Chapter 3. Applying the Classical Paradigm - *Challenger*

Few events in our history have created the public reaction seen in the *Challenger* explosion. The entire nation cried as we viewed over and over again, backwards and forwards, and in living color, the death of seven people and the first ever loss of a space shuttle. As with the assassination of President Kennedy, a generation of Americans will define themselves with the question, "Where were you when the *Challenger* exploded?"

Today we can see clearly what few could recognize at the time. This accident would have a far different effect on the American psyche than the Apollo fire two decades before. In the 1960's America was in the midst of the Cold War. The human space program and the race to the Moon were considered a vital part of our national security efforts. The Apollo failure, while tragic, could not be allowed to impede progress toward the goal of landing a man on the Moon. In contrast, shuttle flights in 1985 had become, in the words of NASA itself, "operational", a term suggesting NASA had "attained an airline-like degree of routine operations."[84]

The long-term result of the system failure was not a traumatized nation, but a nation with a permanently changed outlook on human space flight. NASA lost its reputation for infallibility. America reexamined its course in exploring space and the value of risking human life in these ventures. Risking people and very costly spacecraft without an overwhelming need suddenly seemed a poor bet. Furthermore, citizens and their representatives began to question the need for human space flight in today's society. Balancing risk against gain, many thought the shuttle program fell short. Given this complex reaction to a single accident, understanding this system failure is necessary for anyone studying large complex systems.

Any examination of this seminal event must answer two fundamental questions. (1) What caused the space shuttle *Challenger* to fail?, and (2) What were the consequences of this system failure? These questions follow directly from the classical paradigm described in Chapter 2. They presuppose that concrete answers to each exist and that the analyst can uncover them.

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[84] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p.5.

The analysts studying cause see an opportunity to not only prevent a similar failure within the shuttle program, but a chance to expand our knowledge of system failures in general. The analysts studying the consequences look to the overall impact on the nation, or on specific areas of interest. These analyses also may be used to clarify the ultimate impact of a system failure. Armed with these data, future decision-makers decide on courses of action.

3.1 The Cause of the *Challenger* Failure

To say the decision to launch *Challenger* was well documented may be one of the great understatements of all time. In fact, the inside joke at NASA is that it is time to launch when the pile of documentation reaches the top of the rocket. This documentation was not limited to the operational procedures and policies, but included the overall management policies that defined the roles and responsibilities of each organization at NASA Headquarters and the relevant field centers. In addition, volumes of printed pages and large computerized data bases devoted to the safety and reliability of the shuttle system are prepared for each mission.

The management structure was identical to that in place for the Apollo program. This approach employed the "lead center" concept where the shuttle program office was a tenant at a major field center location.[85] Johnson Space Center , the lead center for human space flight operations was designated lead center for the space shuttle program. Responsibility for developing the shuttle was divided according to its primary components and according to the expertise developed at each field center. The orbiter and mission operations duties were managed by Johnson Space Center. The Marshall Space Flight Center was responsible for the solid rocket boosters, the space shuttle main engines, and the external tank. The Kennedy Space Center was charged with shuttle launch and landing operations as well as shuttle fleet mission preparations.

[85] NASA is comprised of a headquarters organization located in Washington, D.C. and eleven field centers located throughout the country. NASA is further divided by discipline with different field centers responsible for different functions. For example, NASA's human space flight initiatives are managed by the Office of Space Flight and its four field centers: The Johnson Space Center in Houston, Texas; Marshall Space Flight Center in Huntsville, Alabama; Kennedy Space Center in Cape Canaveral Florida; and the Stennis Space Flight Center in Michoud, Mississippi.

The selection and management of contractors employed the same approach found in the Apollo program. NASA conducted a series of competitive procurements that attracted the attention of every major aerospace contractor. These procurements were divided into the concept stage, the design stage, and the development and testing stage. A wide range of concepts and designs were proposed for the new reusable vehicle. Many of the contractors, such as the Chrysler Corporation, that did not win a significant percentage of the shuttle funding permanently left the aerospace industry.

The organizational structure included a large safety contingent. The safety contingent concentrated exclusively on verifying the basic, straightforward safety requirements. No single system, with a few exceptions, could fail and cause destruction of the vehicle. The "program - level requirements [require that]…all subsystems, except primary structure and pressure vessels, shall be designed to fail-operational after failure of the most critical component, and to fail-safe for crew survival after failure of the two most critical components." [86] In addition, each organization had to document and mitigate any safety risks that could arise from virtually any combination of failures in the hundreds of shuttle subsystems. These activities were monitored by a separate group of safety personnel who participated in the management boards for the program. In addition, these safety personnel were required, along with other managers, to certify that each mission was ready to be launched. This system had been used successfully for every human space vehicle since Alan Shepard's sub-orbital flight on a Mercury Redstone rocket in 1961.

The program management and processes were followed exactly as written. The space shuttle program operated according to a carefully controlled set of processes. These process, including management responsibilities, the functioning of configuration control mechanisms, operational procedures, and even the format of documentation were written and available to all participants. The system design accommodated unplanned changes or deviations from standard procedure. Procedures were in place to document these changes and management procedures were used to ensure that all responsible officials had seen and approved of the changes.

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[86] Dennis R. Jenkins, Space Shuttle, (Marceline, Missouri, Walsworth, 1997), p. 83.

The standard preparation template was used to prepare the final *Challenger* mission. There were no unplanned deviations from previous launches. This template established the schedule for preparing the orbiter, mating it to the solid rocket boosters and external tank, and timing its transfer to the launch pad. It also mandated the requirements for crew training, vehicle testing, and mission simulations that tested the ground crew's expertise.

With millions of procedures required for each launch, the standard template inevitably required some changes. All deviations from this standard template, however, were documented and approved by the appropriate management. They represented nothing unusual in shuttle operations. NASA management anticipated such deviations. The process for handling them was well understood by all parties. In the case of the STS-51L mission, no deviation received special consideration in its handling.

Both NASA and shuttle contractors agreed that the flight was ready to be launched and signed a Certificate of Flight Readiness (CoFR) before the *Challenger* crew boarded the vehicle.[87] This document dated to the beginnings of the human space flight program. This certificate was intended to document that senior management in each organization was committed to launching the mission. It removed the ambiguity of a verbal discussion or other less formal launch decision processes. In order to sign this document, each manager had received briefings from subordinate managers who had discussed potential issues with their managers in the reductionist manner of the classical paradigm.

[87] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 15, 97.

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

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

JOE C. KILMINSTER, VICE PRESIDENT
SPACE BOOSTER PROGRAMS

MORTON THIOKOL, INC.
Wasatch Division

Figure 3-1 - Telex of MortonThiokol's final position on the launch of STS mission 51-L[88]

So what went wrong? After all, NASA had written the textbook on how to manage complex technical systems and had demonstrated repeatedly that this system worked. Every action taken in preparing the *Challenger* for launch indicated that all problems were well understood and being handled safely. Hadn't NASA followed its well-defined, well-tested methodology for ensuring that human space flight was safe for the crew? Hadn't there been 24 successful shuttle missions?[89] The investigators focused immediately on how such a now seemingly obvious mistake could have been made. Investigators began the exacting task of uncovering the sequence of events immediately before and after the explosion to determine the cause of the accident.

88 Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 97.
89 See Appendix A

3.1.1 Constant in the Equation: The O-Rings

Within days of the *Challenger* explosion, a burn through in the solid rocket booster's O-rings was quickly identified as the proximate cause of the failure. The speed with which this triggering event was assessed can be attributed to the video documentation of the event and that the O-rings were a known source of risk inside the program before the accident. The O-rings were tracked in the NASA program documents as a Criticality One Item, whose performance was judged to be critical to the system's ability to function and whose failure would bring about a catastrophic loss of the vehicle.[90] Additionally, prior to *Challenger*, several review teams were investigating recent incidents of the O-rings failing to function as desired. When the launch video replays showed a flame emerging from the lower half of the solid rocket booster those within the program quickly began speculating as to the cause of the disaster.

The space shuttle Mission 51-L experienced a catastrophic failure on Tuesday, January 28, 1986 at 11:38 a.m. Eastern Standard Time and by the end of the week the popular press was already "citing sources" pointing to the O-rings' failure to seal properly as the proximate cause. Time wrote in its next week's cover story that:

> Though NASA experts repeatedly objected to all public guessing about what caused the explosion—all employees of the agency were ordered not to speculate—it was virtually impossible to prevent people from doing just that.[91]

The article continues:

> Since the video tapes played early in the week seemed to show a small ball of fire suddenly appearing between one of the solid rocket boosters and the large external tank, most of the speculation centered on the possibility of a failure in either the tank or one of the boosters.[92]

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[90] See Appendix B
[91] Otto Friedrich, "Looking for What Went Wrong," Time, 10 Feb. 1986, p. 36.
[92] Friedrich, p. 36.

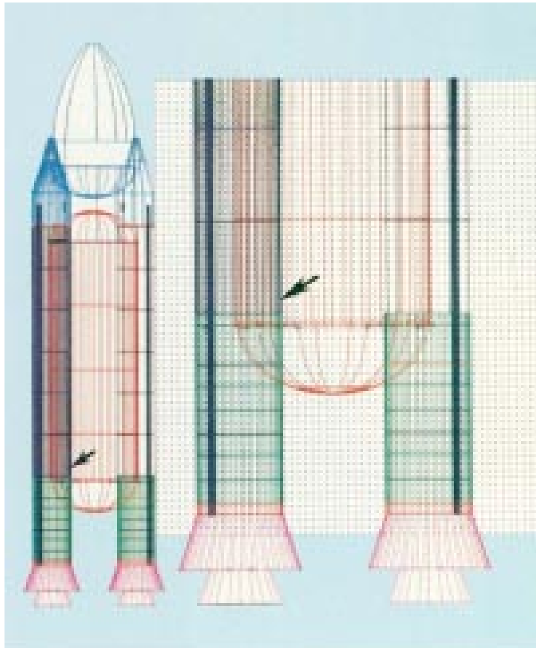

Figure 3-2 - Smoke Source[93]

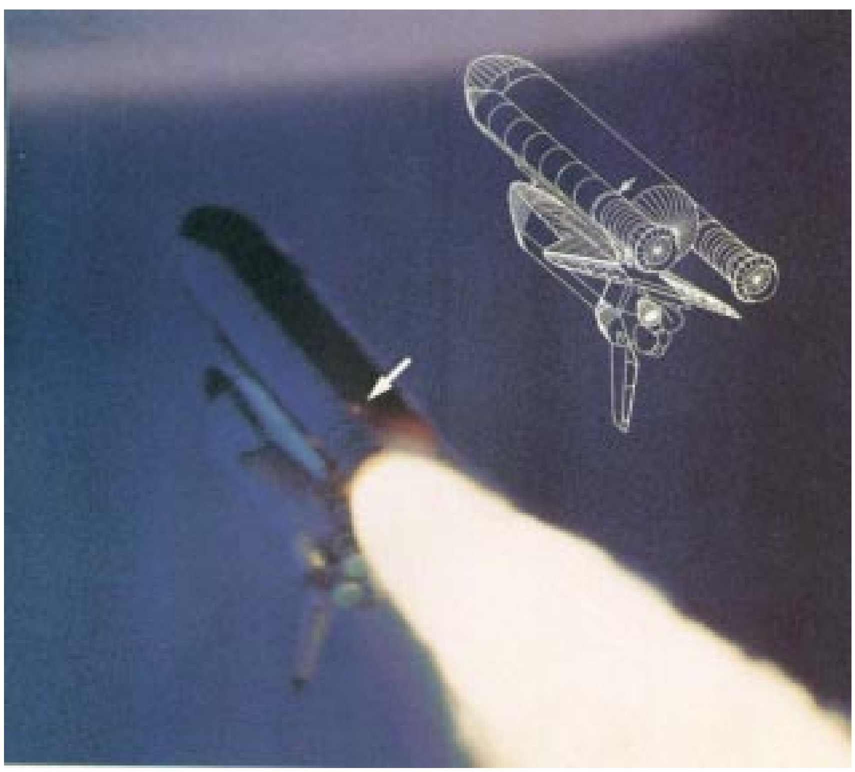

Figure 3-3 - First Flicker of Flame at 58.788 seconds[94]

[93] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 95.
[94] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 26.

Figure 3-4 - At 76 seconds: Tumbling Fragments and Left Booster still Thrusting[95]

[95] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 33.

Figure 3-5 - At 78 Seconds: orbiter's left wing (top arrow), the main engines (center arrow), and forward fuselage (bottom arrow) are hurtling out of the fire ball[96]

[96] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 35.

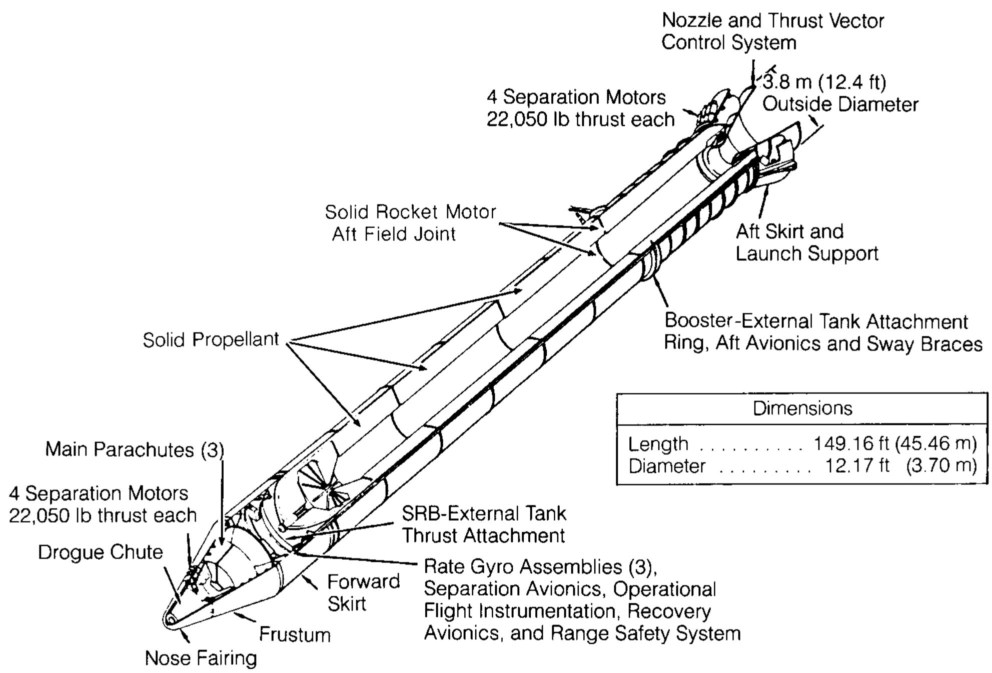

Figure 3-6 - Cutaway solid rocket booster View[97]

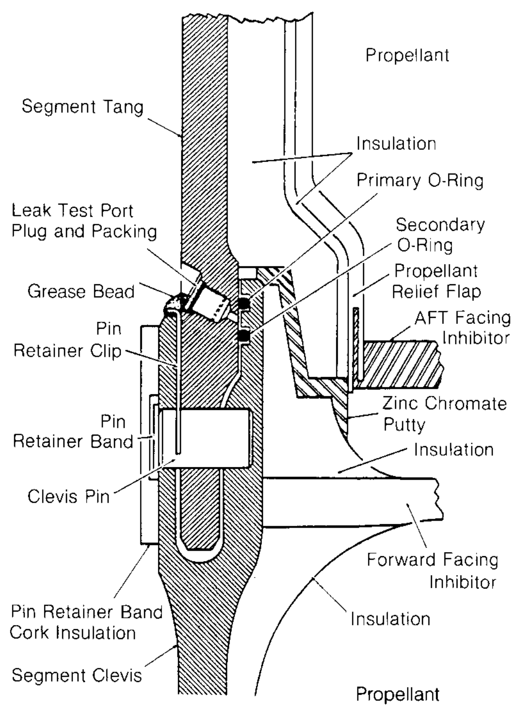

Figure 3-7 - Solid Rocket Motor Cross Section[98]

[97] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 56.
[98] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 57.

Soon, the press began quoting each other. For example, in the same article Time stated that:

> But at weeks end the *New York Times* reported that NASA technicians had found evidence amid the reams of telemetry that seemed to support the burnthrough theory. According to the unnamed source, the data show that the right solid-fuel booster had a pressure drop of nearly 30 lbs. per sq. in. and a loss of 100,000 lbs., or about 4%, of normal thrust about 10 sec. before the explosion—the kind of decrease a burnthrough would have caused. Later the same day, NASA released new pictures and a videotape showing what it called 'an unusual plume' of flame streaking from an apparently enlarging gap in the side of the right booster immediately before the explosion. That seemed to be strong evidence.[99]

Dr. Richard P. Feynman, a Nobel Prize winning physicist and member of the Presidential Commission chartered with investigating the *Challenger* failure, echoes the rapid speed with which the burn through in the O-rings was identified as the proximate cause. He recalls his initial participation in the commission:

> A few days after the *Challenger* accident, on a Friday, I got a call from William Graham, who was acting director of NASA [asking if he would be a member of the Presidential Commission]…The next day, Monday, I got a telephone call at 4pm: 'Mr. Feynman, you have been accepted on to the commission' –which by that time was a "Presidential" Commission, headed by former Secretary of State William P. Rogers. The first meeting would be in Washington, on Wednesday. So Tuesday, I asked Al Hibbs to get people at the Jet Propulsion Laboratory who knew something about the shuttle project to brief me on it right away. I want to say right now that I got nothing but wonderful cooperation from JPL, and that briefing was fantastic.
>
> In order to prove how successful it was; I'll show you the first page of the notes I made in the briefing. You'll find that on the second line it says, "O-rings show scorching in clevis check." That means hot gas has burned through the O-rings on several occasions. Furthermore, they told me that the zinc chromate putty had bubbles, or holes. It turned out that yes, indeed, through those holes the gas came to erode the O-rings. So already, on the second line of my briefing, I was told what was the matter with the shuttle.[100]

Less than two weeks after the space shuttle *Challenger* exploded Feynman elicited testimony at the Presidential Commission Hearings in Washington, D.C. that would virtually seal forever the case for all analysts. He reduced the potential factors contributing to the accident to a single variable, the O-rings. In his approach, he discarded other factors to focus on the most probable immediate cause, illustrating dramatically that the solid rocket booster seal was fatally

[99] Friedrich, p. 37.
[100] Richard P. Feynman, "An Outsider's View of the *Challenger* Inquiry," Physics Today, Feb. 1988, p.26.

flawed. Feynman's reputation and presentation provided little room for disagreement among scientists and commentators. Interviewing Larry Mulloy, the solid rocket booster manager from the Marshall Space Flight Center, on February 11, 1986, the exchange that morning reads like the transcript of a criminal trial:[101]

DR. FEYNMAN: Can I ask a few questions in succession to help explain?

Mr. MULLOY: Yes, Sir.

DR. FEYNMAN: This rubber thing that is put in the so-called O-ring, that is supposed to expand to make contact with the metal underneath so that it makes a seal, is that the idea?

MR MULLOY: Yes, sir. In the static condition it should be sealed to—it should be in direct contact with the tang and clevis of the joint, and be squeezed 20 thousandths of an inch.

Dr. FEYNMAN: And if it weren't there, if it weren't in contact at all and there was no seal at all, that would be a leak. Why don't we take the O-rings out?

Mr. MULLOY: Because you would have hot gas expanding through the joint and destroy---

Dr. FEYNMAN: Pushing the putty through, and so on?

Mr. MULLOY: Yes. You will always push the putty through, because the motor pressure is 900 psi nominally, 1,000 psi at max, and that putty will sustain about 200 psi.

Dr. FEYNMAN: Now, we couldn't put instead of this some sort of material like lead, that when you squash it stays? It has to be that it expands back, because there is a little bit of play in this joint and it has to be able to come back. I mean it is rubber material, so that it comes back when you move a little, and it stays in contact, is that right?

Mr. MULLOY: Yes, sir, that is the purpose of the putty, as a thermal barrier, a thermal barrier. In the data that we have presented to the Commission, as you noted yesterday, we have looked at other alternatives, some of those alternatives are things like—

Dr. FEYNMAN: I'm talking about the rubber on the seal.

Mr. MULLOY: I'm sorry?

[101] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, (Vol. 4, pp. 628-631).

Dr. FEYNMAN: In the seal, in order to work correctly, it must be rubber, not something like lead?

Mr. MULLOY: Yes, Sir.

Dr. FEYNMAN: Because the seal moves a little bit when there is vibration and pressures, it would lift the lead away, which the rubber expands in place?

Mr. MULLOY: Yes, Sir.

Dr. FEYNMAN: So it is important that it have this property of expansion and not be plastic, like lead. And I think you call that resilience, right?

Mr. MULLOY: That is correct. It has to have resiliency, and that is why we use an elastomer.

Dr. FEYNMAN: If this material weren't resilient for say a second or two, that would be enough to be a very dangerous situation.

Mr. MULLOY: Yes, sir.

Dr. FEYNMAN: Thank you.

Feynman revisited this issue later that afternoon. He questioned Mulloy closely about the critical nature of the O-rings and the need for them to move into any gap created in the joint:

Dr. FEYNMAN: We spoke this morning about the resiliency of the seal, and if the material weren't resilient, it wouldn't work in the appropriate mode, or it would be less than satisfactory, in fact it might not work well.

