Space Shuttle Challenger January 28, 1986 Tragedy

36 Years Later

A Retrospective on Causation and Moral Injuries

Thesis

Martin Ditkof
University of Colorado at Colorado Springs
Dr. Christina Jimenez
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ABSTRACT

The January 28, 1986 Space Shuttle Challenger tragedy continues to be used as a teaching experience for leadership, ethics, communication, engineering, and group think classes. Also, asbestos-related injuries and issues remain prevalent in society throughout the world, in many ways governed by politics over science. Combining the two, the claimed involvement of asbestos in the Challenger destruction is a myth worthy of addressing. Using significant original and difficult to obtain primary sources, this essay examines the causes of the Challenger destruction including analyzing the asbestos-containing putties used in the field joints, NASA diverting its focus from mission safety to encompass other priorities, and problems with the field joint design. This essay then concludes with a discussion on the moral injuries suffered by certain Thiokol employees arising from their unsuccessful efforts to fix the technology and to communicate their concerns, and who were eventually overruled in their opposition to the launch.

ARTICLE REVIEWS

“With this thesis, Martin Ditkof has made an important contribution to history. His excellent research and clearly presented analysis makes this work a must-read for anyone who wants to understand the Challenger accident and why it happened.”

— Andrew Chaikin, space historian and author of *A Man on the Moon: The Voyages of the Apollo Astronauts*

“Marty’s extensive research on asbestos and its application to the Space Shuttle Challenger disaster are impressive to say the least. His initial premise that removal of asbestos from industry led to the Challenger was doubtful in my mind, but his continued pursuit of it has convinced me of its validity. It led me to have him and me engage with others (Jerry Burn & Kyle Speas) to provide insights beyond my own to come to agree with the fundamental hypothesis. I feel this work represents another important part of the Challenger story, which has been such an important part of my life.

Marty’s treatment of the moral injuries showed caring in a very human way for those who lived the experience. I appreciated his compilation of the records in this manner, too, particularly of my old friends.”

— Brian Russell, Former Thiokol Employee, Vice Chairman of Thiokol O-ring Task Force

“I have found this a fascinating read. Marty has carried out extensive research into the Challenger accident that shocked the world at the time and then to find out asbestos putty has played a part is beyond belief.”

— Mavis Nye BEM BCAh (hon)DR, President of the Mavis Nye Foundation and Asbestos Mesowarrior since 2009. Named Safety & Health Practitioner’s (SHP’s) Most Influential person in health & safety for 2021 (shponline.co.uk) for her work supporting and raising awareness of the dangers of asbestos exposure and supporting those who are diagnosed with Mesothelioma.

“I enjoyed reading your analysis and study of the Challenger Accident…Great job. I think you nailed it.”

— Kyle Speas, Former Thiokol Employee

“The reevaluation of the Challenger accident as presented in this thesis has been well researched and provided some new aspects on a very old and painful subject. In particular the enhanced probability of failure due to a change in putty has not been fully understood until now. The subject matter in this document is very accurate especially with what was known and unknown at the time of the Challenger disaster. This document provides a good blend of information and facts before and after the joint redesign.”

— Jerry Burn, Former Thiokol Employee, Assigned to Work with the Rogers Presidential Commission from February to June 1986 for Challenger Recovery Operations

"Ditkof's thesis illuminates exceptional, and heretofore unexplored, details relating to ancillary asbestos-related background factors related to the Challenger tragedy in 1986. His meticulous research relies on significant secondary as well as primary sources with some of the most knowledgeable experts in the field - including those involved in resolving the shuttle Rocket Booster Seal problems at the time (e.g., Morton Thiokol's Jerry Burn and Brian Russell) and space historians such as Andrew Chaikin. His tenacity and ability to secure extensive and substantial insights from some of the foremost NASA insiders (e.g., MSFC's Eric Knops and Kyle Speas) is remarkable. Ditkof's work represents a significant contribution to the historical record on Challenger, and is a model of exemplary research, all the more noteworthy for a Master's Thesis. The quality is on par with the highest doctoral-level work I have ever seen. Kudos to "Dr." Ditkof for his invaluable scholarship."

— Mark Maier, Ph.D.
Producer/Director *"A Major Malfunction...": The Story Behind the Space Shuttle Challenger Disaster*
Principal Technical Consultant to *Challenger: The Final Flight* (Netflix, 2020)
Founding Chair, Leadership Programs, Chapman University (Orange, CA)

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PREFACE

My initial goal in researching this thesis and article was to solve the internet controversy on whether the Challenger tragedy was caused by an asbestos substitute that failed. I have wondered about this topic for quite some time since a friend of mine mentioned that he believed it to be so. When I decided to go back to school in 2021 in order to attend the Master of History Program at the University of Colorado at Colorado Springs, this seemed to be the perfect topic for me to research and analyze as my first of three theses. On the injured party side, my father passed from Mesothelioma, the cancer which defines asbestos-related illnesses. On the product defense side, for many years I represented my former employer and several other companies in a capacity which coordinated asbestos-related product liability cases that were filed against them. In addition, I had developed over the years a substantial fascination about the history of asbestos, including compiling an extensive collection of books and articles.

As I began my research, I found that the historiography surrounding the Challenger tragedy was immense and rich with voices about causations ranging from mechanical failures to new social theories about communication. Almost all are discussed in depth by Professor James R. Hansen in his extensive Bibliographic Essay in the book he co-authored with Allan McDonald entitled *Truth, Lies, and O-rings: Inside the Space Shuttle Challenger Disaster* in 2009. Any reader interested in the historical treatment of the Challenger would find the book with its Bibliographic Essay a good place to start and an excellent in-depth analysis of Challenger-related material. For a more simplistic overview, the NASA publication titled *Toward a History of the Space Shuttle, An Annotated Bibliography Part 2, 1992-2011*, Chapter 6, pages 29-33 is a good beginning.

I also discovered an amazing trove of primary sources arising from various publications and, most importantly, the hearings held by the Presidential Commission chaired by Senator William Rogers ("Presidential Commission) resulting in its June 6, 1986 report. The Presidential Commission's report in Volumes IV and V contains 1700 pages of mostly first-hand, eyewitness testimony contemporaneous with the accident. These first-hand accounts were subject to intensive questioning by a panel of thirteen members, including some of the most intelligent and engaged minds of their day such as astronauts Neil Armstrong and Sally Ride, Air Force General Donald Kutyna, Stanford Professor Arthur Walker, and Nobel Prize Winning Physicist Richard Feynman. Their willingness to ask probing questions expanded the details contained in the oral testimony and supporting documents produced. Nothing in my work takes issue with any of the core findings of the Presidential Commission but, rather, this thesis expands on them and sheds fresh light given the passage of time.

I would like to provide particular thanks to Morton-Thiokol retiree Brian Russell (Morton-Thiokol will be referred to as "Thiokol" in this thesis) for his assistance on this article. Without Brian's generosity and input, my work would have solely focused on the asbestos-related matters that quite honestly, did not include some of the more important issues available to research and analyze. Brian's ability to point me in the right and accurate direction has been very much appreciated. When Brian could not provide the information, he deferred to former Thiokol employees Jerry Burn and Kyle Speas. They both went out of their way to ensure that my understanding and interpretation of the science was built on a solid foundation. I would also like to provide my thanks to Morley Cox, Eric Knops, Frank Bares, Andrew Chaikin, and Mark Maier for their willingness to provide information and, at times, thoughtful suggestions. Further, the help provided to me by my wife Carol Hammond and many others to proofread and provide suggestions was critical to the final product; my thanks to each and everyone. Finally, my thanks to the US Air Force Academy Library; Special Collections, and Kathy Wilson in particular, for a Clark-Yudkin Research Fellowship to assist in my research.

Picture near the VAB at Kennedy Space Center during April 1985 of Jack Neale (standing) and seated from left are Gerry Greenleaf, Brian Russell, Scott Stein, and Jerry Burn (with the Coke). They were working on the 51-D solid rocket motor post-recovery disassembly. Photo provided by Jerry Burn.

Asbestos and the Challenger tragedy are perhaps two of the most researched topics in modern times, including for both subject matters discussions on risk, lessons learned, and how they may affect the future. I am fortunate to be able to combine them within this thesis.

Any errors or mistakes within this thesis are solely my responsibility.

ABOUT THE AUTHOR

Martin Ditkof is a Masters of History student attending the University of Colorado at Colorado Springs. Although he returned to school in 2021, he has a strong background in identifying and analyzing risk for major manufacturers in the context of participating in product safety committees, performing safety audits, and defending against product design lawsuits. His work has involved some of the largest and most sophisticated equipment on earth such as paper-making machines, electric mining equipment, and industrial cranes. Marty has always been fascinated with space and remembers watching the Challenger tragedy unfold.

Marty in the early 1990s performing a product safety audit on the boom point sheeve of a Page Strip Mining Dragline at an IMC phosphorus mine near Lakeland, Florida. Photo taken by a co-worker and original possessed in Marty’s files.

Marty has been the General Counsel, Chief Legal Officer, and Chief Compliance Officer at one of the largest manufacturers of industrial cranes in the world.

COUNTDOWN

The January 27, 1986 winter evening was getting dark and long while the conversation continued in the room and across phone lines. In total, thirty-four highly trained professionals at three locations were participating in the call. After all, this was important and time was running out. The fifteen people at NASA Marshall Space Flight Center, fourteen at Morton-Thiokol in Brigham City, Utah, and five at the Kennedy Space Center in Cape Canaveral, Florida were looking at faxed copies of the handwritten and typed analysis.[1] After all, there were no laptops, no internet, and email was yet to be invented.

At the Thiokol plant in Brigham City, Utah, Brian Russell listened intently as Roger Boisjoly and Arnie Thompson once more tried to make their case not to launch the space shuttle solid rocket boosters at less than 53 degrees Fahrenheit to the Company's four vice presidents in the room. Those vice presidents were all technically trained in engineering or math with, between them, 140 years of work experience. Skilled in their jobs, they generally enjoyed the support of those who worked for them and the respect of everyone in the room, whether engineers or managers. The vice presidents' job was to listen to their employees, talk with the client, and make a recommendation to NASA as to whether the solid rocket motors used on the Space Shuttle Challenger were safe to launch the following morning.

In addition to the vice presidents, Thiokol engineers, scientists, mathematicians, and technically-trained and experienced employees were in that room, some of whom had already advanced to lower-level management. These included, among others, Brian, Arnie, Roger, and Bob Ebeling. Due to the urgency of the meeting, each stayed late into the evening, putting their personal plans on hold at the last minute. Other Thiokol employees, such as Allan McDonald and Kyle Speas, attended the call from other locations. Allan, in a room at Cape Canaveral, had already provided his opinion on the issue of the day. Kyle was at Marshall Space Center in Huntsville, Alabama with mostly NASA employees and contractors. Another young Thiokol engineer in attendance at Thiokol in Utah, Jerry Burn, provided his input that included describing prior flight disassembly conditions and an analysis of temperature impacts to the O-ring squeeze in the field joints. During the first phone call in the day, these professionals had been unanimous in their recommendation to the client, providing counsel which the company's senior management supported. This first engineering recommendation was to delay the launch until the weather warmed up based on a concern that a field joint and its components might fail due to the unusual freezing temperatures expected at launch time. During this phone call, however, which was now on hold, the client had disagreed with the recommendation. Based on that discussion, the Thiokol vice presidents asked for five minutes to privately discuss and potentially re-evaluate the company's position. Thirty minutes later, the call was still on hold.

Finally, the discussion led to a decision. The telephone call with the client was taken off hold, the Thiokol management explained to the client that the company had re-evaluated its position, and that Thiokol now supported the client's desire to proceed in spite of the concern with the temperature effect on the field joints.

And suddenly, but without knowing it until the morning, the world as known by everyone involved with that phone call had changed.

Space Shuttle Challenger

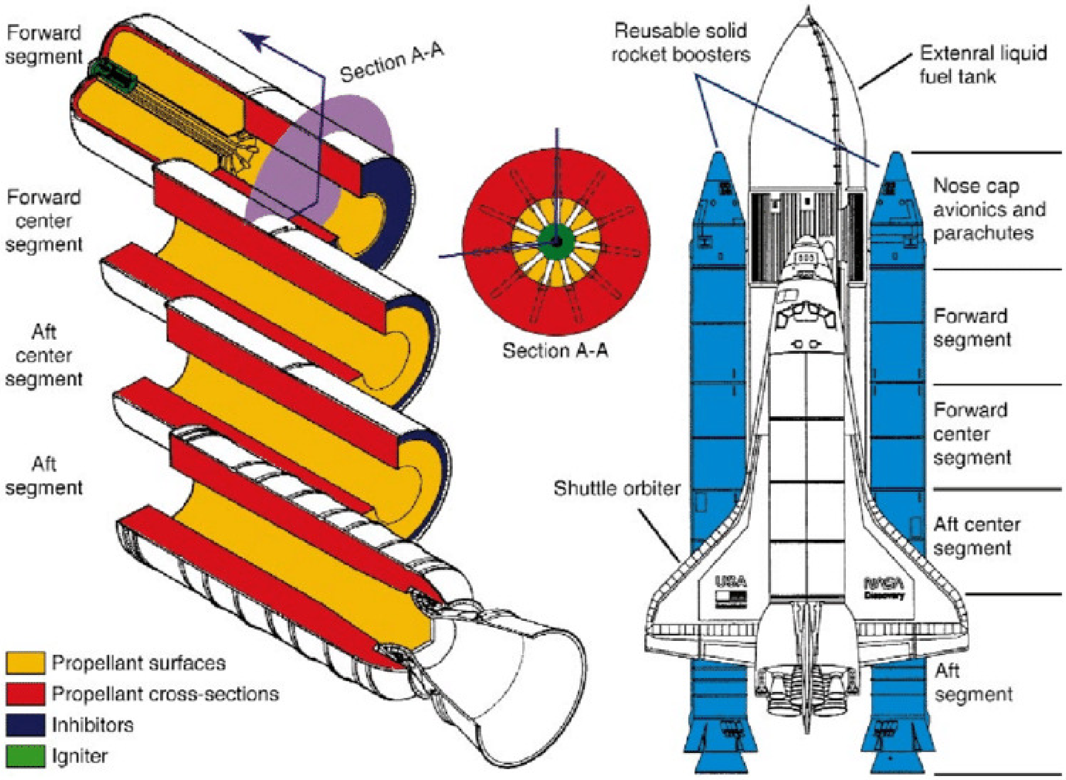
Evening of January 27, 1986

Green Light to Launch, January 28, 1986

THE TECHNICAL CONTEXT

Understanding the technical issues regarding the space shuttle solid rocket boosters, with a focus on the aft field joint at issue, will be critical to analyzing the Challenger explosion.

