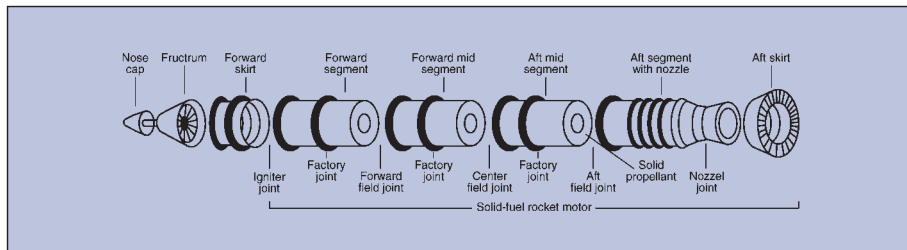# Implications and Ramifications of Engineering Design of Field Joint for Space Shuttle: STS 51-L[1]

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Introduction

Joe Kilminster, the Vice-President of Space Booster Programs at Morton Thiokol, Inc. (MTI), flipped the teleconference switch in the MTI conference room on January 27th, 1986. MTI had successfully created the Solid Rocket Booster, the first solid fuel propellant system, for the NASA Space Shuttle and it had worked without fail in all 24 Shuttle launches. Although MTI and NASA had encountered problems with the Solid Rocket Booster field joint during 1972 to 1980, design modifications of larger O-rings and thicker shims had been instituted to help fix the problem. There had been questions created by a MTI task force and Marshall Space Center management about the reliability of the O-rings. However, during the teleconference on January 27th, Mr. Kilminster was surprised to learn the seriousness of the situation when MTI engineers wanted to reverse the decision of the NASA Flight Readiness Review and persuade MTI and NASA management that Flight 51-L should not be launched the next day. MTI engineers were convinced that the possible effect of freezing temperatures on the SRB field joint could cause major problems within the Space Shuttle systems. As the teleconference proceeded and the engineers and managers debated the issues, it became clear to Mr. Kilminster that a difficult decision must be made. MTI would have to decide whether or not to recommend that NASA launch the STS 51-L, the *Challenger*.

The Launch of the Space Shuttle

On April 12, 1981, the world watched the Orbiter *Columbia* climb into space (Figure 1)[2]. After nine years of designing the first space shuttle, engineers and managers throughout the United States celebrated its first flight. NASA had been working with several contractors since 1972 to produce the Space Shuttle as a means of reusable and cost-effective transportation into space. The roar of *Columbia*'s solid rocket boosters signified a success for the Space Shuttle team.

The ascent of *Columbia* in 1981 marked the first of four test flights of the space shuttle system. These test flights were conducted between April 1981 and July 1982 with over 1,000 tests and data collection procedures. The landing of **STS-4** (Space Transportation System – 4) in July 1982 concluded the orbital test flight program with 95% of the objectives accomplished.

At this point, NASA declared the Space Shuttle "operational" and a heavy launch schedule was planned for the future. An early plan called for an eventual rate of a space mission per week but realism forced revisions. In 1985, NASA published a projection calling for an annual rate of 24 flights by 1990. However, this seemed to be an ambitious goal

since NASA worked very hard to complete nine missions in 1985. William P. Rogers, Chairman of the Rogers Commission, explained:

…the attempt to build up to 24 missions a year brought a number of difficulties, among them the compression of training schedules, the lack of spare parts, and the focusing of resources on near-term problems…. The part of the system responsible for turning the mission requirements and objectives into flight software, flight trajectory information and crew training materials was struggling to keep up with the flight rate in late 1985…It was falling behind because its resources were strained to the limit…[3]

The "routine" sentiment toward the Shuttle operations not only strained resources, but also created a sense of security among the Shuttle team. William Rogers explained this trend:

Following successful completion of the orbital flight test phase of the Shuttle program, the Shuttle was declared to be operational. Subsequently, several safety, reliability, and quality assurance organizations found themselves with reduced and/or reorganized functional capability… The apparent reason for such actions was a perception that less safety, reliability, and quality assurance activity would be required during "routine" Shuttle operations.[4]

In other words, the NASA focus had shifted from developing effective space transportation to using space transportation effectively.

This new NASA focus propelled the achievement of many Shuttle feats in its twenty-four missions between 1982 and 1986. The Orbiter *Columbia* made seven trips into space, the *Discovery* six, the *Atlantis* two, and the *Challenger* nine. In

these 24 missions the Shuttle demonstrated its ability to deliver a wide variety of payloads, to serve as an orbital laboratory, to serve as a platform to erect large structures, and to help retrieve and repair orbiting satellites. Appendix 1 chronologically summarizes the events in this case study. Appendix 2 provides a Marshall and MTI organizational chart. These accomplishments effectively met NASA's goals for the Space Shuttle.

The Space Shuttle

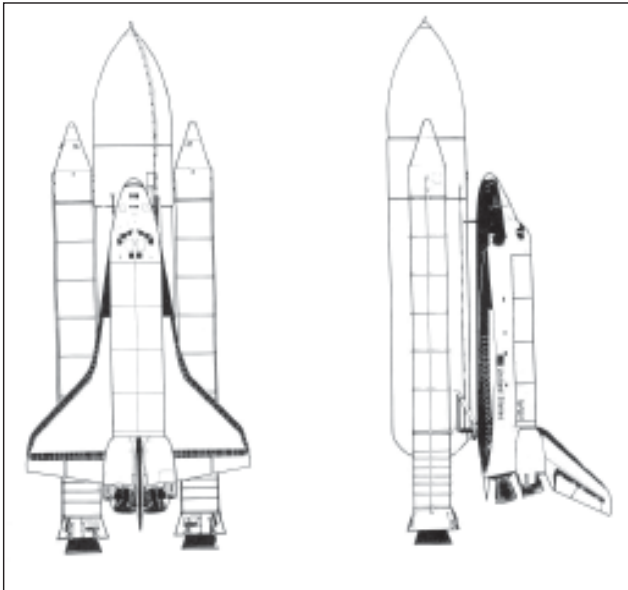The 1970s marked the development of the Space Shuttle (Figure 2). The

Figure 2

countdown, all engines are ignited and the shuttle lifts off from the launch pad. The Solid Rocket Boosters (SRBs) power the Orbiter and the External Fuel Tank during the first two minutes of flight. The SRBs are the largest solid-propellant motors ever flown and the first ever designed to be reused (Appendix 3). They contribute about 80% of total thrust at lift-off and each SRB has an approximate thrust of 3,300,000 lbs. at launch. The Orbiter main engines provide the other 20% of the thrust. Approximately two minutes after lift-off, the SRBs exhaust their fuel and are jettisoned from the Orbiter and External Tank. The SRBs fall into a designated point in the ocean, where ships recover them.

After the SRBs detach, the Orbiter main engines propel the Orbiter and the External Tank to the upper reaches of the atmosphere. Throughout the launch, the External Fuel Tank provides the propellants for the Orbiter's main engines: 143,000 gallons of liquid oxygen, and 383,000 gallons of liquid hydrogen. The External Fuel Tank is made from welded aluminum alloy

that is 154 feet long and 27½ feet in diameter. About 8½ minutes after lift-off the Orbiter jettisons the External Tank. The External Tank breaks up upon atmospheric entry and is the only Space Shuttle component that is not reused.

The flight in space begins when the Orbiter jettisons the external tank. Once the Orbiter is in space, it uses its main engines for maneuverability. The Orbiter is an aircraft-like structure with three parts: the forward fuselage with the pressurized crew compartment, the mid-fuselage with the payload bay, and the aft fuselage with the main engine nozzles and the vertical tail. It can carry up to 8 astronauts, launch 24 tons of cargo into space, and return to Earth with 16 tons of cargo.

After the experiments and activities of the mission are complete, the Orbiter descent/landing section begins. The re-entry into the atmosphere is the first stage of the descent. The Orbiter is covered with delicate high temperature heat tiles to protect it from the intense friction caused by the atmosphere upon re-entry. The Orbiter descends through the atmosphere and lands at either Edwards Air Force Base in California or at Kennedy Space Center in Florida. This landing on the concrete runway concludes the typical mission in space.

Although the mission profile and shuttle design was intricately planned, the

shuttle had three major elements: two Solid Rocket Boosters, an External Fuel Tank, and the Orbiter that houses the astronauts.

With this design, both the Solid Rocket Boosters and the Orbiter would be re-used saving large manufacturing costs and turn-around time. NASA's desire to create a high frequency of flights necessitated a detailed and consistent profile for every shuttle mission. The profile documented the schedule of events that would take place during a shuttle mission (Figure 3[5]).

A shuttle mission consists of three major events: launch into orbit, flight in space, and the descent/landing on Earth. A typical launch into orbit begins with testing of the shuttle systems. Once testing of all systems is complete, the astronauts enter the pressurized crew compartment in the front of the Orbiter. After the
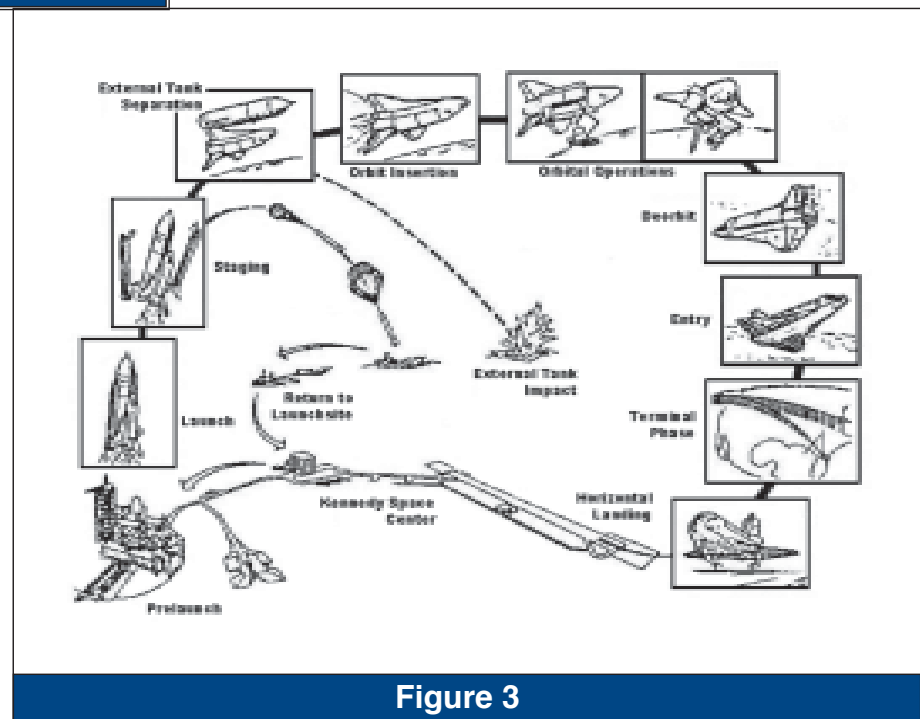

Figure 3

fiscal environment of the 1970s was austere and the planned five-Orbiter fleet was reduced to four. These budgetary issues were compounded by engineering problems that contributed to schedule delays. The initial orbital test flights were delayed by more than two years. The first test craft was the Orbiter *Enterprise*, a full size model of the space shuttle without the engines and other systems needed for orbital flight. The *Enterprise* was used to check the aerodynamic and flight control characteristics of the Orbiter in atmospheric flight. The *Enterprise* was carried atop a modified Boeing 747 and released for a gliding approach and landing at the Mojave Desert test center. Five of these test flights seemed to validate the Orbiter's systems. After the *Enterprise* test flights were completed in 1977, extensive Shuttle ground tests followed. These tests included vibration tests of the entire assembly and tests of the various Shuttle parts.

Joint Rotation on the SRM Field Joint

Morton Thiokol, Inc. (MTI) used many tests including joint lab tests, structural test articles, seven static firings, and two case configuration burst tests to verify the performance of its product, the Solid Rocket Motor. The Solid Rocket Motor (SRM) is the principal component of the Solid Rocket Boosters (SRBs) (Figure 4), the main propellants for the Shuttle during initial launch. A stack of cylindrical segments, each SRB is 149.16 ft long and 12.17 ft in diameter, and weighs approximately 1,300,000 lbs. at launch.

The segmented design allows the boosters to be easily transported by rail between MTI's complex in Utah and Kennedy Space Center in Florida. In Florida, the segments are connected at Kennedy and sent on the mission. After each launch, the booster is split into segments and shipped to Utah, where the solid rocket propellant is replaced and the segments are shipped back to Florida.

The Solid Rocket Motor is comprised of four of the booster segments (forward segment, forward mid-segment, aft mid-segment, and aft segment with nozzle). The SRM is the most important part of the SRB because it contains the propellant for the booster. Each segment of the SRM is attached to another in Kennedy Space Center with three field joints (forward field joint, center field joint, and aft field joint). The field joints not only hold the booster together but also seal the hot gases of the burning propellant within the steel casing of the booster. If gases leak through the joint, they could possibly burn through the wall of the external tank causing an explosion of the fuel. The explosion could result in the loss of the mission as well as the lives of the astronauts.