I did a little experiment here, and this is not the way to do such experiments, indicating that the stuff looked as if it was less resilient at lower temperatures, in ice.

Does your data agree with this feature, that the immediate resilience, that is, within the first few seconds, is very, very much reduced when the temperature is reduced?

Mr. MULLOY: Yes, sir in a qualitative sense. I just can't quantify that at this time.

Dr. FEYNMAN: Then you would say that I would conclude from that and the various things you told me about the need for resilience and the lack of resilience with the first few seconds, and of course, it comes back very slowly, isn't it true, then that the temperature at a low temperature increases the chance of a joint failure.

Mr. MULLOY: The low temperature increases the time that would be required for the O-ring to extrude into the gap, and that would allow greater erosion on the O-ring, yes, sir. [102]

With the image now firmly ingrained in everyone's mind, including the Presidential Commission members, the public, and the press, the final report of the Presidential Commission chartered to investigate the failure nailed the coffin shut on the proximate cause. The Commission, in its official report to President Reagan, concluded that a failure of the O-ring seal at the field joint allowed intensely hot combustion gases to burn through the joint and the outer casing of the booster where they impinged on the external tank causing the shuttle to veer off course and explode.

> The consensus of the Commission and participating investigative agencies is that the loss of the Space Shuttle *Challenger* was caused by a failure in the joint between the two lower segments of the right Solid Rocket Motor. The specific failure was the destruction of the seals that are intended to prevent hot gases from leaking through the joint during the propellant burn of the rocket motor. The evidence assembled by the Commission indicates that no other element of the Space Shuttle system contributed.[103]

All subsequent investigators concurred. Never again would the proximate cause of the failure be debated.

The rapid discovery of an indisputable proximate cause of the system failure, the O-rings, is consistent with the classical paradigm where the proximate cause is a given in the equation. As such, it forms the basis for future analyses of the system failure. The classical analyst uses this starting point both as the beginning and the end of the investigation into what caused the failure in the first place. Starting with the overall failure scenario, the analyst can use reductionism to peel back layers of the failure until he reaches the proximate cause. Continuing, the analyst can start with the proximate cause and use determinism to follow the steps which preceded the accident, allowing the failure to occur.

With the O-rings now firmly established as the proximate cause, the quest then became to determine the "root" cause of the accident.

[102] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, (Vol. 4, pp. 739-741).

3.1.2 The Root Cause Hypotheses

The analysts' conclusions can be grouped into one of five hypotheses. These five hypotheses constitute the most popular answers to the question of what was the root cause of the space shuttle *Challenger* failure. They are by no means meant to be the complete set of hypotheses about *Challenger*, but I believe they provide the reader with good understanding of the challenges associated with root cause analyses.

3.1.2.1 Hypothesis 1

> Senior NASA officials, lacking in integrity, succumbed to political pressures and agreed to a series of budget compromises that resulted in the design and construction of an inherently unsafe space shuttle.

That Senior NASA officials succumbed to political pressures and agreed to accept less money than was required to build a safe space shuttle is frequently cited by analysts as the "root cause" of the *Challenger* failure. Those who support this hypothesis contend that NASA senior managers made a series of unwise and poorly conceived programmatic compromises that eventually led to the design and development of an unsafe system. Proponents of this theory assert that NASA officials compromised their integrity one step at a time, agreeing first to forgo the original goal of moving on to Mars, then the abandoning the orbiting space station, and finally relinquishing the preferred design for a space shuttle. They assert these compromises eventually produced an inherently unsafe design and operational support.

At a crossroads following the dramatic landing of Apollo 11 on the Moon in June 1969, President Nixon asked then Vice President Spiro Agnew to chair a Space Task Group to define America's long-range goals for man in space. Nixon did not push the human space flight agenda and did not actively participate in its deliberations. In September 1969, two months after Neil Armstrong first stepped on the moon, the Space Task Group, developed three options for how to proceed:[104]

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[103] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 40.
[104] Space Task Group Report to the President, The Post-Apollo Space Program: Directions for the Future, September, 1969, pp. 20-21; America's Next Decade in Space: A report for the Space Task Group, prepared by the

Option 1: An aggressive program outlining an integrated space infrastructure with a manned mission to Mars, a space station in orbit around the Moon, and a larger research station in orbit around the Earth which would be serviced by a shuttle vehicle. The space station in orbit around the Moon would allow the country to capitalize on the knowledge of the Apollo program and act as a way station for investigating other bodies in the solar system. Unlike the Apollo program, people would live and work in space aboard the Earth-orbiting space station as a normal extension of life on the ground. The space shuttle would make this effort affordable, replacing the expensive expendable rockets of the past. Then America would continue to explore outward through the manned mission to Mars. The orbiting stations and the Shuttle would bring the cost of such missions within reason by assembling the interplanetary vehicles in space.

Option 2: An intermediate program that still included a mission to Mars. This option deleted the Moon-orbiting space station, but preserved the essential elements of the NASA vision. The Earth-orbiting station and supply Shuttle would preserve the nation's ability to work in space. Also, it would act as a staging platform for exploring Mars.

Option 3: A scaled-back program the principle elements of which were a space station in Earth orbit serviced by a shuttle vehicle. This option represented the least ambitious alternative for continuing a human space flight program. It eliminated the expensive Moon and Mars missions.

With the glory of Apollo fading and unaccustomed to having to compete for budget dollars, NASA accepted the lesser of the three options, a shuttle and a station, only to see this option further halved to just the shuttle in the ensuing budget debates. As a result, proponents of this hypothesis contend the first step was taken in what would eventually be a long string of budget compromises culminating in the construction of a space shuttle system that was doomed for failure.

The decision-making process that delayed the space station in favor of the shuttle illustrates this scaling back of NASA. Proponents, including NASA, of developing the station first and the shuttle later quickly realized that logistical requirements for any sizable station could not be met with the projected funding allocations. Somewhat reluctantly, they agreed to delay the station in favor of the shuttle.[105]

Throughout the 1970s, as NASA undertook the design and development of the space shuttle, the Office of Management and Budget continued to slash NASA's budget. NASA saw

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National Aeronautics and Space Administration, September, 1969; Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p.2.

[105] Barfield, p. 1323.

its human space flight budget cut in constant 1980 dollars from $9.8 billion in 1966 to $2 billion in 1981**,** the year NASA launched the first space shuttle, *Columbia*, into space (Figures 3-8, 3-9).[106] Dale Myers, Associate Administrator for Manned Space Flight at the time, remembers that the budget situation was unfavorable and clearly understood within the agency. In his words, "it became evident that a program above $10 billion would not fly."[107] Cuts were required if the program was going to survive.

[106] Constant 1980 dollars. Data provided 5 October 1998 by Richard J. Wisniewski, NASA's Deputy Associate Administrator for the Office of Space Flight.
[107] Dale D. Myers, "The Shuttle: A Balancing of Design and Politics," Issues in NASA Program and Project Management (Springfield, VA.: National Technical Information Service, NASA SP6101 (05), Spring 1992), p. 43.

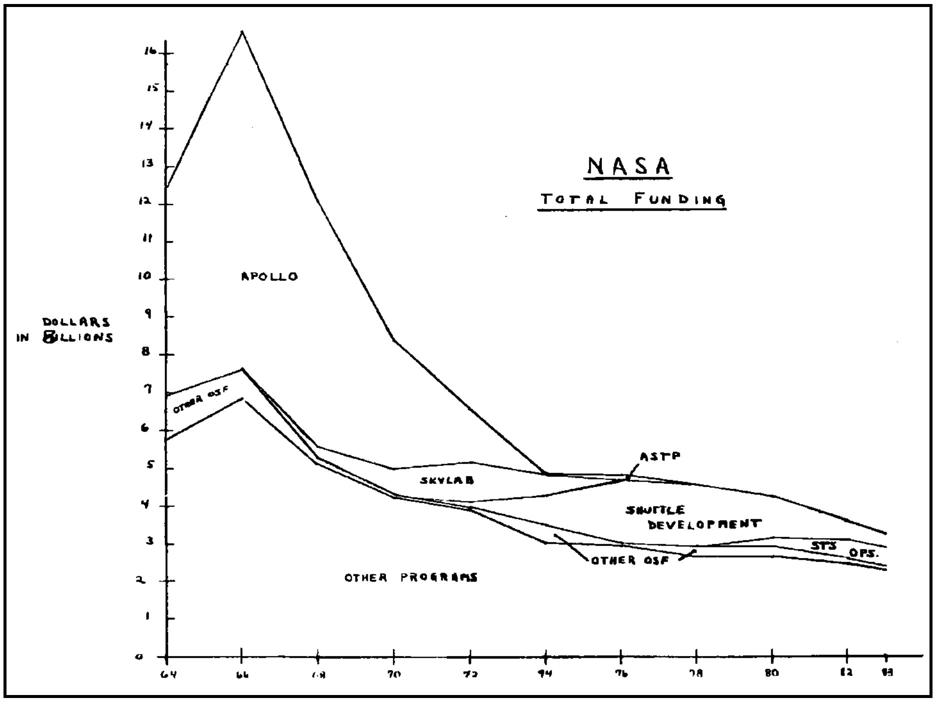

Figure 3-8 - NASA Funding – 1980 Constant Dollars[108]

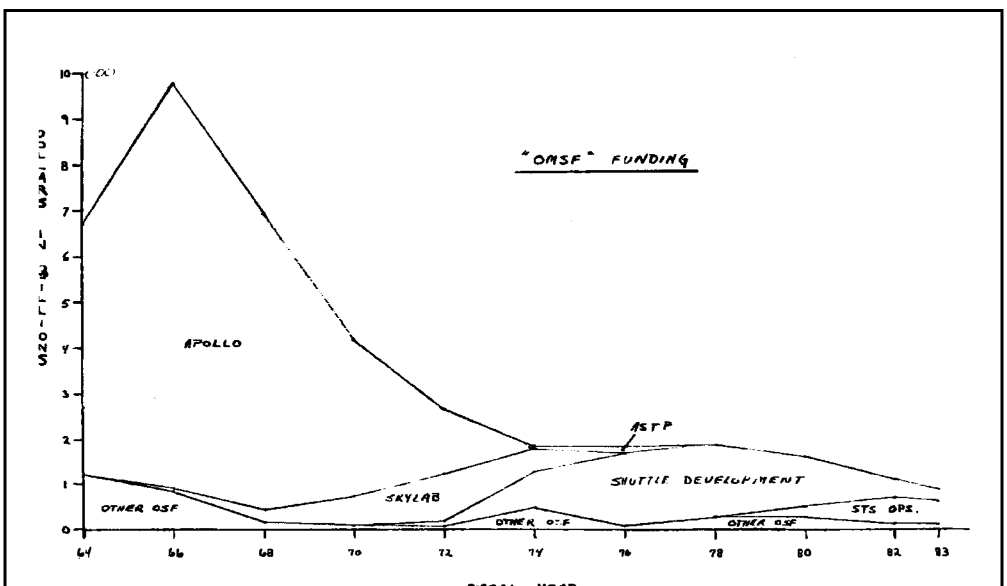

Figure 3-9 – Office of Manned Space Flight (OMSF) Funding – 1980 Constant Dollars[109]

[108] Richard J. Wisniewski, NASA Deputy Associate Administrator OSF, 5 October 1998. OMSF was later renamed the Office of Space Flight.

As the budget pressures on NASA increased, NASA Administrator Dr. James Fletcher readily agreed to compromise after compromise cutting corners wherever possible in an effort to save the shuttle program from being axed altogether. The agency and its contractors recognized that a fully reusable spacecraft design was beyond their grasp. They incrementally began to scale back the blueprints, first doing away with the fully reusable design, then the partially reusable liquid rocket booster option, and finally finding themselves with a partially reusable system that used two solid rockets to help propel it into space.

Even with these changes the program remained expensive and NASA found itself in a fight for the life of the human space flight program. With Senator Walter Mondale leading the charge, a number of prominent members of Congress aggressively attacked the need for a reusable space shuttle and sought to have its development canceled. NASA fought back on several fronts. To obtain critical Department of Defense budget support, the agency enlisted the Air Force as a primary user of the shuttle. The impact from necessary changes to meet these requirements would be great and costly. The NASA shuttle designs did not have the payload capacity to carry the large spy satellites the Air Force needed to carry out its surveillance mission, nor was the shuttle able to conduct short flights of only a few orbits. This requirement increased the "cross range" capability of the shuttle, changing its wing configuration to the delta wing and dramatically limiting its abort options. Ominously, years later, limitations in abort options resulting from these changes would play a large part in the decision to launch *Challenger*.

Challenger had been scheduled to lift off at January 27 at 12:36 p.m. EST, but the launch was scrubbed due to high winds. Managers had two options for launch times on the following day, one for a period beginning at 9:38 a.m. and a second beginning at 3:48 p.m. They selected the earlier time to improve the probability that a landing site used for aborted launches would be available.[110] One can only wonder how different the history of America's human space flight program might be today if NASA been able to wait until later in the day to launch.

To promote the program with the American public, and hence their elected officials, NASA placed shuttle contracts in 48 states with most of the work concentrated in states with the

[109] Richard J. Wisniewski, NASA Deputy Associate Administrator OSF, 5 October 1998.

greatest representation in Congress.[111] NASA reviewed its design and operational concepts with the Office of Management and Budget, which was the executive government organization responsible for overseeing the agency's budget. Suddenly, everyone was a shuttle designer, making recommendations on engineering changes to save the precious development funding.[112]

The designs ranged from short stubby wings like those found on the X-15 research aircraft to lifting bodies which had no apparent wings at all to the now familiar delta wing seen on today's space shuttle. Similarly, propulsion options included large numbers of smaller rockets (as seen on many Russian launch vehicles) to reuse of the old Saturn F-1 kerosene engines to the reusable hydrogen/oxygen engines eventually constructed. All of these options could not be tested or built within the budgetary constraints. Faced with limited funding, NASA was forced to select system designs based on limited analyses. The result was that NASA compromised both design and testing, producing a vehicle based largely on computer and other engineering analysis.

Difficulties and costs which were encountered in the development phase were transferred to the operational phase of the program. Decisions were made which kept development costs within the Office of Management and Budget mandated target.[113] NASA could no longer afford to develop two or more competing designs for each system as they had done in past programs. In 1972, Charles Donlan, NASA's Acting Director for the space shuttle program, described the decision process for selecting the solid rocket boosters over the competing designs. First, he explains that burning the booster rockets in parallel with the space shuttle main engines would take full advantage of the engines' efficiency. Next, he discussed the relative merits of liquid booster versus solid boosters. The discussion hinged around costs for each system, with the solid rocket boosters being the favored option. At no time did NASA consider developing and testing both versions prior to making a final decision.[114]

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[110]"The launch window was shifted back in the morning hours so that the transatlantic abort site would be in daylight and a back-up site (Casablanca) would be available." Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 15.

[111] Interview 23 September 1998 Doyle McDonald, Director, Strategic Planning, NASA's Office of Space Flight, 1989.

[112] See Appendix D for an example of OMB participation.

[113] Myers, p. 44.

[114] Charles J. Donlan, "Space Shuttle Systems Definition Evolution, Issues in NASA Program and Project Management (Springfield, VA.: National Technical Information Service, NASA SP6101 (05), Spring 1992), pp. 46-48.

To save money and meet the schedule, NASA also reduced the number and type of tests to marginal or unsafe levels.[115] Testing was performed on scale models of systems instead of full size systems as had been done for past programs. Also, testing in less-than-operational conditions were substituted for operational testing. For example, the solid rocket boosters were tested in a horizontal configuration instead of vertically as they would be fired during flight. Morton Thiokol engineers explained their early concerns to the Presidential Commission:

> We were concerned very much about the horizontal assembly that we had to do to do the static tests. The Titan had always been assembled vertically, and so there had never been a larger rocket motor to our knowledge that was assembled (horizontally).[116]

Tests were conducted on subsystems one at a time, but there were few end-to-end integrated tests. This was a significant compromise because NASA had put in place an elaborate testing program during Apollo. Entire buildings at the Johnson Space Center were constructed to house the Apollo Command and Service Module dedicated to vibration and acoustic testing. NASA launched boilerplate spacecraft to test the escape system for Apollo. Missions were included to test individual components of the Apollo configuration. For example, the purpose of the Apollo 10 mission was to close within a short distance of the lunar surface only to return to Earth without touching it. Abandoning this heritage, NASA was prepared to fly a completely new vehicle without a single unmanned test flight. And the new features were many. No one had ever flown a new spacecraft for the first time with a crew on-board.

But, perhaps the most fatal compromise NASA made was when it willingly agreed to switch from a fully reusable vehicle with liquid rocket boosters to a partially reusable system with solid rocket boosters. No spacecraft designed to have a human crew had ever used solid rockets. Unlike liquid fueled boosters, these boosters could not be shut down in the event of an emergency. While they were firing, the shuttle crew could not separate from them or eject from the spacecraft. No American rocket had ever been designed without such a bailout option. Donlan, however, estimates that NASA saved $1 billion by choosing solid rocket boosters.[117]

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[115] Robert Reinhold, "Astronauts' Chief Says NASA Risked Life for Schedule: 'Awesome' List of Flaws," New York Times, 9 March 1986, p. 1

[116] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 122.

[117] Donlan, p. 46-48.

The desire to shave dollars off the program was at the center of the Senate Authorization hearings on NASA's budget in 1973 and Dr. George Low, the Deputy NASA, was well aware of this need. Testifying on the shuttle:

> <u>Senator Curtis:</u> Perhaps Dr. Low would want to comment on this question. There have been comments made by prominent persons and articles written in various publications claiming that the Shuttle will cost anywhere from $30 billion to $130 billion. How do you account for the estimate of $5.5 billion?
>
> <u>Dr. Low</u>: Senator, the estimate of $5½ billion number would be less should we decide to select solid rocket boosters instead of the liquid boosters.[118]

In developing these new boosters, NASA once again compromised the safety by using components in ways different from their intended purpose in an attempt to save money. Dianne Vaughan, in her detailed analyses of the *Challenger* accident, refers to comments by O-ring experts who are on record as saying that the solid rocket booster O-ring use was beyond accepted industry practice. She comments that even as early as 1979, a NASA engineer visited two manufacturers who, while recognizing the uniqueness of the design, "…informed [NASA] that the solid rocket booster joint gap size was larger than the recommended industry standard. … Both manufacturers said that the O-ring was being asked to perform beyond its intended design."[119] Feynman also notes this apparent misuse of the O-rings, citing Parker Seal Company's refusal to give advice on the system because the system was outside its base of experience.[120] [121]

Rather than consume limited funds creating an improved design, design flaws discovered in the solid rocket boosters were worked around or the design "patched."[122] The ill-fated design of the solid rocket booster joint is an excellent example. Early tests showed the design did not perform as expected. NASA considered alternative designs, but these were discarded. Started late in the process, the new designs would not meet the development schedule for the first shuttle

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[118] FY 1973 NASA Authorization Senate hearings, March 14, 1972.
[119] Dianne Vaughn, <u>The *Challenger* Launch Decision: Risky Technology, Culture, and Deviance at NASA</u>, (Chicago: The University of Chicago Press, 1996), pp. 102-103.
[120] Feynman, p. 31
[121] See Appendix C
[122] <u>Report of the Presidential Commission on the Space Shuttle *Challenger* Accident</u>, pp. 254-255.

launch and NASA could not afford significant delays and expect the program to survive. Also, there were no funds available to mount a completely new development without curtailing the development of the existing design. NASA chose to use its limited resources to beef up this current design.

Technology was available to improve the sealing system to eliminate the known leakage problem, but improvements were incorporated only as time and funding allowed. Improvements were not permitted to delay missions.[123] The competing (and losing) design for the rocket boosters had a retainer to prevent the joint from separating at ignition. At the time of the accident, NASA was developing advanced solid rocket boosters made from filament-wound cases instead of steel. Building on the experience to date with the shuttle solid rocket boosters, the advanced solid rocket boosters joint design included a latching mechanism that virtually eliminated joint rotation. For the existing boosters, NASA and Thiokol were developing an improved joint design when the *Challenger* failure occurred. Similar to the advance solid rocket booster design, the new joint latching mechanism would eliminate joint rotation. However, implementing this new design was not a requirement for continuing to launch the shuttle. At this time, NASA was focused on reducing the costs of flights and increasing the flight rate.

The significant number of compromises that NASA made in an attempt to keep the shuttle Program alive has led several analysts to conclude that these compromises were the result of NASA Administrator James Fletcher's desire to leave his legacy on America's manned space program.[124] These analysts contend that Fletcher agreed to compromise after compromise, including decisions about the fateful solid rocket boosters, not so much to keep the program, but to ensure this legacy.

In an essay on ethics published in Harvard University Professor Dennis Thompson's Ethics and Politics, Nicholas Carter strongly criticizes NASA management for pushing ahead with the shuttle without "the necessary funds" and citing NASA Administrator Dr. James Fletcher's "ego" as the primary reason NASA built the shuttle design it did.

[123] Reinhold, p. 1.
[124] See Joseph J. Trento, Prescription for Disaster, (New York: Crown Publishers, Inc., 1987) and Nicholas Carter, "The Space Shuttle *Challenger*," in Ethics and Politics, Amy Gutmann and Dennis Thompson, (Chicago: Nelson-Hall Publishers, 2nd ed. 1994).

