The Space Shuttle Challenger: A Case Study in Engineering Ethics

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A Little About This Project

- **Design Modules Based on Appropriate Engineering Case Studies**
  - Space Shuttle Challenger (Risk assessment, dissent, whistleblowing)
  - Chernobyl Power Plant (Professional responsibility, liability)
  - Exxon Valdez Oil Spill (Environmental issues, safety, public service)
  - Tacoma Bridge (Safety, accidents, acknowledging mistakes, ethical problem solving)
  - Hotel Walkway Collapse (Risk assessment, safety, ethical problem solving)
- **Do all case studies have to be disasters? No, I'm working on that.**
- **Provide technical connection to course learning objectives and outcomes**
- **Roll-out to relevant MAE courses and Honors Seminar**
- **Accreditation requirement for engineering ethics**
- **Ethics throughout the curriculum**
  - MAE 1502, 2200, 2301, 3130, 3201, 3501, 4316, 4510

A Personal Story

- **I have been aware of the use of the Challenger Disaster in engineering ethics curriculum for some time…**
- **I had no idea the extent of the literature and where this exploration would take me, as a real rocket scientist…**
- **The Challenger disaster has had a profound effect on a wide range of disciplines…**
- **It has had a profound effect on me personally…**
- **It is the reason that I am here.**

A Brief Note

- **Much of what was written close to the date of the disaster is no longer considered "correct"**
  - In a high profile case, such as this, there are rushes to judgment
  - Processes were to blame, individuals were to blame, corporate culture was to blame – there really is no ONE thing
- **You have to consider the source of the written work very carefully**
  - Much of the ethics debate is formulated by Engineering Professors as part of an engineering ethics curriculum
  - Engineering Professors tend to blame management in a black and white sense
  - There is a new trend in "blaming" corporate culture that tends to make sense
- **This is a complex issue about the most complex system ever built**
- **Engineers have a lot to learn from this disaster well beyond ethical dilemmas**

The Space Shuttle Challenger

- **Tomorrow marks the 28th Anniversary of the Space Shuttle Challenger Disaster**
  - Disaster
  - Accident
  - Incident
  - Explosion
- **Even the wording becomes part of the ethical web we weave**

Francis R. (Dick) Scobee, Michael J. Smith, Ellison S. Onizuka, Judith A. Resnik, Ronald E. McNair, S. Christa McAuliffe, Gregory B. Jarvis

Let's Take a Journey

- **The Timeline**
- **The Technology**
- **The Engineers**
- **The Managers**
- **The Telecon**
- **The Decision**
- **The Launch**
- **The Aftermath**
- **The Ethics**

The Timeline

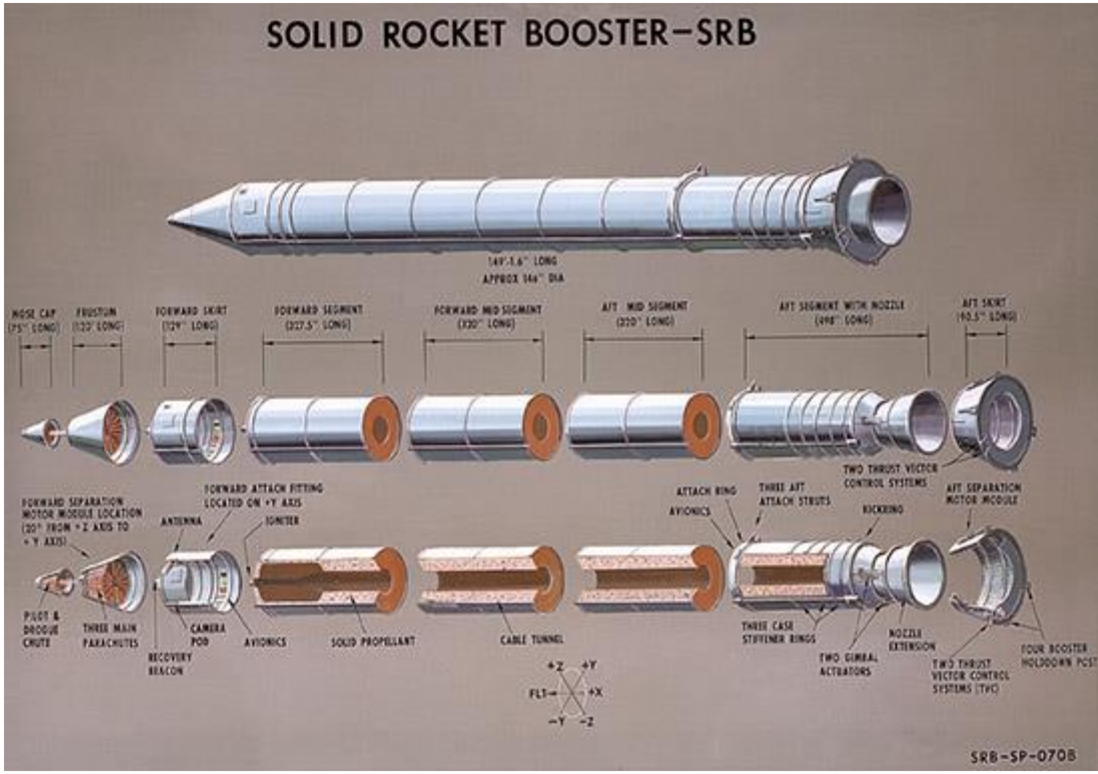
- **1974 – Morton-Thiokol awarded contract to build solid rocket boosters**
- **1976 – NASA accepts Thiokol's design**
- **1977 – Thiokol discovers joint rotation problem**
- **1981 – O-Ring erosion found after STS 2**
- **Jan. 24, 1985 – O-Ring blow-by discovered after flight 51-C**
- **Aug. 19, 1985 – NASA management briefed on o-ring issues**
- **By the end of 1985, there have been 24 successful Shuttle flights**
- **Jan. 27, 1986 – Telecon for Challenger flight go/no-go**
- **Jan. 28, 1986 – Challenger disaster kills 7 astronauts**