The Morton-Thiokol field joint design, based upon the Air Force's Titan III solid-fuel rocket field joint, is illustrated
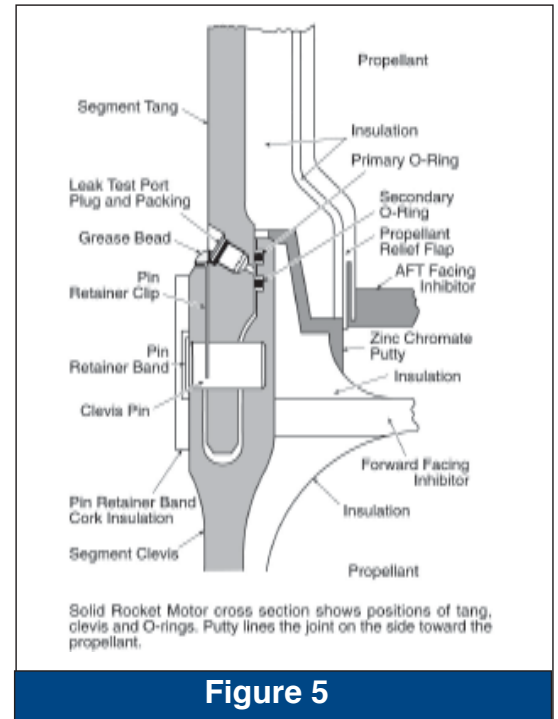

Solid Rocket Motor cross section shows positions of tang, clevis and O-rings. Putty lines the joint on the side toward the propellant.

Figure 5

in Figure 5. The lower edge of the top segment has a protruding tang that fits into the 3½ inch deep clevis of the upper edge of the bottom segment. A total of 177 steel pins go through the tang and clevis to hold the segments together at each joint.

The field joints maintain the structural integrity of the Solid Rocket Booster during launch. Upon ignition of the Solid Rocket Booster, the pressure within the booster peaks at 1000 lbs. per square inch (psi) in less than a tenth of a second. The burning propellant creates hot gases that are at a temperature of 5800 degrees Fahrenheit. There are two O-rings on the inner flange of the clevis that seal the field joint, containing the pressure of the hot gases from the burning propellant. The O-rings are about 1/4 inch in section diameter and are made from heat resistant Viton rubber. However, an extremely small gap of 0.005 +/- 0.004-inch will remain between the tang and the inside leg of the clevis. Zinc chromate putty protects the O-rings from direct exposure to the hot gases. As the combustion gas pressure displaces the putty in the space
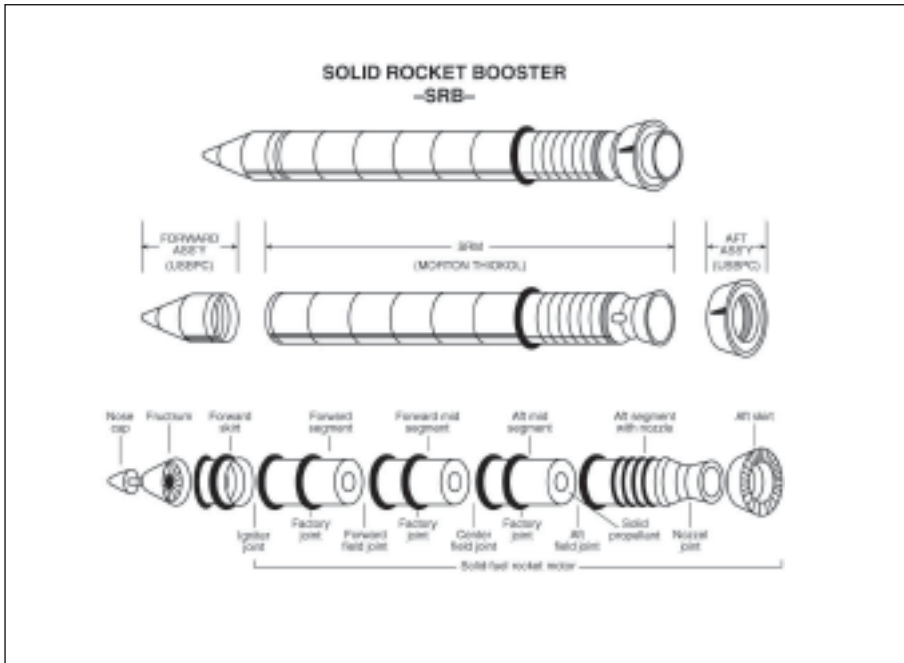

Figure 4

between the motor segments, a mechanism is created that forces the O-ring to seal the casing. The displacement of the putty acts like a piston and compresses the air in front of the primary O-ring, forcing the O-ring into the gap between the tang and clevis. If the hot gases are able to "blow by" the putty and primary O-ring, the secondary O-ring was designed to provide a redundant sealing function. As the segments are stacked during assembly, leak-check ports test the O-ring's sealing ability.

In 1977, Thiokol carried out an important hydroburst test that evaluated the safety margin in the design of the steel case segments. Hydroburst tests are where the SRM case is pressurized with water to $1\frac{1}{2}$ times the expected pressure of the motor at ignition. Although the test showed that the steel case segments met their strength requirement, joint rotation was discovered.

Joint rotation is a movement of a joint's tang and inner clevis flange with respect to each other. Before ignition, the SRBs walls are vertical and both O-rings are in contact with the tang. At the time of ignition, internal pressure of 1000 pounds per square inch (psi) swells each booster section's case by $1\frac{1}{2}$ inches circumferentially. Since the joints are stiffer than the case, each section bulges slightly. The O-ring measurements taken during the hydroburst test showed that because of the swelling, the tang and clevis inner flanges bent away from each
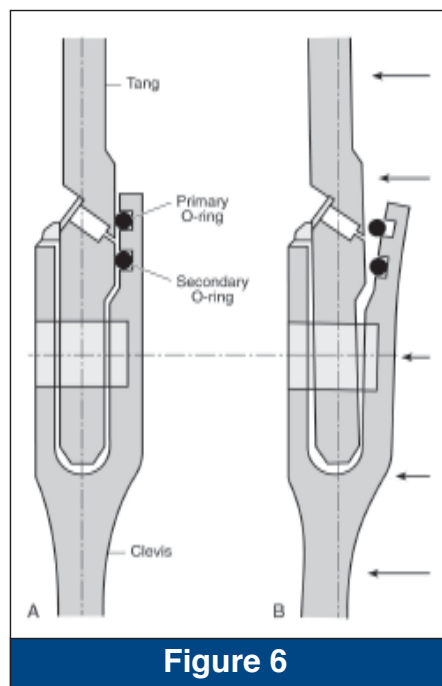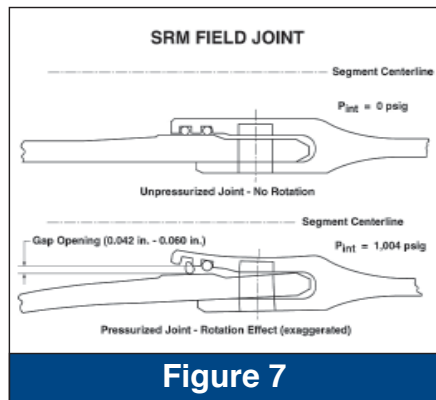

Figure 6

Figure 7

other instead of toward each other. This joint rotation enlarges the gap that the O-ring must seal and reduced the O-ring compression between the clevis and the tang (Figure 6). [6]

From further tests it was established that this **joint rotation** could be disastrous. As seen in Figure 7, the primary O-ring is pushed into the gap between the tang and the clevis. This pushing caused by distortion of the O-rings is known as extrusion.

The joint rotation may also eliminate the secondary O-ring's sealing ability. Since neither O-ring may seal correctly, a momentary drop in air pressure around the O-rings may occur. The seal of highly compressed air, which was supposed to equalize the pressure inside the booster, may not exist for a few hundred milliseconds during the initial pressure surge of the space shuttle. Without the pressure seal, the hot combustion gases from the propellant could cause "**blowby**" through the putty and erode the O-rings. **Erosion** is the decomposition, vaporization, or significant eating away of an O-ring's cross-section by combustion gases. If this erosion became widespread, a flame path could develop and the booster could burst at the joint, destroying the entire booster, and the space shuttle itself.

MTI and Marshall Space Center had to fix this joint rotation problem before they could certify the SRBs as a safe component of the Space Shuttle. William Leon Ray was an engineer with Science and Engineering in the Solid Motor Branch, and it was his job to pursue any possible problems with the SRB. [7] He became concerned about joint rotation after the hydroburst tests and sent numerous memos in the late 1970's to his manager, Robert Glenn Eudy, urging him to recommend a solution to the problem. [8]

In 1977, Leon Ray had recommended

several solutions to fixing the joint rotation problem in a memo (Appendix 4). Ray visited the manufacturers of the O-ring in 1979 and they recommended that "tests which more closely simulate actual conditions [of flight] should be done." [9] Marshall and Thiokol engineers followed this advice and continued tests into 1980. After many tests, Marshall and Thiokol felt confident in the primary O-ring's sealing ability since it sealed in much more severe conditions than was expected in a launch. When they purposely failed the primary O-ring, the engineers found that pressure at ignition activated the secondary O-ring, which sealed the joint, and fulfilled the redundant function. Further tests proved that the joint would seal at compression values lower than the industry standard when three field joint aspects were changed. The three changed aspects were that the shim size was thickened, the joint metal tolerances were reduced, and the O-ring size was increased.

At the completion of these satisfactory tests, engineers at Marshall and Thiokol unanimously agreed that although the performance of the field joint deviated from expectations, it was an acceptable risk. In 1980, with the approaching launch of *Columbia*, Marshall and MTI decided that, instead of redesigning the entire joint to solve the joint rotation problem (Option #4 in the Leon Ray memo), they would use thicker shims (Option #2) and larger O-rings (Option #3) on current hardware, and all new hardware would be redesigned. However, a redesign was not sanctioned until six years later. Therefore, all SRBs used between 1980 and 1986 had the 1977 field joint design with thicker shims and larger O-rings.

In September 1980, the SRM, with the newly modified field joints, was certified by the NASA Space Shuttle Verification/ Certification Committee. Shortly after this certification, the SRM field joints were classified on the Solid Rocket Booster Critical Items List as criticality category 1R (Appendix 5). NASA defines "**Criticality 1R**" as any subsystem of the Shuttle that contains "redundant hardware, total element failure of which could cause loss of life or vehicle." The use of "R", representing redundancy,

meant that NASA believed the secondary O-ring would pressurize and seal the gap if the primary O-ring did not work.

Reclassification of SRM Field Joint to Criticality 1

The SRM field joint was classified under Criticality 1R between November 1980 to the flight of STS-5 in November 1982. Between the first and fifth flight three significant events occurred that caused NASA and Thiokol engineers to rethink the field joint classification:

1. After the second flight, STS-2, in November 1981, inspection revealed the first in flight erosion of the primary O-ring. The erosion of .053 inches occurred in the right SRB's aft field joint and was caused by hot motor gases.

2. In 1982, Thiokol began tests of the method of putty placement and the effect of the assembly of the rocket stages on the integrity of the putty. Thiokol conducted these investigations because they believed blow holes in the insulating putty were a cause of erosion on the STS-2.

3. In May 1982, high pressure O-ring tests and tests of the new lightweight motor case were conducted. These tests convinced Marshall management that the secondary O-ring would not perform its redundant function if the joints rotated when the SRM reached 40% of its maximum expected operating pressure. Since the dual O-rings were not a *completely* redundant system, the Criticality classification was changed from Criticality 1R (Appendix 5) to Criticality 1 in December, 1982 (Appendix 6).

Although the Criticality classification was revised, Marshall management and Thiokol still seemed to believe that the seal was redundant in all but the worst conditions. Dr. Judson Lovingood, the Deputy Manager in the Shuttle Projects Office at Marshall, explained:

> *"…There are two conditions you have to have before you don't have redundancy. One of them is what I call a spatial condition which says that the dimensional tolerances have to be such that you get a bad stackup [the SRB segments not being stacked correctly], you don't have proper squeeze, etc. on the O-ring so that when you get joint rotation, you will lift the metal surfaces off the O-ring. All right, that's the one condition, and that is a worst case condition involving dimensional tolerances. The other condition is a temporal condition which says that you have to be past a point of joint rotation, and of course, that relates back to what I just said. So first of all, if you don't have this bad stackup, then you have full redundancy. Now secondly, if you do have the bad stackup, you had redundancy during the ignition transient up to the 170 millisecond point…but that is the way I understand the Critical Items List.[10] "*

This idea that the secondary O-ring would seal except for in the worst conditions prevailed at both Marshall and Thiokol.

O-Ring Erosion and Putty

Between 1980 and 1984, the O-ring erosion/blowby problem was infrequent. However, the erosion on STS 41-B, launched on February 3, 1984, was more severe and caused concern among Marshall and Thiokol engineers. After this flight, Lawrence Mulloy, the director of the SRB project at Marshall, sent a letter to Thiokol which asked for a formal review of the booster field joint and nozzle joint sealing procedures. Thiokol was required to identify the cause of erosion, determine its acceptability, define any necessary changes, and reevaluate the putty that was in use.