> Dr. James Fletcher was appointed NASA Administrator in 1971. An ambitious man, Fletcher wanted another big, Apollo-like project for NASA to which he could attach his name. Option B did not give Fletcher the funds necessary to develop a manned space shuttle, but he decided to develop the shuttle anyway. Where former NASA administrators demanded the best, Fletcher was willing to proceed with whatever he could get.[125]

Carter further contends that as the Office of Management and Budget continued to force Fletcher and the shuttle budget down from $10 billion to $8 billion and then to $6.5 billion Dr. Fletcher continued to lie in order to keep the shuttle program alive.

> Dr. Seamans...knew that NASA needed much more funding than Fletcher was projecting to develop the shuttle properly. He sensed that Fletcher was distorting the figures because he had a personal stake in the shuttle, wanting to oversee his own great space program.[126]

The pattern is clear according to those analysts who subscribe to this hypothesis. NASA could not obtain the funds to accomplish its grand vision of human space flight exploration. One by one, NASA managers agreed to abandon or defer these goals until the only program left was the space shuttle. And even this goal proved out of reach with the available funding. The agency's management compromised the design, eliminating many of the redundant features present in the original. Decisions were made on the basis of cost, not engineering merit, creating an inherently unsafe design and using components in ways never before used. NASA senior officials succumbed to political pressures and compromised their integrity by agreeing to build the space shuttle for less money than was required to build a "safe" space shuttle. This compromise, it is argued, is the root cause -- the result was *Challenger*.

3.1.2.1.1 Flaws with Hypothesis 1 as the Root Cause

This hypothesis is difficult to accept as the "root cause" of the *Challenger* failure when more closely scrutinized. The space shuttle clearly is the most complex flying machine ever constructed. Moving from a standstill to 17,000 mph in just over 8.5 minutes requires enormous amounts of energy. The story of the shuttle is a story of "firsts" – the first reusable vehicle, the

[125] Nicholas Carter, "The Space Shuttle *Challenger*," in Ethics and Politics, Amy Gutmann and Dennis Thompson, (Chicago: Nelson-Hall Publishers), p. 123.
[126] Carter, p. 123.

first piloted spacecraft capable of landing on a runway, and the first spacecraft able to return large objects from orbit. These capabilities were not accidental, but were purposefully designed and were the product of millions of hours of labor and billions of dollars. It is just too simplistic to believe that the shuttle's complicated development history created an environment where the participants knowingly overlooked inherent flaws in the design.

The requirements for a reusable vehicle could be met by a number of designs. Just as the DC-10 and the Airbus 340 aircraft serve the same passenger airline markets, the shuttle could be built in many configurations. The challenge was intensified as the Department of Defense began to consider using the shuttle to meet national defense needs. As shown in Figures 3-10 through 3-18, nearly one hundred designs were evaluated against many factors.[127] While cost was a major consideration, each design had to meet a series of competing requirements, including safety, operational capabilities, and service life. Balancing these competing priorities inevitably required some compromises.

[127] Figures 3-10 through 3-17 are courtesy Dennis Jenkins, Space Shuttle: The History of Developing the National Space Transportation System, The Beginning through STS-75.

NASA / MSC
SPACE SHUTTLE DESIGNS
CIRCA 1970–72

The following pages detail the major versions of the MSC shuttle designs from 1970 through 1972. The table below contains additional information. It should be remembered that although the designs may have been developed for launch on a particular booster, almost any combination was considered feasible, and many of the designs may well have been used on a variety of boosters.

Some of the designs could not be ascertained from existing documentation, hence the missing numbers in the table below. Other designs underwent such rapid change that it is possible that the description here does not match the design at all points in its life, although it is believed that these descriptions represent the final configuration of each designs.

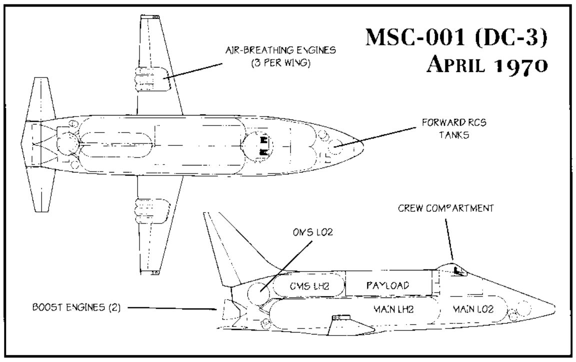
No data could be ascertained for the vehicles not listed (e.g.; MSC-011 through MSC-019, etc.).

ALL SIZES IN FEET, ALL WEIGHTS IN POUNDS

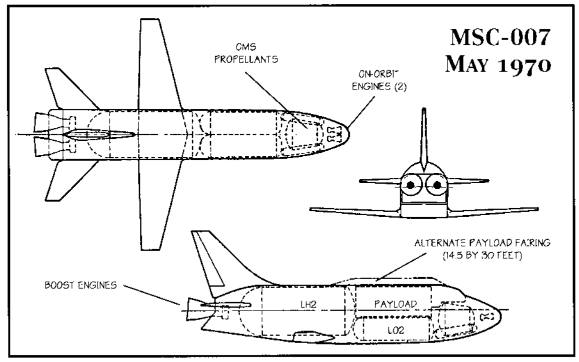
WING LEGEND:
ST = STRAIGHT-WING
LE SW = LEADING EDGE SWEEP
DELTA = DELTA-WING
DBL DELTA = DOUBLE DELTA-WING

VEHICLE	LANDING WEIGHT	WING	PAYLOAD SIZE	PAYLOAD WEIGHT	FEATURES
MSC-001	70,000	ST (AR7)	8 BY 30	15,000	INTERNAL LH2 AND LO2, AIR-BREATHERS, TWO ENGINES, REUSABLE BOOSTER
MSC-002	70,000	ST (AR7)	8 BY 30	15,000	INTERNAL LH2 AND LO2, AIR-BREATHERS, TWO ENGINES, REUSABLE BOOSTER
MSC-004-1	70,000	ST (AR7)	8 BY 30	15,000	INTERNAL LH2 AND LO2, TWO ENGINES, PAYLOAD BAY TUNNEL, REUSABLE BOOSTER
MSC-004-2	70,000	ST (AR7)	8 BY 30	15,000	INTERNAL LH2 AND LO2, TWO ENGINES, REUSABLE BOOSTER
MSC-007	75,000	ST (AR7)	12 BY 30	15,000	INTERNAL LH2 AND LO2, TWO ENGINES, REUSABLE BOOSTER
MSC-008-2	72,000	ST (AR7)	13 BY 17	12,000	INTERNAL LH2 AND LO2, TWO ENGINES, REUSABLE BOOSTER
MSC-009	78,000	ST (AR7)	10 BY 30	15,000	INTERNAL LH2 AND LO2, TWO ENGINES, REUSABLE BOOSTER WITH SRBS
MSC-010	90,000	ST (AR7)	10 BY 30	25,000	INTERNAL LH2 AND LO2, TWO ENGINES, REUSABLE BOOSTER WITH SRBS
MSC-010-1	92,000	ST (AR7)	15 BY 30	25,000	INTERNAL LH2 AND LO2, TWO ENGINES, REUSABLE BOOSTER WITH SRBS
MSC-020	130,000	ST (AR7)	15 BY 30	20,000	EXTERNAL LH2, INTERNAL LO2, FOUR ENGINES, SRB
MSC-021	85,000	ST (AR7)	15 BY 40	20,000	EXTERNAL LH2 AND LO2, ONE ENGINE, SRB
MSC-022	95,000	ST (AR5)	15 BY 40	20,000	EXTERNAL LH2 AND LO2, ONE ENGINE, SRB
MSC-022A	100,000	45° LE SW	15 BY 40	20,000	EXTERNAL LH2 AND LO2, ONE ENGINE
MSC-022B	105,000	DELTA	15 BY 40	20,000	EXTERNAL LH2 AND LO2, ONE ENGINE
MSC-023	135,000	DELTA	15 BY 60	40,000	EXTERNAL LH2 AND LO2, ONE ENGINE, REUSABLE BOOSTER
MSC-024	125,000	ST (AR5)	15 BY 60	40,000	EXTERNAL LH2 AND LO2, ONE ENGINE, STRETCHED MSC-022
MSC-025	130,000	45° LE SW	15 BY 60	40,000	EXTERNAL LH2 AND LO2, ONE ENGINE, STRETCHED MSC-022A
MSC-026	125,000	DELTA	12 BY 40	40,000	EXTERNAL LH2 AND LO2, ONE ENGINE, REUSABLE BOOSTER
MSC-027	95,000	DELTA	12 BY 40	40,000	GLIDER, EXTERNAL MAIN ENGINE, SRB
MSC-028	128,000	DELTA	15 BY 40	40,000	EXTERNAL LH2 AND LO2, ONE ENGINE, SHORTENED MSC-023
MSC-029	142,000	DELTA	12 BY 40	40,000	GLIDER, OMS TANKS AMIDSHIPS, EXTERNAL MAIN ENGINE
MSC-030	103,000	ST (AR5)	15 BY 40	20,000	EXTERNAL LH2 AND LO2, THREE J-2S ENGINES
MSC-031	133,000	ST (AR5)	15 BY 60	40,000	EXTERNAL LH2 AND LO2, THREE J-2S ENGINES
MSC-032	130,000	DELTA	15 BY 40	40,000	EXTERNAL LH2 AND LO2, THREE J-2S ENGINES, SRB
MSC-033	100,000	DELTA	12 BY 40	20,000	EXTERNAL LH2 AND LO2, ONE ENGINE, MODIFIED MSC-026, SRB
MSC-034	95,000	DELTA	15 BY 30	20,000	EXTERNAL LH2 AND LO2, ONE ENGINE, SHORTENED MSC-023, SRB
MSC-035	95,000	45° LE SW	12 BY 40	20,000	EXTERNAL LH2 AND LO2, ONE ENGINE, MODIFIED MSC-033
MSC-035A	135,000	45° LE SW	12 BY 60	40,000	EXTERNAL LH2 AND LO2, ONE ENGINE, STRETCHED MSC-035
MSC-036	110,000	DELTA	15 BY 40	20,000	EXTERNAL LH2 AND LO2, THREE J-2S ENGINES, SRBS
MSC-036A	110,000	DELTA	15 BY 40	20,000	EXTERNAL LH2 AND LO2, THREE J-2S ENGINES, SRBS
MSC-036B	110,000	DELTA	15 BY 40	20,000	EXTERNAL LH2 AND LO2, THREE J-2S ENGINES, SRBS
MSC-036C	110,000	DELTA	15 BY 40	20,000	EXTERNAL LH2 AND LO2, THREE J-2S ENGINES, PRESSURE FED BOOSTER
MSC-037	147,000	DELTA	15 BY 60	40,000	EXTERNAL LH2 AND LO2, THREE UPRATED J-2S, RECOVERABLE BOOSTER
MSC-037A	147,000	DELTA	15 BY 60	40,000	EXTERNAL LH2 AND LO2, THREE SUPER UPRATED J-2S, SRBS
MSC-038	100,000	DELTA	15 BY 40	20,000	EXTERNAL LH2 AND LO2, ONE HIPC ENGINE, SRBS
MSC-039	113,000	DELTA	15 BY 40	20,000	EXTERNAL LH2 AND LO2, THREE J-2S, PRESSURE FED BOOSTER
MSC-040	140,000	DELTA	15 BY 60	25,000	EXTERNAL LH2 AND LO2, FOUR J-2S, PRESSURE FED BOOSTER
MSC-040A	140,000	DELTA	15 BY 60	25,000	EXTERNAL LH2 AND LO2, FOUR J-2S, PRESSURE FED BOOSTER
MSC-040B	140,000	DELTA	15 BY 60	25,000	EXTERNAL LH2 AND LO2, FOUR 'SWING' J-2S, PRESSURE FED BOOSTER
MSC-040C	190,000	DELTA	15 BY 60	40,000	EXTERNAL LH2 AND LO2, THREE HIPC ENGINES, SRBS
MSC-040C-2	190,000	DBL DELTA	15 BY 60	40,000	EXTERNAL LH2 AND LO2, THREE HIPC ENGINES, WING GLOVE, TWIN TAILS, SRB
MSC-040C-3	190,000	50° DELTA	15 BY 60	40,000	EXTERNAL LH2 AND LO2, THREE HIPC ENGINES
MSC-040C-4	190,000	60° DELTA	15 BY 60	40,000	EXTERNAL LH2 AND LO2, THREE HIPC ENGINES
MSC-040C-5	190,000	50° DELTA	15 BY 60	40,000	EXTERNAL LH2 AND LO2, THREE HIPC ENGINES, CANARD, TWIN TAILS
MSC-040C-6	190,000	DBL DELTA	15 BY 60	40,000	EXTERNAL LH2 AND LO2, THREE HIPC ENGINES, CANARD, TWIN TAILS
MSC-041	114,000	30° LE SW	15 BY 60	15,000	EXTERNAL LH2 AND LO2, THREE J-2S ENGINES, PRESSURE FED BOOSTER
MSC-041A	114,000	30° LE SW	15 BY 60	15,000	EXTERNAL LH2 AND LO2, THREE J-2S ENGINES, PRESSURE FED BOOSTER
MSC-042A	110,000	DELTA	15 BY 60	25,000	GLIDER, *TITAN IIIL6* BOOSTER
MSC-042B	110,000	30° LE SW	15 BY 60	25,000	GLIDER, *TITAN IIIL6* BOOSTER
MSC-043	83,000	30° LE SW	10 BY 30	27,000	GLIDER, TWO 'SWING' HIPC ENGINES ON ET, PRESSURE FED BOOSTER
MSC-044	100,000	60° DELTA	10 BY 30	25,000	EXTERNAL LH2 AND LO2, TWO HIPC ENGINES, PRESSURE FED BOOSTER
MSC-047	185,000	DELTA	15 BY 60	40,000	EXTERNAL LH2 AND LO2, TWO HIPC ENGINES, TWIN TAILS, SRBS
MSC-048	205,000	DBL DELTA	15 BY 60	40,000	EXTERNAL LH2 AND LO2, TWO HIPC ENGINES, TWIN TAILS, SRBS
MSC-048A	195,000	DBL DELTA	15 BY 60	40,000	EXTERNAL LH2 AND LO2, FOUR J-2S ENGINES, TWIN TAILS, SRBS
MSC-049	205,000	DBL DELTA	15 BY 60	40,000	EXTERNAL LH2 AND LO2, THREE HIPC ENGINES, TWIN TAILS, 156-IN SRBS
MSC-049A	215,300	DBL DELTA	15 BY 60	40,000	EXTERNAL LH2 AND LO2, THREE HIPC ENGINES, TWIN TAILS, 178-IN SRBS
MSC-051	165,000	33° DELTA	15 BY 60	25,000	GLIDER, CANARD, 156-IN SRBS
MSC-052	175,000	35° DELTA	15 BY 60	25,000	GLIDER, THREE HIPC 'SWING' ENGINES ON ET, CANARD, 149-IN SRBS
MSC-053	185,000	35° DELTA	15 BY 75	25,000	GLIDER, FOUR HIPC 'SWING' ENGINES ON ET, CANARD, 120-IN SRBS
MSC-054	185,000	35° DELTA	15 BY 75	25,000	GLIDER, FOUR HIPC 'SWING' ENGINES ON ET, CANARD, 140-IN SRBS

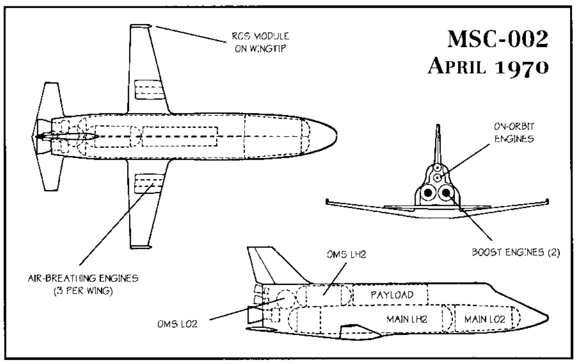
Figure 3-10 - Space Shuttle Designs



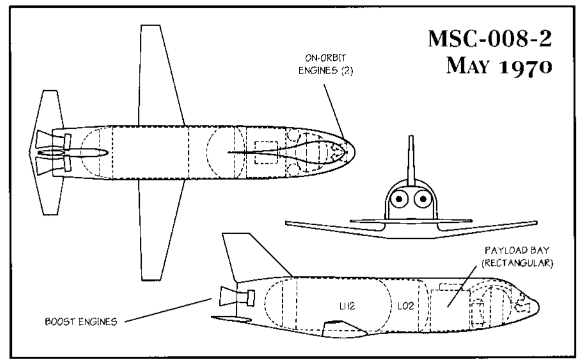
The MSC-001, also known as the DC-3, was the first serious in-house look MSC engineers took at developing an orbiter. This design is discussed in further detail on page 77.



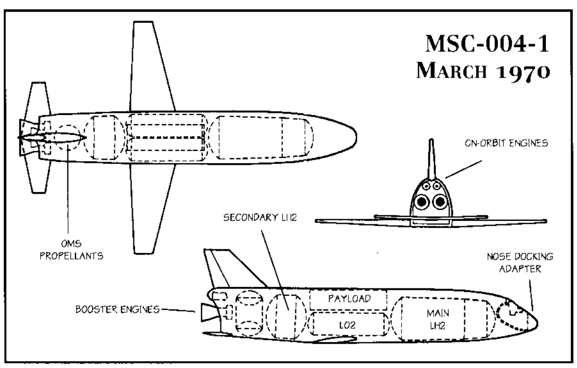
The MSC-007 had two different payload bay door configurations that allowed it to carry over-sized payloads if required. The payload bay itself had grown in size to 12 by 30 feet.



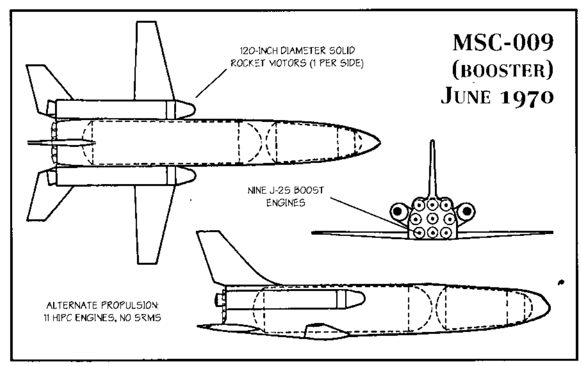
The MSC-002 was a refinement of the earlier MSC-001, and is usually the design that is shown when referring to the DC-3. Primary improvement was in the area of the cockpit.



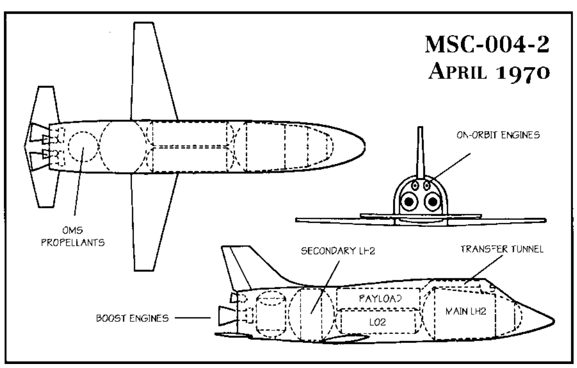
This design attempted to correct some center-of-gravity problems that had been experienced with the earlier designs, but provided an oddly shaped payload bay as a result.



The MSC-004 was begun before the DC-3 report was released. There were two variants, one with a tunnel connecting the cockpit and payload bay (below), and one without (above).



The MSC-009 was one of the first applications of solid rocket boosters to the shuttle program. Several variations of where to attach the SRBs to the booster were investigated.



