineer convinced them to issue a carefully worded warning about cutting off the emergency cooling pumps. He did not know
13 that the new instructions were never sent because the Manager of Customer Services thought such a letter would cause bad customer relations.

For the next 13 months the plant operators at the eight B&W plants (including Three Mile Island) remained uninformed of this problem.

During those 13 months, NRC inspector Creswell called a meeting of all owners of B&W plants to investigate the pressurizer water-level problem. This was the first time a regional inspector had ever called a meeting like this and the NRC management at headquarters was caught off
14 guard. Creswell's supervisor was ordered to "shut him (Creswell) up", so two of Creswell's peers were asked to investigate Creswell's allegations. They found no such problem. Only one of the peers was an engineer and neither had experience with the design of B&W reactors. The two peers (not Creswell) attended the B&W Owners Group meeting called by Creswell, and told the members that the loss of pressurizer level was no longer under investigation and the NRC apologized for the mistake. This episode cemented Creswell's conviction that the regional office was not going to take action.

15 Since the investigation had begun, the NRC office in Chicago was tense; before Creswell was considered abrasive, now he was considered to be abrasive and immature.

The day after the meeting, Creswell telephoned the Commissioner of the NRC, but spoke to the commissioner's assistant. Creswell considered the situation so urgent that he flew to Washington at his own expense, on his day off to meet with the Commissioner. As a result of the meeting, the Commissioner's technical staff was assigned to dig into the matter and confirm it for themselves. Their report was released March 23, 1979, one day after the accident at Three Mile Island, where the scenario described above was repeated resulting in extensive damage to the nuclear plant and to the nuclear industry.

The seven organizations involved in the communication breakdown which had a causal effect on bringing about the event at TMI were:

1. Nuclear Reactor Design & Engineering Firm - Babcock & Wilcox (B&W)

2. Federal Regulatory Agency (as overviewer) - Nuclear Regulatory Commission (NRC)

3. Owners of B&W designed reactors similar to TMI:
    a. Sacramento Municipal Utility District (SMUD)
    b. Toledo Edison Company
    c. General Public Utilities (TMI)

4. Potential owners of B&W designed reactors similar to TMI:
    a. Portland General Electric (PGE)
    b. Tennessee Valley Authority (TVA)

The following analysis of the events leading up to the accident at TMI examines the breakdowns in negative feedback communication within these organizations as well as between them. The communication breakdowns are identified in the Sequence of Events section by a number in the left margin. In the following discussion, the breakdowns are categorized into a generic type of communication and the root causes of the breakdowns are identified/explored. Finally, specific solutions that have already been implemented will be discussed where applicable.

Lack of Negative Feedback Communication Channels

1. The coolant system design change that occurred during the layout of the plant was not effectively communicated, which resulted in the change not being adequately analyzed. No reference indicated whether or not B&W had well established horizontal communication channels to control design changes between the system design groups

and plant design groups. However, the final design drawings were not routed back to the original designer for a final review. Formal horizontal channels must be set up between departments for purposes of planning, internetwork task coordination, and general system maintenance functions such as problem solving, information sharing, and design change feedback.

Since the accident at TMI, B&W and other plant designers incorporated a feedback loop into the design process. With the feedback loop, the final design (called an "as-built") is routed to the original designer for final review and approval.

3. Even though there was a history of the PORV's tending to stick open and an extensive measure was taken to deal with the problem (installation of the block valve), the operators at TMI failed to consider this as a possible problem in the early stages of the accident. This was due to poor dissemination of the historical information and a failure to emphasize the possible impacts.

Extensive corrective action was taken in the nuclear industry in response to this problem. An entire organization called the Institute of Nuclear Power Operations (INPO) was created with the mission to provide a communication network between all the nuclear plants in the country and foreign participants. In turn, INPO developed several systems to achieve this mission. Data bases were established which compile unusual or significant occurrences at all the plants and then distribute the information to other plants which could have the same problem. A question and answer system was set up so that anyone at any plant can direct a question to the industry. Answers from the plants are made available to the industry.

INPO also performs audits during which they compare activities of the plants to each other. This results in a "big picture" viewpoint which helps to put problems into perspective and increase the probability that "real" problems will not be overlooked.

5. B&W solicited negative feedback in evaluating the problem at Davis Besse. The feedback was reported to senior management within B&W; however, the other eight plants with the same problem were not informed.