In April 1983, Thiokol had conducted tests to study the behavior of the joint putty. These tests showed that the STS-2 erosion was probably caused by "blow holes" in the putty, which allowed a jet of hot gas to focus on a point on the primary O-ring. This focused jet of hot gases "impinged" or eroded portions of the O-ring. NASA engineers had identified two different types of erosion. **Blowby erosion** happens when the O-ring has not sealed the joint gap and the edge of the O-ring erodes as the hot gas flows around it. **Impingement erosion** occurs when the O-ring is already sealed and a focused jet of hot gas strikes the surface of the O-ring and removes a portion of it.

Shortly after Mulloy's memo was sent to Thiokol, John Miller, Marshall Chief of the Solid Motor Branch, wrote a memo to George Hardy, Deputy Director of the Science and Engineering Directorate. This memo identified several problems with the putty of 41-B and was mainly concerned with the charred rings on 41-B and "missing putty" that was discovered when the Solid Rocket Boosters were recovered and disassembled (Appendix 7).

Brian Russell, Thiokol's Manager of System's Engineering, decided that the putty and its **layup** (placement) was not at fault for the erosion. Russell argued that the higher stabilization pressure adopted in **leak check procedures**, first implemented in one field joint on STS-9, increased the chance of O-ring erosion. Russell stated that that the air pressure forced through the joint during the O-ring leak check was creating more putty blow holes, which allowed more focused jets on the primary O-ring, thereby increasing the frequency of erosion. This hypothesis is substantiated by the leak check history shown in Figure 8. When the impact of air pressure was only 50 pounds per square inch (psi), 10% of the flights experienced anomalies (blowby or erosion.) When the leak check impact was 100 psi, no flights experienced anomalies. When the leak check was boosted to 200 psi, over half the Shuttle missions experienced O-ring blowby or erosion. This corroborated Russell's theory that putty layup was not at fault for the O-ring erosion but that erosion and blowby were due to high impact by air pressure on the joint.

Although impingement erosion did seem to be a problem, lab tests convinced Thiokol that it should not stop future flights. In April 1981 Thiokol engineers conducted tests on joint putty where they allowed a jet of hot gas to focus on a point on the primary O-ring. They discovered that this focused jet impinged on portions of the O-ring and that the *maximum possible* impingement erosion was .090 inches. Further lab tests proved that an O-ring would seal at 3,000 psi when erosion of .095 inches was simulated. This safety margin convinced Marshall and Thiokol to recommend the flight of STS 41-C on April 6, 1984. The flight was approved by NASA "accepting the possibility of some O-ring erosion due to the hot gas impingement."[11] Although erosion was a problem, Marshall and Thiokol allowed further shuttle flights since there would always be this safety margin. Table

Table 1: Summary of Test Results

Flight No.	Date	SRB	Joint / O-ring	Pressure Field	Pressure Nozzle	Erosion	Blow-by	Joint Temp. (°F)
DM-1	07/18/77	#	#	NA	NA	#	#	84
DM-2	01/18/78	#	#	NA	NA	#	#	49
DM-3	10/19/78	#	#	NA	NA	#	#	61
DM-4	02/17/79	#	#	NA	NA	#	#	40
QM-1	07/13/79	#	#	NA	NA	#	#	83
QM-2	09/27/79	#	#	NA	NA	#	#	67
QM-3	02/13/80	#	#	NA	NA	#	#	45
STS-1	04/12/81	#	#	50	50	#	#	66
STS-2	11/12/81	(Right)	Aft Field / Primary	50	50	X	#	70
STS-3	03/22/82	#	#	50	50	#	#	69
STS-4	06/27/82	unknown	hardware lost at sea	50	50	NA	NA	80
DM-5	10/21/82	#	#	NA	NA	#	#	58
STS-5	11/11/82	#	#	50	50	#	#	68
QM-4	03/21/83	#	Nozzle / Primary	NA	NA	X	#	60
STS-6	04/04/83	(Right)	Nozzle / Primary	50	50	*1	#	67
STS-6	04/04/83	(Left)	Nozzle / Primary	50	50	*1	#	67
STS-7	06/18/83	#	#	50	50	#	#	72
STS-8	08/30/83	#	#	100	50	#	#	73
STS-9	11/28/83	#	#	100	100	#	#	70
STS 41-B	02/03/84	(Right)	Nozzle / Primary	200	100	X	#	57
STS 41-B	02/03/84	(Left)	Forward Field / Primary	200	100	X	#	57
STS 41-C	04/06/84	(Right)	Nozzle / Primary	200	100	X	#	63
STS 41-C	04/06/84	(Left)	Aft Field / Primary	200	100	*3	#	63
STS 41-C	04/06/84	(Right)	Igniter / Primary	NA	NA	#	X	63
STS 41-D	08/30/84	(Right)	Forward Field / Primary	200	100	X	#	70
STS 41-D	08/30/84	(Left)	Nozzle / Primary	200	100	X	X	70
STS 41-D	08/30/84	(Right)	Igniter / Primary	NA	NA	#	X	70
STS 41-G	10/05/84	#	#	200	100	#	#	78
DM-6	10/25/84	#	Inner Gasket / Primary	NA	NA	X	X	52
STS 51-A	11/08/84	#	#	200	100	#	#	67
STS 51-C	01/24/85	(Right)	Center Field / Primary	200	100	X	X	53
STS 51-C	01/24/85	(Right)	Center Field / Secondary	200	100	*4	#	53
STS 51-C	01/24/85	(Right)	Nozzle / Primary	200	100	#	X	53
STS 51-C	01/24/85	(Left)	Forward Field / Primary	200	100	X	X	53
STS 51-C	01/24/85	(Left)	Nozzle / Primary	200	100	#	X	53
STS 51-D	04/12/85	(Right)	Nozzle / Primary	200	200	X	#	67
STS 51-D	04/12/85	(Right)	Igniter / Primary	NA	NA	#	X	67
STS 51-D	04/12/85	(Left)	Nozzle / Primary	200	200	X	#	67
STS 51-D	04/12/85	(Left)	Igniter / Primary	NA	NA	#	X	67
STS 51-B	04/29/85	(Right)	Nozzle / Primary	200	100	X	#	75
STS 51-B	04/29/85	(Left)	Nozzle / Primary	200	100	X	X	75
STS 51-B	04/29/85	(Left)	Nozzle / Secondary	200	100	X	#	75
DM-7	05/09/85		Nozzle / Primary	NA	NA	X	#	61
STS 51-G	06/17/85	(Right)	Nozzle / Primary	200	200	*5	X	70
STS 51-G	06/17/85	(Left)	Nozzle / Primary	200	200	X	X	70
STS 51-G	06/17/85	(Left)	Igniter / Primary	NA	NA	#	X	70
STS 51-F	07/29/85	(Right)	Nozzle / Primary	200	200	*6	#	81
STS 51-I	08/27/85	(Left)	Nozzle / Primary	200	200	*7	#	76
STS 51-J	10/03/85		#	200	200	#	#	79
STS 61-A	10/30/85	(Right)	Nozzle / Primary	200	200	X	#	75
STS 61-A	10/30/85	(Left)	Aft Field / Primary	200	200	#	X	75
STS 61-A	10/30/85	(Left)	Center Field / Primary	200	200	#	X	75
STS 61-B	11/26/85	(Right)	Nozzle / Primary	200	200	X	#	76
STS 61-B	11/26/85	(Left)	Nozzle / Primary	200	200	X	X	76
STS 61-C	01/12/86	(Right)	Nozzle / Primary	200	200	X	#	58
STS 61-C	01/12/86	(Left)	Aft Field / Primary	200	200	X	#	58
STS 61-C	01/12/86	(Left)	Nozzle / Primary	200	200	#	X	58

\# - denotes No Anomaly   NA – denotes Not Applicable

*1 - On STS-6, both nozzles had a hot gas path detected in the putty with an indication of heat on the primary O-ring.

*3 - On STS 41-C, left aft had a hot gas path detected in the putty with an indication of heat on the primary O-ring.

*4 - On a center field joint of STS 51-C, soot was blown by the primary and there was a heat effect on the secondary

*5 - On STS 51-G, right nozzle had erosion in two places on the primary O-ring.

*6 - On STS 51-F, right nozzle had hot gas path detected in putty with an indication of heat on the primary O-ring.

*7 - On STS 51-I, left nozzle had erosion in two places in the primary O-ring.

This table was created based on information provided in "The Challenger Launch Decision- Risky Technology, Culture, and Deviance at NASA", by Vaughan, Diane, University of Chicago Press, 1996.
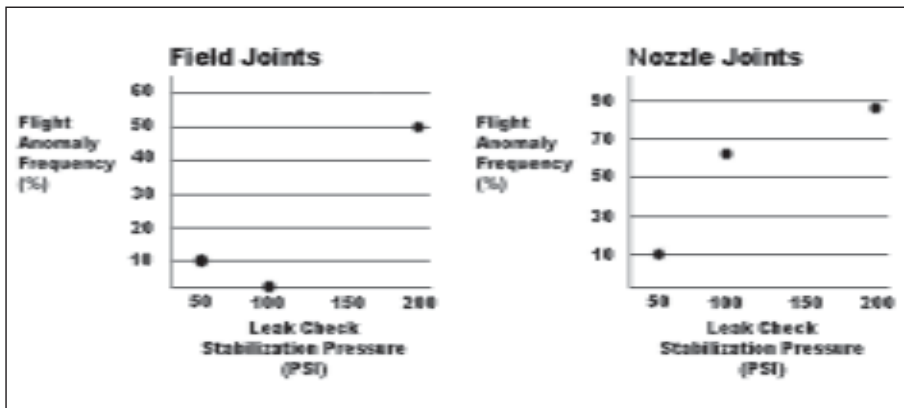
Figure 8

1 lists the incidences of O-ring distress (erosion and blow-by) and related temperature for the flights that took place in the past.

The Launch Decision Process

The decision to launch a space shuttle involves many different levels of management and sources of information. The process, known as the **Shuttle Flight Readiness Review** (Figure 9 and Appendix 8), is a carefully planned, step-by-step activity, established by NASA to certify the readiness of all components of the Space Shuttle. The process is focused upon the Level I Flight Readiness Review, chaired by NASA Associate Administrator for Space Flight and attended by the NASA Chief Engineer and supporting engineers. The Level I Review is held about two weeks before the launch.

The process begins with a directive from the Associate Administrator for Space Flight that outlines the schedule for the Level I Flight Readiness Review and the steps that precede it. At Level IV, the contractors formally certify in writing the flight readiness of their products. These certifications are made to the appropriate Level III NASA managers. At Level III, a review is conducted for both Marshall and Kennedy which verifies the readiness of the launch support elements. The Certification of Flight Readiness is presented to the Level II Program Manager at Johnson Space Center. At this review each Space Shuttle program group agrees that it has satisfactorily completed the manufacture, assembly, test, and checkout of the element including the contrac-

tors' certification of the design and performance of the element. The Flight Readiness Review ends in the Level I Review by the highest NASA administrators and managers.

The initial directive also establishes a Mission Management Team for the particular mission. This team is responsible for the Shuttle's readiness from two days before launch to the landing of the Orbiter. The Mission Management Team also holds a **L-1 meeting** 24 hours before each scheduled launch. The L-1 addresses the closeout of any open work, a closeout of any Flight Readiness Review action items, a discussion of new problems, and an updated briefing on anticipated weather conditions at the launch site and at the abort landing sites in different parts of the world.

The Launch Decision Process for STS 51-L

On January 15, 1986, NASA held the Flight Readiness Review for STS 51-L. Jesse Moore, the Associate Administrator for Space Flight, issued a directive on January 23rd that the Flight Readiness Review had been conducted and that 51-L was ready to fly pending closeout of any open work. No problems with any Shuttle components were identified in the directive. The L-1 Mission Management Team meeting was conducted on January 25th. No technical issues were brought up in the meeting and all Flight Readiness Review items were closed out. The only remaining issue facing the Mission Management Team at the L-1 review was the approaching cold front, with forecasts of rain showers and temperatures in the mid-sixties. There had also been very heavy rain since the Shuttle was rolled out onto the launch pad.