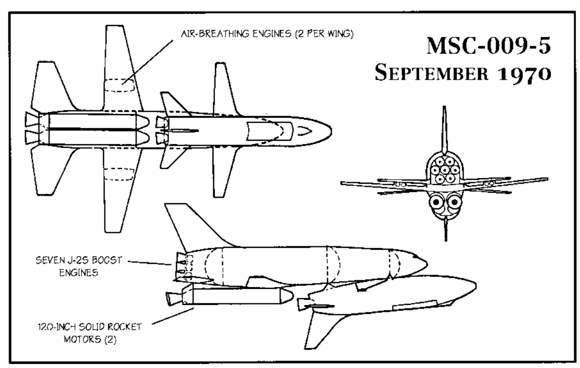
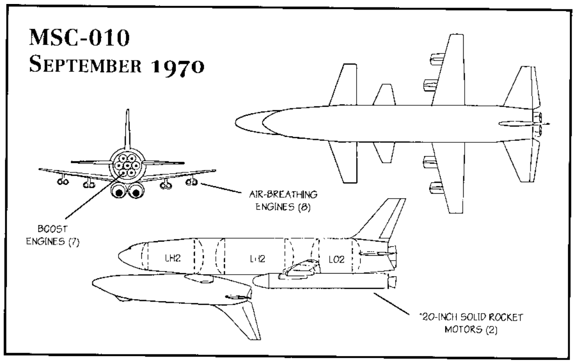
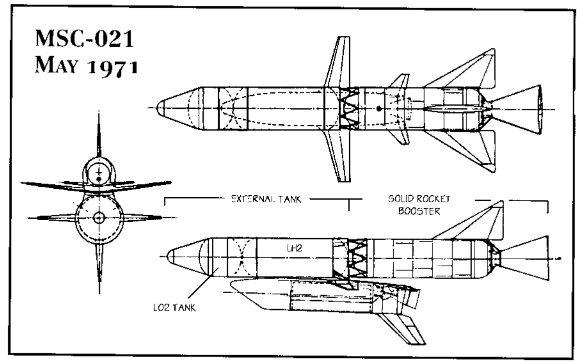


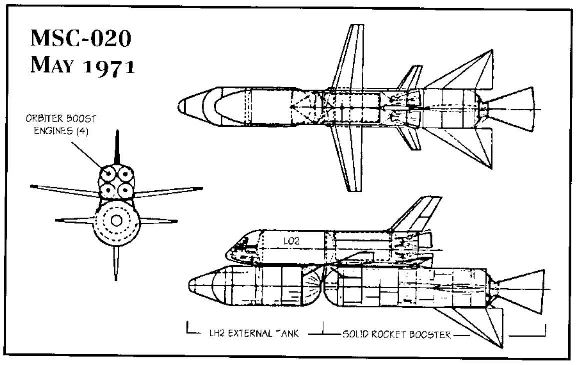
Figure 3-11 - Space Shuttle Designs: 4/70-9/70



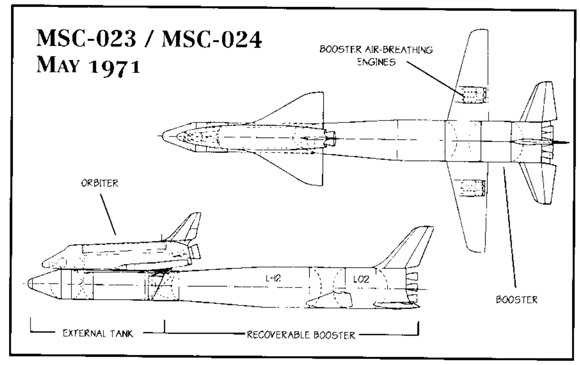
This was a refinement of the MSC-009-5 design, and continued to use two 120-inch SRBs. The payload was beginning to approach usable proportions, a total of 25,000 pounds.



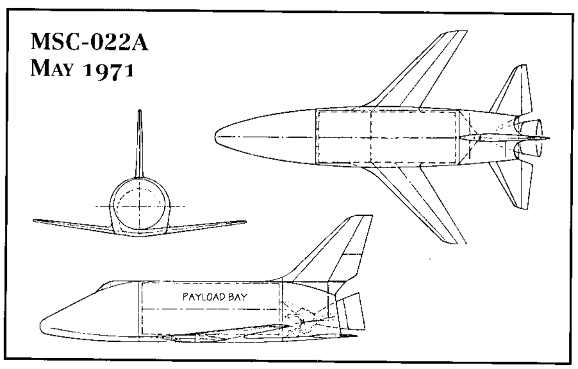
This was a refinement of the MSC-020, and was notable since it moved all propellants out of the orbiter and into an external tank. Again, a single solid rocket booster was used.



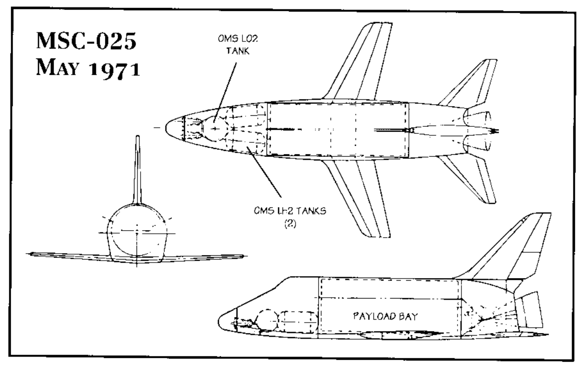
This was the first NASA concept to investigate an 'external tank', with the LH2 being carried in a large tank below the orbiter and in front of the single solid rocket booster.



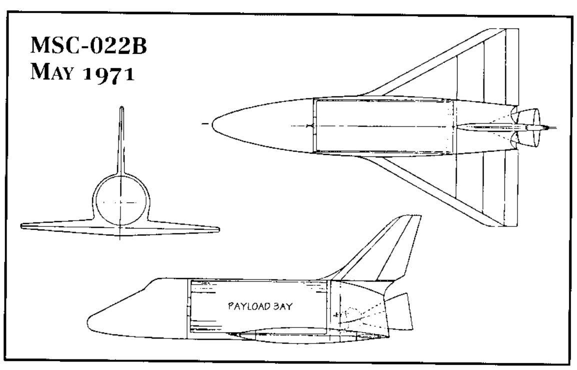
This was basically a MSC-022B with a payload bay measuring 15 by 60 feet instead of 15 by 40 feet. The MSC-024 was a 'stretched' version, with a payload bay 80 feet long.



The basic MSC-022 fuselage found itself attached to a variety of different wings, such as the swept wings of the MSC-022A (above) and the delta-wing of the MSC-022B (below).



A single 550,000 pounds-thrust engine and a 15 by 60 foot payload bay was incorporated into the MSC-025 and MSC-026, which were improvements on the MSC-022 series.



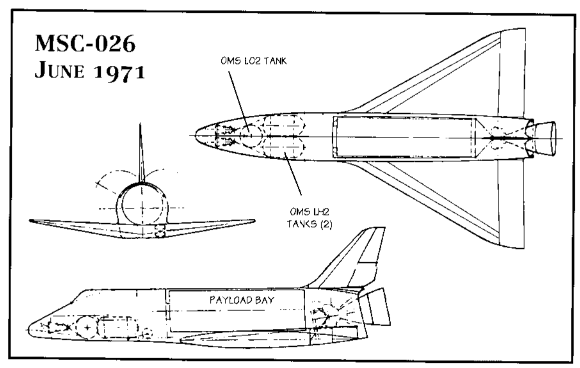
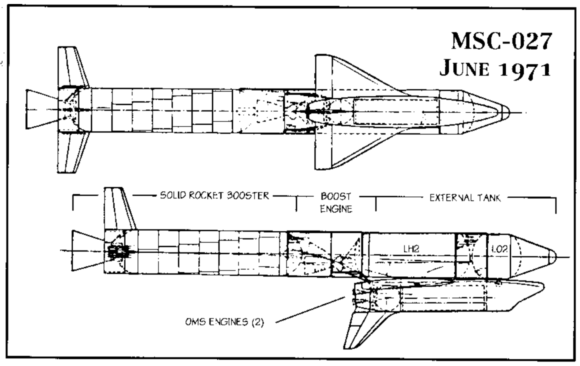
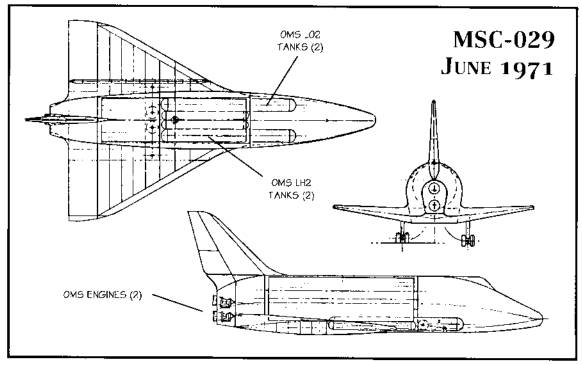


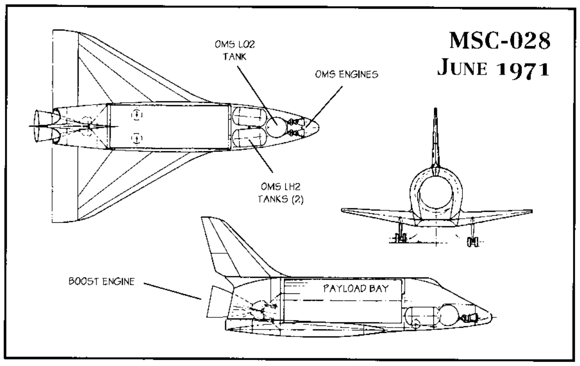
Figure 3-12 - Space Shuttle Designs: 9/70-6/71



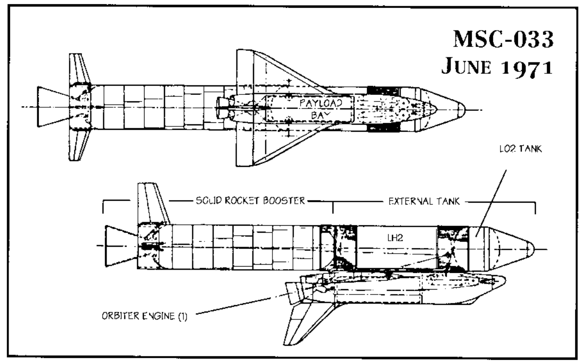
Taking the external tank concept one step further, the MSC-027 moved the main engine out of the orbiter. A 12 by 40 foot payload bay and two OMS engines occupy the fuselage.



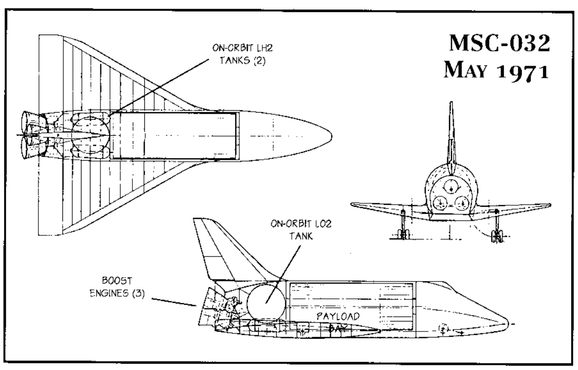
Again, the main engines were moved to the booster, and all that remained in the MSC-029 were small on-orbit maneuvering engines. Propellants were carried under the payload bay



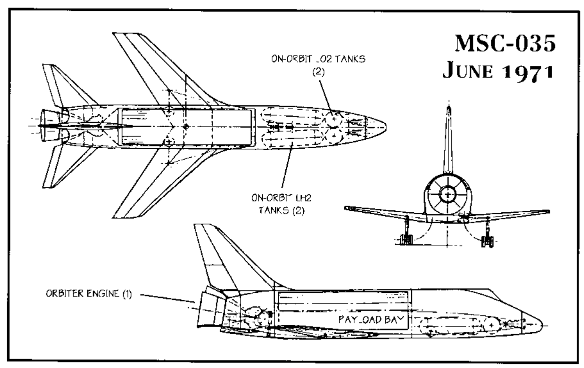
Providing a 15 by 40 foot payload bay, the MSC-028 returned to having a single large boost engine in the orbiter, although all propellants were in the external tank.



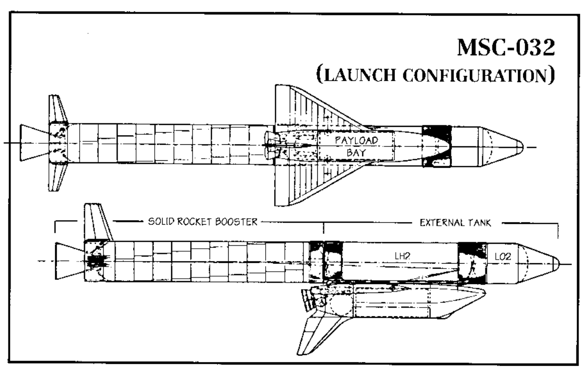
The MSC-033 reversed the trend towards larger payloads with a 12 by 40 foot bay and 20,000 pounds capacity. It was significant in that it could return with an equal payload.



The MSC-032 was converging on the design that would actually be built. It had three engines (J-2S) and most propellants moved into an external tank, ahead of the single SRB.



Two versions of this design were proposed, one with a 12 by 40 foot, 20,000 pound payload capacity (above) and the other with a 12 by 60 foot, 40,000 pound capacity (below).



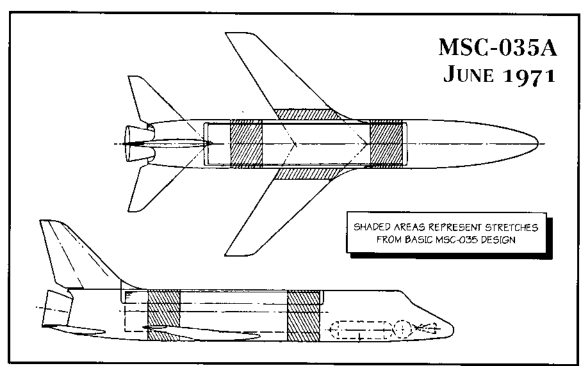
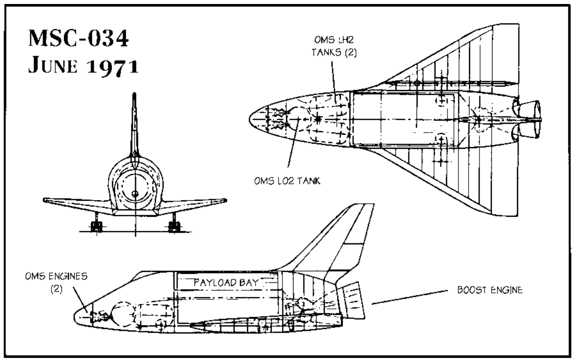
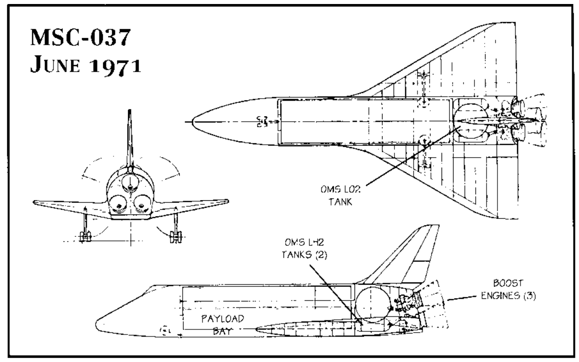


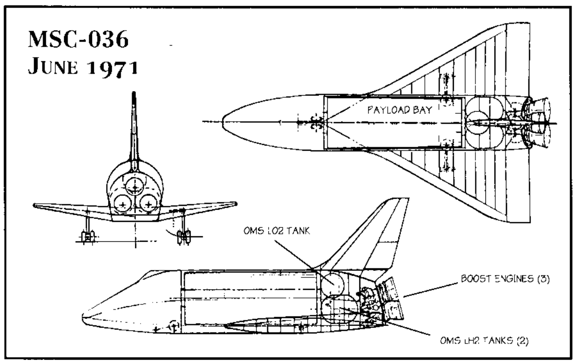
Figure 3-13 - Space Shuttle Designs: 5/71-6/71



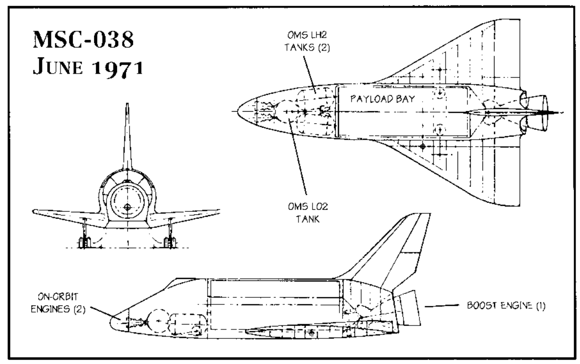
A small 15 by 30 foot payload bay was provided by the MSC-034 which was essentially a shortened MSC-023. A single large solid rocket booster was used as a first stage.



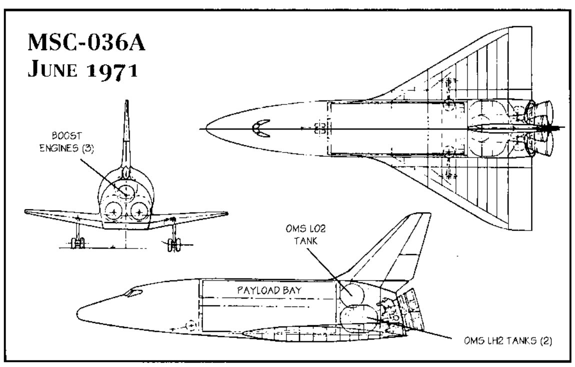
A 15 by 60 foot payload bay and three J-2S engines were features of the MSC-037. The main engines were to be operated at 15 percent thrust for on-orbit maneuvering.



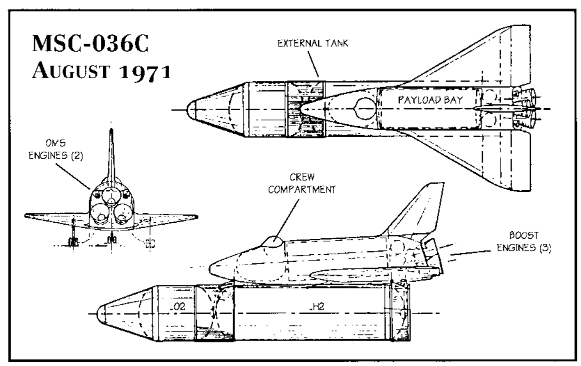
The shape of the production orbiter is beginning to show in the MSC-036. Three J-2S engines and a 15 by 40 foot payload bay capable of carrying 20,000 pounds were provided.



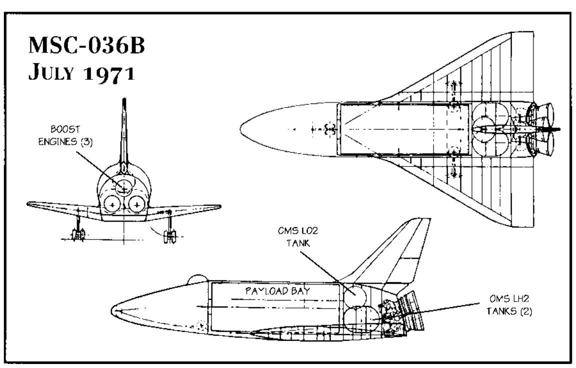
Essentially an improved MSC-036 with a single 550,000 pounds-thrust main engine, the MSC-038 still had a payload bay limited to 15 by 40 feet with a 20,000 pound capacity.



Continued refinement of the basic MSC-036 shape resulted in the MSC-036A and MSC-036B, with most of the changes being limited to the forward fuselage and cockpit.



A further refinement of the MSC-036B, this orbiter greatly resembled the MSC-040A that became the basis for the Phase C/D proposals. The payload bay measured 15 by 40 feet.



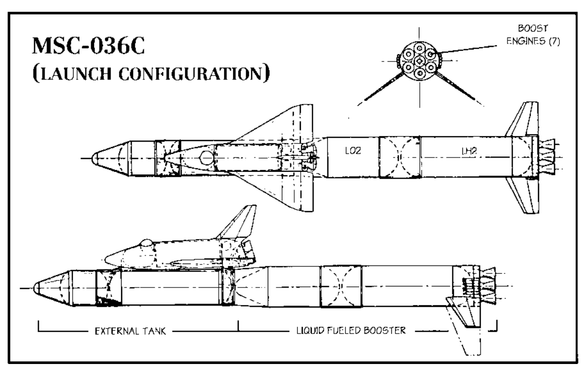
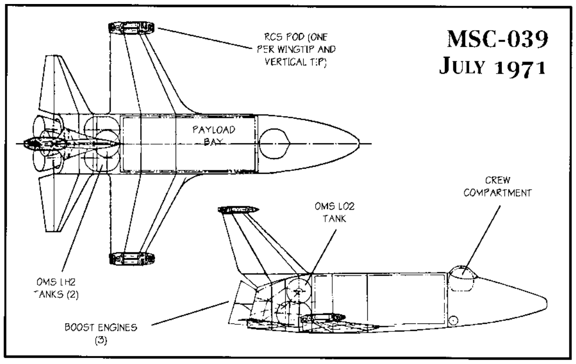
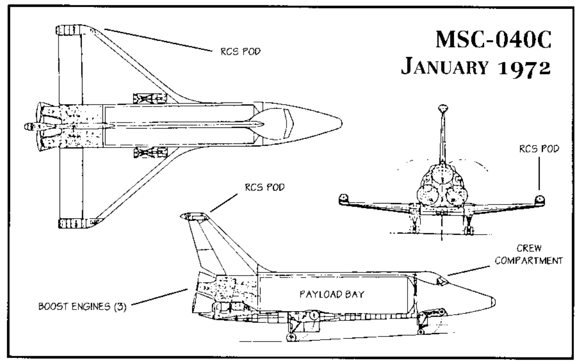


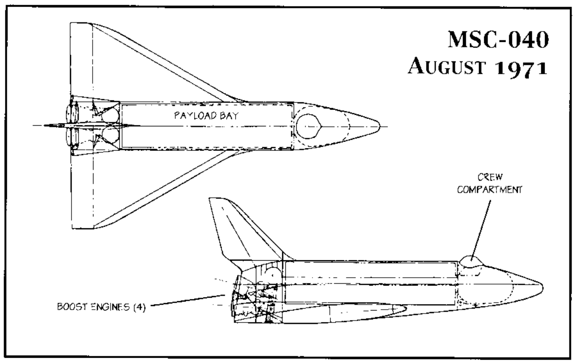
Figure 3-14 - Space Shuttle Designs: 6/71-8/71



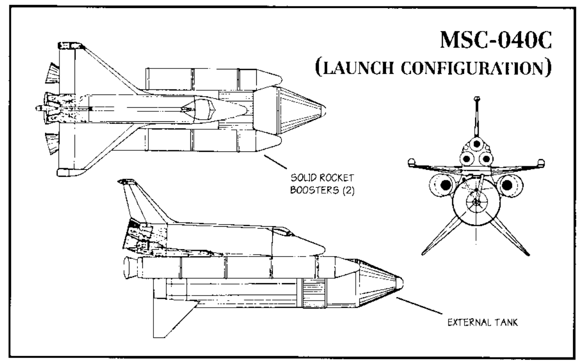
A compromise to the straight-wing, the MSC-039 used a slightly swept leading edge, along with the basic fuselage contours of the MSC-036C. Note the RCS pods on the wing-tips.