This was an example of negative feedback through vertical communication channels. The omitting of horizontal communication between B&W and the eight operating plants was one of the root causes for the TMI accident. The root cause for this omission of horizontal negative feedback was self-preservation by B&W in order to maintain confidence of the industry and therefore future sales. This is still a source of negative feedback breakdown today.

6. The fact that there were parts missing from the valve was not communicated for some reason; for example, adequate tests were not performed to verify the valve was operable or a lack of quality performance existed.

Since the TMI accident, extensive emphasis has been placed on Quality Control (QC). Check points and QC signoffs are now required during equipment installation and system operational checks are mandatory prior to returning the system to service. The company-wide Quality Control organization has authority to place "holds" on any work activities which are questionable until a safety evaluation is completed. In this way the QC organization acts as the insurance that negative feedback is adequately evaluated.

Human Engineering Breakdowns

2. This is an example of a communication breakdown due to poor equipment design. A measurement of one parameter (pressurizer level) was used to infer the value of the critical parameter (reactor coolant level). In today's nuclear power plants, the reactor pressure is monitored directly.

In conclusion, the more indirect a communication is, the less accurate and effective it is. Today the design engineer and the end user communicated on the effectiveness of the finished product through formal horizontal communication channels within each nuclear facility.

4. In this case, the layout of the indicators in the control room did not allow the operators to visualize the systems as a whole. The poor design of the control room had a direct impact on feedback communication of critical information from the electromechanical sensors located through out the plant to the plant operators. Since the TMI accident,

extensive resources have been spent on the design modification of control rooms. In addition, technical support centers have been installed at every nuclear facility, which duplicate control room monitoring for support personnel.

Mindset as Communication Barrier

7. The chief analyst for the emergency cooling system understood the significance of the problem, yet he did not follow through by ensuring that the problem was acted upon, which resulted in a breakdown in communications.

Often when no formal horizontal or vertical feedback communications exist within a company, the motivator behind the negative feedback is the drive, conscience, and ethics of the informed engineer. The ethics of the individual worker is significantly enveloped by the character or "mindset" of the company. Prior to TMI, the "mindset" of the nuclear industry as well as B&W was that nothing could ever go wrong. The presence of this blinding "mindset" was targeted as a root cause for the TMI accident by the NRC special inquiry group.

8. The B&W engineer had to attempt to "create a forum" because one was not already established. Also, not wanting to sound like an alarmist is understandable because he would then probably be ignored. It is difficult to walk the line between sounding like an alarmist and getting the message as well as its impact communicated accurately. It seems that most people tend to at least react to a strong statement; whereas, watered down statements are easy to ignore, write off, or "paper whip".

Prior to TMI, the NRC had established policies and practices for resolving technical disagreements and negative feedback. However in 1978 several NRC employees testified before the Senate on the ineffectiveness of these policies. Employees had been transferred and others had resigned after confronting adverse reactions from NRC management to negative feedback on important safety issues. With the NRC setting that kind of example for the handling of alarmists, it is understandable why the B&W engineer did not push the issue based on his concerns. This was an example of the individual's ethics being compromised by the "mind-set" of the day. After TMI, the NRC modified their policies for addressing negative feedback and in doing so set a "mindset" of acceptance and encouragement of negative feedback in the industry.

9. A likely reason why the B&W engineer did not receive responses to his letter is that the negative feedback was not supported by management and therefore, not taken seriously by subordinates. This resulted in the memo not being acted upon since it was not "required". No system was set up to identify common problems and communicate them through official channels with authority. Even today, effective negative feedback cannot work without management support.

Breakdown due to Personality Conflicts

10. This was an example of top down communications where negative feedback broke down due to emotions, personality, and differences in status. The heightened emotional state of the manager caused him to make his decision without even listening to his subordinates' side of the story. In addition, making decisions before the facts are known and understood is a symptom of an established mindset.

According to Reference 22, an "atmosphere of approval" must be created to encourage communications.

15. Example 15 is an example of personality conflicts resulting in dismissing of a negative feedback message. The root cause of this problem seems to have stemmed out of Creswell's personality. He had a history of not being part of any group of friends that tend to be established at any organization. The solution of this problem should originate with the supervisor, who needs to break down the informal social organizations whenever they get in the way of effective formal organization.