The space shuttle solid rocket boosters included the solid rocket motors (the propellant, case, igniter, and nozzle) manufactured by Thiokol, and then assembled with the other booster components (parachutes, electronics, separation rockets, destruct system, and thrust vector control) into the entire assembly.[2] This thesis will use the terms "motor" and "booster" interchangeably at times as often done in the literature. The following diagrams provide a good overview of the four motor segments and the issues to be discussed in this thesis.[3]

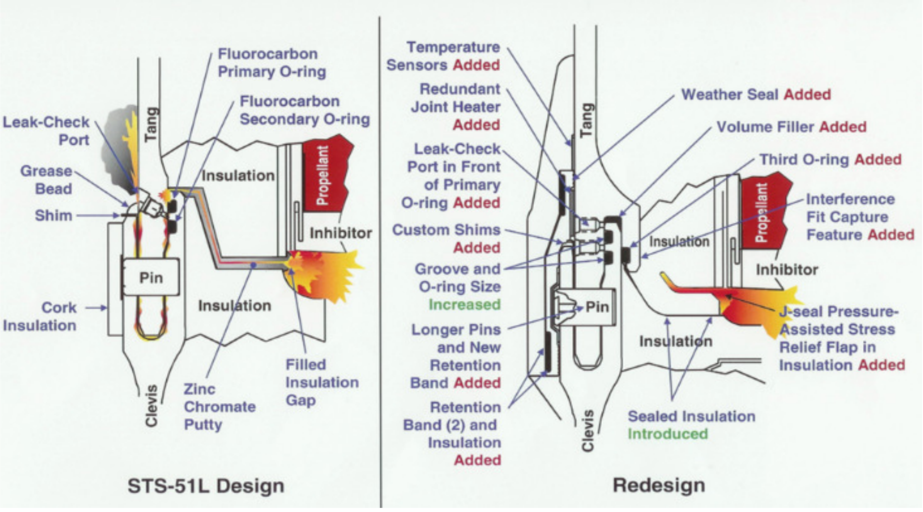


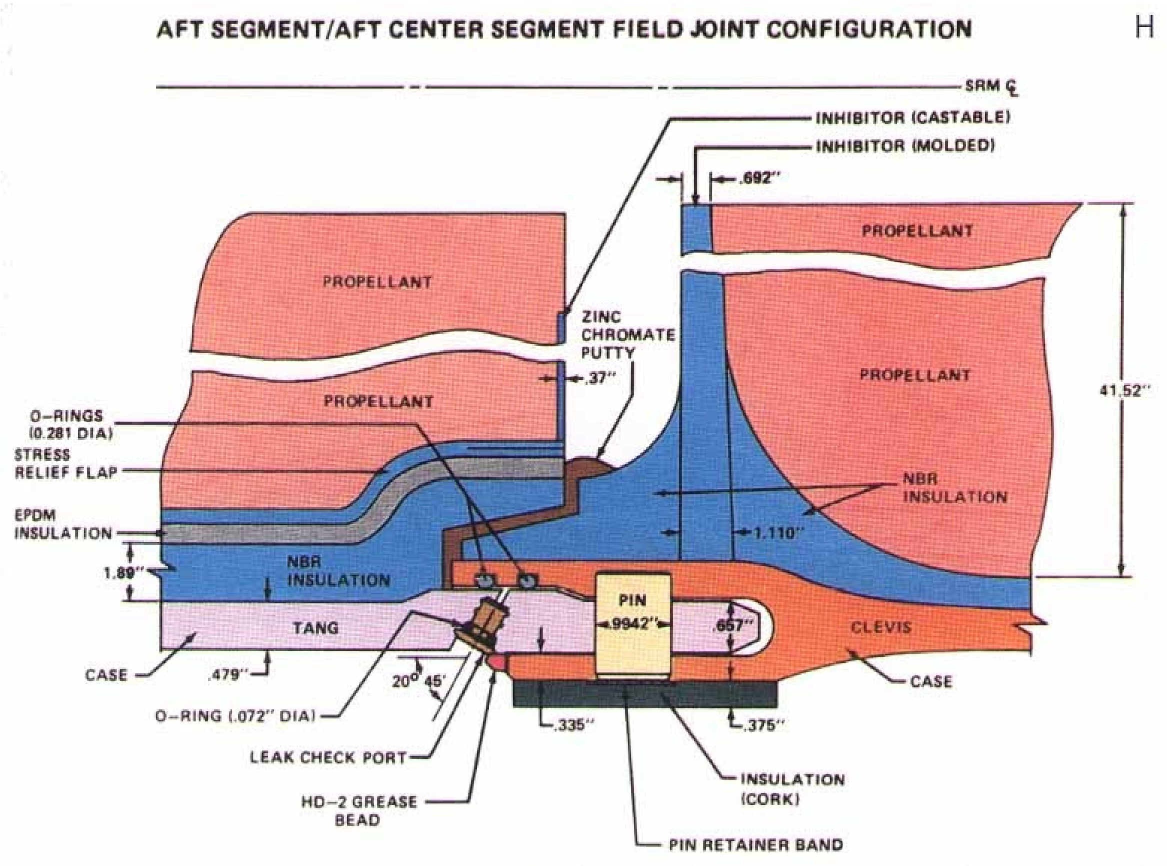
The following is a picture of the Space Shuttle Challenger at launch on January 28, 1986. If you look closely, the reader can see the black smoke coming from the aft field joint at the right hand bottom of the picture. This discovery was a key piece of evidence to show that the failure initiated at that location.

Gas Leakage Past the Joint

For those interested in more technical information, the following two diagrams are useful. The first is a comparison between the field joint design used on the Challenger (STS-51L) with the field joint redesign developed after the explosion for future space shuttle flights. The second is the configuration as used on the Challenger.

FIELD JOINT COMPARISON





Finally, below is a picture of the field joint as recovered from the ocean after the explosion. The failed area is on the bottom front.

Center Aft Segment at Location of Failure[4]

Thiokol manufactured the solid rocket booster motor segments in its plant at Brigham City, Utah and shipped them by rail to Cape Canaveral. Each motor included four segments fully loaded with a PBAN propellant that was 70% ammonium perchlorate: forward, forward center, aft center, and the aft segment.[5]

The assembly process took place in the unheated Vertical Assembly Building (VAB) beginning at the bottom of the motors while stacking the components vertically, and including the other booster components. The joints assembled by attaching the four motor segments in the VAB were called field joints while the joints called "nozzle joints" in the aft segment had been assembled at Thiokol in Utah prior to shipment. Below is a picture of a field joint assembly.[6]

The field joint assembly process involved a number of components and steps. As related to the issues involved in this thesis, first the two rubber O-rings were inserted into their 0.305-0.310 inches grooves (O-rings were 0.281 inches diameter). Next, the vacuum putty in tape form was applied to the insulation surface of the clevis (bottom segment) in order to provide thermal protection to the O-rings during launch.[7] The putty itself had been extruded into a silicone or other releasing paper by the supplier; for Thiokol, that was in strips 3/16" thick and either 3/8" or 3/4" wide. Those rolls were then put into a flat box for shipment. The following picture is only a representative sample as we do not have pictures of the Fuller-O'Brien or Randolph putties that were used on the space shuttles.

The operator would use latex or other similar gloves to unroll the putty a little at a time and then lightly press it onto the insulation surfaces according to the drawing in the instructions as seen in TWR-13484, page 21 marked as TWA-1130.[8] The putty would stick to the rubber surface of the insulation. The operator would then pull the paper away as he or she proceeded around the circumference of the joint. If the putty were to lift off the insulation surface, the operator could use a gloved hand to press it back into place. The operator could also tamp the putty to close the seams between putty strips.[9]

Conoco HD-2 grease was then applied to the exposed metal surfaces as a protection against corrosion and as a lubricant for the O-rings. The top segment was then lowered onto the bottom segment, squeezing the O-rings into their grooves and the putty into the space between the adjoining insulation within the case. All these components required acceptable tolerances in order to perform appropriately; too big or too small a fit, too much or too little space or putty, and the system would not function as designed. The segments were then pinned together using 180 pins, three of which were used for aligning the segments. Once assembled, the field joint underwent a leak test to assure that the two O-rings had sealed and would hold during flight. As there was no ability to look inside the field joint, a leak test was performed to ensure that the O-ring was not damaged during assembly and that there was no contamination of the seal. The leak test had to be at sufficient pressure in pounds per square inch (psi) to ensure that the putty did not mask any problems with the primary O-ring. That stabilization pressure started in the shuttle program at 50 psi and eventually was raised beginning on the tenth shuttle flight to 200 psi. Once the joint passed the leak test, the final field joint operations were completed and the assembly process proceeded with the next segment of the stack. For clarification, and as best stated by Jerry Burn: "Sealing of the O-ring during leak test is a static test with no increased gap opening. The O-ring is sealed with the metal compression on the O-ring. During the leak test at lower pressures (50 psi to 200 psi) the primary and secondary O-rings will deform some with the primary O-ring moving to the front wall of the gland and the secondary O-ring moving to the back wall of the gland. During flight with full motor pressurization (estimated 980 psi) the joint gap opening will increase due to joint rotation and if pressurized the O-ring will be fully seated into the gap at the back of the O-ring gland. This is a dynamic sealing event."[10]

After the solid rocket boosters were assembled, they looked like the following picture.[11]

Once the boosters were stacked and mated with the orbiter and external tank, the assembly moved to the launch pad and might sit for months prior to launch. The metal casing segments were designed to be recovered and reused up to nineteen times so as to provide a cost savings.[12]

INTRODUCTION

The January 27, 1986 discussions were not the beginning of the problem nor did they stand alone; rather, the decision to launch with the then current field joint design in low temperatures was the culmination of many engineering, scientific, and business investigations and discussions over the preceding years. Within the context of those activities, my thesis will address and support four arguments: (1) NASA's original decisions to use field joints on the solid rocket boosters for the space shuttle program, including applying the Fuller-O'Brien asbestos containing 3992 putty to provide a thermal shield for the two O-rings, were both reasonable and necessary under the then existing facts and budgetary constraints; (2) the Fuller-O'Brien Company's decision to cease manufacturing the 3992 putty in June 1980 was based on the Consumer Product Safety Commission's December 1977 ruling to ban such asbestos containing putties from the consumer market; (3) this decision to discontinue the 3992 putty by Fuller-O'Brien set in motion the increased rate of gas paths (also known as blow holes) which, in combination with both a flawed field joint design and NASA decisions based on factors other than safety, increased the risk of joint failure and the likelihood of an explosion such as occurred with the Challenger, STS 51-L; and (4) these occurrences led to the explosion and loss of life on the space shuttle, along with moral injuries to those working at NASA and Thiokol who were involved in the various decisions and felt in some way responsible for the tragedy. In addition to the causation issues, this essay will focus on the moral injuries suffered in the thirty-five years since the Challenger explosion by four of the Thiokol employees who were very involved in the field joint related issues, participated in the January 27, 1986 phone call in opposing the cold weather launch, and who were four of the five people who self-named themselves after the accident as “the Five Lepers”: these four being Brian Russell, Bob Ebeling, Roger Boisjoly, and Allan McDonald.

The first two of the four arguments are primarily foundational for this thesis. Examples of those foundational types of arguments include correcting current misconceptions in published literature that the use of the putty in the field joint design was inappropriate, [13] that the change in putty from Fuller-O’Brien to Randolph was hasty,[14] and the often repeated but inaccurate claim that the Randolph putty chosen as the Fuller-O’Brien replacement did not utilize asbestos fibers.[15] Once these misconceptions are addressed to provide a better understanding of the facts, my thesis will focus on the critical issues: those being the efforts to improve the field joints, the January 27, 1986 recommendation not to launch, the failed January 28, 1986 launch, and the resultant moral injuries arising from the combination of the above with the passage of years.

First, however, we need to discuss acceptable risk in the context of the space shuttles and space flight. Many of those involved in the field joint issues or who supported the January 27, 1986 launch decision have been criticized as taking too much risk.[16] However, the space program inherently involves risk.[17] As far back as 1969, the mission requirements provided by NASA for its vendors in the space shuttle program included acknowledging an acceptable level of risk to the crew survivability and the success of the mission. In particular:

> The goal for crew survival probability and for the probability of successful mission completion has to be at least 0.999 and 0.95 respectively.[18]

Running the statistics with the anticipated 445 missions,[19] that means that one out of every twenty missions will fail (five divided by one hundred) and a 44.5% probability existed that one crew during the life span of the shuttle project would not survive (445 divided by 1000).

In addition, the highest-risk time frame was between launch and the solid rocket booster burn out. This approximately 122 seconds was considered especially vulnerable because the space shuttle system "was not designed to survive a failure of the Solid Rocket Boosters."[20] Although the literature debates the rationale as to why an abort or crew escape mechanism was unnecessary or unworkable,[21] this lack of a back-up for the astronaut safety during the launch required a heightened concern over operational safety until after the solid rocket boosters completed their burn. As stated by the Presidential Commission:

> Because of these factors, **NASA adopted the philosophy that the reliability of first stage ascent must be assured, and that design and testing must preclude time critical failures that would require emergency action before normal Solid Rocket Booster burnout.** That philosophy has been reviewed many times during the Space Shuttle program and is appropriately being reevaluated, as are all first stage abort options, in light of the 51-L accident."[22]

Assistant Director for Space Shuttle Flight Crew Operations Warren J. North in 1984 put it best, stating: "The risks associated with first-stage launch warranted a programmatic attempt to provide crew survival."[23] The need for the solid rocket booster field joints to meet this extra margin of safety was recognized during the initial design in the 1970s. To add an extra layer of safety, the original design as used in the Titan III rocket program was modified to include a secondary O-ring. This additional redundant seal was thought to make the field joint failsafe. Being failsafe, the original design received a Criticality Rating of 1R (1 with redundancy) rather than a 1 (with no redundancy).[24] Criticality 1 (without redundancy) is the highest risk rating and means the failure of the component may lead to the potential loss of mission, crew, or vehicle.[25]

For purposes of convenience, this essay will refer to the philosophy that the design and testing must preclude time critical failures before the 122 seconds required for solid rocket booster burnout as being "the Cardinal Rule." One thing about Cardinal Rules involving risk and safety to minimize potential death: they should never be violated. Those rules, as in the space shuttle situation, may never eliminate the existing risk, but their establishment and uniform enforcement minimizes the chance of a catastrophic accident. Looking back, the aft field joint design failed the Cardinal Rule in spite of many of the Thiokol and NASA employees involvement and efforts. The Criticality rating was changed from 1R to 1 (the redundancy rating was removed) effective on March 28, 1983 based on "the possibility of loss of sealing at the secondary O-ring because of joint rotation after motor pressurization."[26] And yet, no one at NASA or Thiokol fully understood the operational characteristics of the joint and its components that would become evident as the number of space shuttle missions proceeded.[27] Some of these concerns were recognized and internalized by those involved in the design process: such as, Brian Russell having white knuckles worrying about the success of each and every launch.[28] Other concerns and related issues were more visible to NASA and Thiokol, even if not recognized at the time by those involved. As stated by Larry Mulloy in his June 17, 2014 email exchange with Allan McDonald, the acceptance of the flawed joint design "…was a grievous error on the part of me, you, and many others."[29]

All that being said, early on, the goals for the space shuttle program were laid out to minimize risk, and not just in the initial 122 seconds. A discussion on risk must be viewed in light of the program priorities and available funds. As stated during August 1971 by the Space Shuttle Program Office, the overall program goals were:

> Don't exceed much over $1 B in any Year

Keep total Costs Below $12B for 445 Flights

Achieve Approximately $3M/Flight , Direct Costs, at the 445th Flight to Possibly Attract Commercial Traffic

Keep Risks Low – Don't do a Great Deal More than we have Demonstrated Before, Require only a Minimum Advance in TPS and Fracture Mechanics

Keep Flexible to Vary Costs with Traffic Demands[30]

The budget constraints for the shuttle program required NASA to manage its development "in a tight fiscal environment" with restrictive funding.[31] However, per Robert Thompson, although the shuttle program was not "fat" with money, it stayed above the critical threshold required to operate.[32] Not all of the people involved in the space shuttle design and manufacturing agree with Mr. Thompson as the lack of funding limited the purchase of testing equipment and the amount of component testing.[33] As stated by Roger Launius, a Chief Historian for NASA, "[t]he bare-bones funding strategy for the program forced NASA to take short-cuts."[34] In a 1988 survey of NASA employees, 80% responded "agree" or "strongly agree" to the statement: "Cost constraints have forced us to cut corners in carrying out our programs."[35] The funding-related issues will be discussed more below.