At 12:36 p.m. on January 27th, the Mission Management Team cancelled the launch for that day because of high crosswinds at the launch site. The team aimed to launch at 9:38 a.m. on January 28th. At 2:00 p.m. on the 27th, the team met again. The weather was expected to be clear but cold with temperatures in the low twenties for about eleven hours. The predicted temperatures for January 28th were as follows: 30° F at midnight, 22° F at 6:00 a.m., rising to 25° F by 9:00 a.m., and 26° F at launch time. Issues were raised about the cold weather effects on the launch facil-
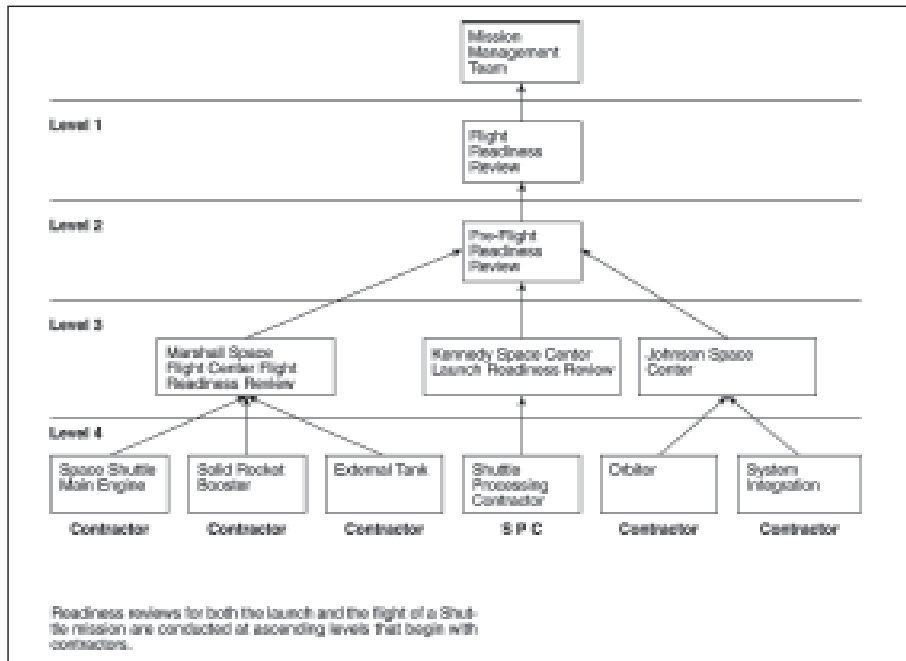

Figure 9

ity and all members of the team were asked to review the situation and call if problems arose.

At 2:30 p.m. on January 27th, Robert Ebeling, an engineer in the SRM project at Morton Thiokol, after learning of the predicted low temperatures, convened a meeting with several Thiokol engineers to discuss the effects of the cold temperatures on the SRM. Ebeling stated that "The meeting lasted one hour, but the conclusion of that meeting was Engineering [personnel]…were very adamant about their concerns on this lower temperature, because we were way below our data base and we were way below what we qualified for.[12]" The SRM had been qualified to fly at an SRM temperature between 40° F and 90° F and the previous lowest O-ring temperature had been 53° F.

Ebeling communicated the concerns to Allan McDonald, the Thiokol liaison for the SRB project at Kennedy Space Center. McDonald informed managers at Marshall and Kennedy of Thiokol's concern and an impromptu teleconference was held at 5:45 p.m. At this teleconference, Thiokol engineers briefly conveyed their concerns to the other offices. Another teleconference was scheduled for 8:00 p.m. so that the Thiokol engineers could prepare a full presentation and all necessary officials could attend.

The Teleconference

At 8:00 p.m. on Friday, January 27th, 1986, engineers and managers from Kennedy Space Center, Marshall Space Center, and Morton Thiokol, Inc, participated in the teleconference. "Telecons" as they were called were accepted, regular methods of conference conversations between NASA and its different contractors. However, this was the first teleconference where a contractor was asking NASA not to launch the shuttle.

The teleconference presentation (Appendix 9) began with Robert (Bob) Lund, the Vice-President of Engineering at MTI, presenting the findings of the Thiokol engineers. Essentially, the engineers felt that the STS-51L should not be launched the following morning due to problems associated with the O-rings in the field joints and cold temperatures. The Thiokol engineers began their analysis of the field joint by describing the O-ring history. This history showed that erosion was a

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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 15-B— 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

Figure 10

</div>

significant problem but did not relate erosion depth to temperature. (Appendix 9) The engineers next explained the concerns about launching at low temperatures. Roger Boisjoly and Arnold Thompson, both Thiokol engineers, presented the argument that lower temperatures resulted in longer primary O-ring sealing time. (Figure 10 and Appendix 9).

The MTI engineers believed that this higher erosion due to cold temperatures was evidenced by the flight of SRM-15 (Flight 51-C, January 1985). Flight 51-C was launched on January 24, 1985. The temperature of the O-rings at launch was 53° F, the coldest to that date. O-ring erosion occurred in both solid rocket boosters with both impingement erosion and blow-by erosion. Roger Boisjoly described the blow-by erosion seen in STS 51-C:

SRM 15 [STS 51-C] actually increased [our] concern because that was the first time we had actually penetrated a primary O-ring on a field joint with hot gas, and we had a witness of that event because the grease between the O-rings was blackened just like coal…and that

was so much more significant than had ever been seen before on any blow-by on any joint…the fact was that now you introduced another phenomenon. You have impingement erosion and bypass erosion [blow-by], and the O-ring material gets removed from the cross section of the O-ring much, much faster when you have bypass erosion or blow-by.[13]

STS 51-C was the first flight where the secondary O-ring had seen the effect of heat. Chemical analysis of the blow-by material on STS 51-C found that it contained both the products of putty and O-ring.

Boisjoly and Thompson then presented several items about the O-ring material. Boisjoly argued that as the temperature dropped, the O-ring material would become harder. This increased hardness would make it more difficult for the O-ring to squeeze between the tang and clevis and seal the joint correctly. Brian Russell, Special Projects Engineer of Solid Rocket Motors at MTI, explains:

Bench test data indicate that the O-ring resiliency (its capability to follow the metal) is a function of temperature and rate of case expansion. MTI measured the force of the O-ring against Instron platens, which simulated the nominal squeeze on the O-ring and approximated the case expansion distance and rate. At 100 degrees F, the O-ring maintained contact. At 75 degrees F, the O-ring lost contact for 2.4 seconds. At 50 degrees F, the O-ring did not re-establish contact in ten minutes at which time the test was terminated. The conclusion is that the secondary sealing capability in the SRM field joint cannot be guaranteed.

Furthermore, the grease within the joint would become thicker due to the lower temperature. This thicker grease viscosity would make it more difficult for the O-ring to move across the grease to seal the joint. The engineers concluded that the hardness of the O-ring material and the thicker grease due to lower temperatures factors would result in a longer time for the primary O-ring to pressurize and seal the joint. This higher primary O-ring pressure actuation time could also result in decreaseed secondary seal capa-

bility. Boisjoly used the data in Figure 11 and Appendix 9 to illustrate this concept. Brian Russell explained this further:

If the primary O-ring were to fail from 0 to 170 milliseconds, there is a very high probability that the secondary O-ring would hold pressure since the case has not expanded appreciably at this point. If the primary seal were to fail from 170 to 330 milliseconds, the probability of the secondary seal holding is reduced. From 330 to 600 milliseconds the chance of the secondary seal holding is small. This is a direct result of the O-ring's slow response compared to the metal case segments as the joint rotates.

• **Filed 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 Reop

      • Bench Testing Showed Capability To Maintain O-Ring Contact During Initial Phase (0-170 Ms) Transient

Figure 11

Boisjoly then compared the erosion on two different SRMs (Appendix 9). SRM 15 (STS 51-C, with an O-ring temperature of 53° F) had worse blow by then SRM 22 (STS 61-A, with an O-ring temperature of 75° F). Although SRM 15 had worse erosion, this made the engineers and managers question the relationship between cold temperature and erosion since both a hot and cold launch had considerable erosion. Boisjoly recalled this incident:

I was asked, yes, at that point in time I was asked to quantify my concerns, and I said I couldn't. I couldn't quantify it. I had no data to quantify it, but I did say I knew it was away from goodness in the current data base. Someone on the net commented that we had soot blow-by on SRM-22, which was launched at [an O-ring temperature of] 75° F. I don't remember who made the comment, but that is where the first comment came in about the disparity between my conclusion and the observed data because SRM-22 had blow-by at essentially a room temperature launch. I then said that SRM-15 [STS 51-C] had much more blow-by indication and that it was indeed telling us that lower temperature was a factor. This was supported by inspection of flown hardware by myself. I was asked again for data to support my claim, and I said I have none other than what is being presented, and I had been trying to get resilience data…since last October…[14]

This information caused the participants at Marshall and Kennedy to consider what the data actually meant. Discussion resumed when Arnold Thompson presented a chart which showed that in static tests, blow-by had not occurred at O-ring temperatures of 30° F or 75° F. (Appendix 9)

Bob Lund's presentation summarized the analysis of the engineers at MTI. Although they agreed that factors other than temperature controlled blow-by, they decided that the launch should not be held outside of the current database. (Appendix 9) The lowest O-ring temperature they had observed was 53° F and the engineers concluded that the O-ring tem-
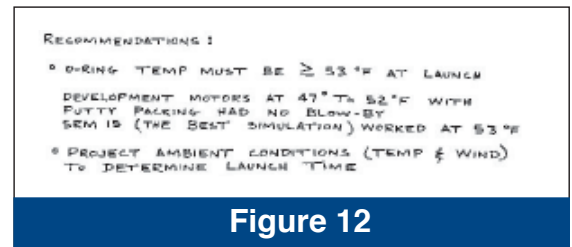

Figure 12

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perature must be at that temperature or higher at launch. (Figure 12 and Appendix 9)

Lawrence Mulloy, the Marshall Space Center Project Manager for the SRB, asked Joe Kilminster, the Vice-President of Space Booster Programs at MTI, for the formal MTI recommendation. Kilminster responded that based on the engineering conclusions, he could not recommend launch at any O-ring temperature below 53° F. Bob Lund explains what happened next:

…the rationale was rejected…Mr. Mulloy said he did not accept that, and Mr. [George] Hardy [Marshall Deputy Director for Science and Engineering] said he was appalled that we would make such a recommendation.

Mulloy assessed the situation and used the same argument as the Criticality Items List for keeping the SRB field joint in use (Appendix 10). Although there might be erosion through blow-by, he expected the shuttle to fly safely. Furthermore, the blow-by of the O-rings could not be correlated to temperature since STS 61-A had blow-by at O-ring temperature of 75° F. Also, STS 51-B (SRM 16), with an O-ring temperature of 75° F, had the worst blow-by and erosion recorded (Appendix 11). Mulloy concluded that the temperature did not seem to increase blow-by or erosion and O-ring erosion was an acceptable risk recognized at all levels of NASA management.

At this point, Kilminster asked for a five minute off-net caucus within MTI. Approximately ten engineers and four managers participated in the caucus. These managers were: Calvin Wiggins, Vice President and General Manager of Thiokol's Space Division; Jerald Mason, Senior Vice President of Wasatch Operations; Joe Kilminster, Vice President of Space Booster Programs; and Robert Lund, Vice President of Engineering. Jerald Mason explains the content of the caucus:

Now, in the caucus we revisited all of our previous discussions, and the important things that came out of that was that, as we had recognized, we did have the possibility that the primary O-ring might be slower to move into the seating position and that was our concern, and that is what we had focused on originally. The fact that we couldn't show direct correlation with the O-ring temperature was discussed, but we still felt that there was some concern about it being colder. We then recognized that, if the primary did move more slowly, that we could get some blow-by and erosion on the primary. But we had pointed out to us in that caucus a point that had not come across clearly in our earlier discussions, and that is that we had run tests where we deliberately cut large pieces out of the O-rings to see what the threshold of sealing was, and we found we could go to 125 thousandths of a cut out of the O-ring and it would still seal.[15]

This realization prompted the rest of the conversation by the managers. Mason stated that a management decision must be made and asked Bob Lund to "take off his engineering hat and put on his management hat.[16]" Lund, who had previously been against the launch, reversed his opinion in the subsequent discussion and agreed with the other managers to recommend a launch. The managers felt that this was the best decision since much of the engineering data had been unsubstantiated and contradictory. Kilminster went on-line again and gave Marshall and Kennedy the MTI recommendation that STS 51-L launch should occur as planned (Figure 13). Mueller, a NASA administrator asked if everyone supported this decision, but no engineer from MTI responded to this question. NASA proceeded with its plans to launch STS 51-L on January 28th, 1986.
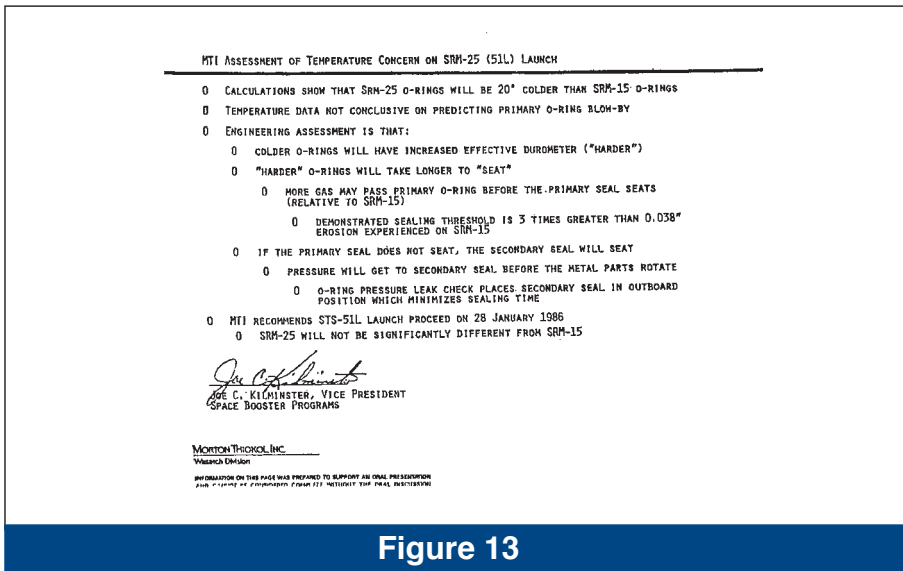

Figure 13

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Student Assignment

The class could be divided into four groups. Each group has the following responsibilities:

Group A: Defend launching STS 51-L.