Organization Climate

11. The actions of Creswell's boss display communication breakdown due to the climate of the organization, which was shaped by former military personnel and decidedly inflexible and authoritarian. The rule was that one does not question a superior. The existence of the superior-subordinate relationship is a given in any organization. The relationship itself cannot be eliminated. It follows that any basic removal of barriers to negative

feedback must deal with the task of mitigating the inhibiting effects of this relationship. Status differences must be de-emphasizes.

Emphasis on status differences is still very prevalent in the nuclear industry as a large percentage of the trained nuclear community are ex-navy personnel who never make the change to civilian management style.

14. Upper management consciously broke down communications by telling Creswell to "shut up" and assigning two personnel who were not qualified to investigate the problem.

Creswell had called a meeting of all the B&W plant owners to discuss the problem in an open forum. A meeting of this kind had never been called before by the NRC. Creswell's manager failed to see the innovative approach to a problem by holding this meeting and thus failed in his function as a change agent. This is an example of management consciously breaking down feedback communications due to fear of an innovative approach. Organizational resistance to change is still present in the industry today.

Communication Overload

12. This is an example of negative feedback through the informal organization between a company and the regulatory agency. The TVA analyst tried to communicate through informal organization channels through his friend at ACRS. The charter of ACRS was to provide negative feedback to the United States Congress on nuclear plant designs.

The fact that the NRC overlooked the message from the ACRS is an example of communication overload. There are limitations to the capacity of any individual or organization to receive, decode, and effectively deal with communications. When that limit is reached, additional information is ignored resulting in a breakdown in negative feedback.

From 1970 until 1976 the Ford Pinto had a design flaw which increased the chances of a gas tank explosion when struck from the rear. During the design phase of the car several engineers voiced their concerns about the vulnerability of the fuel tank in the event of a collision. Their concerns were ignored.

For eight years prior to the 73-second flight of the space shuttle Challenger on January 28th, 1986, engineers at the National Aeronautics and Space Administration (NASA) and at Morton Thiokol knew that the O-rings on the booster rockets required redesign. On the night before the launch, a number of those engineers voiced their concerns to their superiors that the mission should be delayed because of the critical effect of the freezing temperature at Cape Canaveral on the integrity of the rings. These engineers were overruled.

For close to one and a half years before the March 1979 incident at Three Mile Island (TMI), engineers at three separate companies and within the Nuclear Regulatory Commission were aware of the design flaw of the Babcock and Wilcox reactor and the ultimate consequence of that flaw. Not less than five individuals communicated their concerns, recommendations, and warnings to their superiors without success at initiating corrective action.

In each of these three cases, prior to the disastrous consequences, engineers identified a design problem, attempted to communicate its significance to their superiors, and offered solutions to the problem without success in initiating corrective action. For the purpose of this paper, these attempts at identifying, communicating, and resolving a significant design flaw by an individual while working within an organization is referred to as "negative feedback".

A model of communications without negative feedback consists of a sender, a channel of communication (verbal, written, or physical) and a receiver. With negative feedback, the sender becomes the receiver and the receiver the sender, while the channel of communication may become less direct as illustrated below.

Normal Communication Channel

```
SENDER/*RECEIVER -------------------> RECEIVER/*SENDER
       ^                                      |
       |                                      |
       |                                      | Problem
       |                                      |
       |       Negative Feedback Channel      |
       +--------------------------------------+
```

*NEGATIVE FEEDBACK COMMUNICATION

Successful negative feedback accomplishes redirection of the action while the lack of, or failure of negative feedback allows the action to continue, possibly resulting in disastrous events such as those which occurred in the three case studies.

In order to determine why breakdowns in negative feedback occur, the components and necessary conditions of an effective negative feedback system were first identified.

The sender of negative feedback must:

a. Become aware of the need for negative feedback.
b. Have significant motivation to champion the feedback.
c. Identify a receiver.
d. Select a feedback channel of communication.

The communication channel for negative feedback can be:

a. An established policy of vertical and horizontal communications.
b. A functional organization responsible for communications.
c. Informal communications.

The receiver of negative feedback must:

a. Be aware of the feedback.
b. Have significant motivation to understand the feedback.
c. Make a sound decision of the validity of the feedback.
d. Have significant motivation to champion the feedback.