The Timeline (2)

- **Four proposals were submitted to NASA for the SRB design**
  - Thiokol, Lockheed, Aerojet, United Technologies
  - Aerojet's proposal was the only one that included the design as a one-piece case
    - ***Superior reliability and safety***
    - ***Only advantage of a segmented booster is in transportation***
  - The NASA review board ranked Thiokol last for its motor design, development and verification
  - Thiokol's bid was $100M lower than its competitors

The Technology

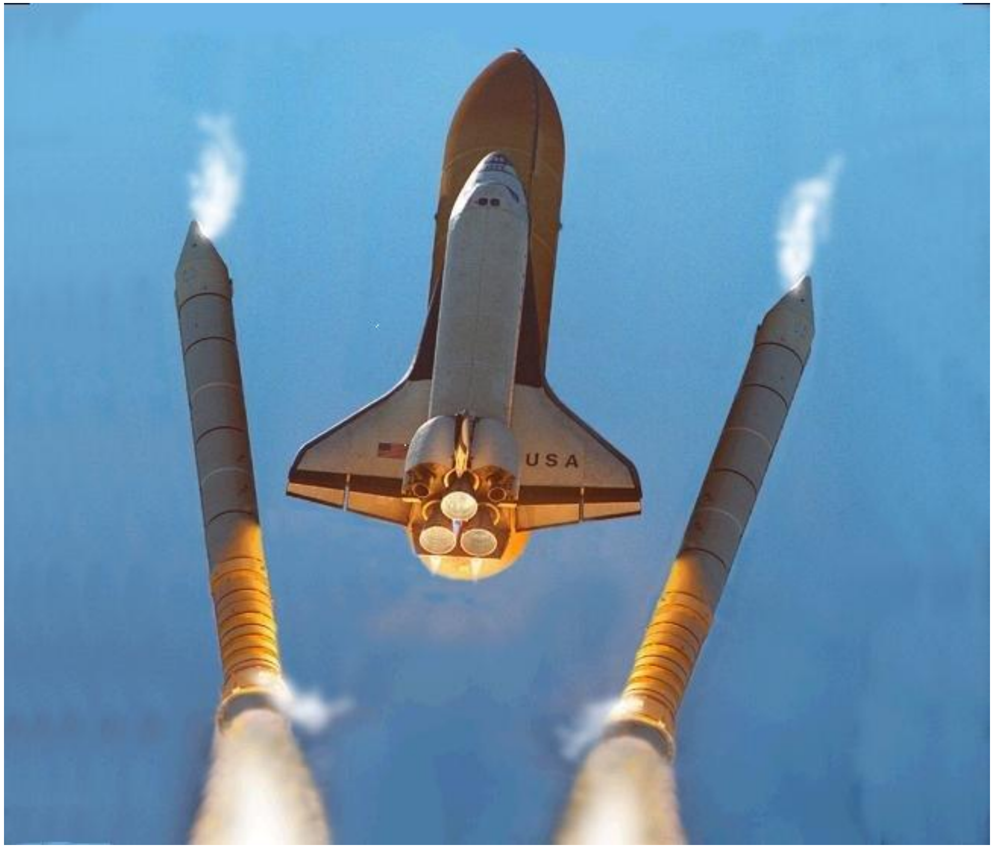
- **Let’s Geek Out a Little**

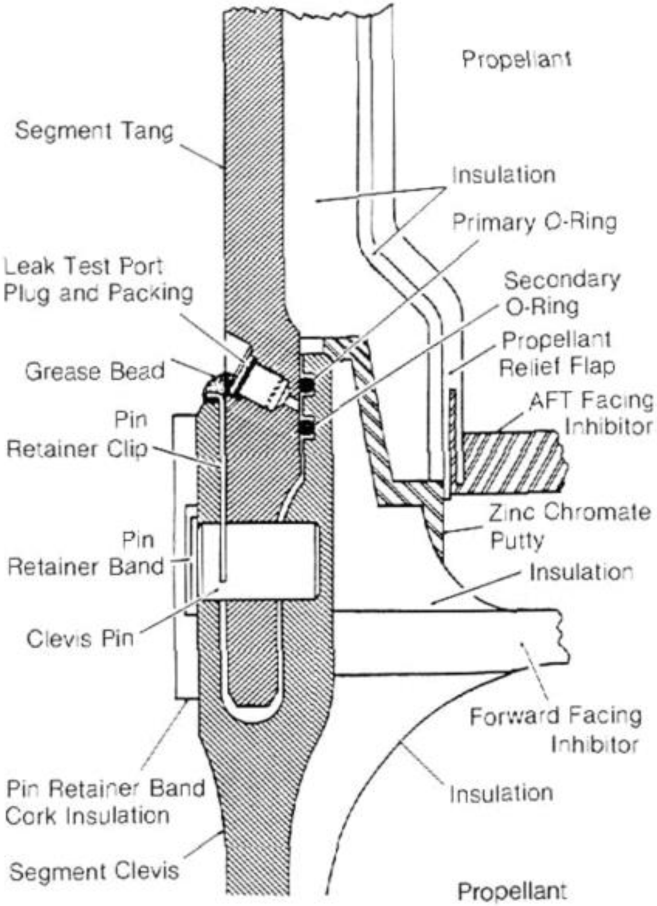


The Technology (2)