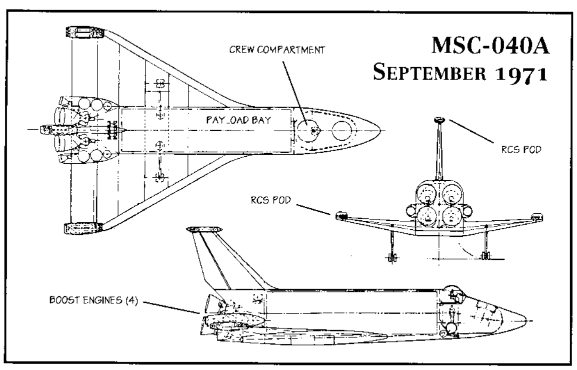
The MSC-040C represented an aerodynamic refinement of the MSC-040A shape, and would be the orbiter ordered into production, although other designs were still being investigated.



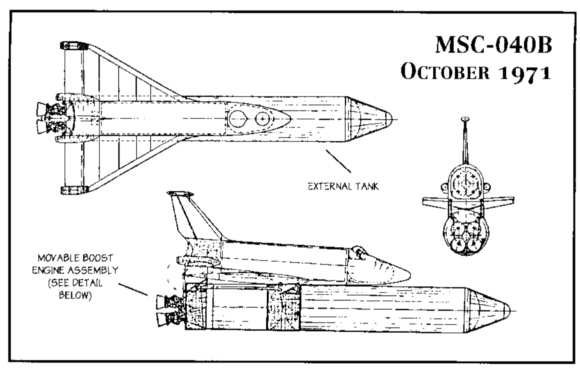
The beginning of the end. The basic MSC-040 shape was penned on 30 August 1971, and would form the basis for the production orbiters. A 15 by 60 foot payload bay was provided.



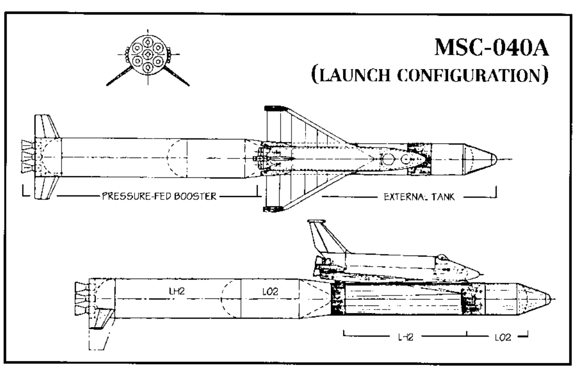
Looking much like the final product, the MSC-040C with an external tank and two 156-inch solid rocket boosters. Note the large stabilizing fins on the external tank.



The MSC-040A added RCS pods to the wing and tail-tips, and OMS pods to the aft fuselage just above the wing. The use of a single pressure-fed booster was envisioned (below).



The MSC-040B was an unsuccessful attempt to explore new propulsion concepts, such as the 'propulsion unit transfer concept' detailed below. This design was quickly abandoned.



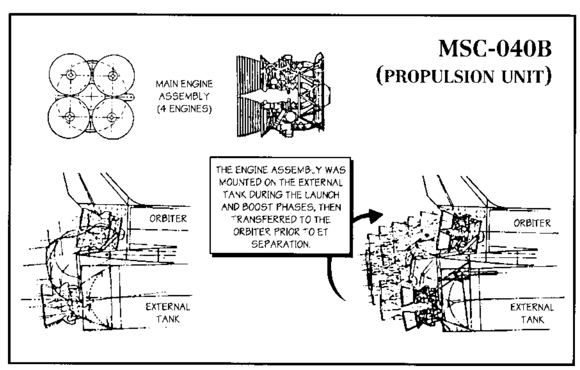
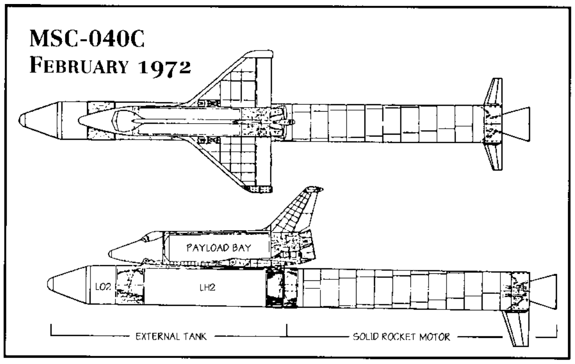
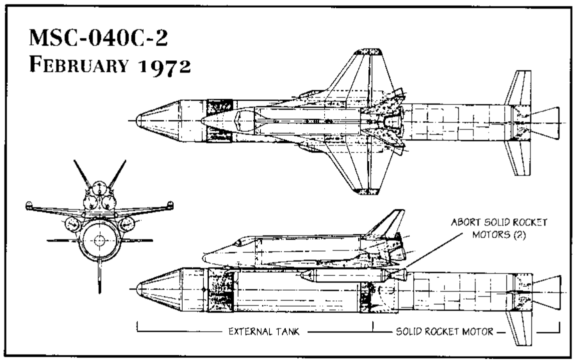


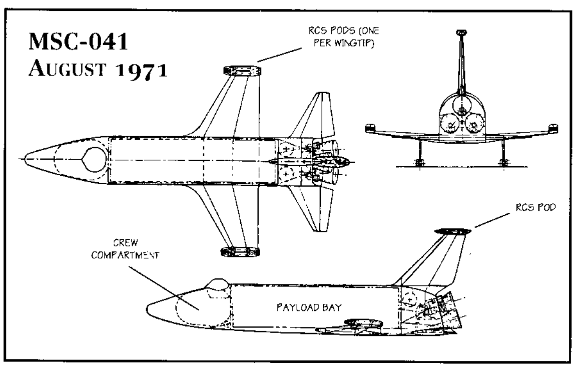
Figure 3-15 - Space Shuttle Designs: 7/71-10/71



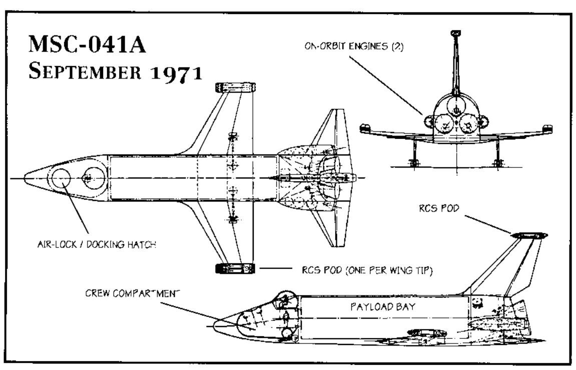
Other boosters were considered by NASA for the MSC-040C orbiter, such as this single large solid rocket booster attached to the aft end of the external tank.

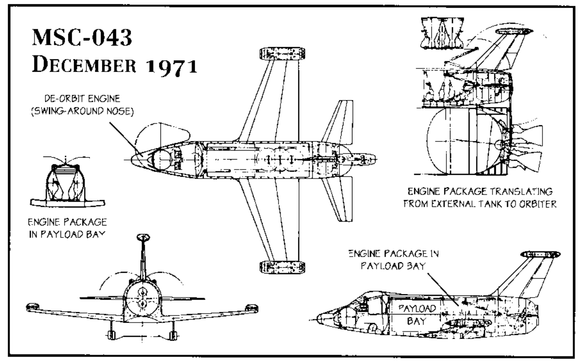


Bearing absolutely no resemblance at all to the MSC-040C, this design was the first of the 'bat' shapes that were inspired by aerodynamic research at the Langley Research Center

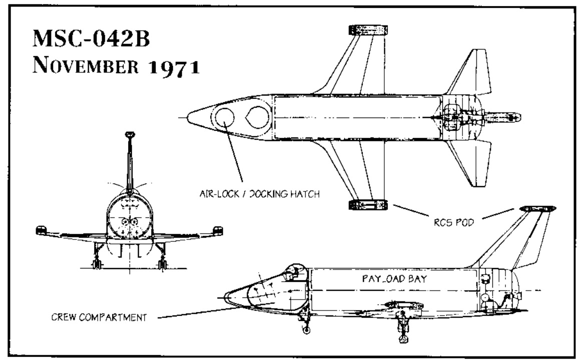


One of the last attempts by the straight-wing advocates was the MSC-041 shape. Although the payload bay had grown in size to 15 by 60 feet, its capacity was only 15,000 pounds.

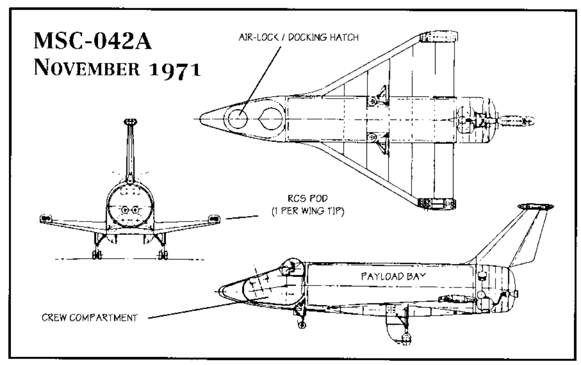




Similar to the MSC-040B in concept, this design used a complicated retracting mechanism to pull the main engine package from the back of the external tank into the payload bay



A straight wing derivative of the MSC-042A (below), this orbiter also contained no propulsion and used a Titan IIIL6 booster. A 25,000 pound payload could be carried.



Basically an MSC-040A shape minus the main engines, this design relied entirely on an uprated Titan IIIL6, essentially a Titan IIIM with six strap-on SRBs, to get it to orbit.

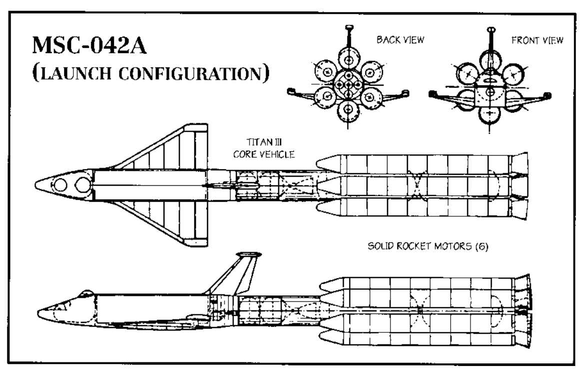
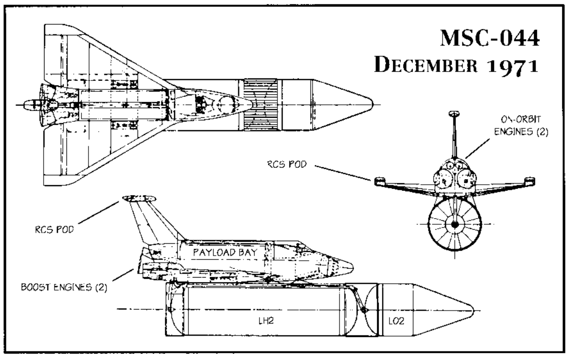
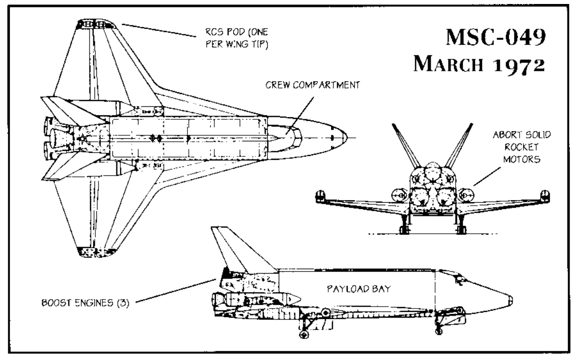


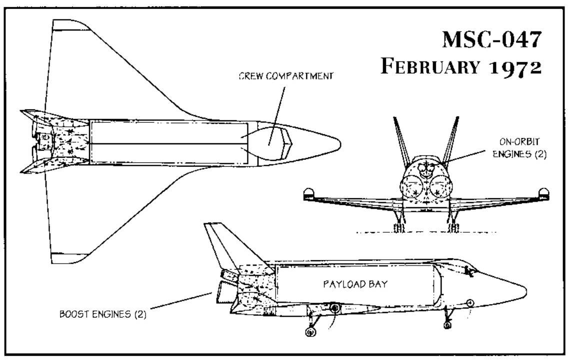
Figure 3-16 - Space Shuttle Designs: 8/71-2/72



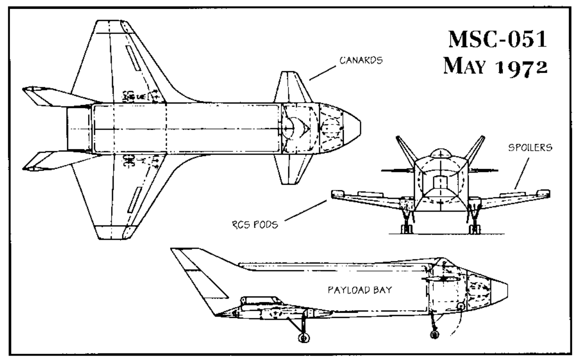
Two 550,000 pounds-thrust boosters of the same type baselined by MSFC for the ASSC study were used by the MSC-044, which could carry 25,000 pounds in a 10 by 30 foot bay.



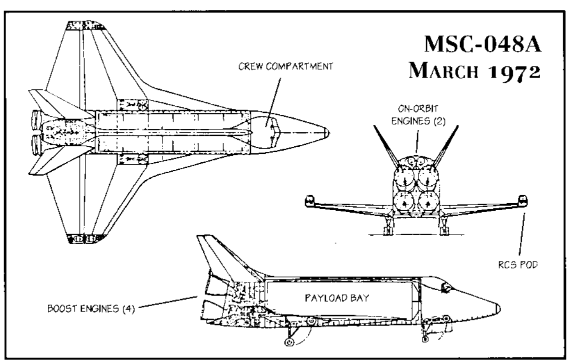
Essentially an MSC-048 with three boost engines, the MSC-049 could still carry 40,000 pounds in its 15 by 60 foot payload bay. Two 62-inch diameter abort SRMs were provided.



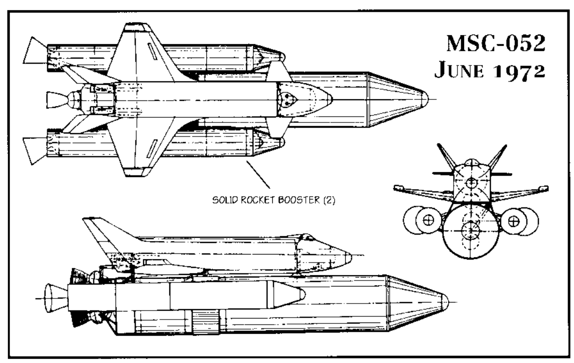
Twin vertical stabilizers marked their return on the MSC-047 design. Two ASSC baseline 550,000 pounds-thrust engines and a 40,000 pound payload capacity were featured.



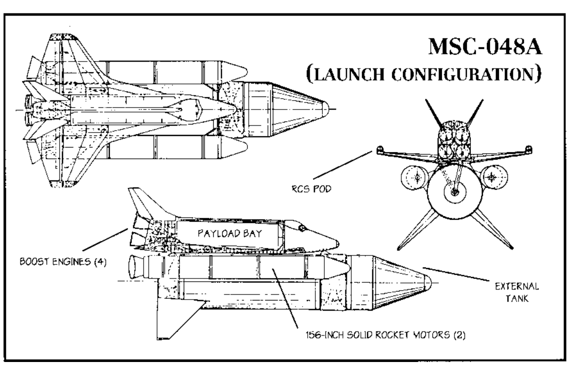
The MSC-051 had no main engines, and could carry 25,000 pounds in its 15 by 60 foot payload bay. The vertical fins were smoothly faired into the sides of the fuselage.



The MSC-048A used four 550,000 pounds-thrust engines, and could lift 40,000 pounds in its 15 by 60 foot payload bay. Several different boosters were investigated (below).



Part of the continuing research to find an method of handling the engines, this design again attempted to retract the engines into the orbiter when the external tank is jettisoned.



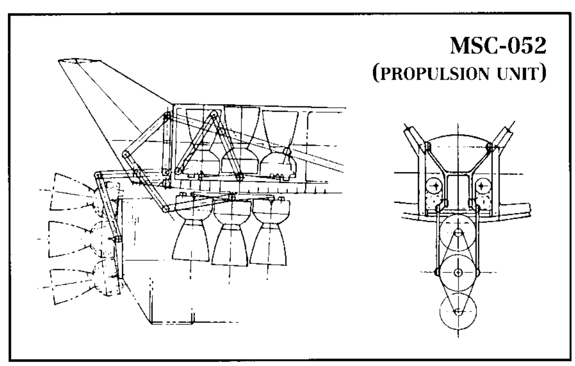


Figure 3-17 - Space Shuttle Designs: 12/71-6/72

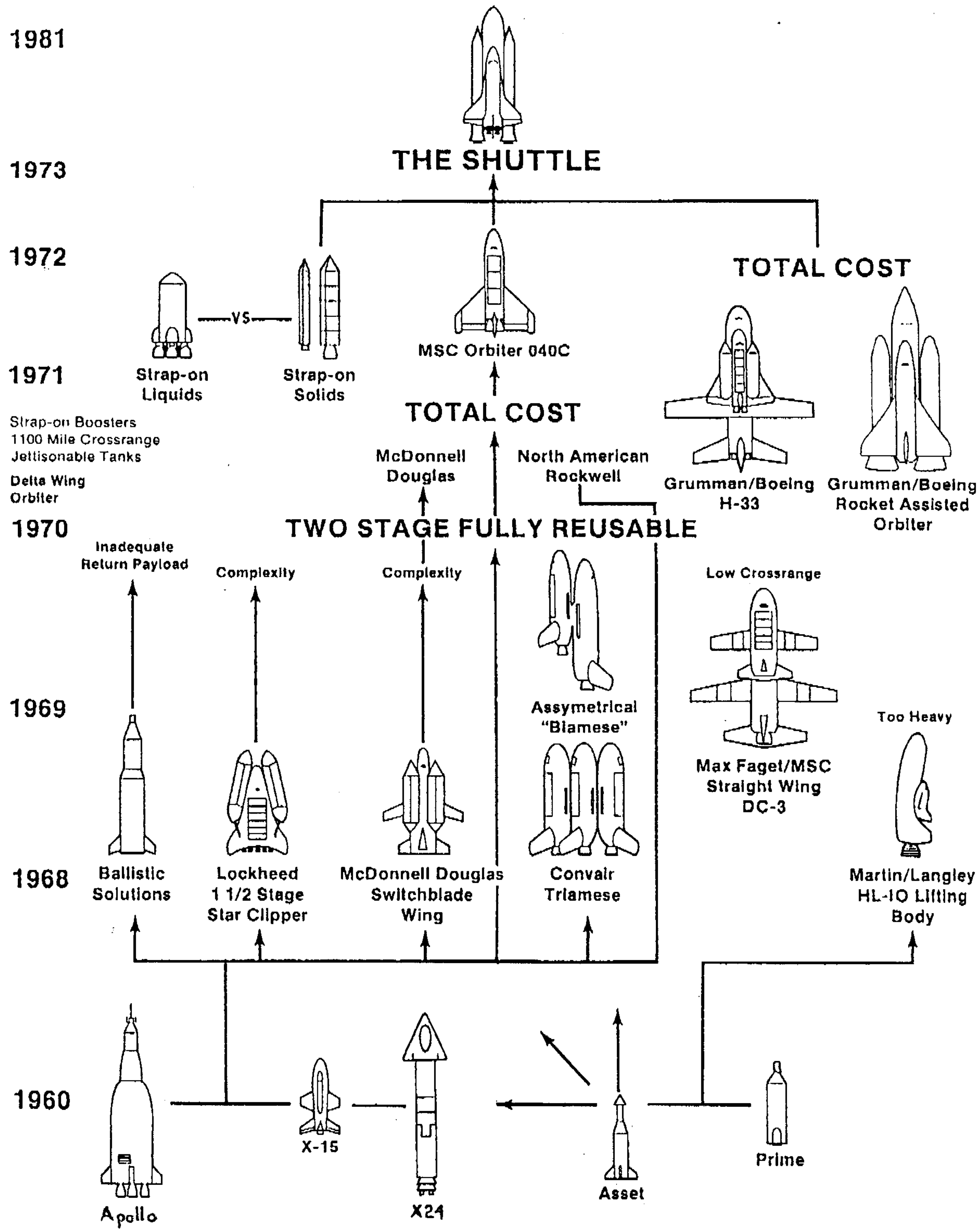


Figure 3-18 - Space Shuttle Design History Overview

Budget compromises, however, are de rigeur in Washington**.** That the final shuttle design was a compromise is anything but unusual. Federal agencies alone do not determine their program budgets; it is a long, drawn out process, with many players and varied interests. Programs compete within their agencies for funds and the agencies in turn compete with other agencies for funds within the executive budget draft. Finally, Office of Management and Budget submits its overall budget to Congress which in-turn modifies it according to its whim. Along the way it is not unusual for the agency, Office of Management and Budget, or Congress to pare a program's budget request. In fact, it is the norm. It is all part of the constant give and take of the federal budget process. Nationally recognized expert on the American budgetary process Aaron Wildavsky notes that "budgeting in any group is a process in which various people express different desires and make different judgments…More or less is easier to compromise than right or wrong."[128] Furthermore, Wildavsky reminds us that "the bicameral system complicates legislation, assuring that many votes will be taken before a final decision is made. It provides numerous opportunities for bargaining."[129] Program managers and agency officials are well aware of this and often prepare several program and budget options, leaving room to negotiate along the way. When Carter, among others, describes how the shuttle budget was gradually pared back to $6.5 billion, this should come as no surprise.