The risk for any particular space shuttle component was identified and managed using a certification process. The certification document was typically a very large spreadsheet with significant attachments discussing the requirements and how those requirements would be met. Thiokol would prepare the certification with NASA reviewing, approving, or sending it back with comments. The certification documents were generally managed by the systems engineers. According to Brian Russell, NASA provided five ways to certify components, running from the least desirable to most desirable as follows:

1. Similarity – This certification standard would only be used if none of the other four was available. As applicable to the putty utilized in the field joints, this would involve investigating other rockets and similar applications, and then determining that the uses and applications were sufficiently similar for the putty to function.

2. Analysis – Analysis certification required reviewing and analyzing data concerning the components functioning under various conditions.

3. Inspection – This certification involved measuring, inspecting, or employing nondestructive methods such as x-rays or ultrasounds.

4. Demonstration – This certification would generally involve assembling components including some testing but without testing at all extremes.

5. Testing – Testing was the most robust certification method, involving testing at flight conditions if at all possible. The goal would be to test at all corners of the box and potentially real world experiences for the component.[36]

This essay will use the above processes, goals, and philosophy as a backdrop on risk and the actions of the involved parties with a focus on ensuring that the design and testing "must" preclude a failure during those approximately first 122 seconds of the launch and flight, including the crew survival probability of at least 0.999. Given the role of the solid rocket boosters, this Cardinal Rule would involve all of their components, except potentially the parachute deployment.

One final comment on risk. NASA eventually instituted a more robust and inclusive process for handling risk. As explained by Bryan O'Connor, retired as Chief of Safety and Mission Assurance after serving a decade during the early 2000s as NASA's top safety and mission assurance official:

> I think of it as the four-legged stool: the technical authority owns the requirements, the safety and mission assurance authority decides whether the risk is acceptable or not, the risk taker must volunteer to take the risk, and then and only then, when those three things have been done, can the program or project manager accept that risk. Those four roles have been stated in the highest documents for governance in the agency. It's flowing down—and in some places it was already there— for the decision making for the high-risk work that we do, especially when there's safety involved.[37]

However, leading up to the 1986 Space Shuttle Challenger launch, this was not the process in place. The failure to address these issues and remedy the faulty processes in the Challenger design resulted in tragedy, not just for the astronauts who lost their lives, but also for those people who suffered moral injuries for their part in the tragedy.

THE ORIGINAL DECISION TO UTILIZE FIELD JOINTS ON THE SOLID ROCKET MOTORS

During the 1960s, four major builders of large solid rocket motors competed for the business of the United States military and NASA: Lockheed Propulsion, Aerojet-General, United Technologies, and Thiokol Chemical. In the early 1970s, NASA hired Thiokol to undertake a study of the solid rocket motor for a space shuttle booster. Thiokol responded with a five-volume analysis on March 15, 1972 in order to assist NASA in the selection of a booster for the space shuttle system.[38] The Thiokol technical response included a segmented booster with various joints including the use of Fuller-O'Brien 3992 Putty which, it asserted, "has demonstrated excellent performance as a joint sealer."[39]

NASA sent out its bid for the space shuttle booster rocket during July 1973. Three of the builders proposed segmented motors while Aerojet responded to the bid request with a proposed single monolithic case free from joints, but which would require transportation by water instead of rail and which posed other technical and logistical issues.[40] The evaluation committee consisted of 289 people whom both read the documents and conducted independent analysis and design studies. The Aerojet bid was judged deficient on its technical merits and thus rated fourth out of the four bids.[41] As to the other three bidders, the choice came down to the Lockheed proposal which had an advantage on the technical aspects and the Thiokol proposal, which was good technically and seemed to have low costs that could be well controlled.[42] The board felt that the Thiokol proposal's weaknesses on technical matters could be corrected and, with the agreement of NASA's management, awarded Thiokol the contract.[43] Some people speculated as to whether the award to Thiokol was based on inappropriate pressure put on NASA administrator James Fletcher by contacts associated with the Church of Jesus Christ of Latter-day Saints so that the motors would be manufactured in Utah. While such pressure clearly was applied, the award on such a basis has never been supported by anything other than inuendo.[44] The Thiokol proposal was strong on both costs and management, and the Lockheed protest over the award was denied.[45] The preliminary NASA contract awarding the design and construction for the solid rocket booster motors, including the use of field joints to connect the segments, was signed with Thiokol on June 26, 1974.[46]

The technical value of segmented solid rocket motor design compared to a one-piece monolithic design has been well known in the rocket science community since the early 1960s. Segmentation of the motors is the key to low-cost construction and allows the operation of very large solid propellant rockets.[47] They are easily transported by rail to the launch sites and then assembled into complete boosters.[48] However, the need to connect the segments adds a degree of risk into the process. As stated by J. S. Butz in a 1961 issue of *Air Force Magazine*:

> Some respected solid-propellant engineers have strongly disagreed with the segmented concept. They believed that the joints between the segments could never be made completely leakproof. If hot-gas leaks developed, the motor in all probability would fail. Therefore, it was theorized that the segmented motor would not have the high reliability of the one-piece or monolithic type in service today.[49]

The advantages and disadvantages of monolithic versus segmented solid rocket motors were studied by the Air Force and NASA both independently and then by the DoD-NASA subcommittee known as the Gollovin Committee starting in August 1961. The Gollovin Committee was tasked with developing a set for specifications applicable to both the DoD and

NASA for large solid booster motors.[50] An important aspect for solid rocket motors was to keep the diameter of the motors to no more than 160 inches to facilitate transportation by standard rail.[51] Another important consideration in using segmented boosters was the easy ability to vary the rockets and number of segments as used by both organizations.[52] Describing the Dyna-Soar program which used a Titan III segmented rocket, Mr. Butz stated in 1962 in *Air Force Magazine*, "The building-block feature of segmented construction will allow a variety of large boosters to be tailored to specific military missions."[53] In summary, the decision to use segmented solid rocket boosters rather than monolithic structures was based on both functionality and costs.

NASA needed to keep the costs of the shuttle program in check, which meant not wanting to re-design the rocket technology from scratch, but, rather, to use what was readily available.[54] According to various sources, the segmented solid rocket motor used in the space shuttle was based on the Titan III(c) design with the field joints modified as follows:

(1) The Titan III(c) used an Inmont asbestos-containing putty instead of Fuller-O'Brien 3992 putty.[55] As the Fuller-O'Brien putty had a strong background with Thiokol of success, along with the use on the Titan 34-D booster rocket joint seal,[56] this likely was just a vendor choice based on its recommendation in the March 15, 1972 study.[57]

(2) The Titan III(c) in the field joint used a single seal instead of a dual seal with two O-rings as used in the space shuttle field joints. The second seal was added to the space shuttle solid rocket booster to meet a safety requirement of redundancy.[58] Remember, this joint needs to have heightened protection during that initial 122 seconds as part of the Cardinal Rule. The success of the Titan experience provided NASA with a degree of confidence, although the Titan joint was stiffer and the rotation was different.[59] The Titan O-ring would seal when 850 psi pushed against the single O-ring.[60] For the space shuttle, the pressurization loads caused axial tension on the whole motor. Due to the joint being stiffer than the case membrane, the membrane deflected outward more than the joint causing the joint to rotate. This joint rotation caused the gap opening at the sealing surface to increase.[61]

(3) The space shuttle diameter was greater than the Titan III(c) and so the O-rings were larger; 142 inches in diameter as compared to 120 inches in diameter. The space shuttle case diameter was 12 feet and the O-rings were each 0.281 inch in diameter.[62]

(4) The space shuttle used 180 pins (3 of which were aligning) while the Titan III(c) used 237 pins.[63]

(5) The space shuttle used shims at each pin driven in by a leather mallet to assist in reducing the gap opening during motor operation which improved the ability of the seal to track the gap opening created during motor operation .[64]

The Titan at that time had no history of field joint failure after twenty-six ground tests, seventy-seven flights tests, and over 800 joint experiences.[65] That said, at least one author believes that the various changes from the Titan to the space shuttle rocket motors, including those involving the field joints, materially increased the risk in spite of the added secondary O-ring.[66]

NASA and the Thiokol engineers did not stop there; rather, they continued to focus on the field joint design to ensure its safety. According to a September 3, 1980 memo, NASA expressed concern that damage to the O-rings used in the joint could allow "hot gas leak which could grow in magnitude and could impinge on the ET [external tank] during flight" and asked that Thiokol again review the assembly procedures.[67] Thiokol responded on December 1, 1982 noting that the use of the case joint design was common, discussed some of the modifications from the Titan rocket, and stated that:

> Experience has shown positive functioning of the primary O-ring in all instances of use in the SRM tang and clevis joint. Testing has indicated positive sealing under adverse conditions beyond the required single pressurization for motor operation. It is concluded that considering the SRM joint as a single O-ring seal, sufficient rationale exists to retain this design with assurance of performance. A data base is also being established in support of the secondary O-ring positive sealing.[68]

Once again, the design was determined appropriate by Thiokol and approved by NASA.

Given the above background, the decision by NASA and Thiokol to use a segmented solid rocket motor as modified from the Titan III(c) design and including the Fuller-O'Brien

3992 putty as a thermal seal for the O-rings was both reasonable and necessary under the then budgetary constraints. Each step of the way was amply supported by the science and fell within the cost constraint requirements including (1) the choice of segmented components instead of monolithic, (2) the use of the Titan III(c) design as beefed up, including a belief in the failsafe redundancy of two O-rings to arrive at a Criticality Rating of 1R (redundancy) rather than the higher risk Criticality Rating of 1 (no redundancy), and (3) the use of Fuller-O'Brien 3992 putty to provide thermal protection to the O-rings within the field joints.

THE FULLER-O'BRIEN DECISION TO STOP SELLING THE 3992 PUTTY

The Fuller-O'Brien 3992 asbestos-containing putty was used as the thermal protection for the O-rings in the field joints from the inception of the space shuttle program including the first space shuttle launch on April 1, 1981. Thiokol used the putty in two formats: tape that was 3/4th by 3/16th inch purchased in 25-foot rolls and 3/8th by 3/16th inch also purchased in 25-foot rolls.[69] The purpose of the putty was to provide a thermal shield to protect the O-rings in the joints, both nozzle and field, during the launch process. The putty was added during mating of the segments in the Vertical Assembly Building at NASA, right after the insertions of the two O-rings and before the joint was pinned. Having the right amount of putty was important as too little left air pockets causing gas paths during assembly and too much would overflow and potentially touch the O-rings; either of which would potentially cause problems or a failed leak test.[70] Even with engineering direction including illustrations to control the putty layup process,[71] there was some art to this manufacturing process to ensure that the putty was correctly applied.

Unbeknownst to Thiokol or NASA, their use of the Fuller-O'Brien putty was about to change. The eventual need to find a replacement for the putty began in July 1976 when the National Resources Defense Council petitioned the Consumer Product Safety Commssion

(CPSC) to ban wall-board patching compounds that contained asbestos in consumer applications as being hazardous under the Federal Hazardous Substances Act.[72] At that time, asbestos was an important ingredient in the putties. As acknowledged by the CPSC: "In addressing the availability of substitute materials, the agency conceded that asbestos possessed unique qualities such as strength, pliability, and temperature resistance."[73]

The CPSC published its final rule on December 15, 1977 and the ruling became effective as scheduled although under the Consumer Product Safety Act.[74] Because the CPSC scheduled the ban timing to minimize the effect on current inventories, no appeal was filed as "no manufacturer of patching compounds or emberizing materials remained interested in using asbestos as an ingredient in the products."[75] As such, the methodology used to initiate the ban, such as the allowed liquidation of inventories, discouraged companies like Fuller-O'Brien from appealing the ruling.

Even though the ban was only effective for consumer products, Fuller-O'Brien eventually decided to cease all manufacture of the putty. As the sales volume of the putty was only 1% of the Fuller-O'Brien total corporate sales, they made the decision to stop making any asbestos product and therefore eliminate all asbestos exposure from its production facilities.[76] As stated by asbestos author Michael Bennett:

> The CPSC ban did not apply to industrial purchasers, such as Morton Thiokol, nor government buyers, such as NASA. But Fuller-O'Brien anticipated that lawsuits – and a total ban on asbestos – would be forthcoming, and just such a total ban was proposed by EPA about the time the Challenger and its crew plunged into the Atlantic ocean.
>
> So, Fuller-O'Brien in 1978, decided to get asbestos out of all its products in one swoop. The company was able to find substitutes for asbestos in all its products – with the sole exception of the putty used, not only in the Challenger shuttle, but also in the Titan 34D rocket, made by Martin Marietta, used to launch spy satellites into orbit.