The stages through which negative feedback communications progress involve essentially the same stages through which an innovative idea progresses:

Stage 1	Idea realization
Stage 2	First introduction into the system
Stage 3	Opposition
Stage 4	Lukewarm support
Stage 5	Confrontation
Stage 6	Resolution - idea dropped or accepted

During the first stage, the "champion" of the negative feedback realizes the problem and commits himself to introducing the feedback into the system. During the second stage the champion utilizes whatever organizational channels for negative feedback are made available to him, or creates his own. In the third stage, the champion meets opposition to change. The source of the opposition is the unwillingness of the organization to accept change. This close minded outlook towards change is referred to as a "mindset" throughout this paper. Once the goals and objectives of the organization are established and the timetable to reach those goals is set, a degree of mindset has been established. The flexibility of the mindset is a function of the organization's ambience (climate).

In stages 3 through 5 the success of the negative feedback is in balance between the personal drive of the champion and the reluctance of the organization to accept the negative feedback.

In stage six the negative feedback is either accepted and the action is redirected for a successful completion; or the negative feedback is rejected and the action continues until the problem resurfaces.

In the three case studies, the negative feedback process was unsuccessful and the problems resurfaced with catastrophic consequences. During the analyses of the three case studies, three general categories of barriers to the negative feedback process were identified: psychological, sociological, and mechanical.

Psychological Barriers

Negative feedback begins with an individual identifying a problem and being compelled to champion its correction. The first place where a breakdown in negative feedback communication can occur is in that individual. Obstacles to the birth of the sender's awareness of a problem are based on his intellectual abilities, his mindset for identifying ideas separate from his peers or superiors, his persistence to do what his ethical conduct dictates is right, and his personality.

Negative feedback remains incomplete until the receiver also develops an awareness of the problem and a need for the solution. Obstacles to the completion of negative feedback are also based on the receiver's intellectual abilities, mindset, personality, personal ethics, and persistence to do what his ethical conduct dictates is right.

The fact is that individuals are involved in communication and, because individuals have different perspectives, the intent is sometimes lost in the communication. This miscommunication between individuals is defined as a psychological barrier.

Sociological Barriers

The second general barrier to negative feedback communication arises from the organization's ambience, which is a result of interactions of individuals. Organizational ambience is molded by the type of management employed, (such as authoritarian versus participative) and upper management's attitudes, beliefs, values and ethics. It is impossible for negative feedback to work for the betterment of the organization if it is stifled at the highest management levels.

The mindset resulting from the ambience of the organization has a strong influence on how successful negative feedback will be in a particular organization.

Mechanical Barriers

The third cause for a breakdown in negative feedback communication comes from the structure of the organization. An organization which does not provide formal channels for negative feedback acts as a mechanical barrier to success. The lack of a functional organization responsible for inter-departmental coordination, the lack of training in communications, the lack of emphasis on the importance of negative feedback communications, and geographical dispersions are all examples of mechanical barriers.

The playing field on which the motivators and barriers of negative feedback play a tug of war is the channel of communication between the sender and receiver. Established channels for negative feedback work to enhance the motivators while lack of established channels is a barrier.

During the analyses of the three case studies, the root causes of the breakdowns in negative feedback communications were investigated. While the detailed analyses are covered in the last section of the individual case studies, the following serves as a summary. For each case study, the root causes for failure of negative feedback were identified and categorized under the three major headings: psychological, sociological, and mechanical.

I. Psychological

- A. Compromise of personal ethics
- B. Differences in individuals
- B. Emotions
- C. Personality differences

II. Sociological Barriers

- A. Mindset
  1. Uncompromising importance of goals and objectives
  2. Duty of loyalty
- B. Management isolation
- C. Engineering credibility
- D. Organization ambience (climate)
  1. Can't do wrong attitude
  2. Ritualization of organization process

III. Mechanical Barriers

A. Organization Structure

B. Lack of established negative feedback communication channels

C. Functional responsibilities

D. Geographical dispersions of the company

The steps that can be taken by individuals and managers to foster successful negative feedback within organizations closely parallel the three types of barriers.

To compensate for the psychological barriers, management and individuals must be made aware of their existence and their influence on effective communication. One option that can be exercised by management is to develop hiring practices that screen for professionals who consider negative feedback communication skills important.

The role of personal ethics is important in negative feedback communication. In many cases the individual engineer must walk a fine line between upholding his personal ethics by pushing to get the concern resolved and being perceived as an alarmist, which may jeopardize his position. Engineers have the responsibility to uphold their personal ethics regardless of the management environment. If the engineer is aware of a situation that compromises the safety of the customer or public, then he is morally obligated to report the concern to management. If management does not act to correct the situation, a number of options are open to him such as:

- Communicating the problem to professional societies, such as the IEEE.
- Communicating the problem to the press.
- Communicating the problem to the Inspector General.