- **O-Ring**
  - Purpose is to prevent hot combustion gases and particles (Aluminum Oxide) from escaping the inside of the booster
  - Two o-rings used for redundancy since humans on-board
  - Heat resistive putty is applied to the inner section of the joint to isolate the o-rings from the hot gases
  - Must be compressed to minimize gap between the tang and clevis
  - Material: Viton (synthetic rubber)

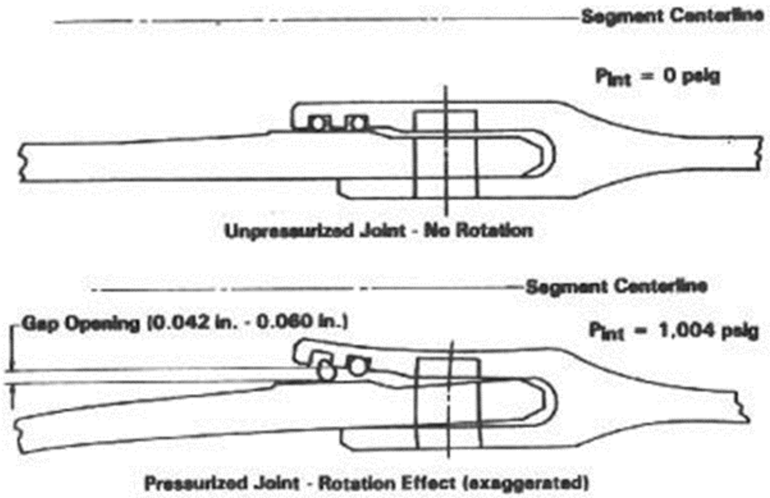
The Technology (3)

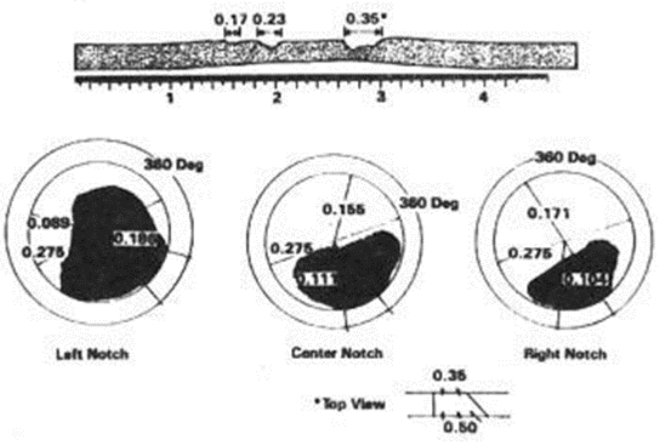




The Technology (4)

- **Joint Rotation**
  - Booster ignition causes the heat resistive putty to displace and increase the air pressure between the putty and the o-ring joint
  - The o-ring is forced into the gap between the tang and clevis causing the gap between the two to open (acting against the compression forces)
- **Erosion**
  - O-Ring material exposed to hot combustion gases char and material is removed
- **Blow-By**
  - First seen on Shuttle Flight 51-C (Jan. 24, 1985) launched in some of the coldest weather in FL history
  - Blow-by was noticed (black soot and grease outside the booster casing) indicating hot gases had penetrated the o-ring seals completely





Questions?

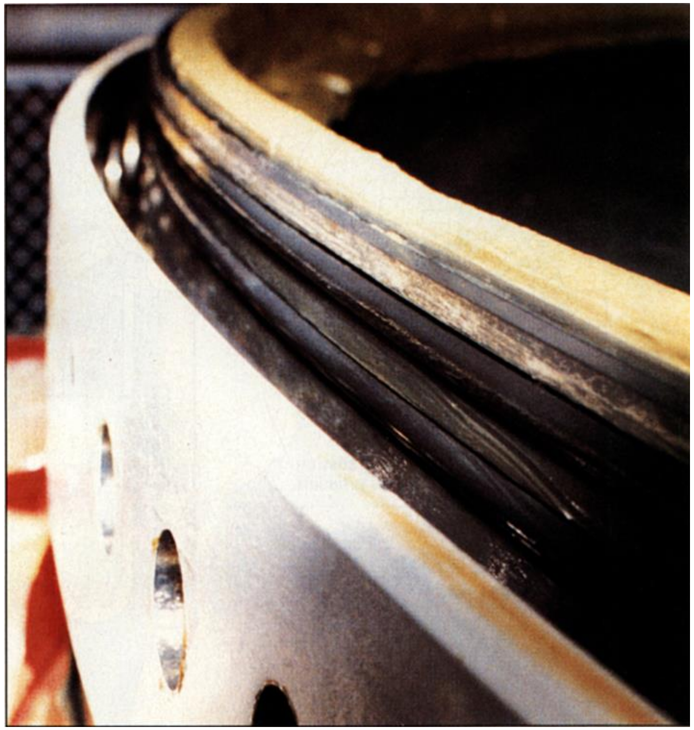
- **As a non-technical manager of a very technical project, what is your role in understanding the smallest details of a technological application?**
- **As an engineer, what is your role in explaining technical details to your superiors?**

The Engineers

- **Roger Boisjoly – Morton-Thiokol, Inc (MTI) leading o-ring specialist**
- **Arnold Thompson – MTI engineer**
- **Allen McDonald – Project Supervisor of solid fuel rocket unit at MTI**
- **Robert Lund – VP Engineering at MTI**