Group B: Defend not launching STS 51-L.

Group C: Assume the role of a consulting team critically evaluating the data provided in the case study with respect to the following and provide recommendations to management:

(a) Engineering design considerations – consider the aspects of risk management, evaluation of test data, and blow-by considerations.

(b) Statistical data analysis – analyze the data provided using statistical methods and interpret the data accordingly.

(c) Ethical considerations – consider the aspects of managing risk, maintaining competence, and behaving responsibly using utilitarianism, Kantianism, and ethical codes.

Group D: Assume the role of NASA and MTI management and make a final decision on the launch of STS 51-L.

Glossary of Terms

Blow-by: passage of gas or debris around an O-ring before it has sealed the joint by moving into its seated position. It may or may not be accompanied by charring or erosion.

Blow-by erosion: the O-ring has not sealed the joint gap and the edge of the O-ring is "eaten away" as hot gases flow around it; erosion caused by blow-by

Criticality usage: Classification of any subsystem of the Space Shuttle that defines the importance and risk associated with the subsystem; i.e. a Criticality 1 element could cause loss of the Shuttle if it fails

Erosion: the "eating away" of portions of the O-ring due to hot gases

Impingement erosion: occurs when the O-ring is already sealed and a focused jet of hot gas strikes the surface of the O-ring and removes a portion of it

Joint rotation: a movement of the joint's tang and inner clevis flange with respect to each other; the movement, which takes place as pressure builds in the boosters at ignition, enlarges the gap the O-ring must seal

L-1 meeting: a meeting held by the Mission Management Team 24 hours before launch to close out any open work, discuss new problems, and update the Shuttle Team on anticipated weather conditions

Leak check: a procedure that pressurizes the leak check port within the field joint to determine whether or not the O-rings are properly sealing the joint

Putty layup: the placement of the putty as the field joint is assembled

Shuttle Flight Readiness Review: a carefully planned step-by-step activity that was established by NASA to certify the readiness of all components of the Space Shuttle before launch

STS nomenclature: stands for Space Transportation System which includes the Orbiter, External Tank, and Solid Rocket Boosters; the numbers after the STS describe the flight's placement. In the early 1980s, the Shuttle was numerically ordered but as the frequency of Shuttle launches increased, NASA created a new system. In the new system, the first number stood for the year in which the flight was launched, the second number stood for the launch site, and the letter stood for the order in which the shuttle was launched. For example, STS 51-L stood for the 12th Space Transportation System launched in 1985 and it was launched from Kennedy Space Center.

Appendices

1. Timeline of Events
2. Marshall and MTI Partial Organizational Charts
3. Recovery of SRB
4. Leon Ray memo
5. Criticality 1R Classification
6. Criticality 1 Classification
7. Memo from John Miller to John Hardy
8. Excerpts from the Flight Readiness Review for STS 51-E
9. Full Thiokol teleconference presentation
10. Lawrence Mulloy recommendations
11. Diagrams of STS 51-B erosion

NOTES

[1] This case was written from secondary public sources, solely for the purpose of enhancing classroom student discussion on engineering design and ethics. We acknowledge the help rendered by Luis Guzman, Jr., in making the figures and appendices readable. This case study is based upon work partially supported by the Division of Undergraduate Education, National Science Foundation under Grant Numbers 9752353 and 9950514. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

[2] Appendix 1 chronologically summarizes the events in this case study. Appendix 2 provides a Marshall and MTI Organizational Chart.

[3] *Report to the President by the Presidential Commission on the Space Shuttle Challenger Accident*, vol. 1, p. 164.

[4] Presidential Commission, vol. 1, p. 160.

[5] Presidential Commission, Vol. IV, p. 87.

[6] Bell, Trudy and Esch, Karl. "The fatal flaw in Flight 51-L," IEEE Spectrum, February 1987, pp. 36-51.

[7] Vaughn, Diane, *The Challenger Launch Decision: Risky Technology, Culture, and Deviance at NASA*, The University of Chicago Press, Chicago, 1996, p. 99.

[8] Presidential Commission, Vol. V, p. 1644.

[9] Presidential Commission, vol. 1, p. 238.

[10] Presidential Commission, vol.1, p. 127.

[11] Presidential Commission, vol.1, p. 132.

[12] Presidential Commission, vol.1, p. 86.

[13] Presidential Commission, vol. 1, 135.

[14] Presidential Commission, vol. 1, p. 89.

[15] Presidential Commission, vol.1, p.92.

[16] Presidential Commission, vol.1, p.93.

Akila Sankar is a student at Emory University in Accounting and Philosophy. These combined interests, along with work at LITEE, led to the development of this case study. She hopes to combine these skills with her strengths in writing and speaking to pursue a future legal career. Aside from her college career, she has leadership roles in service and debate organizations. She has presented a paper in a philosophic conference and another case study at the Southeastern Case Research Association conference.

Chetan S. Sankar is Thomas Walter Professor of Management and has been on the faculty of Auburn University since 1989. He earned his Bachelor of Engineering degree from Regional Engineering College, India, his Master of Business Administration from Indian Institute of Management and his Doctor of Philosophy from the University of Pennsylvania, Wharton School. He has taught graduate and undergraduate courses in MIS, engineering management and global telecommunications management. Professor Sankar has published more than 100 refereed journal and conference articles. He along with Dr. Raju received the 1999 Curriculum Innovation Award from the ASME International for integrating theory, practice, and design in a mechanical engineering design course. A multimedia courseware he created along with Dr. Raju won the Premier Courseware Award of 1998 from NEEDS and John Wiley & Sons for its ability to stimulate active participation and teaming by students. He received the Outstanding Research Award from the College of Business in 1997. Professor Sankar along with Drs. Raju, Halpin, Halpin are actively involved in using research methodologies to develop multi-media instructional materials for use in undergraduate classrooms. These projects have been sponsored by the National Science Foundation.
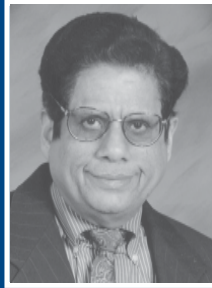
Dr. P.K. Raju is Thomas Walter Professor & Director, Laboratory for Innovative Technology & Engineering Education (LITEE), in the Mechanical Engineering Department at Auburn University. He worked at Purdue; the Catholic University of America in the U.S. and several universities in India before joining Auburn in fall 1984. He was a visiting professor at the Technical University of Berlin (1981), an Invited Professor at the Universite Bordeaux I, France (1994) and an Invited Professor at Universite Du Havre, France (1996). Since 1996 Dr. Raju has been Director (Engineering) Auburn Industrial Extension Service, and Assistant Chairman of the Mechanical Engineering Department.

He has directed and managed a variety of sponsored research and development projects. These projects have dealt with different aspects of acoustics, vibration, noise control, non-destructive evaluation, and engineering education. These projects have been funded by industries (John Deere, Louisiana Pacific Corporation, Wheelabrator, American Gas Association) and government and international agencies (UNDP, NASA, NSF, DOD, DOE, NIST) and totals over $2.5 million. Dr. Raju has authored or edited 10 books, published five book chapters and has published a total of 129 papers in journals and conference proceedings. He also is the co-author of a book titled "Integrating Engineering Theory & Practice" to be published by Prentice Hall.

Dr. Raju received the NSF Novel and Expedited Research Award (1989), NASA innovative research award (1991), Auburn University's outstanding faculty award (1993). He served as a United Nations expert during 1995-1996. Dr. Raju is the recipient of Auburn University's Birdsong Merit Award in 1996 and the Birdsong Superior Teaching Award in 1999 for excellence in teaching. He received the 1997 Thomas C. Evans Instructional Award for the Outstanding paper in Engineering Education from the American Society for Engineering Education. He also received the ASME distinguished Service Award in 1997.

Dr. Raju is a member of the ASME, ASEE, INCE, ASA, ASNT, INCE, and Pi Tau Sigma. He served on the executive committee (1992-1996), and as Chairman of the ASME Noise Control and Acoustics Division (1996-1997), and served as Assistant Vice President Region XI (1994-1995). He also served as president of the Alpha Upsilon Chapter of Phi Beta Delta, Honor Society for International Scholars (1996-1997). He is on the editorial board of the North American Case Research Journal and is the Editor in Chief of the Journal of SMET Education - Innovations and Research.

Vamsee Dasaka graduated from Banglore university, India, in August 1997 with a Bachelor's degree in Mechanical Engineering. After working for Cauvery Ford (India) Ltd., in Bangalore till March '98, he entered Auburn University to pursue his Master's in Mechanical Engineering. He has been working as a Graduate Research Assistant with LITEE since then. He has helped in the developement of technical videos and CD-ROMs for the project in association with the team. He is currently working on his master's thesis "Learning from Failure- The SRB Redesign" and is expected to graduate soon.

Appendix 1

Timeline of Events

1977
- Enterprise flights begin
- Joint rotation is discovered in SRM
- October 21: Leon Ray writes memo detailing options for fixing joint rotation

1978-1979
- Tests conducted on all parts of Space Shuttle
- Tests conducted by Thiokol and Marshall to solve joint rotation

1980
- Marshall and MTI decide to use thicker shims and larger O-rings on field joints instead of redesigning the entire joint
- September 15: SRM is certified
- November 24: SRM is classified as Criticality 1R

1981
- April 12: *Columbia* is launched
- November 14: Inspection reveals first in-flight erosion of O-ring in STS-2

1982
- Thiokol begins tests on putty
- May: Tests of motor case and O-rings convince Marshall that secondary O-ring is not completely redundant
- July 4: Orbital test program is completed and Space Shuttle is declared "operational"
- December 17: SRM criticality classification is changed to Criticality 1R

1983
- April: Thiokol discovers impingement erosion and the "safety margin" so that flights could be launched although erosion would occur

1984
- February 3: STS 41-B erosion is extremely severe
- February 28: John Miller sends a memo to George Hardy identifying problems with the putty
- April: Larry Mulloy sends a letter to Thiokol asking them for a formal review on the joint and erosion
- April 9: Brian Russell identified the leak check procedures as the cause of the erosion
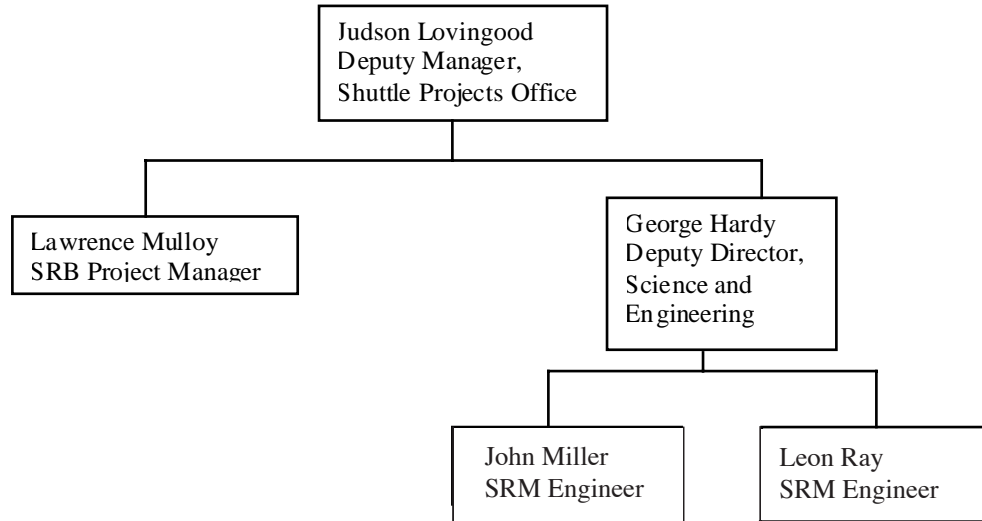
1985
- January 24: STS 51-C (SRM 15), launched at an O-ring temperature of 53°F, has large amount of erosion
- April 29: STS 51-B (SRM 16), launched at an O-ring temperature of 75°F, has worst erosion recorded
- October 30: STS 61-A (SRM 22), launched at an O-ring temperature of 75°F, has large amount of erosion
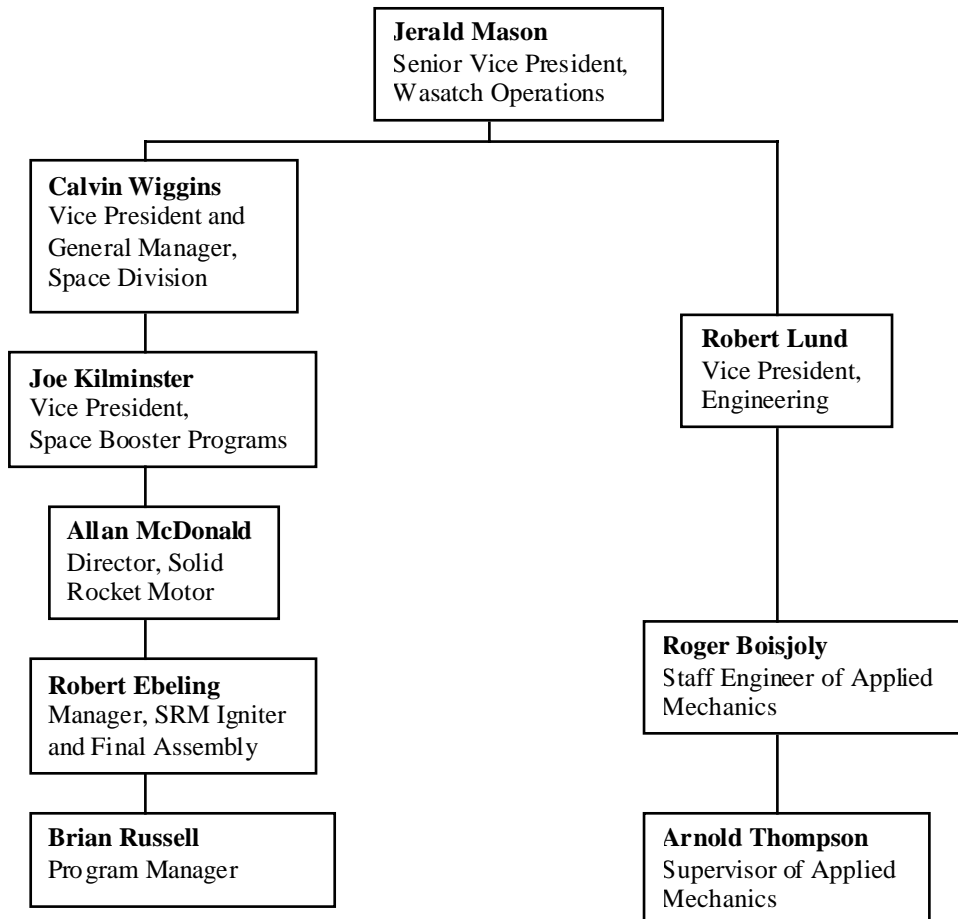
1986
- January 15: Jesse Moore issues STS 51-L Flight Readiness Review directive
- January 25: L-1 meeting conducted for STS 51-L
- January 27, 12:36 p.m.: STS 51-L is cancelled for the 27th and planned for January 28th
- January 27, 2:30 p.m.: Robert Ebeling meets with Thiokol engineers and decide that cold temperatures are not good for SRM
- January 27, 5:45 p.m.: Impromptu teleconference held
- January 27, 8:00 p.m.: Full teleconference held
- January 27, 11:00 p.m.: Kilminster gives MTI final assessment to launch STS 51-L