Management must strive to create an environment in which personal ethics do not have to be compromised. One way is to encourage the practices outlined in the code of ethics of engineers, which is a good platform on which professionals can build their own personal code of ethics for specific situations. Management can also set the right climate by emphasizing ethical values and social responsibility as much as economic efficiency, growth, and loyalty.

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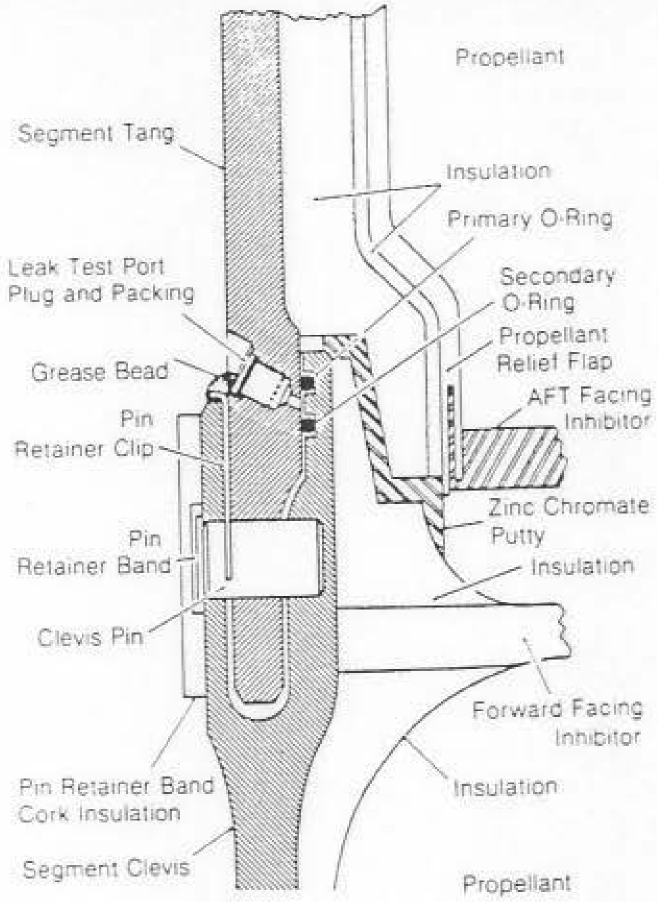
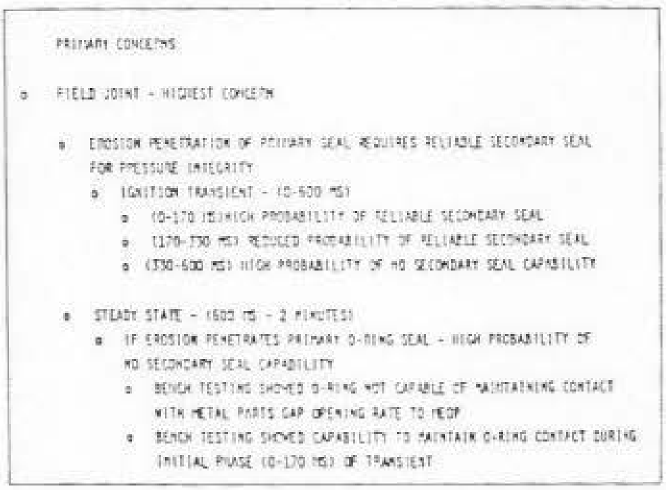


Solid Rocket Motor cross section shows positions of tang, clevis and O-rings. Putty lines the joint on the side toward the propellant.