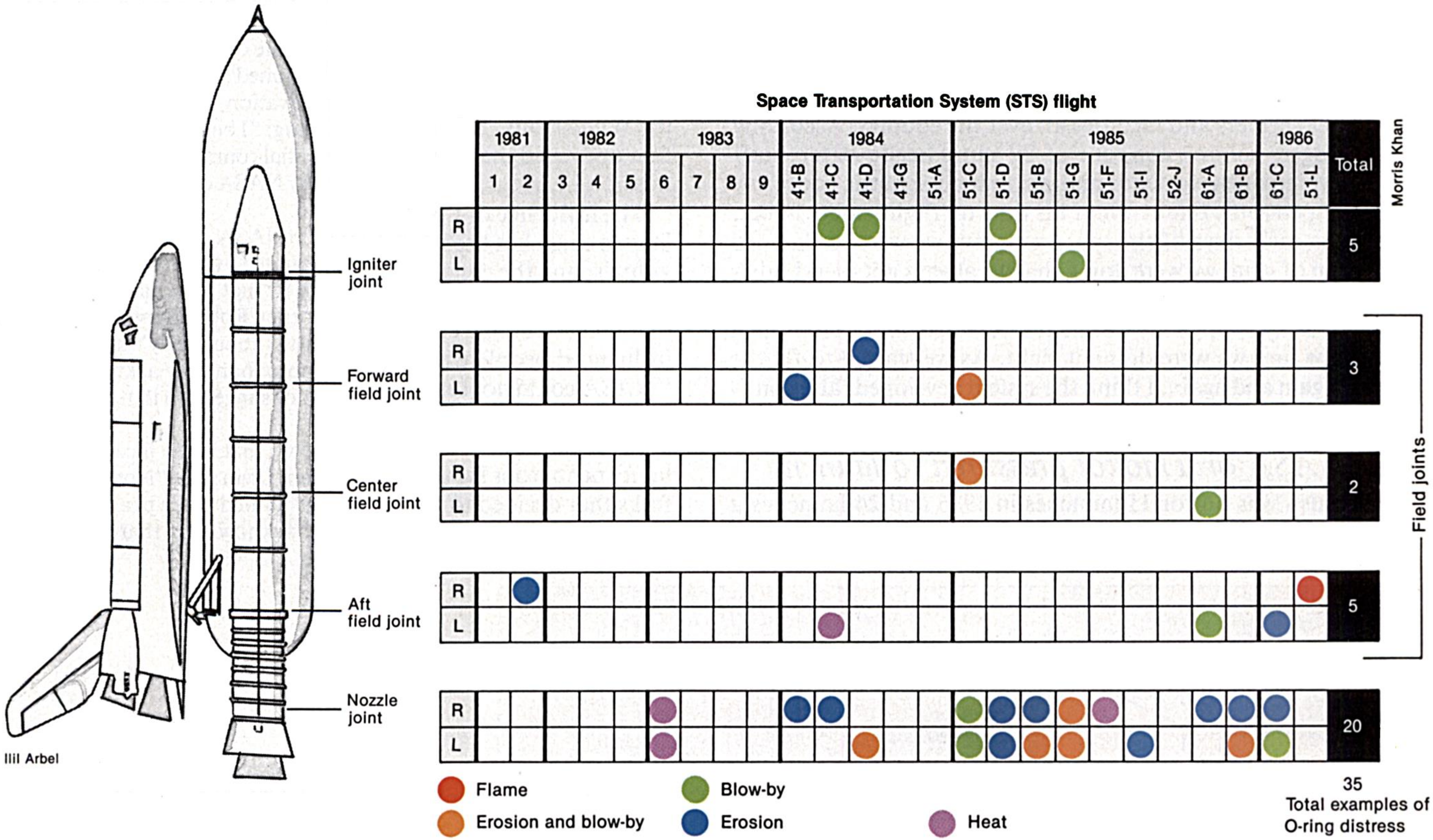
The Engineers (2)

- **The first issue showed up on the second Shuttle flight in 1981**
- **January 1985 flight of Discovery (100th human spaceflight to achieve orbit)**
  - Primary erosion on two field joints
  - Heat affect seen on secondary o-ring for first time (i.e. hot gases got to the secondary o-ring although no erosion was observed).
  - Experienced lowest ambient temperature at launch
  - Blow-by MAY have been enhanced by low temperature
- **March 1985 test on o-ring resiliency showed an issue below 50^{o}F**
- **July 31, 1985 Memo from R. Boisjoly to R. Lund**
  - **Outlines the issue**
  - **"Very real fear" of losing a flight if no action taken immediately**



IEEE Spectrum, Vol. 24, No. 2, pp. 45.

The Engineers (3)



IEEE Spectrum, Vol. 24, No. 2, pp. 47.

Questions?

- **What should be the role of the engineer in this situation?**
- **How much professional, personal responsibility does an engineer have in this situation?**
- **After reading the Feynman article, are you surprised by the actions of the engineers in relaying their message?**
- **What types of retaliation are engineers exposed to when they go against their manager's opinion?**
- **Does an engineer also have a right to protect his/her own job?**

The Managers

- **Larry Mulloy – Manager of solid rocket booster at NASA MSFC**
- **Jerry Mason – Senior VP and General Manager at MTI (Lund's boss)**
- **Joe Kilminster – VP of Space Booster Program at MTI**
- **Robert Lund – VP of Engineering at MTI**
- **George Hardy – NASA Deputy Director of S&E at MSFC**

The Managers (2)

- **L. Mulloy at NASA MSFC is a Level III manager**
  - He reports to a Level II and a Level I position
  - There are other managers at JSF and KSC involved in SRB decisions to fly or not
- **Several meetings took place to inform managers of the low temperature problem with the field joints**
- **Engineers feel that their concerns are not being addressed**

The Managers (3)

- **Was there a pressure to launch?**
  - Previous mission was delayed a record number of times
  - Next launch was a probe to Halley's Comet
    - ***If launched on-time the probe would beat a similar Russian probe***
  - President's State of the Union Address to mention the shuttle and first teacher in space (McAuliffe)
- **After the fact findings suggest that none of the Managers felt pressured to launch (although a common misconception).**

Questions?