> There simply was no substitute for the asbestos in the putty. However, since the share of business commanded by the material was only one percent of Fuller-O'Brien revenues, it was jettisoned.[77]

Fuller-O'Brien Vice President for Technology explained their decision as follows:

> 'We didn't want any law suits,' explained Tim Kelly, Fuller O'Brien's vice president for technology. 'We wanted asbestos off the premises' – and that included all of the company's product lines. The likelihood of any respirable asbestos escaping from the putty would, as a matter of reason, seem extremely remote. But reason was obviously not prevailing, and since the putty represented only one percent of the company's product line, it was obviously expendable.[78]

As such, by the late 1970s, Fuller-O'Brien determined that asbestos was too risky to continue using in its business, simply because of the risk associated with lawsuits and the use of the mineral on its premises.

During June 1980, Fuller-O'Brien notified Thiokol that it was ceasing the manufacture of the 3992 putty.[79] Thiokol then decided to purchase all of the available putty so that it would have time to develop alternatives.[80] Fuller-O'Brien sold the manufacturing rights to Bristol Aerospace Company, but Bristol, when contacted by Thiokol during July 1981, declined to manufacture it.[81] Thiokol continued to use the 3992 putty in the field and nozzle joints until its supply was exhausted after space shuttle flight STS-9 that launched on November 28, 1983. Thiokol also looked to purchase from Fuller-O'Brien the formula for the 3992 putty, but eventually decided not to try to manufacture it or find a manufacturing vendor.[82] Rather, upon receiving the notice of discontinuation from Fuller-O'Brien in 1980, Thiokol investigated the market for alternatives including identifying eleven potential options.[83] Of these candidate materials, the company selected Randolph Seam Paste 801 as the replacement putty.[84]

Thiokol's due diligence to identify, test, and certify a replacement for the Fuller-O'Brien 3992 putty was intensive and not, as claimed by Malcolm Ross, "hasty."[85] As an example, Brian Russell reached out to the Huntsville Division of Thiokol and was told by P. R. McFall of their

Rocket Engineering Section that, in 1977, they successfully replaced the Fuller-O'Brien putty with a replacement putty from Randolph Products Company. Mr. McFall identified that the Randolph putty was still in use on the Castor II, Castor IV, and Patriot motors, although the zinc chromate type of putty had also been used in many other of their historical motor programs.[86] Clearly, the use of putty in segmented joints for motors was the norm and not a band-aid or cheap correction as claimed by sociologist Diane Vaughan in her book.[87]

Much of the history for the selection of Randolph's putty as a replacement is discussed in two reports: Thiokol Report TWR-13705 on the evaluation of the test methods for the putty which was authored on March 4, 1983 by F. E. Bares and Thiokol Report TWR-13719 authored on March 18, 1983 by S.B. Pendleton in Insulation Design, both of which were provided to four recipients including Brian Russell.[88] The TWR-13719 report summary includes noting that the Randolph Seam Paste 801 did not meet the then present specification requirements originally put in place for Fuller-O'Brien as the "material does not have the same composition as the Fuller O'Brien material."[89] As an example, TWR-13705 discusses that the asbestos fibers used in both putties were chrysotile, but the fibers in the Fuller-O'Brien putty were "much smaller in length and diameter than those in the Randolph material."[90] TWR-13719 continued by stating that all of the listed non-conformances had been documented, and then noted the success of this Randolph material in the Castor and Patriot missile programs under Thiokol Huntsville since 1977.[91] The report discussed the significant testing for the eleven putties undertaken under TWR-12855 and the results reported under TWR-12886, Rev A, with the following summary:

> Based on the ablation and char characterization test data, the Randolph Products Co., seam paste 801, was selected as the best material for replacement of the Fuller O'Brien material.[92]

The due diligence on the Randolph product included its history of acceptability by Thiokol Huntsville in their rocket program. Once Randolph's putty was identified as the lead candidate, the operational issues were addressed including testing it on full scale static test motor DM-5, purchasing it in tape form versus in bulk, investigating various layup methods, and similar requirements in order to put it to use.[93] Similar to the Fuller-O'Brien putty, the Randolph putty was required to contain a minimum asbestos fiber content of .45%.[94] The new specification required for both the Fuller-O'Brien and Randolph putties was issued on July 28, 1983. The requirements governed "two types and three classes of putty-like compound with permanently elastic properties."[95] The specification listed as certified material to use on the solid rocket motor nozzle and field joints only the Fuller-O'Brien 3992 putty and its replacement, the Randolph Seam Paste 801.[96]

In summary, the decision by Fuller-O'Brien to stop selling the 3992 putty was reasonable based on their concern over future asbestos regulations and litigation exposures. In addition, the actions by Thiokol and NASA to purchase the available putty stock and then investigate and select the Randolph putty as its replacement was backed by significant actual experience in rocket motors and substantial testing.

The performance of Fuller-O'Brien 3992 putty was seemingly flawless over time with two exceptions: first, Space Shuttle Columbia on flight STS-2 (the second space mission) launched on November 12, 1981. During the post-fight disassembly inspection "a burned primary O-ring was discovered."[97] This incident raised a serious concern, resulting in a substantial investigation including the test plan contained in Thiokol Report TWR-13423 and the discussion contained in Thiokol Report TWR-13484 issued on April 21, 1983. As stated in TWR-13484:

> Close inspection of the field joint revealed remnants of a burn path through the zinc chromate vacuum putty which fills the gap between the NBR insulation interface in the field joint… The dimensions and configurations of the blow path through the vacuum putty on to the primary O-ring were unknown, as most evidence was destroyed upon disassembly of the field joint. The burn path did, however, cut into the face of the NBR Insulation …. [98]

This report was sent to three people, including Brian Russell. The investigation focused on the field joint assembly procedures that affect the rheology (material flow) of the putty. This included a mock field joint assembly to better understand the geometric configuration of the putty layup prior to assembly, the flow of the putty as the field joint is compressed during assembly, and the potential effect on the putty during the post-assembly leak test (the test to ensure that the O-rings will seal correctly).[99] Although Thiokol did not reach any firm conclusions as to the cause of the blow path through the putty and onto the primary O-ring, the test recommendations included increasing the leak test stabilization pressure from 50 psi to 150 psi to ensure that the seal is in place and not leaking.[100] The putty could mask a seal leak if the leak test pressure was not high enough. Interestingly, the conclusion also stated that the Randolph putty was superior to the Fuller-O'Brien putty in that, (1) the Randolph putty was easier to handle during layup due to it being less tacky and (2) the Randolph putty was capable of resisting a blow-through during the 50 psi leak test for a longer time frame, and so the report recommended using the Randolph putty over the Fuller-O'Brien putty.[101]

As such, the Cardinal Rule was most seriously considered in the STS-2 blowhole investigation. The single abnormality was examined, analyzed, and found to the best knowledge of all involved, to be within acceptable risk to future missions or astronauts. As noted by Thiokol after completing an O-ring seal behavior and capability summary during August 1982, the secondary seal "provides a pressure seal if primary O-ring is initially nonfunctional."[102] As such, the engineers were satisfied that the Cardinal Rule was still intact. The Thiokol engineers were still concerned after STS-2. However, they felt that the facts surrounding their analysis, testing, and experience demonstrated that a sufficient safety margin existed in the then current field joint design.

The second exception was on flight STS-6 launched on April 4, 1983 during which the post-recovery examination evidenced a blowhole and O-ring char in the nozzle joint. The Thiokol engineers felt that these issues were minimal compared to STS-2 and were justified as being acceptable within their database.[103] As such, NASA and Thiokol continued to believe that the solid rocket booster as designed was safe to fly. However, with the Fuller-O'Brien putty used up on the STS-9 Columbia mission launched on November 28, 1983, that was all about to change.

THE RANDOLPH PUTTY CAUSATION OF GAS PATHS

> for want of a nail, the shoe was lost;
> for want of a shoe the horse was lost;
> and for want of a horse the rider was lost,
> being overtaken and slain by the enemy, all for want of care
> about a horseshoe-nail.
>
> —Benjamin Franklin [104]

As discovered during the post-Challenger tragedy re-design, the original field joint design was flawed regardless of whether the putty used in the field joint was manufactured by Fuller-O'Brien or Randolph.[105] However, the Randolph putty was statistically worse than the Fuller-O'Brien putty at causing the gas paths to occur. In particular, the change to the Randolph putty increased gas paths in the field joints from 2.6% of the time to 8% of the time and in the nozzle joints from 12.5 % of the time to 66.7% of the time.[106] The chart compiled by Jerry Burn in coordination with information supplied by Brian Russell shows as follows:[107]

Putty Comparisons

23 SRM Flight Motors were used in this analysis. STS-4 splashed into the ocean and was not recovered

2 of 6 joints on STS-8 had Fuller O'Brien which accounts for the 6.33 Motors

Field Joint FLIGHT PUTTY TYPE EVALUATION Not Including Challenger	Flights	Joints	Gas Paths	%
Fuller O'Brien Putty	6.33	38	1	2.6
Randolph Putty	16.67	100	8	8.0
TOTAL	23	138	9	
Conclusion: Randolph Putty had 3.1 times more Gas Path occurrences on Field Joints than Fuller O'Brien				

STS-41B 10th flight and subsequent flights changed to Randolph Putty on two N-T-C Joints

N-T-C FLIGHT PUTTY TYPE EVALUATION Not Including Challenger	Flights	Joints	Gas Paths	%
Fuller O'Brien Putty	8	16	2	12.5
Randolph Putty	15	30	20	66.7
TOTAL	23	46	22	
Conclusion: Randolph Putty had 5.3 times more Gas Path occurrences on Nozzle to Case Joints than Fuller O'Brien				

The critical nature of this increase in risk cannot be overstated as the existence of a gas path was essential for blowby and O-ring erosion.[108] As such, the higher the probability of a gas path, the higher the probability of an O-ring failure, and the higher the probably of a joint failure like the one which caused the Challenger tragedy. To be clear, gas paths in the joints were not created by cold temperature at launch. Rather, those cold launch temperatures affected the O-rings such that they could not respond in time to the launch dynamics as the cold caused them to be harder and therefore less responsive.[109]

The Randolph putty came into partial use on STS-9 and full use on the STS-41-B (the 10th shuttle launch) Challenger Space Shuttle mission which launched on February 3, 1984. It was the only putty then certified and available to use in both the field joints connecting the segments of the solid rocket motors and the nozzle joints.[110] Unfortunately, almost immediately after the introduction of the Randolph putty, both the nozzle joints and the field joints began to experience serious problems.[111] At the outset, this included joint-related issues with STS-11 (burned O-ring) and STS-13 (missing putty). As of July 1, 1983, Thiokol had noted the following "special problems" with the Randolph putty: (1) one putty container was extremely stiff, (2) the chromate level was inconsistent, a different color, and more tacky, and (3) a lack of cooperation from Randolph concerning the formulation, raw material sources, and mix facilities.[112] Based on the above, the Thiokol report recommended that they continue to incorporate the Randolph putty as it was the "only qualified material available," obtain the Fuller-O'Brien formulation to investigate Thiokol manufacturing the putty, and continue to investigate alternative sources.[113]

All involved at NASA and Thiokol recognized that these were serious problems which required immediate attention. Two Thiokol reports issued after the Challenger explosion, "O-Ring Erosion History,"[114] *TWR-15481A* and "SRM Joint History, April 1984 – January 1986"[115] detail the formation of a Vacuum Putty Team during June 1984 along with sixteen documented presentations, twenty-three undocumented presentations, eighteen post-flight test evaluations, nine problem reports, ten Flight Readiness Reviews, one Program Plan, three Analyses, and thirteen engineering test reports. The program plan entitled "Vacuum Putty/O-Ring Erosion Study and Program Plan,"[116] issued during October 1984, over fifteen months prior to the Challenger explosion, was forty-six pages long that included various criteria for O-ring protection and potential solutions which might satisfy those criteria. The plan included recommendations both for the short term and long term.

At the same time, the Cardinal Rule was being diluted to accommodate other priorities. The documentation by Roger Boisjoly and others concerning the need for a higher profile for the joint problems and more manpower for their resolution is well documented.[117] At the same time, NASA felt that the search for a better putty needed to focus on finding a non-asbestos substitute. As stated during July 1985 by L. M. Thompson of NASA during their later investigation into the Randolph putty problems:

> A second important goal is elimination of all material containing asbestos before we are forced in this direction.
>
> At this time, MTI has only one qualified putty material and it contains asbestos.
>
> The goal of this study is to define alternative materials with improved processing/performance characteristics (compared to Randolph) and without asbestos.[118]

Unfortunately, even with all of the efforts by both NASA and Thiokol, a workable solution was not found and implemented in time to prevent the tragedy.[119] In Thiokol Report TWR-15481 created by Brian Russell after the Challenger accident to provide the O-ring erosion history, Thiokol noted the following problems:[120]

Inspection Results	**Number**	**Percentages**
Field Joints with Primary O-ring erosion	6 of 138	4.3%
Field Joints with Soot Blowby Past Primary O-ring	4 of 138	2.9%
Field Joints with Erosion or Soot Blowby	8 of 138	5.8%

Nozzle Joints with Primary O-ring Erosion	16 of 46	34.8%
Nozzle Joints with Soot Blowby past the Primary O-ring	8 of 46	17.4%
Nozzle Joints with Erosion or Soot Blowby	17 of 46	37%

On January 27, 1986, the above issues came to a head in the evening meeting as discussed at the beginning of this essay under "Countdown." The Thiokol engineers recognized that the solid rocket motor nozzle and field joint designs were problematic and they were concerned about launching in weather colder than their prior coldest flight, 51-C, which was at 53 degrees Fahrenheit. In summary, they were not comfortable with any launch outside of their database.[121] All of the above effort proved for naught, the Thiokol management gave in to the NASA pressure to approve the launch, and the rest gave rise to the tragedy.

CAUSATION OF THE JANUARY 28, 1986 CHALLENGER TRAGEDY

"In God we Trust, all others bring data."

The Challenger explosion was preventable.[122] This essay addresses the two areas in which human factors in combination with a gas path, led to the explosion: (1) NASA intentionally violating and diluting the Cardinal Rule which had required a heightened concern about safety during the first 122 seconds after ignition, and (2) NASA and Thiokol not fully understanding the internal workings of the field joints.