Appendix 2

NASA Marshall Space Center Partial Organization Chart, 1986

```
                    Judson Lovingood
                    Deputy Manager,
                    Shuttle Projects Office
                    ┌──────────┴──────────┐
        Lawrence Mulloy                    George Hardy
        SRB Project Manager                Deputy Director,
                                           Science and
                                           Engineering
                                    ┌──────────┴──────────┐
                              John Miller              Leon Ray
                              SRM Engineer             SRM Engineer
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Morton Thiokol Inc. Partial Organization Chart, 1986

```
                    Jerald Mason
                    Senior Vice President,
                    Wasatch Operations
        ┌──────────────────┴──────────────────┐
Calvin Wiggins                            Robert Lund
Vice President and                        Vice President,
General Manager,                          Engineering
Space Division                                │
    │                                         │
Joe Kilminster                                │
Vice President,                               │
Space Booster Programs                        │
    │                                         │
Allan McDonald                                │
Director, Solid                               │
Rocket Motor                                  │
    │                                    Roger Boisjoly
Robert Ebeling                           Staff Engineer of Applied
Manager, SRM Igniter                     Mechanics
and Final Assembly                            │
    │                                    Arnold Thompson
Brian Russell                            Supervisor of Applied
Program Manager                          Mechanics
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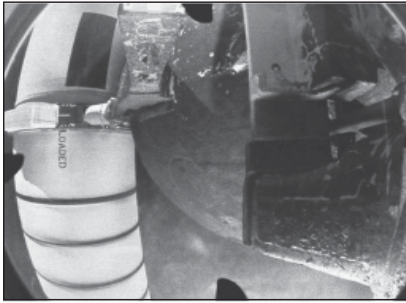
Appendix 3
Recovery of SRB

Figure 1: Detatchment of the SRB from the Shuttle

Figure 2: SRB aided in its fall to the earth by parachutes

Figure 3: SRB lands in the ocean and is retrieved by ship

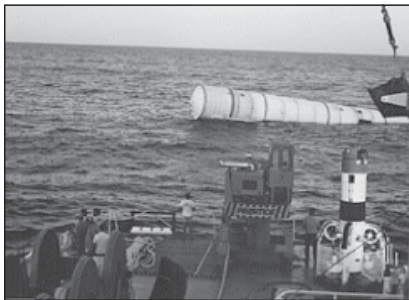**Figure 4:** The Frustrum of the SRB is loaded on to the ship

Figure 5: The body of the spent SRB is loaded on to the ship

Figure 6: The spent SRB is loaded on to the ship to be transported back to the manufacturer

Figure 7: The spent SRB is transported back to the manufacturer by a special vessel

Figure 8: The spent SRB reaches the manufacturer to be checked and readied for next mission

Appendix 4

Leon Ray Memo

ORGANIZATION	MARSHALL SPACE FLIGHT CENTER	NAME. LEON RAY
EP25	SRM CLEVIS JOINT LEAKAGE STUDY	DATE. OCTOBER 21, 1977

DESIGN OPTIONS

OPTIONS	REMARKS
1. NO CHANGE	o UNACCEPTABLE -TANG CAN MOVE OUTBOARD AND CAUSE EXCESSIVE JOINT CLEARANCE RESULTING IN SEAL LEAKAGE. o ECCENTRIC TANG/CLEVIS INTERFACE CAN CAUSE O-RING EXTRUSION WHEN CASE IS PRESSURIZED.
2. SHIMS BETWEEN TANG AND CLEVIS (OUTSIDE)	o ACCEPTABLE SHORT-TERM FIX IF PROPER SHIM SIZE IS USED. o PROBABILITY OF ERROR IN CALCULATING PROPER SHIM SIZE. o REQUIRES INCREASED ASSEMBLY TIME FOR SHIM INSTALLATION AND JOINT CENTERING.
3. OVERSIZED O-RINGS	o UNACCEPTABLE SOLUTION - HIGH PROBABILITY OF O-RING DAMAGE OR CLEVIS DISTORTION DURING ASSEMBLY. o DEPARTS FROM RECOMMENDED DESIGN PRACTICES.
4. REDESIGN TANG AND REDUCE TOLERANCE ON CLEVIS	o BEST OPTION FOR LONG-TERM FIX - ELIMINATES USE OF SHIMS WHEN ALL REDESIGNED HARDWARE IS USED. o PREVENTS THE TYPE OF ERROR WHICH COULD RESULT IN CALCULATING JOINT CLEARANCE FOR SHIM INSTALLATION.
5. COMBINATION OF REDESIGN (AS IN OPTION 4) AND USE OF SHIMS	o ACCEPTABLE APPROACH. SHIMS WILL BE REQUIRED IN SOME CASES WHEN REDESIGNED HARDWARE AND PRESENT HARDWARE IS JOINTED. o SHIMS WILL BE DISCONTINUED WHEN PRESENT HARDWARE IS PHASED OUT.

Appendix 5

SRM Criticality IR Classification

A. DESIGN

-Each O-ring pair is designed to effect a seal. The design is based upon similar single seal joints used in previous larger diameter, segmented motor cases.

A small MS port leading to the annular cavity between the redundant seals permits a leak check of the seals immediately after joining segments. The MS plug, installed after leak test, has a retaining groove and compression face for its O-ring seal. A means to test the seal of the installed MS plug has not been established.

The surface finish requirement for the O-ring grooves is 63 and the finish of the O-ring contacting portion of the tang, which slides across the o-ring during joint assembly, is 32. The joint design provides an OD for the O-ring installation, which facilitates retention during joint assembly. The entry portion of the tang provides 0.125-inch standoff from the O-rings contact portion of the tang during joint assembly. The design drawing specifies O-ring lubricant prior to the installation. The factory assembled joints (dwg. 1U517623) have an additional seal provided by the subsequently applied case insulation.

The field assembled joints (Dwg. 1U50747) and factory assembled joints (Dwg. 1U51768) benefit from the increased O-ring compression resulting from the centering affect of shims .032-.036-inches between the tang O.D. and clevis I.D. of the case joint. However, redundancy of the secondary field joint seal cannot be verified after motor case pressure reaches approximately 40% of MEOP. It is known that joint rotation compression occurring at this pressure level with a resulting enlarge extrusion gap causes the secondary O-ring to lose compression as a seal. It is not known if the secondary O-ring would successfully re-seal if the primary O-ring should fall after motor case pressure reaches or exceeds 40% MEOP.

B. TESTING

A full scale clevis joint test verified the structural strength of the case and pins (TWR-1C547). A hydroburst life cycle test (TWR-11564) demonstrated the primary seal's ability to withstand four times the flight requirement of one pressurization cycle and the secondary seal's ability to continue to seal under repeated cycling (54 cycles0 with the primary seal failed. The joint seals withstood ultimate pressure of 1483 psi during the burst tests, yielding a safety factor of 1.58. The Structural Test Article (STA-1) verified the seal's capability under flight loads and further verified the redundancy of the secondary seal.

The joint seals have performed successfully in four developmental and three qualification motor static firings.

Appendix 6

SRM Criticality Classification 1

Case, P/N, 1U50129, 1U50130, 1U50185, 1U51473, 1U50715, 1U50716, 1U50717

A.   DESIGN

The SRM case joint design is common in the lightweight and regular weight cases having identical dimensions. The SRM joint uses centering clips which are installed in the gap between the tang O.D. and the outside clevis leg to compensate fro the loss of concentricity due to gathering and to reduce the total clevis gap which has been provided for ease of assembly. On the shuttle SRM, the secondary O-ring was designed to provide redundancy and to permit a leak check, ensuring proper installation of the O-rings. Full redundancy exists at the moment of initial pressuriza-tion. However, test data shows that a phenomenon called joint rotation occurs as the pressure rises, opening up the O-ring extrusion gap and permitting the energized O-ring to protrude into the gap. This condition has been shown by test to be well within that required for safe primary O-ring sealing. This gap may, however, in some cases, increase sufficiently to cause the unenergized secondary O-ring seal to lose compression, raising question as to its ability to energize and seal if called upon to do so by primary O-ring failure. Since under this latter condition only the single O-ring is sealing, a rationale for retention is provided for the simplex mode where only one O-ring is acting.

The surface finish requirement for the O-ring grooves is 63 and the finish of the O-ring contacting portion of the tang, which slides the O-ring during joint assembly, is 32. The joint design provides an OD for the O-ring installation, which facilitates retention during joint assembly. The tang has a large shallow angle chamfer on the tip to prevent the cutting of the O-ring at assembly. The design drawing specifies application of O-ring lubricant prior to the installation. The factory assembled joints have NBR rubber material vulcanized the internal joint faying surfaces as a part of the case internal insulation subsystem.

A small MS port leading to the annular cavity between the redundant seals permits a leak check of the seals imme-diately after joining segments. The MS plug, installed after leak test, has a retaining groove and compression face for its O-ring seal. A means to test the seal of the installed MS plug has not been established.

The O-rings for the case joints are mold formed and ground to close tolerance and the O-rings for the test port are mold formed to net dimensions. Both O-rings are made of high temperature, low compression set flurocarbon elastomer. The design permits five scarf joints for the case joint seal rings. TheO-ring joint strength must equal or exceed 40% of the parent material strength.

B.   TESTING

To date, eight static firings and five flights have resulted in 180 (54 field and 126 factory) joints tested with no evidence of leakage. The Titan III program using a similar joint concept has tested a total of 1076 joints successfully.

Routing Slip

Mail Code		Name	Action
TO:	EE01	Mr. Hardy	Approval
			Call me
THRU:	EE11	Mr. Coates	Concurrence
			File
			Information
			Investigate and Advise
			Note and Forward
			Note and Return
			Per Request
			Per Phone Conversation
			Recommendation
			See me
			Signature
			Circulate and Review

SUBJECT: Burned O-Rings on STS-11

The recent experience of two burned O-rings (nozzle/case boss and forward/forward center joint) on STS-11 coupled with the "missing putty" finding at disassembly raise concern with STS-13.