All engineering designers face technical, cost, and schedule constraints. The space shuttle was an incredibly complex research and development program that presented the developers with all of these constraints in multiple areas. Nothing like the shuttle had ever been built in the history of humankind; here was a reusable spacecraft that could carry both people and cargo to low earth orbit. In low earth orbit it could serve, *inter alia*, as a multifaceted experimental platform allowing the United States to carry out life sciences, microgravity and planetary research, and serve as a return and rescue vehicle for satellites. To determine exact costs for a project like this was an inexact science at best. Representative Preston (D-Ga.), chairman of the Congress and Related Agencies Appropriations Subcommittee, is quoted as saying that he:

[128] Aaron Wildavsky, The New Politics of the Budgetary Process (New York: Harper Collins Publishers, 1992, p. 4.
[129] Wildavsky, p. 21.

> cannot recall any project of any size that has ever been presented to this committee –that came out in the end like the witness testified it would be at the outset," the problem is not always one of self-interested bureaucrats estimating on the low side, but of not knowing how to do better.[130]

Also, it is important to understand was that there was more than one way to build this reusable space vehicle. Hence, as NASA's engineers designed the shuttle they were confronted with a myriad of options every step of the way. The engineers assigned to the shuttle project could always think of a million ways to make the shuttle bigger and better and their original designs reflected many of these desired options. DeGeorge put it well when he pointed out that a Mercedes is safer than a Pinto.[131] However, to make the Pinto approach the same level of safety would require approximately the same cost. Design becomes a balance between the competing program goals of cost, schedule, and performance.

Joe Shea, Apollo program manager, faced a similar situation during the early years of the Apollo program; there was a multitude of different ways to approach the design and overseeing the costs of the many desired options was a constant task.

> The better is the enemy of the good, Shea told them again. The biggest problem with a new product in its developmental phase, Shea thought, was that a good engineer could always think of ways to make it better…[132]

Even assuming that Fletcher was such an egomaniac as to willingly to compromise safety to ensure his legacy, it is impossible to believe that he could have succeeded in hoodwinking the world. Many analysts have reviewed this record and come to similar conclusions. Professor John Logsdon, of the Center for Space Policy Studies at the George Washington University, has emphasized that not only was there no evidence that any data were distorted, but Fletcher actually had a good grasp of the shuttle development activities.[133] Even assuming that Fletcher or other NASA senior managers were attempting to suppress unfavorable data, such a move would have had to take place in front of the thousands of people working at all levels of the program as well as in Congress, Office of Management and Budget, and the rest of the executive branch.

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[130] Wildavsky, p. 78.
[131] Richard P. DeGeorge, "Ethical Responsibilities in Large Organizations: The Pinto Case," Business & Professional Ethics Journal, Vol. 1, Fall 1981, p. 7.
[132] Charles Murray and Catherine Bly Cox, Apollo: The Race to the Moon, (New York: N.Y.: Simon & Suhuster, 1989), p. 175.
[133] John Rhea and Tony Reichhardt, Correcting the Mistakes of the Past: A Conversation with John Logsdon, Space World, August 1986, p. 12.

NASA is the subject of numerous congressional hearings. Many of these hearings, spearheaded by Sen. Walter Mondale, were aimed at nothing less than killing the shuttle program outright. They questioned the basic need for the vehicle; they were skeptical of NASA estimates on flight rate and costs; and they attempted to convince their fellow legislators the funds could be better used elsewhere. Mondale and his allies lost the argument. Sixty-one senators voted, in May 1972, to endorse the program. These votes came after the facts of the program, its risks, and the alternative uses for the funding had been debated at length. Certainly any data that indicated the system might be less than safe would have been used in the argument.[134]

As an executive branch agency, NASA is closely monitored. With the close of the Apollo era, NASA entered into a new relationship with the executive branch. Rather than enjoying the relative freedom provided to meet the goal of landing on the Moon, the agency had to compete with other federal agencies for the limited federal dollars. With the nation facing a considerable domestic agenda and the War in Vietnam raging in the Pacific, these funds were not easy to come by. NASA estimates, both technical and fiscal, were scrutinized carefully by the Office of Management and Budget and the Office of Science and Technology. Thousands of pages of documents were provided to the executive branch to whet their appetite for more detail. In the end, the Office of Management and Budget became an almost surrogate designer for the shuttle system.[135] Data were shared freely and no one raised any questions about the safety of the booster system.

NASA's activities are public and widely reported in the press. As would be expected when dealing with a completely new spacecraft, the interest in the shuttle from the technical press was high. Publications such as *Aviation Week and Space Technology* and *Space World* published extensive articles on the design and the status of system development. They chronicled any difficulties encountered and kept close tabs on slips in the schedule. The shuttle also captured the imagination of the general public. Newspapers and periodicals across the country printed articles on the program. Some of these were critical, even questioning the safety of new technology, such as the heat resistant tiles that covered the vehicle or the complexity of

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[134] Claude E. Barfield, "Technology Report: NASA broadens defense of space shuttle to counter critic's attacks," National Journal, 19 August 1972, p. 1323.

[135] See Appendix D

the huge shuttle main engines. Prior to *Challenger*, no one wrote publicly that the solid rocket boosters would one day lead to a catastrophic system failure of the space shuttle.

There are literally thousands of people working on the program and each was free to report any problems. NASA has long maintained a tradition of openness in discussing potential issues. In addition to the normal management reporting chain, individuals could raise questions in decision forums that cut across organizational lines. Finally, an individual who remained dissatisfied could discuss it directly through one of the several anonymous safety hotlines.[136]

The NASA and external safety oversight was present throughout the program. In general, the successful management structure used in Apollo was adopted for the shuttle program. NASA had great success using this structure, and it had demonstrated resiliency during crises such as the Apollo 1 fire and later the Apollo 13 failure. Safety checks and balances had functioned as designed, with the triumph of Apollo proving its worth. As one method for reducing risk, NASA chose to follow this management template for developing the shuttle.

Finally, the alternative liquid fueled boosters were a completely new design and had many moving high pressure components that produced its own set of safety concerns.[137] Liquid boosters were complicated, and would have been difficult to recycle. No existing designs could be used intact or adapted to fit the shuttle needs. In fact contrary to what many would like to believe today the judgment of the engineers at the time was that the solids rocket boosters were the less risky choice. Dennis Jenkins writes that:

> It was felt that the separation dynamics related to the series-burn systems [solids] were significantly more straightforward than those for a parallel-burn system [liquids]. Experience and relative risk were in favor of the series-burn systems because of the long history of successful sequential staged launches (Titan, Saturn, etc.)…It was felt that the liquid propellant system was more flexible because of the ability to tailor the thrust at almost any point in the ascent phase, however, the development risk appeared to be in favor of the solids because of their greater simplicity and that recovery of the liquid boosters presented more of a challenge, since they were more fragile. Ground handling of the solid boosters was also considered easier.[138]

[136] NASA Procedures and Guidelines: 8715, Section 1.1.8.
[137] Jenkins, p. 123.
[138] Jenkins, p. 123.

In contrast, no solid rocket booster had ever failed; presenting a record that made such boosters an attractive choice for a safety conscious NASA. The design was an adaptation of that used successfully on the Titan III rocket and their simplicity aided in refurbishment and their reliability reduced the need for extensive proof-of-concept testing. As Dale Myers, Head of the Office Manned Space Flight, at the time remembers that:

> There was also a 100 percent reliability record for large solids at that time. In the final review concerning choice of solids or liquids, we were presented evidence that we could cancel the solid motor thrust in flight, and even abort from them. Later, we found that we could not escape from the solids, but would be better off riding them out. But, at the time, we concluded that we had very low development cost, very high reliability, an abort capability, and a means of reducing the cost per flight by recovering and reusing the solids.[139]

The space shuttle program has been a tremendous success. NASA developed a re-usable space system that is the most technologically advanced and complex machine on Earth. There have been as many shuttle flights flown in five years as there were manned Mercury, Gemini, and Apollo flights flown in ten years, with enough space age firsts to fill an almanac. If the shuttle flights up to *Challenger* were tacked "on to Mercury, Gemini, Apollo, Skylab, the record would show that over a 25-year period NASA had successfully flown 133 men and women in space without an in-flight loss of life."[140]

Did Senior NASA officials willingly make unwise compromise after unwise compromise in an attempt to keep the program alive and quench their personal egos? This is simply too difficult for serious analysts to accept as "the root cause." To say that NASA was perhaps too optimistic in its calculations about the capabilities of its systems and had to operate within a political era of rapidly and significantly constricting budgets is closer to the truth. NASA's comptroller during the shuttle design and development years, Tommy Newman, likes to remind people that "anyone who thinks that they can launch a rocket and return it safely also thinks they can do it cheaper and quicker. You've got to be an optimist in this business".[141] But remember, the original cost estimates for the system assumed a 50-60 flights schedule, a second launch port in California and a fully reusable system.[142] Their were so many different decisions made on the

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[139] Myers, p. 44.
[140] Michael Collins, Liftoff: The Story of America's Adventure in Space, (New York, N.Y.: Grove Press, 1988), p.
[141] Interview, 7 January, 1992.
[142] Myers, p. 44.

path to the space shuttle and variables and factors complicated and intertwined that to directly link all these decisions into a conspiracy theory is just too difficult to accept as the root cause.

3.1.2.2 Hypothesis 2

> The NASA culture, blinded by its successes, collectively engaged in groupthink.

Several analysts, including Diane Vaughn and Russell Boisjoly, attribute the root cause of the accident to a NASA culture which had grown arrogant with its continued successes and collectively began to think that they could do no wrong. NASA had never experienced any injuries or deaths during a space flight. The only fatal accident involving a flight crew had occurred twenty years in the past, and occurred during a ground test. The success of the shuttle had been stunning. This success gave NASA and its contractors great confidence in the system used to develop and operate the shuttle. The basic rubric was that if one followed the proper procedures, success would result.

Proponents of this hypothesis contend that an air of invincibility led NASA managers to ignore the warning signs that had been slowly building over the years. In addition to the identified design problems, NASA had operational evidence that there was a problem with the solid propulsion system. As early as the second space shuttle mission, erosion could be seen in the solid rocket boosters. The first sign that the joint sealing system did not perform as expected came on this mission, which took place in November 1981. When the solid rocket boosters used on that mission were retrieved for disassembly, the engineers found erosion in the primary O-ring on one joint. Morton Thiokol engineers postulated that this erosion was created by holes in the putty that allowed heat to reach the O-rings. However, this unanticipated finding was not recorded in the program's anomaly tracking system and was not discussed at the STS-3 Level 1 Flight Readiness Review as were other STS-2 anomalies.[143]

Continuing and sometimes more severe erosion was found on several later shuttle missions. The O-ring erosion appeared again on STS-41B mission that flew in February 1984, with two separate joints having erosion of the primary O-ring. This anomaly was entered into the program's problem tracking system, but its resolution was not documented as a constraint on future flights. The rationale used was that the extent of the erosion was well within the maximum amount considered safe as determined from analyses conducted by NASA and Morton Thiokol.[144]

The STS-41B mission also was the second mission that had solid rocket boosters that had been subjected to a modified joint leak check used to ensure that the O-rings were properly installed in the joints. NASA had doubled the pressure used in the checks from 50-pounds/square inch to 100-pounds/square inch. After this change was made, 56 percent of all subsequent missions had erosion of at least one O-ring in the solid rocket booster nozzle joints. After the test pressure was increased again to 200-pounds/square inch, 88 percent of flights had erosion or blow-by of hot gases past the O-rings. In response, NASA asked Morton Thiokol to conduct tests to determine if the increased leak check pressure was creating blowholes in the insulating putty and allowing hot gases to reach the O-rings.[145]

Despite these ominous warning signs NASA continued to fly. The STS-51C mission, launched in January 1985 experienced a new level of erosion and blow-by in the joints. For the first time, a secondary O-ring had indications that it had been exposed to heat during the time the booster was fired. In addition, in the joints where erosion occurred, the erosion was almost a third of the way around the circumference of the booster. This launch was the coldest to date for the shuttle program and engineers believed that the O-rings could have become less resilient, contributing to the increased erosion. Tests conducted subsequently by Morton Thiokol confirmed that the O-ring performance was sensitive to temperature with colder temperatures making the O-rings stiffer and slower to react.[146]

In June 1985, the STS-51B mission produced a still higher level of erosion, with the first evidence that a primary seal had failed to operate at all. At this point, Marshall managers placed a launch constraint on the system. These lower level managers for all flights that followed, including STS-51L subsequently waived this constraint.[147] Marshall and Thiokol managers discussed the erosion problem with program level managers, but recommended that flights

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[143] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 125.
[144] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 128.
[145] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, pp. 133-134.
[146] Vaughan, p. 153.
[147] Vaughan, p. 153.

continue.[148] Also at this time, Morton Thiokol formed a group to study the erosion problem and recommend design changes that would eliminate the erosion. No design changes were made prior to the STS-51L launch.

As the solid rocket boosters continued to work despite the warning signs, NASA management grew bolder and bolder relaxing the readiness of flight requirements governing what was acceptable erosion. As a result of further high-pressure tests of the solid rocket booster joints, Marshall managers changed the criticality rating of the booster in December 1982. The tests had shown that the second O-ring did not provide the redundant seal as previously thought. At this point, NASA chose to accept the single primary seal as sufficient for continuing to fly. The rationale provided in the NASA documentation for accepting a single or "simplex" seal was:

> The Solid Rocket Motor case joint design is common in the lightweight and regular weight cases having equal dimensions. The joint concept is basically the same as the single O-ring joint successfully employed on the Titan III Solid Rocket Motor. On the Shuttle Solid Rocket Motor, the secondary O-ring was designed to provide redundancy and to permit a leak check, ensuring proper installation of the O-rings. Full redundancy exists at the moment of initial pressurization. However, test data shows that a phenomenon called joint rotation occurs as the pressure rises, opening up the O-ring extrusion gap and permitting the energized ring to protrude into the gap. This condition has been shown by test to be well within that required for safe primary O-ring sealing. This gap may, however, in some cases, increase sufficiently to cause the unenergized secondary O-ring to lose compression, raising question as to its ability to energize and seal if called upon to do so by primary seal failure. Since, under this latter condition only the single O-ring is sealing, a rationale for retention is provided for the simplex mode where only one O-ring is acting.[149]

In addition, program waivers were continuously approved, which allowed launches to proceed in violation of standard processes. This change in criticality status required a waiver of the shuttle requirements that "the redundancy requirements for all flight vehicle subsystems… shall not be less than fail-safe. 'Fail-safe' is defined as the ability to sustain a failure and retain the capability to successfully terminate the mission."[150] Level 2 (mid-level) and Level 1 (program) management in March 1983 approved this waiver.[151]

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148 Vaughan, pp. 164-165.
149 Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 126.
150 Vaughn, p. 129.
151 Vaughn, p. 133.

These issues surrounding the solid rocket booster joint seals, which had been developing over the last decade surfaced again in the hours prior to the *Challenger* accident. As the launch approached and it became evident that the temperature would be colder than ever before experienced, the NASA and Morton Thiokol personnel once again discussed the possible effect of temperature on the launch decision and once again decided to go fly. NASA managers from the Marshall Space Flight Center discussed the issue at length with the Morton Thiokol engineers. Cold temperatures were considered a problem, but there were no requirements or restrictions on launching in such conditions. The technical evidence showed a vague link between the temperature and seal performance, but these data were not conclusive. Without indisputable data to back up the claims, the Morton Thiokol engineers were overridden first by their own management and then by NASA. Larry Mulloy, the Marshall Space Flight Center manager responsible for the solid rocket boosters, summed up the issues by asking the engineers if he should wait until April to launch when the weather was warmer.

Reviewing the decision process used the night before launch, Moorhead., et. al., write "The Presidential Commission that investigated the accident pointed to a flawed decision-making process as a primary contributory cause…. In this paper, we report results of our analysis of the Level I Flight Readiness Review meeting as a decision-making situation that displays evidence of groupthink."[152] To support their argument, one needs only to look at the NASA decision making process. All parties were convinced that if they followed the mandated procedures, the safety of the system would be maintained. At no time did anyone step outside the system to view critically its capability to make tough decisions with less than concrete data. It had always worked in the past, they were following the rules, and therefore it would work for this launch.

Vaughan contends that the pressure toward uniformity described in groupthink was present, but that it derived from the NASA culture and structure. She argues this pressure originated in

- principles of the original NASA culture from its early history,
- the bureaucratic accountability derived from the management structure,

[152] Moorehead, et al., p. 540.

- the political accountability required of NASA in the public environment of the mid-1980's.[153]

NASA had entered into a virgin field when it began to develop human space flight. These managers and engineers were accustomed to going into uncharted territory. The can-do attitude had served them well in past programs and had become ingrained in the NASA culture. At the same time, however, the agency had aged in the time since the Mercury program. What were once *ad hoc* procedures, were now inviolate rules of business. Guenter Wendt, the Pad Leader for the Kennedy Space Center launch complex, recalls that they decided smoking was a bad idea when they realized that oxygen was being vented on the pad. Now, smoking is not allowed anywhere in the vicinity of the launch complex. In a second example, the STS-1 crew did not launch on the first attempt and were left sitting on their backs for six hours. Six hours became the limit for the duration of launch attempts.[154] The loose organizational structure had become a rigid organization chart controlled by the civil service system. In this new environment, everyone made sure that they had performed their task to the letter. However, few considered whether they were executing the proper task or how these tasks fit together. This situation is illustrated by the Presidential Commission discussion of the decision to launch the *Challenger*. The Commission found that all parties executed the procedures, but that uncertainty surrounded whether Rockwell International or NASA understood the meaning of the results of their actions.[155]

Kovach and Render are equally harsh in their judgment, condemning the agency by writing "The management style of NASA managers, revealed through a series of tests conducted between 1978 and 1982, is characterized by a tendency not to reverse decisions and not to heed the advice of people outside the management group." [156] They further assert that NASA managers were trained to believe that their world was so complex and so unusual as to make advice from outside observers irrelevant. When forced, they listened patronizingly to these advisors and continued to behave as they had in the past. This group viewed the situation as "us

[153] Vaughn, pp. 211-214.
[154] Interview, Johnson Space Center Oral History Project, 23 January 1998, NOH-OHP-14.
[155] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 117-118.
[156] Kenneth A. Kovach and Barry Render, "NASA Managers and *Challenger*: A Profile and Possible Explanation," IEEE Engineering Management Review, Vol. 15, March 1988, p. 2.

vs. them" and did not consider seriously changing their basic assumptions on flight safety. NASA's decision to continue to fly the shuttle in the face of evidence concerning solid rocket booster seal erosion is indicative of this groupthink mentality.

Operating within its system, NASA followed its standard procedures and all relevant management agreed to the changes. When the solid rocket booster joints did not behave as anticipated NASA and Thiokol changed the rules, convincing themselves that "now we understand it." The path to the launch of *Challenger* was well documented inside the NASA process. With no action taken without the proper paperwork, it is easy to see that NASA's safety system was ineffective in stopping the erosion of flight safety. Changes in launch rules were made based on incremental evidence derived from what had happened in preceding flights. For example, in the first appearance of blow-by of the hot gases in the solid rocket booster joint, NASA was not too concerned because the secondary seal was available. The agency rationalized that although gases were unexpectedly leaking by the primary seal, the secondary seal would prevent any damage to the solid rocket booster. By the time it was determined that the secondary seal did not provide redundancy as previously thought, NASA had determined that the actual charring of the primary O-ring was acceptable as long as it did not exceed a certain percentage of the total seal. When this limit was exceeded, NASA continued to believe that the charring was less than the amount which would present any danger.[157]

Perhaps the most damning evidence that NASA was seized by groupthink is that no one stood up and said absolutely that the flight should not launch. After the accident, many people came forward to express their doubts about the wisdom of launching in such cold weather. Others stated that they had known that the O-rings were not performing as intended, but had not alerted top-level management. These after-the-fact statements provide insight into the prevailing attitude prior to the launch. These sincere individuals, who could see so clearly after the *Challenger* failure, saw nothing prior to the shuttle's launch – they were all collectively engaged in groupthink.

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[157] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 126.