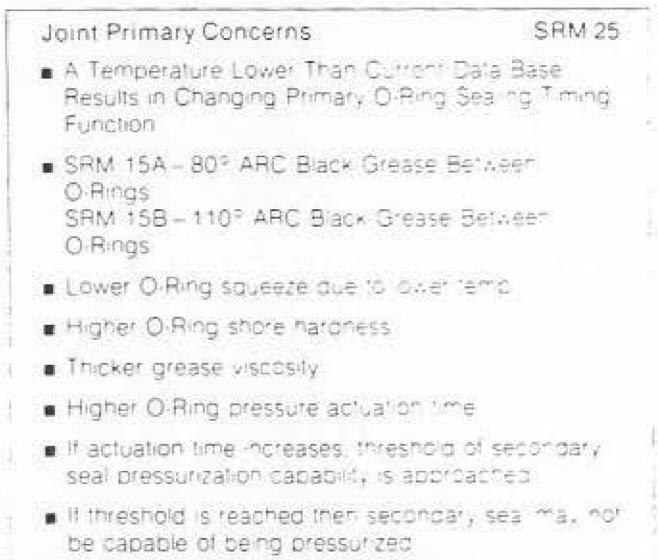
Figure 1



PRIMARY CONCERNS

- FIELD JOINT - HIGHEST CONCERN
  - EROSION PENETRATION OF PRIMARY SEAL REQUIRES RELIABLE SECONDARY SEAL FOR PRESSURE INTEGRITY
    - IGNITION TRANSIENT - (0-600 MS)
      - (0-170 MS) HIGH PROBABILITY OF RELIABLE SECONDARY SEAL
      - (170-330 MS) REDUCED PROBABILITY OF RELIABLE SECONDARY SEAL
      - (330-600 MS) HIGH PROBABILITY OF NO SECONDARY SEAL CAPABILITY
  - STEADY STATE - (600 MS - 2 MINUTES)
    - IF EROSION PENETRATES PRIMARY O-RING SEAL - HIGH PROBABILITY OF NO SECONDARY SEAL CAPABILITY
      - BENCH TESTING SHOWED O-RING NOT CAPABLE OF MAINTAINING CONTACT WITH METAL PARTS GAP OPENING RATE TO MEOP
      - BENCH TESTING SHOWED CAPABILITY TO MAINTAIN O-RING CONTACT DURING INITIAL PHASE (0-170 MS) OF TRANSIENT

Chart 2-1 presented by Thiokol's Roger Boisjoly summarizing primary concerns with the field joint and its O-ring seals on the boosters



Joint Primary Concerns SRM 25

- A Temperature Lower Than Current Data Base Results in Changing Primary O-Ring Sealing Timing Function
- SRM 15A – 80° ARC Black Grease Between O-Rings
  SRM 15B – 110° ARC Black Grease Between O-Rings
- Lower O-Ring squeeze due to lower temp
- Higher O-Ring shore hardness
- Thicker grease viscosity
- Higher O-Ring pressure actuation time
- If actuation time increases, threshold of secondary seal pressurization capability is approached
- If threshold is reached then secondary seal may not be capable of being pressurized

Boisjoly's Chart 2-2 indicating concern about temperature effect on seal actuation time (handwritten)

Figure 2

RECOMMENDATIONS:

- O-RING TEMP MUST BE ≥ 53 °F AT LAUNCH

  DEVELOPMENT MOTORS AT 47° TO 52 °F WITH PUTTY PACKING HAD NO BLOW-BY
  SRM 15 (THE BEST SIMULATION) WORKED AT 53 °F

- PROJECT AMBIENT CONDITIONS (TEMP & WIND) TO DETERMINE LAUNCH TIME

Initial Thiokol recommendation Chart presented by Robert K. Lund at second teleconference prior to Thiokol caucus

Figure 3

MTI ASSESSMENT OF TEMPERATURE CONCERN ON SRM-25 (51L) LAUNCH

- CALCULATIONS SHOW THAT SRM-25 O-RINGS WILL BE 20° COLDER THAN SRM-15 O-RINGS
- TEMPERATURE DATA NOT CONCLUSIVE ON PREDICTING PRIMARY O-RING BLOW-BY
- ENGINEERING ASSESSMENT IS THAT:
  - COLDER O-RINGS WILL HAVE INCREASED EFFECTIVE DUROMETER ("HARDER")
  - "HARDER" O-RINGS WILL TAKE LONGER TO "SEAT"
    - MORE GAS MAY PASS PRIMARY O-RING BEFORE THE PRIMARY SEAL SEATS (RELATIVE TO SRM-15)
      - DEMONSTRATED SEALING THRESHOLD IS 3 TIMES GREATER THAN 0.038" EROSION EXPERIENCED ON SRM-15
  - IF THE PRIMARY SEAL DOES NOT SEAT, THE SECONDARY SEAL WILL SEAT
    - PRESSURE WILL GET TO SECONDARY SEAL BEFORE THE METAL PARTS ROTATE
      - O-RING PRESSURE LEAK CHECK PLACES SECONDARY SEAL IN OUTBOARD POSITION WHICH MINIMIZES SEALING TIME
- MTI RECOMMENDS STS-51L LAUNCH PROCEED ON 28 JANUARY 1986
  - SRM-25 WILL NOT BE SIGNIFICANTLY DIFFERENT FROM SRM-15