Specifically concern is raised about the type II Randolph zinc chromate putty (ZCP) sensitivity to humidity and temperature. The thermal design of the SRM joints depends on thermal protection of the O-ring by the ZCP. ZCP failure to provide a thermal barrier can lead to burning both O-rings and subsequent catastrophic failure. Adhesion service-life and sensitivity to temperature and humidity of the type II ZCP must be reassessed and verified in the light of recent experience. The O-ring leak check procedure and its potential effect on the ZCP installation and possible displacement is also an urgent concern which requires expedition of previously identified fullscale tests. Effect of cavity volume size (cavity between the ZCP and primary O-ring) on O-ring damage severity must also be assessed.

Your support in this urgent matter is requested.

John Q. Miller
Chief, Solid Motor Branch

cc:
EE01/Mr. Scheinghamer
EH43/Mr. Hill
SA41/Mr. Malloy
SA42/Mr. Venc
EP01/Mr. McCool
EP21/Mr. McCarty
EP23/Messrs. Powers/Ray

Name	Tel. No. for Conf. & Ex.
John Q. Miller	453-3702
Code for other disposition: EP23	Date: 2/28/84

NASA FORM 26   JUN 73   PREVIOUS EDITIONS MAY BE USED.

Appendix 8

Excerpts from STS 51-E Flight Readiness Review

SRM Preboard (January 31, 1985)

Flight Readiness Assessment For STS 51-E

- Concern
    - STS 51-C Primary O-Ring Erosion On Two Field Joints
    - STS 51-C Soot Between Primary And Secondary O-Rings On Both Field Joints First Time Observed On Field Joint
    - Evidence Of Heat Affect On Secondary O-Ring Of A68 (Right Hand) Center Field Joint But No Erosion

- Conclusion
    - STS 51-E Could Exhibit Same Behavior
    - Condition Is Not Desirable But Is Acceptable

- Rationale For Acceptance
    - O-Ring Erosion On STS 51-C Was Within Experience Data Base
    - Momentary Gas Passage By The Primary Seal Was Seen On The STS 14-A Nozzle Joint
    - Secondary Seal Heat Effects Were Well Below Analytical Worst Case Predictions
    - Gas Jet Penetrates The Primary Seal Prior To Actuation And Sealing
    - Tests Show That O-Rings Will Seal At 3000 PSI Within 0.095 Inch Of Missing Material (Which Is Greater Than The Worst Case Prediction And Almost Twice The Erosion Seen On Any SRM Motors)
    - Primary O-Ring Erosion Observed To Date Is Acceptable And Will Always Be More Than Erosion On Secondary O-Ring If It Occurs
        - Primary O-Ring Leak Check Pushes O-Ring In Wrong Direction – Secondary O-Ring Is Sealed By Leak Check
        - Gas Volume In Front Of Primary O-Ring Is 50% Greater Than Free Volume Between O-Rings
        - Gas Will Cool As It Passes Primary O-Ring And Diffuses Circumferentially
    - Secondary O-Ring Is A Redundant Seal Using Actual Hardware Dimensions

- Evaluation Summary
    - STS 51-C Primary O-Ring Erosion On Two Field Joints
    - STS 51-C Soot Between Primary And Secondary O-Rings On Both Field Joints – First Time Observed On Field Joint
    - Evidence Of Heat Affect On Secondary O-Rings Of A68 (Right Hand) Center Field Joint But No Erosion

- Conclusion
    - STS 51-C Consistent With Erosion Data Base
        - Low Temperature Enhanced Probability – STS 51-C Experienced Worst Case Temperature Change In Florida History
        - Erosion In Two Joints Observed Before – STS 11 And 14
    - STS 51-E Could Exhibit Same Behavior
    - Condition Is Acceptable
- STS 51-E Field Joints Are Acceptable For Flight

Appendix 9

MTI Teleconference Presentation

Slides 1 & 2: Temperature Concern on SRM Joints, 27 Jan 1986

History of O-Ring Damage of SRM Field Joints

| | SRM No. | Cross Sectional View | | | Top View | | Clocking Location |
		Erosion Depth (in.)	Perimeter Affected (deg)	Nominal Diameter (in.)	Length of Max Erosion (in.)	Total Heat Affected Length (in.)	(deg)
61A LH Center Field**	22A	None	None	0.280	None	None	36° - 66°
61A LH Aft Field	22A	None	None	0.280	None	None	338° - 18°
51C LH Forward Field**	15A	0.010	154.0	0.280	4.25	5.25	163
51C RH Center Field (prim)***	15B	0.038	130.0	0.280	12.50	58.75	354
51C RH Center Field (sec)***	15B	None	45.0	0.280	None	29.5	354
41D RH Forward Field	13B	0.028	110.0	0.280	3.00	None	275
41C LH Aft Field*	11A	None	None	0.280	None	None	
41B LH Forward Field	10A	0.04	217.0	0.280	3.00	14.5	351
STS-2 RH Aft Field	2B	0.053	116.0	0.280			90

* Hot gas patch detected in putty. Indication of heat on O-Ring, but no damage.

** Soot behind primary O-Ring.

*** Soot behind primary O-Ring, heat affected secondary O-Ring.

　　　Clocking location of leak check port - 0 deg.

　　　Other SRM-15 Field Joints had no blowholes in putty and no soot
　　　near or beyond the primary O-Ring.

　　　SRM-22 Forward Field Joint had putty path to primary O-Ring, but no
　　　O-Ring Erosion and no soot blowby. Other SRM-22 Field Joints had no blowholes in putty.

Slide 3: Same as Figure 11

Slide 4: Same as Figure 10

Slide 5: Same as Figure 7

Slide 6: Blow-by History
- SRM-15 Worst Blow-by
  - 2 case joints (80°), (110°) Arc
  - Much Worse Visually Than SRM-22
- SRM-22 Blown-by
  - 2 case joints (30° - 40°)
- SRM-13A, 15, 16A, 18, 23A, 24A
  - Nozzle Blow-by

Slide 7: O-Ring (Viton) Shore Hardness Versus Temperature

°F	Shore Hardness
70°	77
60°	81
50°	84
40°	88
30°	92
20°	94
10°	96

Slide 8: Secondary O-Ring Resiliency

Decompression Rate: 2"/minute (Flight approx. 3.2"/min)

(°F)	Time To Recover
50°	600
75°	2.4
100°	*

   * Did Not Separate

Right Durometer (2)

Slide 9: Blow-By Tests (Preliminary)

Argon:

(°F)	Results (in^3 / in. seal)
75	No Leakage
30	No Leakage

F-14:

(°F)	Results (in^3. / in. seal)
75	No Results Yet
30	No Results Yet

Slide 10: Field Joint O-Ring Squeeze (Primary Seal)

Motor	FWD	CTR	AFT
SRM 15-A	16.1 (.045)*	15.8 (.044)	14.7 (.041)
SRM 15-B	11.1 (0.31)	14.0 (.039)**	16.1 (0.45)
SRM 25-A	10.16 (.028)	13.22 (.037)	13.39 (.037)
SRM 25-B	13.91 (.039)	13.05 (.037)	14.25 (.40)

* 0.010" Erosion
** 0.038" Erosion

Slide 11: History of O-Ring Temperatures (°F)

Motor	MGT	AMB	O-Ring	Wind
DM-4	68	36	47	10 mph
DM-2	76	45	52	10 mph
QM-3	72.5	40	48	10 mph
QM-4	76	48	51	10 mph
SRM-15	52	64	53	10 mph
SRM-22	77	78	75	10 mph
SRM-25	55	26	29	10 mph
			27	25 mph

1-D Thermal Analysis

Slide 12: Conclusions
- Temperature of O-Ring is not the only parameter controlling blow-by.
- SRM 15 with blow-by had an O-Ring temperature at 53°F. SRM 22 with blow-by had an O-Ring temperature at 75°F. Four development motors with no blow-by were tested at O-Ring temperature of 47° to 52°F.
- Development motors had putty packing that resulted in better performance.
- At about 50°F, blow-by could be experienced in case joints.
- Temperature for SRM 25 on Jan. 28, 1986 launch will be 29°F at 9 am and 38°F at 2 pm.
- Have no data that would indicate SRM 25 is different than SRM 15 other than temperature.

Slide 13: Same as Figure 12

Recommendations:
- O-Ring temperature must ≥ 53°F at launch. Development motors at 47°F to 52°F with putty packing had no blow-by SRM is (The Best Solution) worked at 53°F.
- Project ambient conditions (temp & wind) to determine launch time.

Note: All tables are reproduced from original documents.

Appendix 10

## Assessment Made by Lawrence Mulloy Based on the Teleconference

Cold O-Ring Assessment

- Blow-By Of O-Rings Cannot Be Correlated To Temperature STS 61-A Had Blow-By At 75 Degrees Fahrenheit.
- Soot Blow-By Primary O-Rings Has Occurred On More Than One Occasion, Independent Of Temperature.
- Primary Erosion Occurs Due To Concentrated Hot Gas Path Thru Putty.
- Max Allowable Erosion And Still Seat Demonstrated By Test Is 0.125"
- No Secondary O-Ring Erosion Or Blow-By To Date In Field Joints
- Colder Temp May Result In Greater Primary O-Ring Erosion And Some Heat Effected Secondary Because Of Increased Hardness Of O-Ring Resulting In Slow Seating
- Early Static Tests (Hydrotests) With 90 Durometer Showed Seating (0.275" O-Ring Diameter)
- Squeeze At 20 Degrees Fahrenheit Is Positive (>0.020")
- Secondary Seal Is In Position To Seat (200 PSI / 50 PSI Leak Check)
- Primary May Not Seat Due To Reduced Resiliency - However, During Period Of Flow Past Primary – Secondary Will Be Seated And Seal Before Significant Joint Rotation Occurs.

Conclusion

- Risk Recognized At All Levels Of NASA Management Is Applicable To STS 51-L

Appendix 11
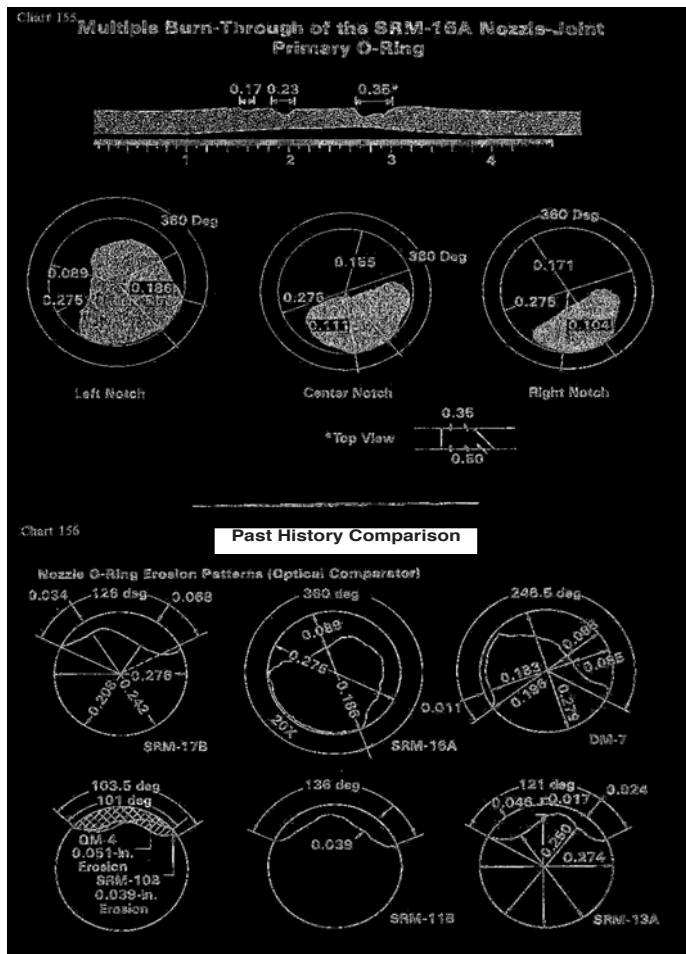
Instructor's Manual

Implications and Ramifications of Engineering Design of Field Joint for Space Shuttle:STS 51-L

1. Educational Objectives

The objectives of this case are for students to:
1. Evaluate the consequences of choosing an engineering design.
2. Critically evaluate several options by applying engineering design considerations, statistical methods, and principles of ethics, to the information provided.
3. Make a decision and defend it.

2. Definition of the Intended Field for the Case

This case study could be used at undergraduate and graduate courses in engineering design, operations management, and industrial design. It would also be useful in engineering and business ethics courses. It could be covered in either a 2-hour session or two 1-hour sessions.

3. Theoretical Basis of Research

The material in this case study has been written based on material available from secondary sources and has been checked with NASA engineers to verify the accuracy. The ethics material has been based upon principles from professional codes of ethics. The codes of ethics from the following professional societies were provided to students as supplementary material: AIAA, ASCE, ASME, IEEE, IIE, and NSPE. In addition, the students could be provided an introduction to the principles of ethics including Kantianism or Utilitarianism.

4. Possible Answers for Class Presentations

In the following discussion, we will list the engineering, ethical, and statistical reasons for launching and not launching STS 51-L. The students could use some of these points in answering their questions and playing the roles.