3.1.2.2.1 Flaws with Hypothesis 2 as the Root Cause

Although there is no doubt that the decision to launch was a mistake, this hypothesis identifying groupthink as the "root cause" ignores several important factors. First, proponents of this hypothesis conveniently forget that this is the same culture that successfully took our country to the Moon and back again safely against overwhelming odds. The NASA workforce was composed of people with great confidence in their abilities, and there were many with egos to accompany this confidence. The overwhelming impetus was to perform the job right and this included doing it safely. These individuals would argue vociferously for their position, but never according to former space shuttle flight controller, Dave Herbek, would they meekly attempt to "go along to get along." [158][159]

This culture actively promotes identifying dangers publicly and dealing with them openly. NASA had many mechanisms for elevating problems. In fact, according to Edward Pickett, a long-time flight controller, it was considered a service to the team to uncover problems so that they might be fixed. Any person could work the issue through their management chain.[160] As an alternative, the person could present any issues to the management boards that controlled the space shuttle program. These groups were not part of the line organization, but dealt specifically with shuttle problems. A third alternative was to enter the concern into the safety alert network maintained by the safety organization as outlined in the controlling document for the space shuttle program, NSTS 07700. Finally, the NASA Office of the Inspector General was available to look into technical or management issues within NASA. All such calls were taken seriously and investigated.

The participants were accustomed to facing new challenges and overcoming them as a coordinated team. The participants in the shuttle program knew they were following an uncharted path by continuing to reuse a space vehicle. Much attention was paid to identifying, monitoring, and analyzing trends in the behavior of the shuttle systems. The results were discussed in decision meetings and were circulated widely within the community. However, this teamwork should not be confused with the disappearance of individual initiative. It was

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[158] Flight controllers are the individuals who monitor the health and status of the Space Shuttle while it flying. These controllers follow the progress of each mission and advise the astronauts on how to accomplish their mission.
[159] Interview, 17 September 1998, David Herbek, Space Shuttle Flight Controller, 1981-1992.

expected, and came about, that there would be disagreements among team members who each were trying to make the vehicle as safe as possible. The program was driven largely by the consensus decisions developed as a result of these sometimes-heated disagreements. However, once decisions were made, all members of the team implemented them.

The O-ring seals, while a critical component, were one of many issues being worked every flight and did not receive any treatment different from the way other complicated technical issues were being handled. They were not, as some analysts would contend, ignored. Rather, no one was really completely sure of the design limits of the solid rocket boosters. The data, as presented to management prior to the *Challenger* failure, were far from conclusive. The data showed some increases in seal erosion in colder temperatures, but some of the worst erosion had occurred at higher temperatures. Also, the launch constraints carried temperature limits for many systems. Such restrictions were not present for the solid rocket booster seals. The argument that raged between the Morton Thiokol engineers and management over these points on the night before the launch indicates anything but groupthink. Making management decisions and having them carried out was a normal part of doing business, not evidence that all involved were collectively deluding themselves. While in hindsight it was evident that cold weather adversely affected the seals this data was not inconclusive prior to launch and only became clear once the evidence provided by the failure of the *Challenger* mission had been placed in the puzzle.

Also, NASA and the contractors had in place a myriad of anonymous reporting channels that could have been easily accessed had Roger Boisjoly[161] or any other member of the NASA team so desired. Following the accident, several people came forward to state that they knew it was unsafe to launch the *Challenger* on its final mission. These statements give rise to a series of questions. If they knew, why didn't they take advantage of the independent channels for reporting issues? While this wisdom made public only in hindsight may have shown a crisis of will on these people's part the night before the launch, it certainly does not support a charge of groupthink.

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[160] Interview, 10 October 1997, Edward Pickett, Gemini, Apollo, and Space Shuttle Flight Controller, 1964-1984.

[161] Roger Boisjoly was a staff engineer at Morton Thiokol at the time of the *Challenger* accident. He has been widely cited in many articles and books as arguing against the launch of *Challenger*. He was a member of the engineering team that was responsible for investigating anomalies with the O-rings and was part of the famous late night telecon the night before launch.

NASA manager, Larry Mulloy, responsible for the solid rocket boosters followed the procedures to the letter, asking no one to subvert the standard process. Following the explosion, Mulloy was accused of forcing the Morton Thiokol management to accept his position that it was safe to launch the shuttle. The evidentiary record does not support this allegation. He argued his case strongly, but stated repeatedly that he would not give the go-ahead without support from Morton Thiokol. He allowed all parties to state their positions, and gave each additional time to develop more data that brought more insight into the situation. Throughout the debate, he adhered to the long-standing decision-making mechanisms within the program, insisting that the Morton Thiokol management document its decision to launch and sign the Certificate of Flight Readiness before he told the Level II management that he supported the decision to launch.[162]

NASA is regularly subjected to congressional and Government Accounting Office investigations as well as numerous independent advisory board and panel reviews. Many of these reviews focus on the NASA management structure and its impact on the way each program, including the shuttle program, are executed. These reviews consider safety of paramount importance. The findings and recommendations from these reviews emphasize ways to reduce costs and streamline interfaces across the agency. During the period prior to the *Challenger* failure, none identified the management structure as adversely impacting flight safety, or as preventing risks from being identified and acted on. None of them ever cited this emerging groupthink culture as a potential problem

Disregarding the above reasons, this hypothesis falls short of constituting the "root cause" for a very simple reason. In the aftermath of any system failure, it is easy to point to the decisions made by any group and assign responsibility for errors in them using groupthink or culture as the reason the failure occurred. At one time or another many major failures have been attributed directly to groupthink including The Bay-of-Pigs, the Diem Coup, Watergate, and of course *Challenger*.

Were the proponents of this hypothesis not doing exactly what Erving Goffman predicted they would do – finding what they are looking for and arriving at a predetermined answer?[163] In

[162] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, pp. 96-97.
[163] Erving Goffman, Frame Analysis: An Essay on the Orgnization of Experience, (Boston: Northeastern University Press, 1986), p. 449.

a program as complicated as the shuttle program, there necessarily are decisions that must be made where it is mandatory that all members of the team follow them. Maintaining strict configuration control of the process, the status of the vehicle, and operational procedures is a group effort, but this is not groupthink. Was *Challenger* a result of groupthink any more than the Apollo missions or the first twenty-four space shuttle missions? These missions were carried out using a process identical to that followed in the preparations for the *Challenger* mission. America never would have reached the Moon if a group of individuals had not believed so strongly in their abilities that they overlooked contrary evidence and took considerable risks in reaching their goal. Hailed as great team efforts led by a visionary management team, these Apollo missions apparently are immune to such charges. One has to wonder what the literature would contain had Apollo 13 not returned successfully.

In a more recent space-related example, the Mars Pathfinder team attributes its unprecedented success directly to what many analysts would classify as groupthink. They extol its virtues of developing a tightly knit, supportive team and severely criticize the observers who had previously condemned their mission as implausible. The team dismissed outside skepticism, never doubting that they were on the right path. The NASA project manager at the Jet Propulsion Laboratory, Anthony Spear, asks, "What if we had listened to them and lost heart? What a tragedy that would have been. We had our fights and arguments, but we always got together as a team".[164]

Finally, what decision mechanism would have made the NASA team impervious to this charge? Yes, they agreed on the goals of the program and the basic approach to flying the shuttle. Yes, they accepted the decisions of management, but this was necessary to prepare the vehicle and operate it. Yes, they dealt with competing, sometimes conflicting priorities, developing a unified approach to satisfying these requirements. Does this mean that the team fell into a pattern of groupthink? Or is this hypothesis simply a convenient after-the-fact method for discovering the root cause we were looking for all along?

[164] Mark Carreau, "Pathfinder team tracks its success," Houston Chronicle, 12 July 1997, Sec. 1, p. 21, col. 1.

3.1.2.3 Hypothesis 3

> The check and balance system was out of alignment. An ineffective safety organization permitted risky decision-making.

This hypothesis, put forth by a number of analysts and labeled the silent safety program by the Presidential Commission, states that NASA's traditional emphasis on safety had been allowed to erode to an ineffective level. The final report of the Presidential Commission states:

> The Commission was surprised to realize after many hours of testimony that NASA's safety staff was never mentioned. No witness related the approval or disapproval of the reliability engineers, and none expressed the satisfaction or dissatisfaction of the quality assurance staff. No one thought to invite a safety representative or a reliability and quality assurance engineer to the January 27, 1986, teleconference between Marshall and Thiokol. Similarly, there was no representative of safety on the Mission Management Team that made key decisions during the countdown on January 28, 1986. The commission is concerned about the symptoms that it sees.
>
> The unrelenting pressure to meet the demands of an accelerating flight schedule might have been adequately handled by NASA if it has insisted upon the exactingly thorough procedures that were its hallmark during the Apollo program. An extensive and redundant safety program comprising interdependent safety, reliability, and quality assurance functions existed during and after the lunar program to discover any potential safety problems. Between that period and 1986, however, the program became ineffective. This loss of effectiveness seriously degraded the checks and balances essential for maintaining flight safety.[165]

The referenced decline came from a reduced agency-wide emphasis on safety. In the aftermath of Apollo, NASA was forced to layoff thousands of people reducing its human space flight program workforce from approximately 35,000 in 1966 to 15,000 in 1981 (Figures 3-19, 3-20).[166] As a result, the staffing for safety functions had fallen to levels where the personnel could no longer be involved in the critical decision making processes. There were not enough safety personnel to attend all of the management meetings. In addition, no longer could they oversee activities at the working level where many of the critical designs were made. The simultaneous development of the orbiter, external tank, and solid rocket boosters further stretched the resources of the safety organization.

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[165] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 131.
[166] Data provided 5 October 1998 by Richard J. Wisniewski, NASA's Deputy Associate Administrator for the Office of Space Flight.

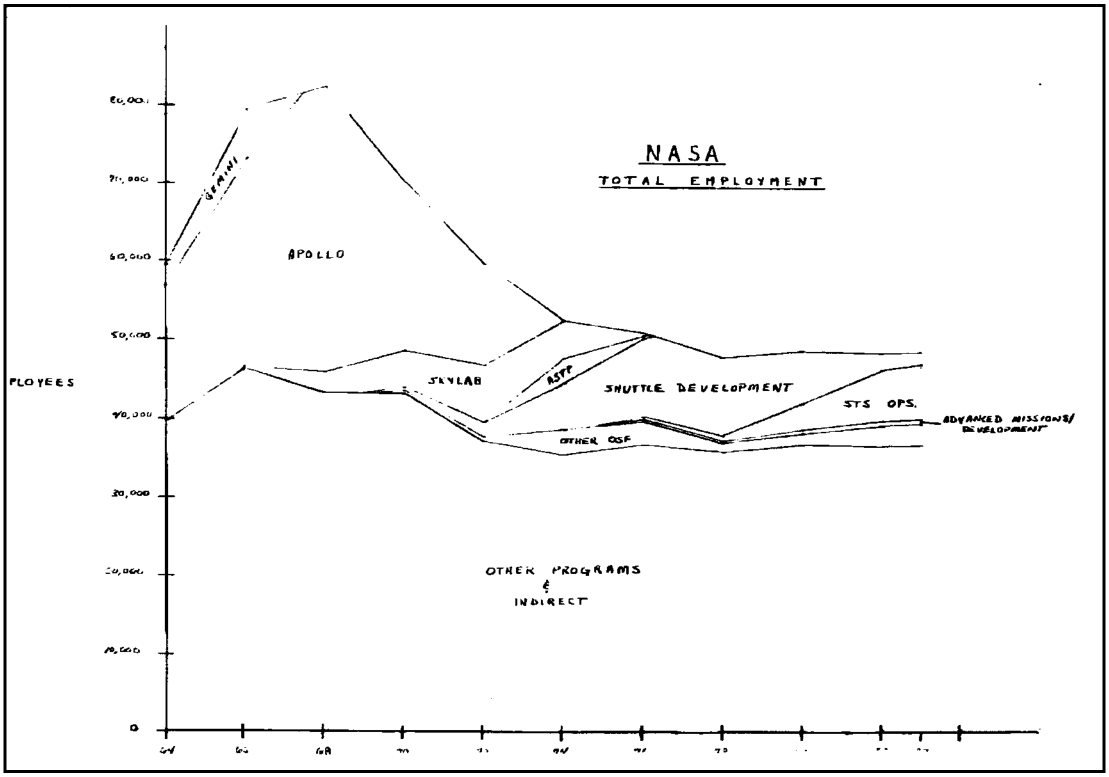

Figure 3-19 - NASA Employees[167]

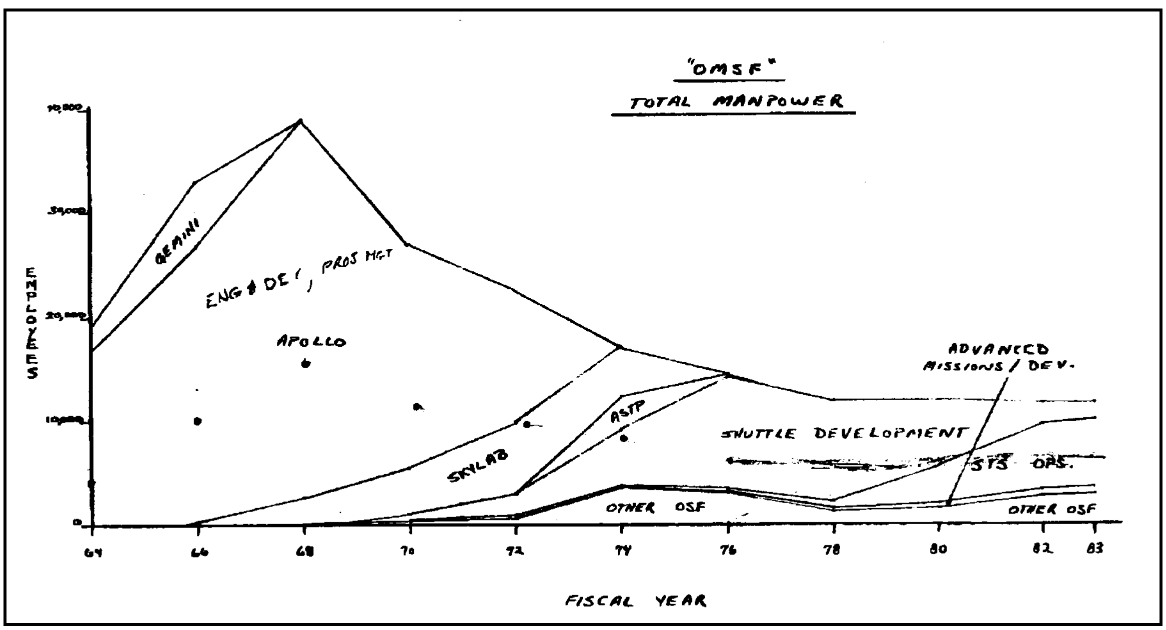

Figure 3-20 – Office of Manned Space Flight (OMSF) Employees[168]

[167] Richard J. Wisniewski, NASA Deputy Associate Administrator, Office Of Space Flight, 5 October 1998.
[168] Richard J. Wisniewski, NASA Deputy Associate Administrator, Office Of Space Flight, 5 October 1998.

After Apollo, the safety organization lost its remaining independence as NASA underwent a series of reorganizations that resulted in the safety organizations and the line organizations being combined. In this new structure, safety personnel reported directly to the managers responsible for the work to be monitored for unsafe conditions. This change had two adverse effects on the quality of the safety program. First, it became more difficult for the safety personnel to work objectively when they were criticizing the work of their colleagues and indirectly, the manager responsible for their performance evaluations. Second, in many organizations, the safety function was not assigned to specific individuals, but became the collective responsibility of all members. With all being responsible, no one was responsible.

No safety person was present during the O-ring discussions held the night before the launch. "Similarly, there was no representative of safety on the Mission Management Team that made key decisions during the countdown on January 28, 1986."[169] None of the participants thought to call one either. These discussions related directly to the safety of flight and were conducted over a period of several hours. This omission illustrates that there was no expectation that the safety organization was required to resolve working level issues. Even after Morton Thiokol management and Mulloy made the decision to launch, safety managers were not notified of any of the concerns discussed.[170] Mulloy did discuss the issues with his management, but they did not ask whether safety personnel had been involved in the process.

Several analysts argue that this reduced emphasis on safety reflects a new willingness on the part of NASA management "to launch at risk to human life". As Nicholas Carter asserts, this represents a dramatic change in culture from the Apollo program. Since its first days, NASA had a staff that made safety a priority, and the new willingness to launch at risk to human life surprised many of those who participated in the pre-launch teleconference.[171] In Apollo, NASA had the political backing and the necessary funding to proceed at a more cautious pace, and never was compelled to risk the lives of astronauts to meet schedule or accommodate other outside pressures.[172]

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[169] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 152.
[170] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 152.
[171] Carter, p. 121.
[172] Carter, p. 122.

Those participating in the decision to launch the *Challenger* did not exhibit this caution, but instead demanded reasons why the vehicle should not be launched. This approach was a dramatic shift from prior programs and even from earlier shuttle missions. The Presidential Commission emphasized this change, "In this situation, NASA appeared to be requiring a contractor to prove that it was not safe to launch, rather than proving it was safe."[173] NASA had long maintained that the team had to demonstrate that it was safe to launch. The corollary to this requirement was that if there was a known problem while the vehicle was still on the ground, it stayed there until any residual concerns were alleviated. Now, NASA was asking its contractors to prove conclusively that it was not safe to launch. Given the limited data available from the previous 24 missions, this requirement proved impossible for the Morton Thiokol solid rocket booster engineers to meet.

As a result of these reductions in personnel and changes in organizational responsibilities, NASA's safety organization was not as effective as the one that had been in place during the Apollo era. Without a strong safety organization, program managers began to take risks that were unheard of during the safety conscious Apollo era. This "silent safety program" coupled with the new willingness to "to launch at risk to human life," leads several analysts to conclude that this was the root cause of the space shuttle *Challenger* system failure.

3.1.2.3.1 Flaws with Hypothesis 3 as the Root Cause

Those who advocate this hypothesis as the root cause exhibit a selective memory of the past. Apollo, although a great success, lost three astronauts and almost lost two missions. Does this mean that the safety system in place then was flawed? While mistakes were made in deciding to launch the *Challenger*, to state that risks were not taken in the Apollo program and that NASA had acquired a "new willingness to launch at risk to human life" is naive, foolish, and unfounded. Analysts such as Nicholas Carter do not understand that spaceflight is and shall continue to be a risky business for many years to come. In remembering the great feats of the Apollo program, Nicholas Carter and those who advocate this hypothesis have selectively forgotten its many risks and dangers.

[173] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 118.

The silent safety program and the launch-at-risk arguments may have provided a subtle change in the outlook at NASA. However, to argue that NASA management had such a cavalier attitude is completely without foundation. Shuttle managers did not launch that day even though they understood there to be a greater risk to human life. They launched that day because they felt the issues being presented to them were either ill defined and without merit or they did not make a conclusive case when compared to the history of shuttle successes. NASA management may have been lulled into a sense of safety due to the history of the shuttle program, but it can be said unequivocally that NASA managers did not launch the shuttle based on accepting a greater level of risk. Testimony before the Presidential Commission by senior NASA managers led the Commission to conclude that no manager believed he was launching in an unsafe environment.[174] As Vaughn points out when showing graphical representations of the shuttle flights with and without O-ring burnthrough as a function of ambient temperature, NASA managers did not have access to such clear, concise charts. The managers had tables showing the past erosion of O-rings, but these charts were not organized by temperature at launch time. As a result, the pattern of erosion was not clearly shown.[175]

Carter states that in the early years NASA was capable of putting a man in space before the Soviet Union, but chose not to because the risks were too great.

> ...Kennedy poured money and support into space exploration. There would be no cutting corners. Things were going to be done right. Most importantly safety was made a top priority, even at the expense of losing out to the Soviets in the short run. For example, in 1961, James Webb, NASA's administrator under Kennedy (and Johnson), was under tremendous pressure to attempt to send the first human being into suborbital flight. The Soviets were on the verge of accomplishing the feat themselves, and America was ready. But Webb, like T. Keith Glennan before him, knew that safety had to come first.[176]

Contrary to how Nicholas Carter remembers history, the race to the Moon was fast and furious. NASA took risks during the Apollo program that would never be taken today. For example, about a month after the Soviets launched Yuri Alexeyevich Gagarin into space, Shepard and his Mercury Redstone were ready. Shepard's flight was designated MR-3, MR-2 was the flight of Ham, the chimpanzee, and MR-1 was an unmanned flight that failed miserably

[174] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 116-117.
[175] Vaughn, p. 383.
[176] Carter, p. 122.

when the Redstone did not lift off the pad. Placing a human in a rocket that had failed once in only two attempts has to be considered risky. Following Shepard's flight, NASA prepared for John Glenn's three-orbit mission in February 1962. Astronaut Mike Collins remembers the risks.

> The first problem confronting Yardley and his NASA customer was the Atlas booster. The Atlas had had a checkered history going back to 1946....Bob Gilruth had testified before a committee of the Congress that "The Atlas...has enough performance... and the guidance system is accurate enough, but there is the matter of reliability...Reliability is something that comes with practice." ...this reliability did not seem to be coming. Seven out of eight sequential launches were failures. Sometimes the Atlas staggered off course, sometimes it blew sky high...The Atlas was less certain. Its overall safety record was not an enviable one.[177]
>
> A year earlier Max Faget had calculated that the Atlas' record for reaching orbit safely was 40%; now it seemed even worse than that, yet at least 80% reliability was required before risking a man atop this fiery, fragile gasbag.[178]

Eighty percent! In other words, we were hoping to lose only one out of every five missions. Following the completion of the Mercury and Gemini programs the clock was quickly winding down on the decade. If America were to keep its date with destiny, NASA would have to pick up the pace. And then, in the course of this race to save our Nation's honor, there was the tragic fire aboard Apollo 1.