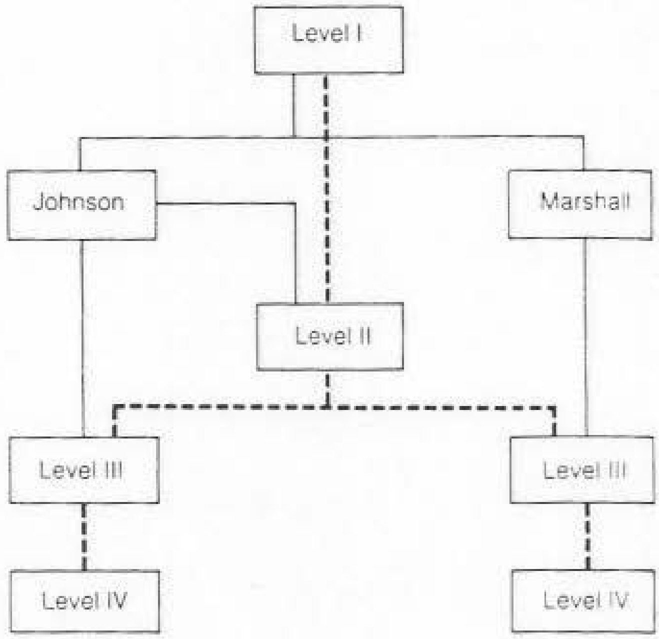
JOE C. KILMINSTER, VICE PRESIDENT
SPACE BOOSTER PROGRAMS

MORTON THIOKOL, INC.
Wasatch Division

Copy of telefax sent Kennedy and Marshall centers by Thiokol detailing the company's final position on the January 28 launch of mission 51-L

Figure 4

Shuttle Program Management Structure



———— Institutional Chain
.... Program Chain

Level I: The associate administrator for Space Flight. Oversees budgets for Johnson, Marshall and Kennedy. Responsible for policy, budgetary and top-level technical matters for Shuttle program.

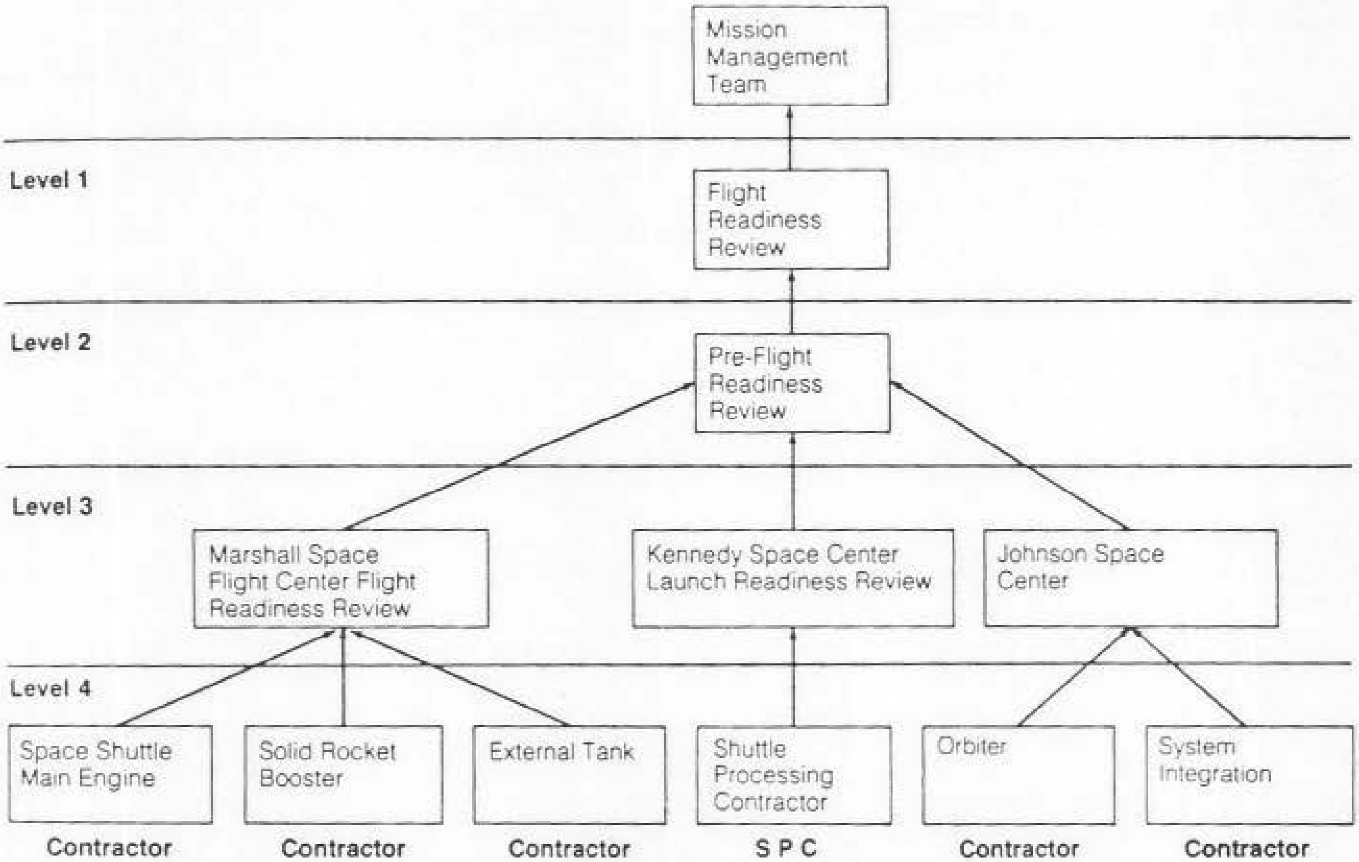
Level II: Manager, National Space Transportation Program. Responsible for Shuttle program baseline and requirements. Provides technical oversight on behalf of Level I.