I. Defend the launching of STS 51-L
STS 51-L should be launched for the following reasons:

(A) Engineering Design Considerations
a) There were 24 successful launches in which O-ring erosion did not pose any serious threat to flight safety
b) Of the 24 launches, only 7 STS missions had O-ring distress.
c) The secondary seal was redundant in all but worst case scenarios.
d) There was a .005 inch "safety margin" of erosion on the primary O-ring. Lab test showed that the O-ring would seal at 3,000 psi with .095 inches of erosion far above the launch pressure and any previous after flight erosion.
e) There has been extensive testing between 1980-86 qualifying the abilities of the SRM.
f) Past erosions has always been within acceptable limits.
g) If the SRB had to be redesigned, it would set the space shuttle launch back two years. Some risks must be taken to pursue new innovations.

(B) Statistical Data Analysis:
a) Blow-by of O-rings cannot be linked to cold temperatures since two SRMs had severe blow-by at 75° F.
b) There is no test data that conclusively links cold temperatures to severe O-ring damage. A launch at 70° F had more O-ring erosion than a launch at 53° F.
c) There is no test data for 26° F which shows that this temperature would be unacceptable.
d) The probability of failure of both O-rings is estimated to be very low.

(C) Ethical Considerations:
Utilitarianism is based upon the principle of utility which states that the goal of every action is to provide the greatest good over bad. Let us now weigh the different options to decide which option will create a greater balance of happiness over unhappiness. Positive numbers will show happiness and negative numbers will show unhappiness.

1. Do Not Launch the Shuttle

Beneficial/ Not Beneficial		Amount of people
+ Benefits the astronauts	(+)	7
- Does not benefit NASA (costs money and will be behind schedule)	(-)	1000's
- Does not benefit MTI (image of being incompetent)	(-)	100's
- Does not benefit the citizens (wasted tax dollars)	(-)	Millions
TOTAL	**(-) Millions**	

2. Launch the Shuttle

Beneficial/ Not Beneficial		Amount of people
- Does not benefit the astronauts (they die)	(-)	7
+ Benefits NASA (on schedule, satisfies Congress and citizens)	(+)	1000's
+ Benefits MTI (good product)	(+)	100's
+ Benefits citizens (no wastage of tax dollars)	(+)	Millions
TOTAL	**(+) Millions**	

This indicates that launching STS 51-L is an ethical choice.

(D) Summary:

The launch of STS 51-L seems to be ethical and safe from an engineering standpoint. Since the secondary O-ring will be redundant in most cases and the probability of failure of both O-rings is very low, NASA should continue with the launch.

II. Defend not launching STS 51-L.

STS 51-L should not be launched for the following reasons.:

(A) Engineering Design Considerations:

a) Lower O-ring squeeze due to the lower temperature and higher O-ring shear hardness increases the time for the primary O-ring to seal. If the primary O-ring does not seal, blow-by could occur and the secondary O-ring may also not seal. (This is the argument given by engineers shown in Appendix 8).

b) Joint rotation increases the gap that the O-ring must seal. When the gap is bigger, the O-ring may not seal the entire gap and then gases might leak out of the gap.

c) Cold temperature increases joint grease viscosity (makes it thicker) which increases the O-ring sealing time.

d) If actuation time of the primary O-ring is increased, secondary O-ring sealing is less likely. Between 600 milliseconds and 2 minutes of the primary O-ring not sealing, there is a high probability that the secondary O-ring would not seal.

e) A warm O-ring that has been compressed will return to its original shape much more quickly than a cold O-ring. Thus, a warm O-ring will follow the opening of the tang-to-clevis gap while a cold O-ring may not. A compressed O-ring at 75°F is five times more responsive in returning to its uncompressed shape than a O-ring at 30°F.

f) SRM 15 on Flight 51-C, the coldest O-ring temperature launch, had severe erosion.

g) If an accident occurs, NASA could suffer severe setbacks such as schedule delays, legal costs, etc.

(B) Statistical Data Analysis[1]

Appendix 9 in the case study shows incidents of O-ring distress and temperature. A graphical representation of that material is shown in Figure 1. Based on this chart, Boisjoly and other MTI engineers were unable to correlate temperature and O-ring erosion because of the severe erosion at 75 degrees (STS 61A).
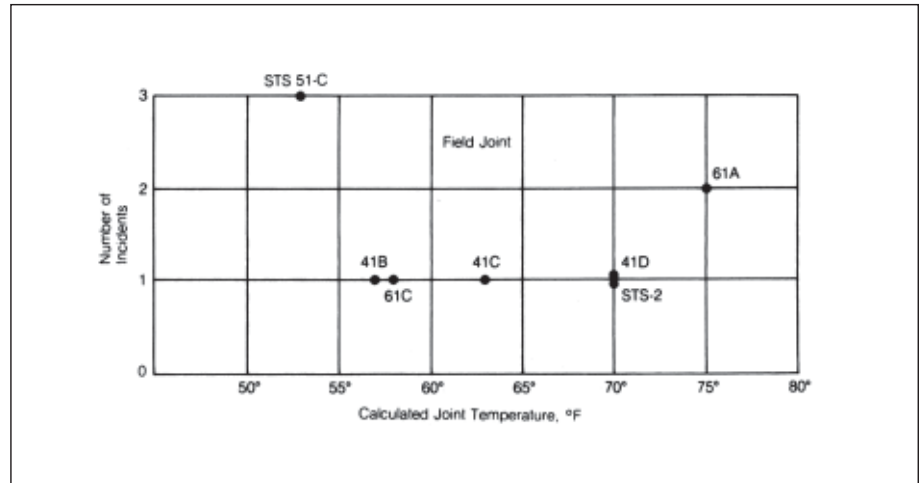

Figure 1: STS Missions with O-ring Distress (Erosion, Blow-by)

Figure 2 shows all of the STS missions, those that had incidents of O-ring erosion, as well as those that did not based on the information given in Table 1 of the case study.
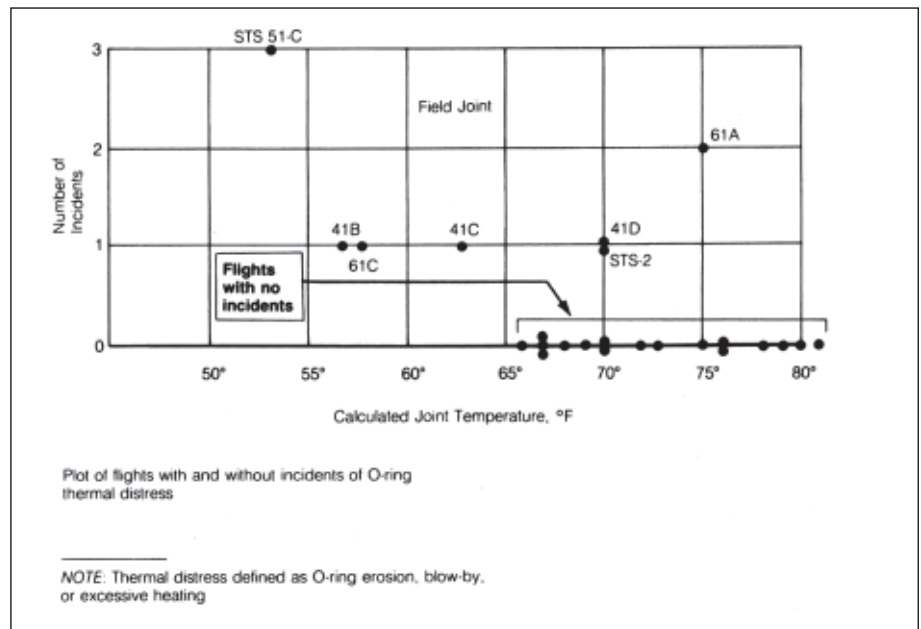

Plot of flights with and without incidents of O-ring thermal distress

NOTE: Thermal distress defined as O-ring erosion, blow-by, or excessive heating

Figure 2: Complete Plot of STS Missions

As shown in Figure 3, by fitting a curve to the data points, it is possible to see the correlation between temperature and O-ring distress. A Median Polish curve is an empirically generated curve that connects medians of subgroups of data points. By performing this analysis, the data point of STS 61-A could be classified as a statistical outlier. In addition, a linear regression analysis was performed on the data in Table 1 showing the regression line in Figure 3. Both statistical analyses demonstrate that the 26°F launch of STS 51-L might cause 2 or more O-ring thermal distress incidents.
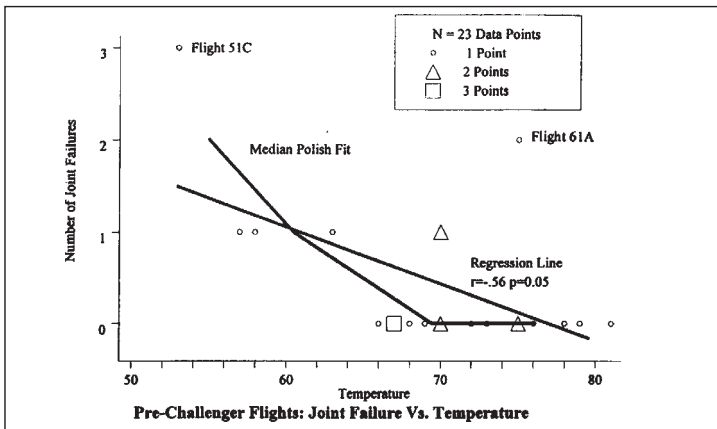
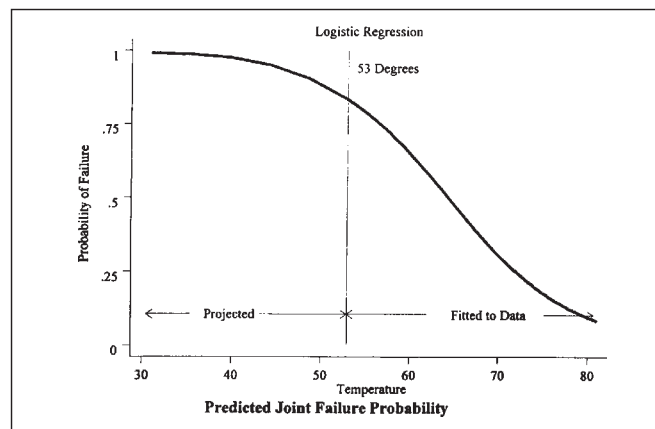**Figure 3: Regression analysis of data in Table 1**

Figure 4: Logistic Regression Analysis of Data in Table 1

Figure 4 shows a logistic regression analysis of the data in Table 1. The probability of failure at 26° F (the Challenger launch temperature) is close to 100%. At 53 degrees, the probability is estimated to be approximately 80%. Therefore, from a statistical point of view, the launch should not proceed.

(C) Ethical Considerations:
Utilitarianism is based upon the principle of utility which states that the goal of every action is to provide the greatest good over bad. Let us now weigh the different options to decide which option will create a greater balance of happiness over unhappiness. Positive numbers will show happiness and negative numbers will show unhappiness.

1. Do Not Launch the Shuttle		
Beneficial/ Not Beneficial		Amount of people
+ Benefits the astronauts	(+)	7
- Does benefit NASA (no law suits or bad reputation)	(+)	1000's
- Does not benefit MTI (image of being incompetent)	(-)	100's
Neutral to the citizens (wasted tax dollars versus lack of anguish)		0
TOTAL	**(+)**	**1000's**

2. Launch the Shuttle		
Beneficial/ Not Beneficial		Amount of people
- Does not benefit the astronauts (they die)	(-)	7
Neutral to NASA (satisfies Congress and citizens versus intense scrutiny of operations)		0
+ Benefits MTI (good product)	(+)	100's
Neutral to citizens (wastage of tax dollars versus costly redesign)	(+)	0
TOTAL	**(+)**	**100's**

This indicates that not launching STS 51-L is an ethical choice from utilitarianism.

Kantianism states that all parties involved must be aware of every aspect of the problem and be able to make a rational decision based on the information presented. In the decision regarding STS 51-L, it is very clear that the astronauts who were very much a part of the team, had no idea of the problem at all. They were completely in the dark regarding the temperature of launch and so were their families to a large extent. Had the astronauts known about the problem and its related results, they would have surely not accepted to launch the shuttle on that fateful mission. Since the astronauts are the ones who are actually in the Shuttle at the time of launch, they should have been notified of the problem and their suggestion should have also been considered. If the astronauts had been informed about the problem and they had made a choice to launch

after considering the pros and cons of the problem, then the principle of Kantianism would have been satisfied. It was a risk and it would have been a calculated risk had everyone involved been notified about it. The decision to launch or otherwise would have had to be unanimous and not of a few people in the higher rungs of the organizational structure. Therefore, deciding not to launch is ethically appropriate from both utilitarianism and Kantianism.

(D) Summary:
Not launching STS 51-L seems to be ethical and correct from an engineering standpoint. Since cold temperatures negatively impacted the sealing capability of the O-rings and joint rotation is a continuous problem, NASA should not launch and spend resources to redesign the field joint.

[1] The material in this section has been adapted from Rosa Lynn B. Pinkus, Larry J. Shuman, Norman P. Hummon, and Harvey Wolfe, *Engineering Ethics: Balancing Cost, Schedule, and Risk - Lessons Learned from the Space Shuttle*, Cambridge University Press, Cambridge, UK, 1997.