- **What are the relationships between individual and organizational responsibilities?**
- **What are the responsibilities of large corporations?**
- **Are engineer/manager relationships inherently adversarial? Should they be?**
- **What is the role of trust?**

The Telecon

- **Predicted 18^{0}F ambient temperature the night before the launch (27 Jan) precipitated a telecon between MTI, MSFC, and KSC**
  - **The engineers prepared 14 viewgraphs that identified the field joint as the highest concern**
  - **Low temperature effect on resiliency of o-ring**
  - **O-Ring will not be able to respond to the gap opening in a timely manner – harder o-rings would take longer to seat**
  - **If erosion penetrates the primary seal, then a high probability of no secondary seal capability**
  - **RECOMMEND: Delay launch until ambient temperature is above 50 ^{0}F**

The Telecon (2)

- **The MTI engineers and management FULLY support the original decision not to launch below 50 ^{0}F**
- **After the engineering presentation, L. Mulloy (MSFC) asks J. Kilminster (MTI) for his launch decision. Kilminster did not recommend launch**
- **Mulloy asks G. Hardy (NASA) for his launch recommendation**
  - **Hardy is “appalled” at MTI’s recommendation at this late hour**
  - **However, Hardy does not recommend launch over the contractor’s objection**
- **Mulloy concludes that the MTI data presented was inconclusive**
- **Mulloy: “The eve of a launch is a hell of a time to be inventing new criteria”, “My God, Thiokol, when do you want me to launch, next April?”**

The Telecon (3)

- **Things get tricky**
  - Inconclusive data MUST result in a no-go decision
  - NASA culture requires contractor to prove their systems are ready to fly
  - By this statement, Mulloy now puts a burden of proof on proving the system is NOT ready to go.
  - MTI requests a 5 minute caucus to go over

The Telecon (4)

- **Lund would not sign off on the launch, then…**
- **During the MTI caucus, J. Mason said to Lund, "take off [your] engineering hat and put on [your] management hat"**
- **Lund capitulated and agreed to the launch**
- **Kilminster told Mulloy that Thiokol had reassessed the situation. There was cause for concern, but the available data was inconclusive as to the seriousness of the concern.**
- **McDonald argues again that the data might be inconclusive but the launch should be scrubbed citing:**
  - Ice over the launch pad
  - A serious storm over the Atlantic had ships heading back to shore that were sent out to recover the SRBs
- **NASA managers suggest that none of that was his concern.**
- **Mulloy tells upper level managers that Thiokol recommends a launch**
  - Later testimony shows that the upper level managers were not told of the concerns that Boisjoly and McDonald raised

Questions?

- **What answers would you as an engineer give to Mulloy about inventing new criteria and launching in April?**
  - Sir, it has never been this cold at the launch site before.
  - Sir, not next April; how about just after lunch?
- **The burden of proof was shifted from prove we can go to prove we can't. Was this appropriate?**
- **What was the culture at NASA and MTI at this time?**
- **Thiokol was purchased by Morton (yes, the salt people) for its chemical division. Are there potential issues with this?**
- **Do the engineers and managers feel the same way about risk? Do they interpret risk the same way?**
  - Russian roulette example
  - What to you think after reading Feynman's paper?

The Decision

- **We all know what that was.**
- **NASA Culture has something to do with it**
  - **Success bred complacency with managers**
  - **The flaws in the o-ring had been there in the past during those successes**
  - **Flaws (erosion and blow-by) were deemed normal**
  - **Each successful launch was interpreted as REDUCING THE RISK**
  - **Projected likelihood of failure became minimal**

The Decision (2)

- **Later findings by R. Feynman assigned to the Presidential Commission**
  - Engineers believed the risk of failure of the field joint was about 1 in 200.
  - Managers believed the risk to be about 0%, well 1 in 100,000 if you pushed them hard for a reasonable answer.
  - In cold weather, engineers believed the risk of blow-by to be nearly 100%.

The Decision (3)

- **Much of the “faith” in the joint , as Kilminster later said, came from previous experience with the same design in the Titan launch vehicle program**
- **The Shuttle joints were designed with two o-rings giving redundancy**
  - It was known that under rare conditions, the machining tolerances between two segments <u>might</u> combine so that the secondary seal would not be in contact with the adjoining face
  - Temperature extremes <u>could</u> change tolerances in machined parts
  - What we now know, in effect, is that no redundancy existed at the time of launch
  - False sense of security in a redundant system that really wasn’t in all cases

The Decision (4)