1. Causation Factor 1. Violation and Dilution of the Cardinal Rule

All agree that NASA correctly considered the first 122 seconds of the launch, the time frame between ignition and the solid rocket booster burn out, as critical for safety because of the lack of an abort or crew capture system. As stated by NASA Assistant Director of Space Shuttle Flight Crew Operations Warren J. North in his May 4, 1984 summary on this particular risk:

> After completion of the ALT phase in 1977 the program reflected on the consequences of deleting the abort rockets and SRB TT. **The risks associated with first-stage launch warranted a programmatic attempt to provide crew survival.** Token software capability was incorporated in 1978 when external-tank fast-separation was approved to 'give the crew a last ditch attempt to survive.'[123]

The Presidential Commission investigating the Challenger tragedy was in full accord with the sentiment expressed by Mr. North. As stated by the Commission:

> Because of these factors, NASA adopted the philosophy that the reliability of first stage ascent must be assured, and that design and testing must preclude time critical failures that would require emergency action before normal Solid Rocket Booster burnout.[124]

As clear and as important as this mandate, NASA over time failed in this mission in a number of ways which potentially led to the Challenger explosion.

Initially, in the original solid rocket motor design for the space shuttle program, the field joint was modified in design from the Titan III(c) to add a redundancy so that the failure of an O-ring would have a secondary O-ring as a backup. This design was accepted as a redundancy protecting against catastrophic failure on November 24, 1980;[125] basically, determining that the joint was failsafe. During 1982, NASA realized that this Criticality Rating 1R (redundant) was a mistake given the potential risk based on the joint rotation after motor pressurization, and so Larry Mulloy and Michael Weeks signed off on changing the field joint to a Criticality 1 (without redundancy) effective March 28, 1983 with the joint no longer being considered failsafe.[126] This, of course, put the Cardinal Rule in jeopardy and should have led to extensive additional investigation and safety considerations when the field joint issues first developed during November 1981 on STS2 (erosion on the primary seal), long before the investigations and redesign program initiated during the Spring of 1984. Merely as one example, NASA could have investigated the potential availability and effectiveness of an abort or crew escape mechanism to replace the elimination of the failsafe redundancy. However, it did not.

NASA had a poor track record when it came to considering how to add a launch abort or crew protection system for the space shuttle. As such, this issue was not new. The original shuttle solid rocket motor design criteria required a thrust termination system, but that concept was eliminated in April 1973 as it would have added 4,000 pounds in weight per booster and have been relevant in only three situations, including a case burn-through. The engineers noted that "of the 2,233 solid motors they had data for, there had only been 15 burn-throughs, mostly during the early 1960s." [127]

Most importantly, less than six months after the elimination of the redundancy of the field joint Criticality Rating, NASA initiated and then abandoned discussions concerning developing such a crew escape not because of technology, but because of political considerations. As stated by Mr. North:

> A telecon between JSC and Langley … was convened in August 1983 to request a Langley assessment of several crew escape options for Shuttle. After several weeks of delay the JSC request was shelved apparently because of adverse public response that might evolve from overt NASA concern for crew safety.[128]

Mr. North's May 4, 1984 Memorandum to the Deputy Manager, National STS Program and copied to three additional interested parties was very specific on his view of the failure of the space shuttle program to adequately investigate a crew protection system. Mr. North stated:

> Long deliberations during the Shuttle RFP review process established that the advanced technology high-pressure engines and complex systems warranted launch safety and crew survival provisions similar to that provided during Mercury, Gemini and Apollo.
>
> ***
>
> Superficial and inflated cost estimates have deterred abort/escape hardware enhancement. In view of the longevity planned for the shuttle system and the available escape system

> expertise at Langley, it seems technically and morally appropriate to request a Langley design and integration assessment of Shuttle escape concepts.[129]

No such devices were implemented and so just under two years later, the Challenger astronauts were without survival options during those first critical 122 seconds. It is difficult to know whether any such device would have provided the necessary protection in any given accident scenario, but clearly a device not developed and implemented provides no options or hope.[130]

NASA took their eye off of the need for enhanced consideration of safety during the first 122 seconds of flight in other ways. As an example, they diluted the attention of the Thiokol employees investigating the problems with the Randolph putty by mandating that Thiokol give equal consideration to finding a non-asbestos containing substitute rather than just focusing on finding an improved putty.[131] Given the limited resources and budgets provided to Thiokol for this investigation, such a request necessarily detracted from the main, otherwise sole focus, of safety related to the field joint. In addition, the production demands were a significant competitor to the joint investigation and resolution for resources, so much so that the Thiokol employees were concerned.[132] Roger Boisjoly was so alarmed, that he penned what has now become his famous July 1985 warning, six months prior to the Challenger tragedy:

> This unofficial team is essentially nonexistent at this time.
>
> ***
>
> It is my honest and very real fear that if we do not take immediate action to dedicate a team to solve the problem with the field joint having number one priority, then we stand in jeopardy of losing a flight along with all the launch pad facilities.[133]

Six months later, his prediction proved directly on point and an opportunity to address the issues in advance was, again, lost.

The violation of the Cardinal Rule was also evident during the January 27, 1986 meetings between Thiokol and NASA over whether the Challenger should launch in the cold weather expected on the following day. The facts and story of how Thiokol, under pressure from NASA, came to agree to approve the launch during the fateful January 27, 1986 meeting are well-documented in the historiography. Even given this documentation, the history of these events are subject to numerous interpretations, inuendo, claims of conflict, and disagreement over intent or interpretation. Nevertheless, the scholarly work on these events agree on one core aspect. They consistently mention that the requirement imposed by NASA on Thiokol was to prove it was unsafe to launch, rather than asking Thiokol to prove it safe to launch.[134]

Notably, under all interpretations of the January 27, 1986 meeting, NASA violated the Cardinal Rule about enhanced safety. As to the details, (1) NASA was aware of field joint-related issues and knew that certain Thiokol employees had safety-related concerns over launching with those joints in the cold weather,[135] (2) Thiokol initially recommended not to launch under 53 degrees Fahrenheit,[136] (3) NASA rejected the request and asked for Thiokol to reconsider its position, (4) after reconsideration, Thiokol's Senior Management decided not to accept the recommendation of some of its most experienced employees to not launch and, instead, authorized NASA to launch the Challenger during the following morning,[137] and (5) NASA knew that the space shuttle had no abort or crew escape system should in fact one of the six field joints fail. Based on those facts without delving into the details, safety was not the highest priority as envisioned by Mr. North in his May 4, 1984 memo. Brian Russell, a Thiokol scientist who developed much of the written material used during the January 27, 1986 meeting and attended it in full, agreed, stating that "the decision was made without the Cardinal Rule of safety."[138]

The violation by NASA of the Cardinal Rule was in full view to Thiokol in terms of the lack of funding focused on improving the joints prior to the Challenger explosion. The files are replete with pleas by Roger Boisjoly and others [139] that they lacked the resources and people to properly address the issues that were known by all to be Criticality 1 (no redundancy). NASA's response to proposed long-term and short-term solutions were largely funding and cost dependent.[140] Those items, of course, are important. Further, predicting which problems will result in catastrophic results is hard to do. However, hazard analysis methodologies exist to assist such discussions.[141] Finally, safety, when the potential damages and injuries are catastrophic, must remain the primary focus.[142]

NASA was not only ignoring the Cardinal Rule related to the first 122 seconds of the launch with Thiokol. In addition, NASA ignored this rule with Rockwell Space Division, the prime contractor for the space shuttle orbiters, prior to the launch on January 28, 1986. During that morning, Rockwell expressed to NASA that it was concerned about an elevated risk for the orbiter thermal protection system (barrier that protects the orbiter in space and during atmospheric reentry) because they had no experience with lifting off with ice on the launch pad.[143] Similar to Thiokol's employees' concerns about the solid rocket boosters, NASA was asking Rockwell to make decisions that were outside of their experience base.[144] In spite of Rockwell's recommendation, and their expressed concern with launching in view of the weather conditions,[145] NASA decided to proceed with the launch without requesting any additional input from Rockwell.[146] In fact, Rockwell employee Bob Glaysher testified to the Presidential Commission that he told NASA that "Rockwell cannot assure that it is safe to fly."[147] This was the first potential launch in which Rockwell took the position that it was "unsafe to fly."[148] Although Arnie Aldrich of NASA stated that he would not overrule a "no go" by Rockwell,[149] in fact from the Presidential Commission testimony, he effectively did so.[150] Clearly, once again, NASA violated the Cardinal Rule in order to launch the Challenger, with disastrous results.

2. <u>Causation Factor 2. Failure to Understand the Inner Workings of the Field Joint Design</u>

Based on the information learned during the post-Challenger explosion re-design, the recommendation by Thiokol's engineers that the Challenger was safe to launch at 53 degrees Fahrenheit or higher was wrong. Rather, the field joints were fundamentally flawed and could fail at any temperature, albeit they were more likely to fail in cold weather due to the O-ring resiliency and its decreased ability to re-seal and seat under pressure prior to the gas blowby eroding the two O-rings to the extent that they were not functional.[151] The secondary seal had slightly less gap opening and this all happened so fast while the secondary O-ring was also trying to track the case hardware. As such, the secondary O-ring also had the same ability to fail as the primary, but due to less gap opening it had a better chance to seal.[152]

The basic error was that Thiokol did not have a good database or seal requirements on which to base their fly/no-fly decision and had insufficient experience to fully understand the creation of gas paths in the putty.[153] As an example, the Thiokol database from prior launches did not take into account certain indeterminable variations in the field joints, including the geometry of the putty layup, the flow of the putty, the effect of the leak check on the putty, and the insulation surface dimensional variations, all of which could affect whether a gas path existed at the time of the solid rocket booster assembly in the VAB.[154] Statistically, the Fuller-O'Brien putty was significantly less likely to have a gas path than was the Randolph putty used at the time of the Challenger explosion, but it had still occurred. As the O-rings were sealed upon assembly and the putty was not visible, the existence of a gas path was not capable of being known prior to the space shuttle launch. Further, the creation and existence of gas paths was never subject to "as flight condition" as all such tests involved horizontal instead of vertical motors and additional putty was tamped into the joint in order to limit it from malfunctioning during the test.[155]

The effect of the temperature on the field joint was very much gas path dependent. If the joint was gas path free upon assembly at the VAB, then the cold temperature on launch day would not cause a blow-by or any O-ring erosion. If the joint had a gas path upon assembly at the VAB, then it was at risk for failure at any temperature, although significantly more so during cold weather. As stated by Brian Russell:

> The lower the temperature, however, the greater was the risk that the timing function that Roger mentioned could be altered sufficiently by the slower reacting o-rings to put the flight in danger. That was my fear that night. As I have stated before, I still feel our charts were sufficient to express that risk and to justify the 53 degree temperature limit.
>
> In the meantime, we were pursuing design and process changes to improve the situation. Would we have come up with the outstanding fix we did? No, but it might have been sufficient. We had already ordered case forgings with a capture feature lip at company risk. NASA had not authorized it yet in 1985.
>
> I admit that I favored continued launches while we worked to improve the joint. Though there were arguments as you stated, no one brought forth a formal rebuttal to fly. In fact, we either relied on previous worst-case analyses or created new ones. It's easy to see now that we should have shut things down and fixed the problem. The business climate then made that choice highly improbable if not impossible.[156]

As early as February 1984, two years prior to the Challenger tragedy, NASA knew that the Randolph putty was sensitive to humidity and temperature, and that its failure to provide the thermal barrier to the O-rings could "lead to burning both O-rings and subsequent catastrophic failure."[157] It became a race between the O-ring sealing and seating before the gas reached the O-ring creating seal damage to cause a failure. As stated by Jerry Burn, this was very much Russian Roulette.[158]

Although the above information would have been useful during the January 27, 1986 telephone discussion, it was not available. Much of the joint dynamics were discovered by Thiokol employees during the redesign process after the Challenger explosion.[159] In addition, all pre-Challenger tragedy testing involving the field joints did not simulate actual flight conditions as they were undertaken with the segments lying horizontal rather than vertical and the space between the insulation was tamped with additional putty to minimize any air gaps.[160]

MORAL INJURIES

Everyone who attended the January 27, 1986 meetings to discuss whether the Challenger should launch was fundamentally changed by the experience. Those at NASA and Thiokol who were in favor and approved the launch, were devastated. Those at Thiokol who opposed the launch were equally devasted, especially if they also had been involved in the failed attempts to understand the joint-related issues. Each individual had to handle their feelings, potential guilt, sadness, and fear of the unknown in their own way. For some, their involvement gave rise to moral injuries, typically evidenced by guilt arising from a moral failing or trauma.

For one small group of Thiokol employees consisting of Allan McDonald, Brian Russell, Bob Ebeling, Arnie Thompson, and Roger Boisjoly, their injuries did not stop with the explosion. Rather, they helped the Presidential Commission and others to investigate and determine the truth and to make the situation transparent. For this, they at times were ostracized at work, potentially demoted, and otherwise made by some co-workers or senior management to feel unwelcome. Because of this treatment, they at times felt isolated at work and dubbed themselves as "the Five Lepers." In contrast, however, they also received support from many of their co-workers and so this feeling of ostracization was felt more by some than by others.[161]

The injuries sustained by the Thiokol employees were not just related to the January 27, 1986 telephone discussion in combination with the employees' desire post-tragedy to assist in a complete and transparent investigation. These five employees were put in a very difficult position by NASA in the months and years leading up to the explosion due to the time and funding constraints that ultimately compromised the level of acceptable risk, reduced the possibility of finding an effective putty replacement and solution, and contributed to the failure to have a Launch Commit Criteria or dataset under which to examine cold weather launches.

The "what ifs" and "what might have been" are especially brought home in Roger Boisjoly's unpublished manuscript describing his February 12, 1985 conversation with Larry Mulloy and Allan McDonald, one year prior to the Challenger explosion, on whether the 53 degrees should be a flight constraint. Larry Mulloy rejected such a suggestion.[162] As stated by Mr. Boisjoly in his manuscript:

> On February 11, 1985, Roger and a similar group of engineers and managers traveled to MSFC for the NASA upper middle management Pre-Flight Readiness Review presentation to the Center Board on February 12th. Some time before the presentation was to be made on the 12th, Al McDonald and Roger approached Larry Mulloy with the suggestion that he should place a flight constraint for launch below 53 degrees but Mulloy resisted that suggestion by stating that the extreme temperature that had been experienced on SRM-15 was the worst case in Florida weather history. He further stated that the condition experienced was analogous to a 100 year storm and that the field joints would certainly be redesigned before another 100 year storm happened. Al and Roger were not able to refute that logic so a flight restraint of 53 degrees became a moot issue.[163]

Such a close call to having created a limitation which might have prevented the Challenger and similarly situated flights from ever launching would certainly weigh heavily on one's mind.