Level III: Program managers for Orbiter, Solid Rocket Booster, External Tank and Space Shuttle Main Engine. Responsible for development, testing and delivery of hardware to launch site.

Level IV: Contractors for Shuttle elements. Responsible for design and production of hardware.

Figure 5

Readiness Reviews



Readiness reviews for both the launch and the flight of a Shuttle mission are conducted at ascending levels that begin with contractors.

Figure 6

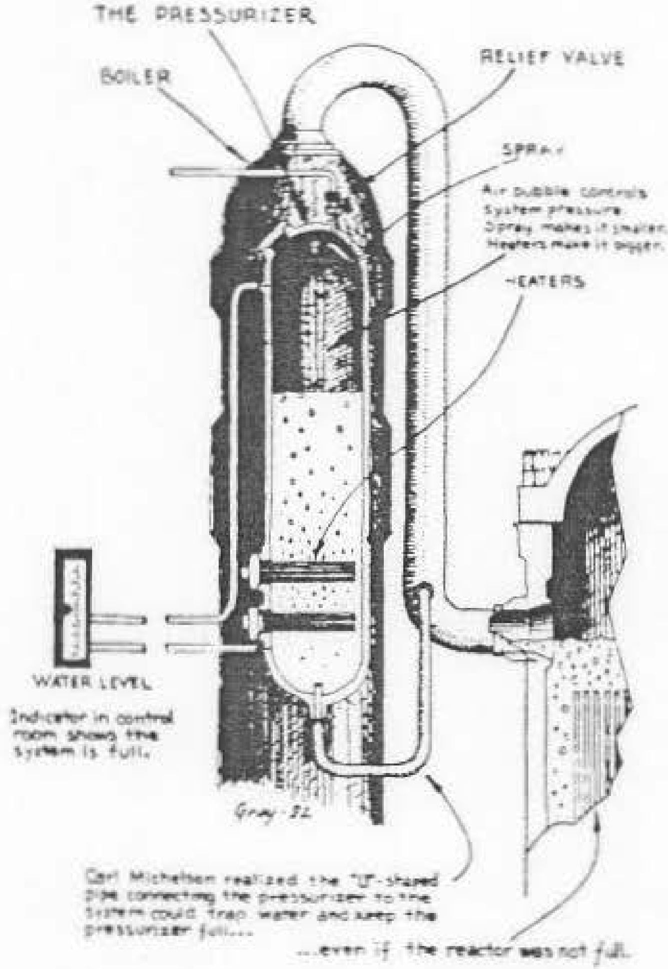


Figure 1. The pressurizer. In normal operation, it acts as a shock absorber for the reactor coolant system.