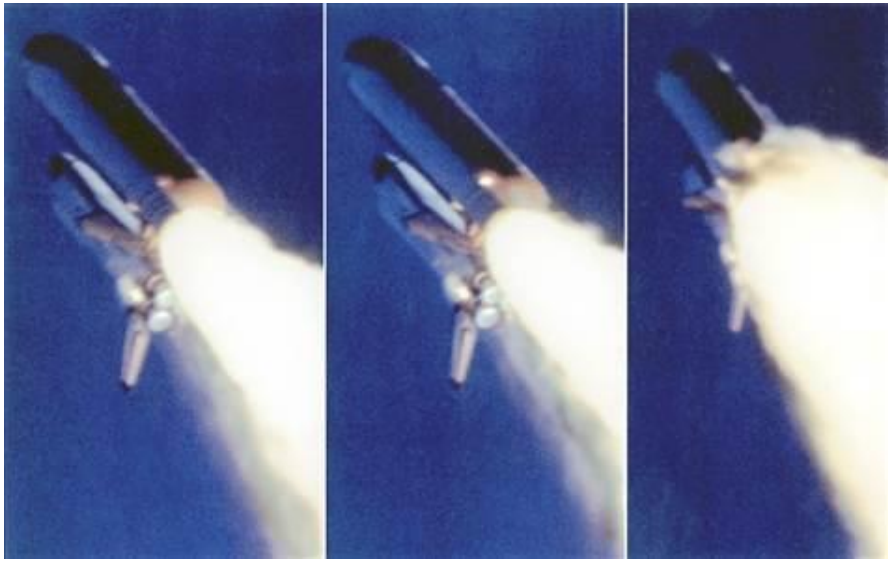
- **Why did Thiokol management capitulate on the night of Jan. 27**
  - They were in the midst of negotiating the next production buy with NASA
  - They were being “threatened” with a second source connection with that bid
  - Keeping the customer happy was very important
  - Redesign would be extensive leading to the suspension of Shuttle flights, redesign of the SRB, and the scrapping of the existing stockpile
  - The budget implications were immense

Questions?

- **In your opinion, what decision should have been made?**
- **Did Thiokol management do the right thing?**
- **What could NASA have done differently?**
- **Is corporate culture a factor in the decision to launch?**
- **Spaceflight is inherently risky. What are acceptable risks in this situation?**
  - If you were told the risks were 1 in 200 would you have launched?
  - If you were told the risk was 100% failure during the program's lifetime, would you have launched?
  - If you were told an acceptable fix would take several years, would you have launched?
- **What could the engineers have done differently to convey their concerns to management?**
- **What is the role of the scientific processes in the decisions that were made?**
- **Was there a real issue in trusting the results of the engineers and launching later in the day when the air temperature was above 50 ^{0}F?**

The Launch

- 0.7 seconds into the launch, photographic data showed a puff of gray smoke in the vicinity of the aft field joint on the right SRB. The area that the puff emanates from faces the external tank.
- Vaporized material streaming from the joint indicates that the o-ring is not sealing completely.
- Between 0.9 and 2.5 seconds 8 more distinct puffs are recorded.
- The black color of the puffs suggests that the grease, joint insulation, and rubber o-rings in the joint seal are being burned and eroded by the combustion gases.



The Launch (2)

- **At 37 seconds, the first high-altitude wind shear event is encountered. This is the largest wind shear event ever encountered by a shuttle during launch. All thrust vectoring engines respond as necessary.**
- **All engines power down during passage of maximum dynamic pressure as planned.**
- **As Challenger's main engines are "go at throttle up" to 104%, a flame is seen on the right SRB at the aft field joint.**
- **The first flame is detected at 59 sec.**
- **The flame is directed by aerodynamic flows towards the external tank.**

The Launch (3)

- **The external tank is breached at 64.6 sec.**
- **Telemetry confirms a hydrogen leak from the propellant tank.**
- **A series of events happen between 72 and 73 seconds that terminated the flight.**
- **Structural failure of the external tank occurs and Challenger is engulfed in the explosive burn when the oxygen tank ruptures at Mach 1.92 and an altitude of 46,000 feet.**

Questions?

- **Put yourself in the engineer's place. How are you feeling?**
- **Put yourself in the manager's place. How are you feeling?**
- **From an ethical perspective, what things need to be done immediately?**
- **What things should not be done immediately?**

The Launch (4)

- **Evidence shows the crew survives the initial explosion and breakup…**

Questions?

- **Does the fact that the astronauts did not perish immediately affect your thoughts or answers to previous questions in any way?**
  - Put yourself in the engineer’s place. How are you feeling?
  - Put yourself in the manager’s place. How are you feeling?

The Aftermath

- **A Presidential Commission is formed.**
  - William Rogers, Former Secy of State
  - Neil Armstrong, Astronaut
  - Dr. Eugene Covert, MIT
  - Dr. Richard Feynman, CalTech
  - Robert Hotz, EIC of Aviation Week & Space Technology
  - David Acheson, VP, Communications Satellite Corporation (lawyer)
  - Maj. Gen. Donald Kutyna, USAF, Director Space System 3C
  - Dr. Sally Ride, Astronaut
  - Robert Rummel, VP for TWA, Aero Engineer
  - Joseph Sutter, VP Boeing, Aero Engineer
  - Dr. Arthur Walker Jr., Stanford University
  - Dr. Albert Wheelon, VP Hughes Aircraft Co
  - Brig. Gen. Charles Yeager, Test Pilot
  - Dr. Alton Keel Jr., Asst Secy of Air Force for Research

The Aftermath (2)

- **The cause:**
  - Specific failure was the destruction of the seals intended to prevent hot gases from leaking through the joint between the two lower segments of the right SRB.
  - The SRBs were assembled using approved procedures.
  - Significant “out-of-round” conditions existed between the two segments joined at the aft field joint.
  - The ambient temperature at launch was 36ºF (15ºF colder than next coldest launch).
  - O-Ring resiliency is directly related to its temperature.
  - NO other element of the Space Shuttle system contributed to the failure.