The moral injury affected each of the employees differently. Bob Ebeling, who coined the term "the Five Lepers," never recovered. Having also suffered the suicide of his son prior to the Challenger, he was no stranger to sorrow.[164] Although he was assigned to the re-design team, he took a leave of absence and then retired. Over the next thirty years, he donated substantial time and money to a nearby bird refuge.[165] Shortly after his passing in 2016, Howard Berkes of NPR provided an epitaph stating "Bob Ebeling spent a third of his life consumed with guilt about the explosion of the space shuttle Challenger. But at the end of his life, his family says, he was finally able to find peace."[166] The Challenger explosion became so central to his life, that his obituary focused on it and its effect on his life:

> Obituary – Robert "Bob" Vernon Ebeling, 89, of Brigham City, Utah, was a man of deep and abiding faith who has joined the God and Savior he unshakably cherished.
>
> Bob played a major role in a tragic and historic event in 1986. He was one of five engineers at booster rocket maker Morton Thiokol, Inc., who tried to stop the fatal launch of the Space Shuttle Challenger. He had also warned Thiokol in an October, 1985, memo marked "HELP!" that a task force setup to address problems with the joints in the shuttle boosters faced unnecessary delays in its work. "This is a red flag." the memo concluded.
>
> The Challenger tragedy left Bob distraught and consumed by guilt. "I could have done more," he told NPR at the time. "I should have done more." He soon retired from Thiokol and sought solace in volunteer work at the Bear River Migratory Bird Refuge near his home.[167]

The Washington Post stated: "This is what Bob Ebeling planned to demand of God, when he saw him: "Why me? You picked a loser."[168]

Roger Boisjoly suffered from issues compounded by a similar situation where he was at risk of being fired after refusing to sign off on an unsafe practice occurring at a prior employer, Hughes Helicopter.[169] In regard to the Challenger, Boisjoly regretted that he did not do more to stop the January 28, 1986 launch. As noted by sociologist Diane Vaughn, "Boisjoly tortured himself with thoughts that he might have been able to stop the launch by calling the newspapers."[170] In addition, Boisjoly believed that he was blackballed from the industry by Thiokol's management and could not find a job until changing professions to become an expert witness for attorneys in California.[171] As stated by Boisjoly in his unpublished manuscript:

"However, the bottom line was very clear to the Commission, Roger and Al were being punished for their previous testimony, period."[172] As stated by Chairman Rogers, when it became clear that Thiokol was punishing the employees who were being forthcoming:

> I want to make a comment to Mr. Kilminister, I guess, but to the company as a whole. I am very upset about the testimony Mr. McDonald gave. It's a very serious matter. In this kind of an accident where people come before a Commission and tell the truth and then they are treated as he believes he has been treated, which obviously in some way punishment or retaliation for his testimony, it is extremely serious, and the whole idea of the program is to have an openness and to have an honest exchange of views. And in this case, Mr. McDonald and Mr. Boisjoly and others, Mr. Thompson and others, were right. If their warning had been heeded that day and the flight had been delayed, there's no telling what would have happened. We might never have had the accident. And to have something happen to him that seems to be in the nature of punishment is shocking, and I just hope that you convey that to management. I don't know how the others feel, but that is how I feel. I would think you would want him in all of your discussions, and Mr. Boisjoly and he shouldn't be treated that way. He should be treated the other way, that he was right and you were wrong, and others who changed their decisions were wrong, and they were right, and to have something that seems to me to be in the nature of punishment is very, very distressing, and I just wanted you to know that.[173]

Back at Thiokol, it wasn't any easier. Again, from the Boisjoly unpublished manuscript:

> It didn't take very long after the news releases by the Commission before those who had testified, Roger, Arnie Al, Bob and Brian started to feel the backlash from their colleagues at MTI. All of a sudden there was a ground swell of resentment by their colleagues because their colleagues were mostly in a Subjective evaluation mood and were blaming those who testified for the future potential "Layoffs" that were surely to come because of the testimony. The feeling against the five escalated quickly and the five began referring to themselves as "The Five Lepers" since very few colleagues would even acknowledge their existence in the plant.[174]

Boisjoly paid the price economically and professionally for being a high-level whistleblower.

As to Allan McDonald, his feelings immediately hit home. As stated in his book chapter entitled "A Leper in the Limelight":

> I had a difficult time going to sleep that night, because I was starting to get the feeling that the whole world was against me. I dreaded going out to the plant the next day and facing all of those people. I was also totally exhausted to a point that I was so emotionally drained and tired that I couldn't relax.[175]

The pressure and treatment related to McDonald continued after his testimony before the Presidential Commission. Fortunately, he still had friends who supported him:

> Sometime later, I received a telephone call and a note in the mail from Wiley Bunn, the Director of Reliability and Quality Assurance Office at NASA Marshall, supporting my actions and testimony and warning me that Marshall management was plotting against me and that I should watch my backside.[176]

For the remainder of his career at Thiokol, McDonald felt that the management at Thiokol would have pushed him out or made it uncomfortable for him to stay if not for the protection he received from those on the Presidential Commission.[177]

Brian Russell has felt and continues to feel the touch of moral injuries arising out of the Challenger tragedy. Mr. Russell has not been vocal about the injuries as they are private and subject to much reflection over the years. But, he has found his way. For several months after the explosion, he was lost and without a sturdy foundation in how to move forward. At that time, Mr. Russell realized that he had a life to continue to lead and, as such, worked to be as good a husband, father, co-worker, and friend as he could be. He vowed to never allow a similar situation to occur, became the moral conscience (in his own mind) of those co-workers around him, and was known at work as a Boy Scout, in the good sort of way. He has also strongly relied on his religion, the Church of Jesus Christ of Latter-day Saints, not as a missionary or to try to convince others but, rather, to build and support his internal strength.[178]

As to Arnie Thompson, we do not have good information. We know that he continued to work at Thiokol and remains living in the Brigham City, Utah area.

Each of the self-identified Five Lepers handled the tragedy and self-examination in very individualized ways. Such uniqueness makes sense as the injuries arose from the trauma experienced by each of the individuals based on their beliefs that they, individually or collectively, could and should have done more to prevent the tragedy. The underlying failures include their unsuccessful work to improve the aft field joint and management's rejection of their January 27, 1986 recommendation to delay the launch because of the anticipated cold weather. In addition, these moral injuries may have been exacerbated by their viewing of the explosion live as a group, their post-accident involvement with the press and government investigations, certain negative experiences in the Brigham City community, and their emotional separation from certain Thiokol employees and potentially their communities arising from the post-accident investigation cooperation. These injuries arose from all that happened and never fully healed.

CONCLUSION

The Space Shuttle Challenger tragedy may well have been caused by the unavailability of the Fuller-O'Brien asbestos-containing 3992 putty in the marketplace. The March 1983 testing and comparisons showed significant differences both in the asbestos and non-asbestos material properties. The statistical analysis shows that the replacement Randolph putty developed significantly more gas paths, thereby setting the stage for the 5800 degrees Fahrenheit gas to race towards the O-rings and, in the Challenger situation with the cold weather launch, catch and destroy both of the O-rings before either could seal and seat. This led to the Challenger destruction, the deaths of the astronauts, and the moral injuries felt by so many.

The additional gas paths caused by the Randolph putty exposed two weaknesses that were the secondary causes of the tragedy. The first was the decision-making process by NASA, including its focus on day-to-day issues and priorities without resolving or fully understanding the joint related safety issues arising during the critical first 122 seconds of the flight. The record is replete with NASA ignoring warnings prior to the January 27, 1986 launch discussion meetings. Further, NASA then changed the rules by requiring its vendors (both Thiokol on the solid rocket motors and Rockwell on the orbiter) to prove that a cold weather launch outside of the relevant databases was unsafe instead of presuming such a launch to be unsafe absent acceptable data supporting the safety. This was the ultimate mistake on January 27, 1986 and the day of launch, January 28, 1986. As often heard at NASA, “In God we Trust, all others bring data.”

The second weakness was the flawed field joint design that had previously been masked by the rheological qualities of the Fuller-O’Brien putty. In summary, because of the Fuller-O’Brien putty material flow and better consistency during changing humidity and temperatures, NASA and Thiokol did not realize the full extent of the flaws in the original field joint design until after the January 28, 1986 tragedy and their work to re-design the field joints for future shuttle flights. Without a gas path forming during the assembly process, there is no field joint failure. With a gas path having formed, a great number of unknowns came into play.

Some of the issues related to these weaknesses, such as the working dynamics of the field joints, were not well understood until after the post-Challenger field joint was re-designed for future space shuttle flights. Others, however, such as the requirement for a heightened safety focus when a failsafe Criticality Rating 1R (with redundancy) is changed to a Criticality Rating 1 (without redundancy) seemed to merely become part of the normal give and take in the design and manufacturing process in competition for resources and attention with other daily concerns, pressures, and needs of the program.

EPILOGUE

Three of the four Thiokol employees discussed by this essay in the context of their moral injuries have, over the past 35 years, passed away: Roger Boisjoly on January 6, 2012 from cancer, Bob Ebeling on March 21, 2016 from cancer, and Allan McDonald on March 6, 2021 from a tragic accident.

Brian Russell, with support from his family and many friends, continued his career at Thiokol, helped re-design the space shuttle, and has managed to live a productive, satisfying, and useful life. He still feels that if he had spoken up more during the January 27, 1986 meeting, it may have made a difference, at least to the NASA people attending the meeting. He continues to carry the burden of guilt, not all-consuming as it was for the first four months after the accident, but it never completely goes away.

Brian Russell also takes great solace in having been contacted by Alison Smith Balch, daughter of Challenger pilot Michael Smith, after the April 2021 Netflix documentary on the Challenger explosion. She reported to Mr. Russell that she is happy, has a family, and has been strengthened by her faith. Both feel that such is the way to honor those loved ones lost on that day.[179]

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Notes

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[1] Roger Boisjoly, *Challenger Book Material*, unpublished manuscript (In author's possession), (1998-1999), pages 340-341.

[2] "Space Shuttle Solid Rocket Booster," *Wikipedia*, Accessed October 30, 2021. https://en.wikipedia.org/wiki/Space_Shuttle_Solid_Rocket_Booster.

[3] All diagrams and pictures within The Technical Context section of the essay were taken from materials provided by Jerry Burn unless otherwise stated.

[4] Jerry Burn, "Post-Challenger Solid Rocket Booster Redesign Learning from the Aftermath," Unpublished PowerPoint presentation, (In author's possession, April 27, 2021).

[5] Picture from NASA. Accessed December 3, 2021. https://www.nasa.gov/mission_pages/shuttle/behindscenes/srb_inspection-gallery.html.

[6] Picture from Wikipedia. Accessed December 3, 2021. https://en.wikipedia.org/wiki/Space_Shuttle_Solid_Rocket_Booster.

[7] Boisjoly, "Challenger Book Material," 546.

[8] J. W. Furgeson, "SRM Field Joint Zinc Chromate Vacuum Putty Test Report," *TWR-13484 Rev B*, (In author's possession, April 21, 1983), 21.

[9] Brian Russell, email to Martin Ditkof (In author's possession, October 31,2021). In this email, Mr. Russell describes the process of using the putty in assembling the field joints.

[10] Jerry Burn, email and memo to Martin Ditkof (In author's possession, November 25, 2021).

[11] Picture from Wikipedia. Accessed December 3, 2021. https://en.wikipedia.org/wiki/Space_Shuttle_Solid_Rocket_Booster

[12] E. S. Sutton, "AIAS 99-2929, From Polymers to Propellants to Rockets – A History of Thiokol," *American Institute of Aeronautics and Astronautics,* (In the author's possession, June 20-24, 1999), 30 of 43.

[13] Diane Vaughan, *The Challenger Launch Decision: Risky Technology, Culture, and Deviance at NASA.*, (Chicago: University of Chicago Press (1996), 121 ("This putty, which after the disaster appeared to some to be a Band-Aid, on-the-cheap correction…").

[14] Malcolm Ross, "Letter to the Editor: Mineralogy and the Challenger Disaster." *Elements Magazine: An International Magazine of Mineralogy, Geochemistry, and Petrology*, 1

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(1): February 2008, 5. ("…the hasty substitution of the Randolph putty – can actually increase risk, even create risk.").

[15] A number of respected commentators have claimed that the Randolph putty used at the time of the Challenger explosion in the field joints did not contain asbestos, including Roger Boisjoly. Robison, Wade et al, "Representation and Misrepresentation: Tufte and the Morton Thiokol Engineers on the Challenger," *Science and Engineering Ethics* (2002), 8, 59-81, 73 (Note J) and Roger Boisjoly, *Challenger Book Material*, 1998-1999, unpublished manuscript possessed by Chapman University Leatherby Libraries, 437. The myth on the Internet has grown in terms of the Challenger explosion being allegedly caused by an asbestos substitute which failed. Some of these commentators use the myth for their own political purposes. See Don Fife, "Environmental Hysteria Can Kill." Edited by National Association of Mining Districts. Prod. *Property Rights Foundation of America*. Washington D.C., (January 2002). Accessed April 11, 2021. "https://prfamerica.org/2002/EnvironmentalHysteriaCanKill.html (Discussing the claimed elimination of asbestos from the O-ring "sealant," stating: "Also, there have been billions of dollars lost in our space shuttle program as well as the world-wide humiliation of having needlessly lost Mrs. Christa McAuliffe and other Challenger astronauts."). See also, "Asbestos Scare Led to Challenger Disaster," (1999). Accessed November 18, 2021. https://www.aim.org/publications/weekly_column/1996/02/col029.htm. Other experts, such as noted asbestos expert David Egilman, have accidentally misguided the public by making other claims, such as that the O-rings themselves had at one point contained asbestos, and that the substitution of silicone for that asbestos caused the Challenger to explode. David Egilman, "Mesothelioma Interview." Accessed November 18, 2021. https://www.mesotheliomaweb.org/egilman530474.htm. The author's hope is that this essay debunks these and other similar growing internet myths concerning the components used in the field joints.

[16] Ross, Letter to the Editor, 5. Richard C. Cook, *Challenger Revealed: An Insider's Account of How the Reagan Administration caused the Greatest Tragedy of the Space Age,* (New York City: Thunder's Mouth Press, 2006), 7. Jerry Burn believes that NASA and Thiokol took too much risk with the Challenger launch as it was outside their flight database with technical points that indicated they would have worse results at lower temperatures. Jerry Burn, comments on first draft. (In author's possession).

[17] Presidential Commission on the Space Shuttle Challenger Accident. "Report to the President on the Space Shuttle Challenger Accident." *Report to the President*, (Washington D.C., June 6, 1986). (Cover letter stating "It fully recognizes that the risk associated with space flight cannot be totally eliminated.").

[18] C. B. Peterson, Memo to distr, MSC, "Integral Launch and Reentry Vehicle Study Information Package," 28 February 1969, *ILRV MISSION REQUIREMENTS*, undated, and *NAR PROGRAM STUDY OUTLINE FOR INTEGRAL LAUNCH AND REENTRY VEHICLE SYSTEM*, 25 February 1969, as quoted in "A Shuttle Chronology 1964 – 1973: Abstract Concepts to Letter Contracts," *Management Analysis Office Administrative Directorate* (Houston: NASA, Lyndon B. Johnson Space Center), Volume I (December 1988), Chapter II, part 3, II-75, number 15.

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[19] W.F. Hoyler, “A Collection of Data and Thoughts Concerning Shuttle Configurations and Development Sequence, *Space Shuttle Program Office, Manufacturing & Test Office (August 3, 1971).*

[20] Presidential Commission, Volume I, 186.

[21] See the Presidential Commission, Volume 1, 180 which identifies “limited utility, technical complexity and excessive costs in dollars, weight, or schedule delays” in comparison with the Warren J. North, “Shuttle Contingency Abort and Crew Escape,” *Memorandum to Deputy Manager, National STS Program* (In author’s possession, May 4, 1984) which includes in paragraph 12 the risk of adverse publicity arising from NASA overt concerns “for crew safety.”

[22] Presidential Commission, Volume I, Page 180. Emphasis added.

[23] Warren J. North, “Shuttle Contingency Abort and Crew Escape,” paragraph 7.

[24] Presidential Commission, Appendix D page 239, SBR Critical Items List, (November 24, 1980).

[25] Presidential Commission, Volume I, 84 and Volume IV, 834, 860.

[26] Presidential Commission, App D, page 241.

[27] Jerry Burn, “Cause of Gas Paths in Field and Nozzle to Case Joints,” Memo (In author’s possession, November 12, 2021), 3. Brian Russell, “To Sum up: erosion was no a significant threat?, Comments by Brian Russell” (In author’s possession, December 7, 2021), 1 (“But as good as we were, we were not capable of understanding and analyzing all the variables in the joint operation.”).

[28] Brian Russell Oral Interview with Martin Ditkof (In author’s possession, October 23, 2021).

[29] Larry Mulloy, Email to Allan J. McDonald (In author’s possession, June 18, 2014 at 4:26.05 a.m. MDT), copied to Diane Vaughn.

[30] W. F. Hoyler, “A Collection of Data and Thoughts Concerning Shuttle Configurations and Development Sequence, *Space Shuttle Program Office, Manufacturing & Test Office (August 3, 1971).*

[31] Robert Thompson, “STS Oral History Interview by Edward C. Ezell,” contract historian (In author’s possession, May 12, 1981), 21.

[32] Ibid., 22.

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[33] Jerry Burn, Oral Interview with Martin Ditkof (In author's possession, October 23, 2021).

[34] Roger D. Launius, "Toward an Understanding of the Space Shuttle: A Historiographical Essay," *Air Power History* (Winter 1992), 6. See also, Dennis R. Jenkins, *Space Shuttle: Developing and Icon – 1972 – 2013*, (Volumes I, II, and III), (Forest Lake, MN: Specialty Press, 2016), Volume I, page 271 ("Almost all of the original space shuttle studies had a mandate to lower the cost of access to space.").

[35] Howard E. McCurdy, *Inside NASA: High Technology and Organizational Change in the U.S. Space Program (*Baltimore: The Johns Hopkins University Press, 1994), 177.

[36] Brian Russell, Oral Interview with Martin Ditkof (In author's possession, October 23, 2021) and Jerry Burn, Oral Interview with Martin Ditkof (In author's possession, October 23, 2021).

[37] Bryan O'Connor Interview by Matthew Kohut, *Ask Magazine*, Insight. (Unknown date, Accessed October 24, 2021), 20, 23. https://www.nasa.gov/pdf/616735main_45i_interview.pdf.

[38] Thiokol, "Study of Solid Rocket Motor for Space Shuttle Booster, Volume II Technical Book 2 of 5," *TWR-5672* (In author's possession, March 15, 1972), cover page.

[39] Ibid., 5-25.

[40] Dennis R. Jenkins, *Space Shuttle: Developing and Icon – 1972 – 2013*, Volume II, 264.

[41] T.A. Heppenheimer, *Development of the Space Shuttle, 1972-1981* Volume II (Washington D.C.: Smithsonian Books, 2002), 70-71.

[42] Ibid.

[43] Ibid., 72-73.

[44] Ibid., 73-74.

[45] Ibid., 76-78.

[46] Dennis R. Jenkins, *Space Shuttle: Developing an Icon 1972 – 2013*, Volume II, 264-265.

[47] Ibid., Volume II, 251-257.

[48] J. S. Butz, Jr., "Solid Boosters," *Air Force Magazine*, (October 1961), 33-36.

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[49] Ibid., 36.

[50] NASA, “Help from the Department of Defense,” *Chariots for Apollo*, ch 2-7. Accessed July 15, 2021. https://www.hq.nasa.gov/office/pao/History/SP-4205/ch2-7.html.

[51] Butz, “Solid Boosters,” 36.

[52] J.S. Butz, Jr., “Dyna-Soar plus Titan III,” *Air Force Magazine* (February 1962), 33-37, 34.

[53] Ibid., 34.

[54] Hoyler, “A Collection of Data and Thoughts,” “Goal.”

[55] Presidential Commission, Volume IV, page 251.

[56] Malcolm Ross, “Did risk reduction backfire in space?” *The Washington Times,* January 28, 1999, Page B3.

[57] Thiokol, “Study of Solid Rocket Motor for Space Shuttle Booster, Volume II Technical Book 2 of 5,” *TWR-5672* (In author’s possession, March 15, 1972), page 5-25.

[58] Presidential Commission, Volume IV page 264. Richard S. Lewis, *Challenger: The Final Voyage*. (New York: Columbia University Press, 1988), 63.

[59] Presidential Commission Volume IV, 267-268.

[60] Ibid., 268.

[61] Ibid., 287. Jerry Burn, comments from the first draft (In author’s possession).

[62] Jerry Burn, email to Martin Ditkof (In author’s possession, November 19, 2021).

[63] Presidential Commission, Volume IV, 287.

[64] Ibid., 287 and Jerry Burn, comments to first draft (in possession of author).

[65] Presidential Commission, Volume IV, 283.

[66] Claus Jensen, *No Downlink: A Dramatic Narrative About the Challenger Accident and our Time,* Translated from Danish by Barbara Haveland (New York: Farrar Straus Giroux, 1996), 269-273.

[67] NASA, “Propulsion,” Memo (September 3, 1980), as contained in the Presidential Commission, Volume V, 1653.

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[68] Howard McIntosh, “Retention Rationale, SRM Simplex Seal,” *Thiokol TWR-13520 Rev A* (December 1, 1982), as contained in the Presidential Commission, Volume V, 1672.

[69] Thiokol, “Summary of Vacuum Putty History and Experience,” *TWR-13891* (In author’s possession, date is July 1, 1983 per Brian Russell), 2.

[70] Jerry Burn, “Gas Path Assessment related to the change from Fuller O’Brien Putty to Randolph Putty,” Memo (In author’s possession, November 15, 2021-Rev A), 1 (“The mating processes were very well controlled but not controlled enough with putty … to preclude gas paths.”).

[71] Furgeson, “SRM Field Joint,” 21, (TWA-1130) (In author’s possession).

[72] Richard A. Merrill, “CPSC Regulation of Cancer Risks in Consumer Products: 1972-1981,” *Virginia Law Review*, Volume 67, No 7 (October 1981), 1332.

[73] Ibid., 1335.

[74] The rule was issued under the Consumer Product Safety Act on December 15, 1977 in order to avoid rule making procedures under the FHSA and because of the commissions ability to evoke civil penalties for enforcement. 42 FR 63354 (December 15, 1977).

[75] Richard A. Merrill, “CPSC Regulation,” 1339.

[76] Michael J. Bennett, *The Asbestos Racket: An Environmental Parable* (Bellevue, WA: Free Enterprise Press, 1991) 77-80.

[77] Ibid., 78.

[78] Ibid., quoted on page 78 by Michael J. Bennett.

[79] Thiokol, *TWR-13891*, 2.

[80] Ibid.

[81] Ibid.

[82] Ibid., 9 and Brian Russell, Oral Interview with Martin Ditkof, (In author’s possession, May 6, 2021).

[83] S. B. Pendleton of Thiokol, “Recommended Disposition for DR 97783 Vacuum Seal Putty STW4-2847,” *TWR-13719,* (In the author’s possession, March 18, 1983), 2 and (no page). These eleven putties were (1) H. B. Fuller 95A non-asbestos, (2) Schnee Morehead 5120-C non-asbestos, (3) Schnee 5126-I non-asbestos, (4) Ram Chemical 49-02 non asbestos, (5) Airtech

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International 6S213 non-asbestos, (6) Inmont 590.5 asbestos, (7) Inmont 579.6 asbestos, (8) Inmont 582.1 asbestos, (9) Inmont 579.6 non-asbestos, (10) Randolph Products 801 asbestos, and (11) Aerospace 37 non-asbestos).

[84] Ibid.

[85] Malcolm Ross, "Letter to the Editor," 5 ("…the hasty substitution of the Randolph putty – can actually increase risk, even create risk.").

[86] P.R. McFall, "Use of Zinc Chromate Putty in Huntsville Division Motors," to Brian Russell (In the author's possession, date unreadable), produced by NASA in FOIA Response on page 412 of 918.

[87] Diane Vaughan, *The Challenger Launch Decision: Risky Technology, Culture, and Deviance at NASA.*, (Chicago: University of Chicago Press, 1996), 121 ("This putty, which after the disaster appeared to some to be a Band-Aid, on-the-cheap correction…"). Asbestos containing putties have been used in joints since the 1800s. See for example "Bell's Asbestos," *The Shipping World – Advertisements,* June, 1883, viii.

[88] S. B. Pendleton of Thiokol, "Recommended Disposition."

[89] Ibid., 2.

[90] F. E. Bares, "Evaluation of Test Methods for Zinc Chromate Putty," *TRW-13705*, March 4, 1983, 8. The difference in length and diameter is often significant in the performance of chrysotile asbestos. This can be critical in terms of tensile strength and brittleness of the fibers. See Ralph E. Oesper, translation to English from German of Hans Berger, *Asbestos Fundamentals: Origin, Properties, Mining, Processing, Utilization*, (New York: Chemical Publishing Company, 1963), 48, 65-95. As stated by the National Research Council (US) Committee on Nonoccupational Health Risk of Asbestiform Fibers (1984) at https://www.ncbi.nlm.nih.gov/books/NBK216753/, "One of the properties shared by high quality fibers of asbestos, whiskers, and glass is their diameter-dependent strength. That is, the strength of the fibers per unit of cross-section area increase as the diameter decreases." (Accessed January 20, 2022). As such, the increased diameter asbestos fibers in the Randolph putty may well have provided less strength than the much thinner diameter fibers in the Fuller-O'Brien putty, thereby allowing additional and more extensive gas paths. With this in mind, an argument exists that, for the lack of skinnier asbestos fibers in the joint putty, in combination with other material property changes, the Challenger was lost. However, although the argument is worth consideration, insufficient information and too many variables exist to analyze the accuracy or inaccuracy of such a claim. Even the temperature thermal stress variations among the asbestos fibers can vary depending on their use; as an example, chrysotile fibers in plastic laminate will last seconds in a dry heat over 1500 degrees centigrade (2732 degrees Fahrenheit). Oesper at 93. All that said, the change in the asbestos fibers is one of several candidates for further investigation and consideration as the initial failure mode for the field joint.

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[91] S. B. Pendleton of Thiokol, “Recommended Disposition”, 2-3.

[92] Ibid., 5.

[93] Ibid.

[94] Ibid., 14, 16, 18-19, and 21-22. See the discussion in Note 9 as to the myths found on the internet which provide inaccurate information to the public, such as claiming that the Randolph replacement putty was asbestos-free or that the O-ring at one time contained asbestos.

[95] Thiokol Corporation, “Specification Putty, Vacuum Seal, STW4-2847B,” *FSCM 07703* (In author’s possession, July 28 1983), 1.

[96] Ibid., 21.

[97] Furgeson, “SRM Field Joint,” 1.

[98] Ibid., 1.

[99] Ibid., 1 and 7.

[100] Ibid., Appendix A, page A-3

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[101] Ibid., 3 and 5.

[102] Thiokol, “SRM Clevis Joint O-ring Seal Behavior/Capability Summary,” *TWR-13486* (In author’s possession, August 6, 1982). The author notes that Jerry Burn disagrees with this analysis. He believes that the secondary O-ring had the same opportunity to fail as did the primary if the primary failed. Jerry Burn, comments to first draft. Brian Russell believes, that in hindsight, Jerry Burn is correct. Brian Russell in “Comments on Marty’s Thesis draft, dated 11(20) 2021,” (In author’s possession, undated).

[103] Brian Russell, email to Martin Ditkof (In author’s possession, October 29, 2021). Jerry Burn believes that this justification was to move the shuttle on the next launch. Looking back, he believes that this was the beginning of the allowing for deviant behavior in the joint as this was not the design expected and the cause of damage was not understood. Jerry Burn, comments to the first draft. Jerry Burn, Root Cause, 1. Brian Russell believes, that in hindsight, Jerry Burn is correct. Brian Russell in “Comments on Marty’s Thesis draft, dated 11(20) 2021,” (In author’s possession, undated).

[104] Benjamin Franklin, (Richard Saunders, philomath), *Poor Richard’s Almanack. Selections from the prefaces, apothegms, and rimes, with a facsimile in reduction of the almanack for 1733. Ed. By Benjamin E. Smith.* (New York: The Century Co., 1898), 50. The Butterfly Effect which is reflected in this saying is based on small actions building together to have very large effect. The Butterfly Effect has been applied to the Space Shuttle Challenger

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disaster. See Richard Elfers, " 'Butterfly effect' brings change, good or bad, in all our lives," *The Courier-Herald*, (September 20, 2019), Accessed on December 5, 2021. https://www.courierherald.com/opinion/butterfly-effect-brings-change-good-or-bad-in-all-our-lives/. This analysis would also apply to the decision process beginning with the CPSC banning asbestos-containing putty in the consumer market leading to the Space Shuttle Challenger explosion and the resulting damages to the space program, the deaths of the astronauts, and the moral injuries as discussed in this essay. Further, the Law of Untended Consequences applies to the Challenger disaster, but that discussion is outside the scope of this essay.

[105] Jerry Burn, "Gas Path Assessment related to the change from Fuller-O'Brien Putty to Randolph Putty," Rev A (In author's possession, November 15, 2021).

[106] Ibid.

[107] Ibid.

[108] Ibid.

[109] Jerry Burn, Comments to untitled document, emailed to Eric Knops (In author's possession, October 30, 2021).