The Aftermath (3)

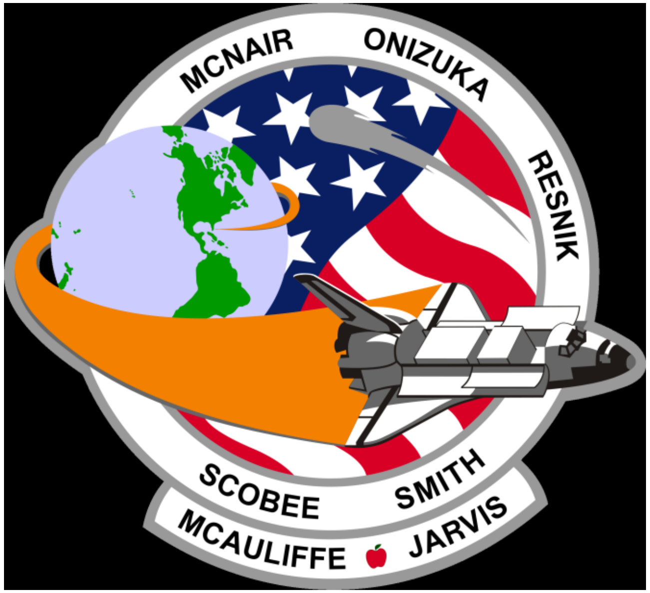
- **Other Factors**
  - The decision to launch Challenger was flawed
  - Those who made the decision were unaware of the recent history of problems concerning the o-rings and the joint
  - They were unaware of the initial written recommendation of the contractor advising against launch at temperatures below 53ºF
  - They were unaware of the continued opposition (to launching) of the engineers at Thiokol after management reversed its position
  - Management structure at Thiokol and NASA are to blame for not allowing the flow of information to those that needed it.

The Aftermath (4)

- **Congress (House of Representatives Committee on Science and Technology) holds its own hearings**
  - Fundamental problem was poor technical decision making over a period of several years by top NASA and contractor personnel
  - Information on the flaws in the joint design and on the problem encountered in mission prior to 51-L (Challenger) was widely available
  - Information had been presented to all levels of Shuttle management
  - There was no sense of urgency to correct the design flaws by either Thiokol or NASA
  - Meeting flight schedules and cutting cost were given priority over safety

The Aftermath (5)

- **"On the Space Shuttle Challenger Accident" – June 6, 1986**
  - "It (the commission) fully recognizes that the risk associated with space flight cannot be totally eliminated."
  - "The nation's task now is to move ahead and return to save space flight and to its recognized position of leadership in space."
  - "There could be no more fitting tribute to the Challenger crew than to do so."



Questions?

- **Did the astronauts sign on for what happened?**
- **How many other lingering problems needed correction? Columbia.**
- **What happens if you correct ALL the known problems before you launch?**
- **How do politics enter the scene? Is this ethical?**
- **What opinions do you have after reading the article by Feynman?**

The Ethics

- **Was Malloy negligent?**
  - Our worst erosion was at one of the highest (launch) temperatures
  - "Our conclusion was that there is no correlation between low temperature and o-ring erosion"
  - "I concluded that we're taking a risk every time. We all signed up for that risk."
  - "The conclusion was, there was no significant difference in risk from previous launches."

The Ethics (2)

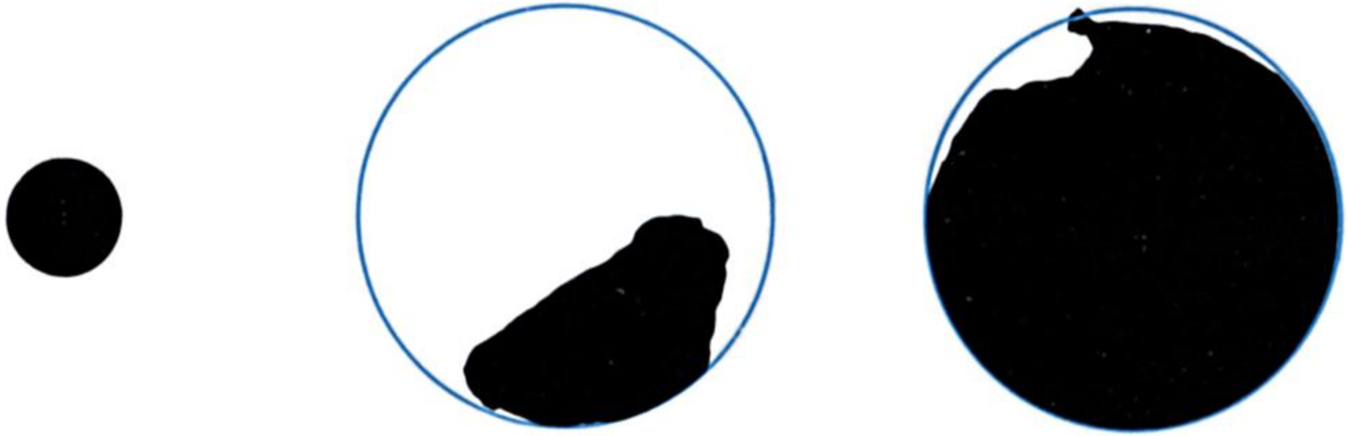
- **What happens in the face of uncertainty?**
  - Personal Knowledge
  - Personal Experience
  - Personal Preference
  - Personal Bias
  - Group Think

The Ethics (3)

- **Why didn't Boisjoly go around his superiors to stop the launch?**
  - Thiokol culture
  - Morton culture
  - NASA culture
- **Why couldn't Boisjoly be more persuasive?**
  - Belief in chain of command
  - Reporting channels
  - Loyalty

The Ethics (4)

- **Was NASA upper management (Level I and II) really unaware of the potential problems with the o-ring?**



Diameter of unaffected O-ring

Eroded primary O-ring from STS 51-B

Eroded SECONDARY O-ring

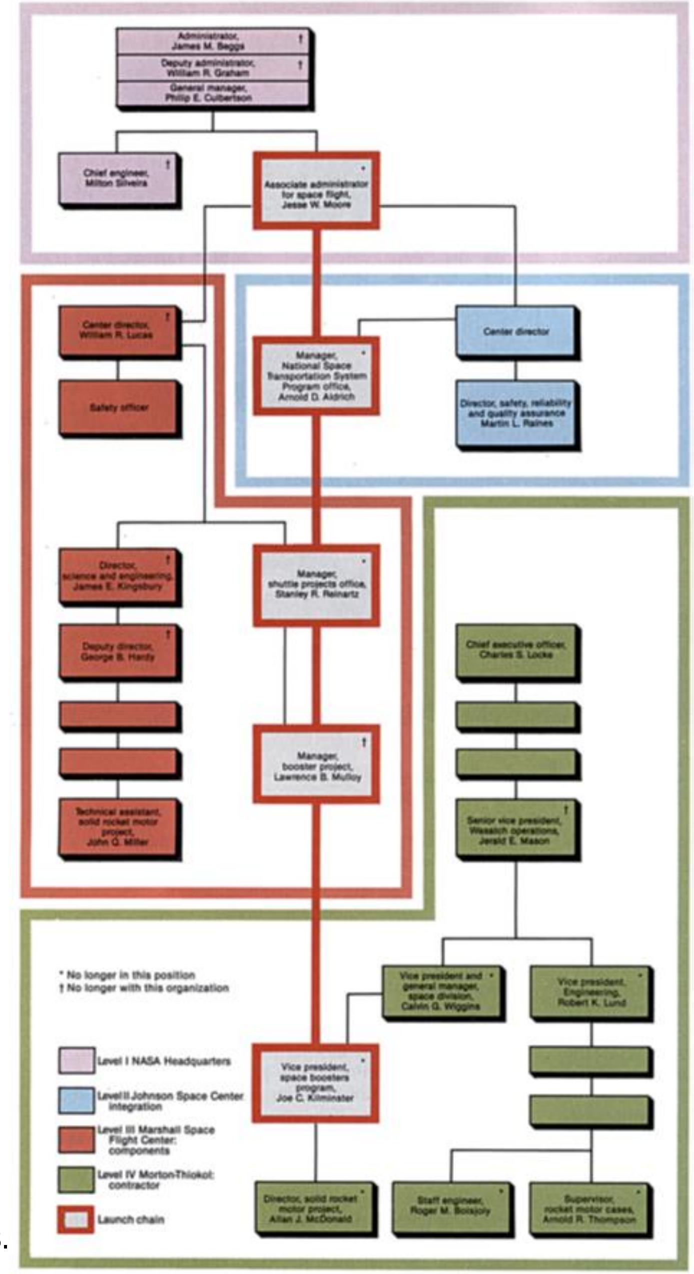
IEEE Spectrum, Vol. 24, No. 2, pp. 50.

The Ethics (5)

- **Hierarchy dynamics**
  - A bench engineer has a concern and reports it to their direct supervisor
  - As the information goes up the hierarchy, information gets distorted (game of telephone)
  - Personal interests, experiences, and preferences are added at each level modifying the original fear or concern
  - At the top of the hierarchy, the message might be…
    - ***Level II manager, "Joe found an issue. It isn't a big deal; I don't know why I'm even telling you this."***
    - ***Level I manager, "Who is Joe?"***
- **Is it conceivable that NASA upper management was unaware of the problem? The severity of the problem? The temperature issue as it related to the problem?**

The Ethics (6)

- **Complex systems have complex management structures**
- **This is one enormous game of telephone especially when one person in the chain can literally change everything**



IEEE Spectrum, Vol. 24, No. 2, pp. 38.

Questions?

- **Did any of the players in this disaster neglect their professional responsibilities?**
- **Was there a true breakdown in personal or corporate ethics?**
- **What Daniels Fund Ethics Initiative Principles are at play in this case?**
  - Integrity, Trust, Accountability, Transparency, Fairness, Respect, Rule of Law, Viability

"The future is not free: the story of all human progress is one of a struggle against all odds. We learned again that this America, which Abraham Lincoln called the last, best hope of man on Earth, was built on heroism and noble sacrifice. It was built by men and women like our seven star voyagers, who answered a call beyond duty, who gave more than was expected or required and who gave it little thought of worldly reward."

- President Ronald Reagan, January 31, 1986

Engineering Ethics Education

- **The problem is that everybody thinks of engineering as an exact science**
  - IT IS NOT
  - Complex systems react in ways quite different than the sum of their parts
  - A great deal of judgment goes into design - human judgment
  - All the answers are not known up front
  - Testing is expensive

Engineering Ethics Education

- **L.L. Bucciarelli, "Ethics and Engineering Education," European Journal of Engineering Education, Vol. 33, No. 2, pp. 141-149, 2008.**
  - Reform the whole of the engineering programme to enable students and faculty understanding of the social as well as instrumental challenges of contemporary professional practice and what this might mean for the profession's "social responsibility" and ethical behaviour of the practicing engineer
  - Show how social and political interests contribute in important ways to the forms of technologies we produce
  - Open up the engineering classroom to discussion and debate

Acknowledgements

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- **The Online Ethics Center for Engineering and Research for Roger Boisjoly's story (www.onlineethics.org)**
- **Many pictures provided courtesy of NASA**

References