[110] Thiokol Corporation, "Specification Putty, Vacuum Seal, STW4-2847B," *FSCM 07703* (In author's possession, July 28 1983). See also L. M. Thompson, "SRM/SRB Putty Evaluation," (In author's possession, July 1985). See also, S. B. Pendleton of Thiokol, "Recommended Disposition."

[111] Brian Russell, "Putty and Leak test Joint History Spreadsheet, Rev A" (In author's possession, November 16, 2021).

[112] Thiokol, *TWR-13891*, 25-28.

[113] Ibid., 28.

[114] Thiokol, "O-Ring Erosion History," *TWR-15481A* (In author's possession, undated but per telephone discussion with Brian Russell on October 29, 2021 it was drafted likely in February 1986 and certainly after the Challenger accident).

[115] Thiokol, "SRM Joint History: April 1984—January 1986," *TWR-15501* (In author's possession, February 1986).

[116] Thiokol, "Vacuum Putty/O-Ring Erosion Study and Program Plan," *TWR-14653* (October 16, 1984). Jerry Burn, "Root Cause."

[117] Boisjoly, "Challenger Book Material," at 75, 86 ("All any manager had to do was read the memos and the pleas for help that were constantly being circulated internally."), 155, 508, 549-551.

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[118] L. M. Thompson, "SRM/SRB Putty Evaluation," (In author's possession, July 1985) produced by NASA in response to FOIA, page 497 of 918.

[119] Lessons Learned from Challenger," *Headquarters, National Aeronautics and Space Administration, Safety Division, Office of Safety, Reliability, Maintainability and Quality Assurance,* Washington D.C. (February 1988), pages 12, 48, and 51. This report identified inadequate putty specifications, the lack of adequate controls on the putty quality, consistency, and manufacturing processes, and unknown putty behavior. The Randolph putty "characteristics … changed substantially as a function of humidity. It was difficult to apply in both the dry climate of Utah and dampness of Florida." Page 51 (24.2.1.A.).

[120] Thiokol, *TWR-15481A*.

[121] Allan J. McDonald, and James R. Hansen, *Truth, Lies, and O-rings: Inside the Space Shuttle Challenger Disaster.* (Gainesville, FL: University Press of Florida, 2009) (Apple Version), 297, 306-307.

[122] Jerry Burn agrees with the discussion by sociologist Diane Vaughn in her book that deviant behavior became ingrained in a way that would have made it difficult to prevent the decision making process which led to the explosion.

[123] Warren J. North, "Shuttle Contingency Abort and Crew Escape," *Memorandum to Deputy Manager, National STS Program* (May 4, 1984). (Emphasis Added).

[124] Presidential Commission, Volume I, Page 180.

[125] Presidential Commission, Appendix D from Volume 1, SRB Criticality Report, 229.

[126] Presidential Commission, Appendix D from Volume 1, 241-244.

[127] Dennis R. Jenkins, *Space Shuttle*, Volume II, page 263.

[128] Warren J. North, "Shuttle Contingency Abort and Crew Escape," *Memorandum to Deputy Manager, National STS Program* (May 4, 1984, Page 3, paragraph 12.

[129] Ibid., 1.

[130] After the Challenger accident, NASA developed a crew escape device first used in 1988. See Mark Betancourt, "They Said it Wasn't Possible to Escape the Space Shuttle. These Guys Showed it Was. But the circumstances had to be just right," *Air & Space Magazine*, (September 2020) https://www.airspacemag.com/airspacemag/escape-speeding-shuttle-180975606/ (Accessed November 2, 2021). See Also, NASA, "Crew Escape Systems 21002," *United Space Alliance* (January 17, 2005). Accessed November 2, 2021. https://www.nasa.gov/centers/johnson/pdf/383443main_crew_escape_workbook.pdf.

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[131] L. M. Thompson, "SRM/SRB Putty Evaluation," (July 1985) produced by NASA in response to FOIA, page 497 of 918. See also another document from Mr. Thompson with the same title and date discussing the putty material and O-ring erosion in which he states "Secondarily, but just as important is elimination of all materials containing asbestos before we are forced in this direction." Brian Russell disagrees that the effort was diluted by searching for a non-asbestos substitute as they looked at all putties for a better one. Brian Russell in "Comments on Marty's Thesis draft, dated 11(20) 2021," (In author's possession, undated).

[132] Boisjoly, "Challenger Book Material," at 15 ("However, due to the crush of work and limited manpower and resources this problem continued to manifest itself …"), 24, 67, 69 ("This is pointed out not to criticize anyone in another department outside engineering but to rather illustrate that the problem of scarce manpower and lack of necessary resources was felt by all departments on the SRM program at Thiokol."). McDonald, *Truth*, 101-103.

[133] Roger Boisjoly July 31, 1985 Memo to R. K. Lund as reproduced in the Presidential Commission, Volume IV, 249.

[134] Ibid., 542 ("Our engineers could not prove that it was unsafe to fly at less than 53 degrees F.") and McDonald, *Truth*, 554-5.

[135] McDonald, *Truth*, 135 and 144. ("Nonetheless, the point was made: cold temperatures can dramatically reduce the ability of O-rings to seal on surfaces that were moving away from each other, as in our field-joint.") and ("NASA should consider delaying the launch until late afternoon," I told them, when temperatures are expected to reach 48 to 50 degrees."), 240 (In regard to McDonald refusing to sign the go-ahead for launch recommendation on January 27, 1986, "It could be the smartest thing I've ever done in my life.") 242 and 670 (The accident was "preventable and caused by well-known problems that were never fixed.").

[136] McDonald, *Truth*, 138 and 270. NASA testified before the Presidential Commission that the actual ambient temperature at launch was 38 degrees and the O-ring temperature is approximately the same temperature with a short lag time given that there is no insulation between the O-rings and the outside. Presidential Report, Volume IV, 405. Allan McDonald disagreed with this estimate and felt that the temperature at launch time was probably closer to 14 degrees to 16 degrees. McDonald, *Truth*, 338. However, the temperature at the field joint that failed on January 28, 1986 was potentially as low as 10 degrees Fahrenheit. Presidential Commission, Volume IV, 426. The belief is that this exceptionally low temperature at that specific location arose from cryogenic venting and vapors, and it is certainly possible that the field joint failure was caused or contributed to because of that venting. McDonald, *Truth*, 338. NASA did not believe that this temperature was a problem as, testified to by Arnie Aldrich, he did not know that the temperature was "a constraint on the performance of the solid rocket booster as a system or any of its elements." Presidential Commission, Volume IV, 427.

[137] Brian Russell, email to Eric Knop (In author's possession, November 9, 2021), stating: "The lower the temperature, however, the greater was the risk that the timing function

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that Roger mentioned could be altered sufficiently by the slower reacting o-rings to put the flight in danger. That was my fear that night. As I have stated before, I still feel our charts were sufficient to express that risk and to justify the 53 degree temperature limit."

[138] Brian Russell, untitled note to Eric & Co (In author's possession, November 2, 2021).

[139] Boisjoly at 15, 24, 67, 69, 126, 157, and 611 (post-Challenger tragedy). See also the discussion in McDonald, *Truth*, 102, discussing a memo by Scott Stein and a report written by Bob Ebeling, each on October 1, 1985, complaining about the lack of support and Ebeling pleading for "HELP!" from top management in order for the O-ring task force to be successful.

[140] Ibid., 772 and 775. McDonald, *Truth,* 39, 101 ("NASA instructed us to submit our engineering change proposal (ECP) with a cost-benefit analysis.").

[141] The author is very experienced in hazard analysis existing during the mid-1980s for heavy complex machinery and systems. This includes analyzing frequency, vulnerability, and potential harm (bodily injury and property damages) resulting from the potential failure.

[142] Stenning Schueppert, "Safety is not optional as global compliance requirements evolve," *Total Safety* (March 30, 2012), Accessed October 31, 2021, https://www.totalsafety.com/safety-is-not-optional-as-global-compliance-requirements-evolve/.

[143] Presidential Commission, Volume IV page 58.

[144] Presidential Commission, Volume IV page 237 and Volume V page 1012-1014.

[145] Presidential Commission, Volume V page 988.

[146] Presidential Commission, Volume IV page 238.

[147] Presidential Commission, Volume V page 1013.

[148] Presidential Commission, Volume V page 1014.

[149] Presidential Commission, Volume V page 1033.

[150] Presidential Commission, Volume V, page 1062, summary by Chairman Rogers. Also, on page 1014 in response to Chairman Rogers question: "Mr. Glaysher, did you make clear that you felt there was a safety aspect and that you were not approving the launch?" to which Mr. Glaysher responded "Yes, we actually discussed our position and I stated more than once during the meeting Rockwell's position that we could not assure that it was safe to fly."

[151] Jerry Burn, "Gas Path." Jerry Burn, "Root Cause." See also Dennis R. Jenkins, *The History of the American Space Shuttle*. Atglen, PA: Schiffer Publishing, 2019, 99 ("Contrary to popular perception, it was not cold weather or the O-rings that were at fault; it was a bad joint

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design. Cold weather, and its effects on the O-rings, did not help, but they were not the root cause.").

[152] Jerry Burn, "Comments to untitled document, emailed to Eric Knops" (In author's possession, October 30, 2021).

[153] Thiokol, "Case and Nozzle Joint Configuration Review," *TWR-15084* (July 2, 1985), 6, in which Thiokol felt that the gas paths may be created during assembly, leak checks, or ignition. Post-Challenger re-design proved that to be inaccurate as the gas paths could only be created during the assembly in the VAB, and not either during a leak test or during launch. Jerry Burn, "Cause of Gas Paths in Field and Nozzle to Case Joints," Memo (November 15, 2021 Rev A. Brian Russell (not impossible at ignition, but unlikely) and Kyle Spies basically agree with Jerry Burn in this regard. Jerry Burn, "RE: Field & Nozzle to Case Joint Gas Path Generation Analysis by Jerry Burn," email to Brian Russell (October 16, 2021) and Brian Russell, "Blowhole formation," memo (November 16, 2021). Kyle Speas, "RE: Field & Nozzle to Case Joint Gas Path Generation Analysis by Jerry Burn," email to Martin Ditkof (In author's possession, November 15, 2021), and Jerry Burn, "Root Cause."

[154] Furgeson, "SRM Field Joint." Jerry Burn, "O-ring erosion Questions, Comments in red by Jerry Burn" (In author's possession, December 7, 2021), 1 ("NO the risk was not manageable. I sincerely do not believe it was manageable with the join design we had."). Brian Russell, "To Sum up: erosion was no a significant threat?, Comments by Brian Russell" (In author's possession, December 7, 2021), 1 ("But as good as we were, we were not capable of understanding and analyzing all the variables in the joint operation.").

[155] Jerry Burn, "Gas Paths."

[156] Brian Russell, "Re: [EXTERNAL] Re: My Thesis, Complete First Draft," email to Eric Knops (In author's possession, November 9, 2021).

[157] John Q. Miller, "Burned O-Rings on STS-11," Routing Slip to Mr. Hardy (In author's possession, February 28, 1984). This document was copied to many people, including Larry Mulloy.

[158] Jerry Burn, "Gas Paths."

[159] Jerry Burn, "Gas paths in Field and Nozzle to Case Joints," Memo (In author's possession, November 12, 2021).

[160] Brian Russell email to Martin Ditkof (In author's possession, October 25, 2021, 7:49 p.m.).

[161] Brian Russell, Oral Interview with Martin Ditkof (In author's possession, September 30, 2021).

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[162] Roger M. Boisjoly, "Challenger Book Material" (unpublished 821 page manuscript possessed by Chapman University Library) (1998-1999), 205. This language within the manuscript was first identified by Eric Knops who is a Marshall Space Flight Center Contract Engineer. The author gives full credit to Mr. Knops for discovering this language and applauds his diligence in identifying its potential significance.

[163] Mr. Boisjoly throughout the Challenger situation gave up his career to speak the truth, and all involved including his former co-workers Brian Russell, Kyle Spies, and Jerry Burn believe that he would only make such a statement if he believed it to be true. Per Jerry Burn, "… Boisjoly was the most credible person I know. If he said he said something I believe he did." Jerry Burn, Response to "Questions for Jerry Burn," (In author's possession, December 4, 2021). How Boisjoly's statement is analyzed in comparison to his, McDonald's, and Malloy's other statements is an open issue.

[164] Sarah Kaplan, "Finally Free from Guilt over Challenger Disaster, an engineer dies in peace," *The Washington Post,* March 22, 2016, Accessed November 21, 2021. https://www.washingtonpost.com/news/morning-mix/wp/2016/03/22/finally-free-from-guilt-over-challenger-disaster-an-engineer-dies-in-peace/.

[165] Duane M. Cox, *When the Spirit Whispers: Experiences with the Holy Ghost & The Untold Story of the Challenger Accident* (Logan, Utah: Watkins Printing, 2017) 96.

[166] Howard Berkes, "Challenger Engineer who Warned of Shuttle Disaster Dies," *NPR,* March 21, 2016, Accessed September 24, 2021. https://www.npr.org/sections/thetwo-way/2016/03/21/470870426/challenger-engineer-who-warned-of-shuttle-disaster-dies.

[167] Find A Grave, "Robert Vernon 'Bob' Ebeling," Accessed November 17, 2021. https://www.findagrave.com/memorial/160000593/robert-vernon-ebeling.

[168] Sarah Kaplan, "Finally free from guilt over Challenger disaster, and engineer dies in peace," *The Washington Post,* March 22, 2016, Accessed November 21, 2021. https://www.washingtonpost.com/news/morning-mix/wp/2016/03/22/finally-free-from-guilt-over-challenger-disaster-an-engineer-dies-in-peace/.

[169] Boisjoly, Challenger Book Material, 7 and 741.

[170] Diane Vaughan, *The Challenger Launch Decision: Risky Technology, Culture, and Deviance at NASA.* (Chicago: University of Chicago Press, 1996), 381.

[171] Boisjoly, Challenger Book Material, 749 and McDonald, *Truth*, 662.

[172] Boisjoly, Challenger Book Material, 458.

[173] Ibid.

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[174] Ibid., 459. Jerry Burn acknowledges that there were some co-workers with negative feelings toward Boisjoly, but that his colleagues at Thiokol (including Jerry) continued to respect him and believes that had Boisjoly stayed with the company and worked on the re-design, that he might have felt differently. Burn considered Boisjoly a mentor. Jerry Burn, Oral Interview with Martin Ditkof, (In author's possession, November 23, 2021).

[175] McDonald, *Truth*, 241.

[176] McDonald, *Truth*, 273-4.

[177] McDonald, *Truth*, 665.

[178] Brian Russell, Oral Interview with Martin Ditkof (In author's possession, September 30, 2021).

[179] Brian Russell, Comment to draft thesis (In author's possession, November 3, 2021), 45.