NASA took other risks during the Apollo years. It sent Apollo 8 to the moon with no lunar module and launched Apollo 12 into a thunderstorm. It is difficult to imagine NASA ever taking these risks today. Today, the space shuttle has a 99% success ratio (including the *Challenger* accident) and is the safest launch vehicle in the world. The argument that NASA reduced its emphasis on safety between the Apollo program and the space shuttle program is difficult to support. If anything, NASA did exactly the opposite, continuing every year to improve its safety program. The difference is not that NASA was willing to take fewer risks during the Apollo years than with the shuttle, the difference was that during Apollo these risks were acceptable. Our nation's honor was at stake.

Dr. Chistopher Kraft led Johnson Space Center , the home of the astronaut corps and mission control, through an era that is fondly recalled by analysts who ask why NASA can no

[177] Collins, p. 134.
[178] Collins, p. 247.

longer carry out its programs in the quick and safe Apollo style. In an interview, Kraft stated, "When we went to the Moon in the '60s it was risky. We were taking a chance every time we went, and anybody who says differently does not know what they are talking about. The space shuttles are infinitely more safe and reliable than anything we flew in the '60s."[179]

All of this attention is in addition to the scrutiny that results from the standard NASA safety process. Each system on the shuttle followed an identical process that identified all possible failure modes and any effects from each failure. These data were reviewed by the line managers within an organization and by the independent safety group. The joint design problems were well documented in the NASA safety files.

NASA utilized a safety analysis approach called the "Failure Modes and Effects Analysis.," which analyzed each shuttle component and determined the failure modes, i.e., the various ways the component could fail and stop operating properly. Those items that could result in loss of vehicle or crew were placed on the Critical Items List and were specifically approved by management after a determination was made to make changes to the hardware in question or simply accept the risk. The solid rocket booster Case Critical Item, noted that one of the causes of failure was "Leakage at case assembly joints due to redundant O-ring seal failures or primary seal and leak check port O-ring failures." In addition, in the Failure Effect Summary, it was noted that the ultimate result of the failure occurring was "Actual Loss – Loss of mission, vehicle, and crew due to metal erosion, burnthrough, and probable case burst resulting in fire and deflagration."

The proposed resolution of problems followed the standard processes. Decision-making boards that were composed of senior representatives from across the shuttle program evaluated each change. The membership included participants from the NASA safety organization, NASA headquarters, and the contractor management. Each item was discussed in an open forum, with the conversation and decisions recorded in meeting minutes. Occasionally, items were resolved outside the standard board process, but these were limited to those where all participants already had agreed on the decision.[180]

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[179] "Interview with Christopher Kraft, Former Director, Johnson Space Center," Space News, 24-30 August, 1992, p. 22.

[180] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, pp. 13-15..

Also, a different organizational structure does not mean that safety is being shortchanged. Is safety not everyone's job? Has anyone testified that they were pressured to not raise any safety concerns? The approach used by the shuttle program prior to the *Challenger* failure is used successfully by many technically complex organizations. For example, Southwest Airlines, the only U.S. flag carrier that has never experienced an accident involving a fatality has no safety organization. Its approach is similar to that used by NASA, with all parties concerned responsible for maintaining safety. The approach also mirrors the methodology used by the military. Squadron safety officers come from the very organization performing flight operations. As Harold Taylor, former head of Safety and Mission Assurance for the International Space Station points out, "Even the Presidential Commission recognized the effectiveness of this approach when they noted that the head of the very effective safety panel for the Apollo program reported directly to the Apollo Program Manager. It is possible to provide an effective safety program from within the organization responsible for the management of the endeavor."[181]

This hypothesis also brings with it the sinister assumption that without a safety watchdog looking over the shoulders of the workers, the workforce will allow safety to decay. At the time of the *Challenger* accident, the majority of the NASA and contractor employees had worked in the space program their entire careers. Older employees remembered the Apollo fire. Many of the NASA and contractor employees knew and had personal relationships with the *Challenger* crewmembers. They went to church together, they played on the same softball teams, and they had children in the same school classes. It is hard to believe that this group would knowingly neglect safety or allow a crew to enter an unsafe spacecraft.

The shuttle safety system also had adopted the problem identification, tracking, and resolution tools used in Apollo, and had expanded them. This process was operating for the *Challenger* launch and its procedures were followed. The system was designed to ensure that no problem went undocumented and that management had access to all necessary data for making a decision. The history of solid rocket booster problems was well documented in this system.

Considering the preponderance of similarities over differences between the Apollo program and the shuttle program and the improvements made in the shuttle processes, there is

[181] Interview with Harold Taylor, Former Department Head, Safety and Mission Assurance, NASA's Johnson Space

just as much justification for arguing that the "root cause" of the accident was the holdover safety system from the Apollo program. Following 24 successful flights, and with a new seal design in development, what if the weather had been seasonally warm in Florida on launch day? Would we still think that this hypothesis alone is the "root cause?"

3.1.2.4 Hypothesis 4

> Management erred in not listening to the warnings of the first-line engineers.

This is probably the most popularly cited "root cause" for the failure of space shuttle Mission STS-51L.[182] As discussed earlier, the joints in the solid rocket boosters had been a known problem since the beginning of the shuttle program. NASA and Morton Thiokol jointly had established several studies of the erosion problem and were working to find a solution. The problem had been elevated to Michael Weeks, NASA Headquarters' Deputy Associate Administrator for Space Flight, who assigned an engineer from the Office of the Chief Engineer to review the performance to date and the actions being taken to eliminate the seal erosion.[183]

These analysts contend that tests were conducted as early as 1977 that clearly pointed to a flawed O-ring design. In these tests, engineers found that the two halves of the solid rocket booster joint moved away from one another during the first milliseconds following ignition. The concern was raised that this larger opening might exceed the O-rings' sealing capability. Some engineers recommended that the joint be modified using a mechanism which clamped the two halves together, but these changes were rejected because of their impact to the development schedule. The original design was approved for full-scale development, and was used on every shuttle flight beginning with STS-1.[184]

Engineers at the Marshall Space Flight Center continued to question the acceptability of the joint design, using results from several ground tests and in 1980, their concerns were noted by

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Center, September, 20, 1998.

[182] This is consistent with Charles Perrow's argument in Normal Accidents that sixty to eighty percent of all system failures are attributed to individual or "operator error". The operator in the case of *Challenger* was the management team whose responsibility it was to make the launch decision.

[183] Vaughan, pp. 172, 177.

[184] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 123.

a NASA propulsion committee charged with verifying the flight worthiness of the systems.[185] The committee noted that the leak test performed on each joint actually provided pressure from the outside of joint, where in an actual firing the pressure would come from inside the joint. This called into question the validity of the test. Also cited were questions about the performance of heat resistant putty placed in the joints to protect the O-rings from the high temperature gases found in the solid rocket booster. Finally, the committee questioned whether the secondary O-ring actually would seal and provide any redundancy should the primary O-ring fail. It noted that the secondary seal had never been independently tested and that the proposed failure modes could prevent its proper function. If the primary seal failed because of joint rotation, the resulting position of the secondary seal would make it even less likely that this seal would contain the hot gases escaping from the joint.

NASA managers changed some of the test parameters and scheduled additional tests to determine the effect of external vs. internal leak tests on the performance of the joint. Stating that these modifications satisfied the "intent" of the committee's recommendations, NASA closed the issue.[186]

The problem of erosion in the O-ring was considered so serious that Thiokol's Vice President of Engineering, Robert Lund, had assigned a special task force. Roger Boisjoly was an engineer on the Thiokol task force that worked over several months to find a pattern as to why the seal was not behaving as anticipated. However, the task force members remained in their original jobs, with the task force assigned as an additional duty. Consequently, activities took place as their workload permitted and moved along very slowly. Boisjoly became convinced that the task force was a sham and wrote several scathing memos to Thiokol management warning them of the potential dangers.[187] [188]

In his book, *Challenger*: A Major Malfunction, Malcom McConnell notes that "Bob Ebeling, another Thiokol task force engineer, was equally concerned." McConnell states that "In a message to Allan J. McDonald, Thiokol's Director of the Solid Rocket Motor Project, Ebeling

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185 Vaughan, p. 107.
186 Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, pp. 124-125.
187 Malcolm McConnell, *Challenger*: A Major Malfunction: A True Story of Politics, Greed, and the Wrong Stuff, (Garden City, N.Y.: Doubleday & Company, 1987), p. 179.
188 See Appendix E

began with the now notorious exclamation: "HELP!"[189] Morton Thiokol management took no action as the result of this plea. In addition, they did not notify NASA that the task force had been largely ineffective and was making little progress toward a resolution of the erosion problem.

On August 19, 1995 NASA and Morton Thiokol engineers briefed the problem at the flight readiness review at NASA Headquarters in Washington D.C. This briefing included a history of flight problems experienced to date, the cause of these problems (as understood at the time), and the steps the program was taking to improve joint performance. The briefing included the fact that the joint had been downgraded from a redundant sealing system to a single O-ring sealing system. At the end of the meeting, the seal system was listed as a concern to be tracked while the joint improvements were being developed, but it was not a constraint to continuing shuttle flights.[190]

This trend of managers at both Morton Thiokol and the Marshall Space Flight Center ignoring the dire warnings of its engineers would continue in the days and hours leading up to the launch of *Challenger*. The events that followed and the approximate time of their occurrence providing a chilling insight into the decision process:[191]

January 27

1:00 p.m. Larry Wear, the Manager of the Solid Rocket Motor Project Office at Marshall asks his counterpart at Morton Thiokol, Boyd Brinton, Manager of the Space Booster Project, if Morton Thiokol has any concerns about the projected low temperatures at launch time in light of the STS-51C O-ring erosion. Brinton telephones Morton Thiokol office is Utah and asks two engineers, A.R. Thompson and Robert Ebeling to evaluate this question.

2:00 p.m. The NASA program and mid-level managers hold a mission management team meeting to discuss the effects of cold temperatures on the shuttle and the associated ground facilities. The manager for the solid rocket booster project, Larry Mulloy, and the Marshall Space Flight Center Director, William Lucas attends the meeting.

[189] McConnell, p. 180.
[190] McConnell, p. 178.
[191] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, pp. 104-111.

2:30 p.m. Ebeling convenes a meeting at Morton Thiokol to discuss the predicted low temperatures. Present is Roger Boisjoly, a member of the seal task force set up to resolve seal problems.

4:00 p.m. Allan McDonald, Morton Thiokol Director of the solid rocket booster project, present at the Kennedy Space Center, calls another manager to obtain the latest temperature predictions up through launch. The data are sent to Morton Thiokol and McDonald schedules a teleconference to discuss them.

5:15 p.m. McDonald calls the Marshall Space Flight Center resident manager at Kennedy to inform him that Morton Thiokol had concerns about the effect of the low temperatures on the O-rings. The manager tells McDonald that he will set up a teleconference with Marshall and Morton Thiokol.

5:45 p.m. Stanley Reinartz, Manager of the Shuttle Projects Office at Marshall, and his deputy, Judson Lovingood, hold a teleconference with NASA and Morton Thiokol personnel to discuss the temperature concerns. Morton Thiokol recommends delaying the launch until noon or later. Another teleconference is scheduled for 8:15 p.m.

6:30 p.m. Lovingood calls Reinartz, stating that if Morton Thiokol continues to object, the launch should not occur. Reinartz suggests notifying the NASA mid-level manager, Arnold Aldrich, to prepare him for a program management teleconference should the launch be postponed.

8:45 p.m. The problems with the O-rings are once again a hot topic at this meeting was attended by virtually all NASA and Morton Thiokol Level project and engineering managers. Also present are the engineering staffs involved with the solid rocket boosters. At the teleconference Roger Boisjoly presents several charts and discussed this history of O-ring erosion in the solid rocket boosters. Data include flight data, test results, and ground-based firings. Data show that the O-rings will respond slower in the lower temperature and the STS-51C data are reviewed.

In the engineering judgment of Roger Boisjoly and his team, NASA should delay the launch until the temperature at Kennedy Space Center was at least 53 degrees Fahrenheit. Lund, Vice President for Engineering at Morton Thiokol recommends that the launch be delayed until the O-ring temperature reaches 53 degrees, the same temperature experienced by STS-51C. NASA management’s reaction is harsh. They severely criticize the engineers’ data as being inconclusive at best and lambaste them for making such serious recommendations based on this data.

Mulloy asks Joe Kilminster, Morton Thiokol Vice President for Space Booster Programs, for a recommendation. Kilminster, based on the engineering recommendation, states that he cannot recommend launching. Reinartz states that he believes the solid rocket booster to be flight qualified in a temperature range of 40-90 degrees. There is disagreement among the engineers and Kilminster asks for a 5-minute recess.

10:30 p.m. The Morton Thiokol personnel at their facility in Utah discuss the issues of temperature effects on O-rings and the O-ring erosion for approximately 30 minutes. Thompson and Boisjoly object to the launch. Four senior Morton Thiokol vice presidents, including Kilminster, conduct a private meeting, where Lund is asked to "put on a management hat" by Mason, Senior Vice President for Wasatch (Utah) Operations. They agree that there is sufficient margin to have erosion three times worse than any experienced to date, and that the secondary O-ring will seal if the primary fails to do so. The managers override Boisjoly's recommendations that it is not safe to fly.

11:00 p.m. The teleconference reconvenes with Kilminster stating that Morton Thiokol has reassessed the situation and found the data inconclusive. After he explains his rationale, NASA asks that he write down his rationale and fax it to Kennedy and Marshall.

11:15 p.m. At Kennedy, McDonald continues to argue against launch because of the low temperatures, high winds at sea where ships are waiting to recover the solid rocket boosters after launch, and icing conditions on the launch pad. He is told that his concerns will be forwarded to the appropriate people making the decision.

11:45 p.m. Morton Thiokol's recommendation to launch, signed by Kilminster, is sent to Kennedy.

11:30 p.m. Mulloy and Reinartz discuss the icing issue and the concern over recovery ships with Aldrich.

<u>January 28</u>

1:30-3 a.m. Inspection teams find large quantities of ice on launch pad and report it to launch controllers.

5:00 a.m. Mulloy discusses the Morton Thiokol's concern over temperature with Lucas and shows him the Kilminster fax.

7:00-9 a.m. An inspection team measures the temperature of the left solid rocket booster at 25 degrees and the right at 8 degrees in the aft region. The crew reports sheet ice on the left solid rocket booster.

8:00 a.m. Lovingood discusses the previous night's events with T.J. Lee, Deputy Director of Marshall. He tells Lee that Thiokol recommended not to launch, reconsidered, and provided the launch recommendation in writing.

9:00 a.m. The mission management team discusses the icing condition at the launch pad. The O-ring seals are not discussed.

10:30 a.m. Inspection teams report icing conditions at the launch pad, including ice on the left solid rocket booster, to the mission management team.

11:38 a.m. Launch

Although the data were not conclusive, NASA and Morton Thiokol must have recognized the level of concern expressed by the engineers most familiar with the design of the joint sealing system. If these professionals thought the system was unsafe in their qualitative assessments, the launch should have been delayed. In addition, NASA had changed the rules on the engineers. They were incapable of proving it was unsafe to fly. As Dwortzey points out:

> The accident would have been bad enough if it had been unavoidable. But the engineers knew that the O-rings … might be unreliable in cold weather. The engineers even tried to stop the launch from proceeding … but were overruled, though, because NASA had schedules to keep.[192]

A specific time window in which it had to be launched did not restrict this particular mission. The unseasonably cold weather was forecasted to be over by the next morning. A delay of one day would have cost little, and saved so much. But, management seemed destined to continue to ignore warnings of its engineers and their dire predictions of failure. The problems with the solid rocket booster's, which had been documented and the focus of countless review teams, was once again swept under the rug on that fateful evening prior the launch of *Challenger*. No matter how hard Roger Boisjoly or any of the other engineers argued their case, management was in charge and they were determined to go fly. Subsequently, many analysts conclude that the failure of management to heed the warnings of its solid rocket booster engineers was the root cause of the space shuttle *Challenger* failure.

[192] Tom Dworetzky, "Return of the Shuttle," Discover, July 1988. p. 47.

3.1.2.4.1 Flaws with Hypothesis 4 as the Root Cause

While hindsight has proven this decision to launch catastrophic, the assertions that management ignored concerns of the engineers and recklessly took chances with peoples lives is a gross indictment of the men and women who dedicate their careers to human space flight. Upon closer examination it is difficult to label this hypothesis as the “root cause” for several reasons.

To begin with, the solid rocket booster problem was just one of several hundred technical issues being worked in this highly complex system. As with any organization, NASA concentrated its resources on the areas identified as producing the greatest risk. The solid rocket boosters were not on this list. While the consequence of the O-rings failing to work properly may have been a listed as catastrophic the perceived likelihood of this scenario coming to pass was generally noted as being relatively low. As such it did not receive the attention that many of the larger technical issues on the table were receiving. Pinkus, et al. note that

> James Kingsbury, director for engineering (1975-86) at the MSFC, has commented that: ‘The real challenge in shuttle, however, was the SSME. It was an unproven technology. Nobody had ever had a rocket engine that operated at the pressures and temperatures [of] that engine, or the [rotational] speeds of the equipment. That just hadn’t been done before because it demanded some advancements [sic] in technology.[193]

All tests were thoroughly documented and resulting issues were worked. NASA carefully documented all instances where the solid rocket booster joints did not perform as expected. These deficiencies were not limited to the O-rings, but to the methods used to install them, test their integrity, and handle the solid rocket booster components between missions. After identifying problems, NASA and its contractors worked diligently to understand anomalous conditions and correct deficiencies. In this way, the solid rocket boosters actually received more attention than most systems with the perceived risk they presented to vehicle safety. NASA utilized its configuration management system to ensure that no issues, once raised, were dropped or allowed to languish. Issues with the solid rocket boosters were presented to senior NASA managers, who assigned individuals to investigate any unanticipated performance in the solid rocket booster system. Providing an additional level of scrutiny, NASA moved to obtain independent assessments of the system. NASA and Thiokol both formed special task forces to review the design. Although both groups acknowledged deficiencies in the original joint sealing system, neither found these shortcomings to present risks to flight safety. After all, the current design had worked for 24 preceding flights. And while NASA was planning to change the design, the agency saw this as one of a series of continuing improvements, not as a safety-related fix.

Second, prior to every launch there are a whole host of issues being worked, all of which could adversely affect the safety of the mission. In fact, the O-ring issue was not even on the top of everyone's agenda that flight. According to astronaut Dr. Robert Parker, it was not unusual for these sorts of debates to take place.[194] Each time NASA prepares for a space shuttle launch there are always a half dozen or so people ready to question the decision to launch. No one wants his or her piece of the puzzle to be the one that fails. While management understood the risks associated with failure, the objections being raised by Boisjoly that day were not unusual. Engineering judgment always plays a large part in the decision whether to act on these objections or to proceed with launch. Inevitably, the objections of one engineer are weighted against contrary positions of other engineers. Someone had to make the always difficult decision to "go fly". Pinkus, et al., note this phenomenon in their discussion of the *Challenger* failure.

> Hans Mark, a former deputy director of NASA who left his position six months before the *Challenger* accident, has observed that he participated directly in twelve shuttle launch decisions. In each instance, there was always one group of engineers who, like those at Thiokol, advised against the launch, claiming that the shuttle, would experience catastrophic failure. 'Sometimes we took their advice and postponed the launch, and at other times we went ahead and flew in spite of the advice we were given. The mere fact that a group of engineers opposed the launch because they were afraid one of their subsystems would not work was not enough to cancel the launch.' Mark observed that the shuttle is such a complex and advanced technology that top management at NASA grew accustomed to dealing with these claims of disaster.[195]

Third, as a number of scholars have accurately pointed out Boisjoly's data as presented was far from conclusive. When Boisjoly, Thompson, and the rest of the Thiokol and NASA team gathered together in Huntsville, Alabama the day before the scheduled *Challenger* flight,

[193] Rosa Lynn B. Pinkus, "Engineering Ethics: Balancing Cost, Schedule, and Risk: Lessons Learned from the Space Shuttle" (Cambridge, United Kingdom: Cambridge University Press, 1997), p. 225.
[194] Interview, 7 January 1992.

not everyone was of the same opinion. While today we know differently, at the time there were many that remained unconvinced that the O-ring evidence presented by Boisjoly was significant. The O-rings, after all, were one of more than over a million different components on the shuttle, the evidence was not conclusive, and to date there had never been an O-ring failure.

Tufte contends that the solid rocket booster engineers' failure to properly convey the available data illustrating past problems with the O-rings was the primary cause of the *Challenger* explosion. He argues that "had the correct scatterplot or data table been constructed, no one would have dared to risk the *Challenger* in cold weather."[196] He does not accept the widely held view that the engineers were nobly attempting to prevent the accident, only to be overridden by management. Instead, he assigns the engineers the responsibility for making their case and faults them for their inability to do so.

Given the inconclusive data and the fact that there were many issues being worked that evening it is not at all surprising that Mulloy made the decision to push forward that he did. That is why managers get paid - to make the tough decisions. Tough decisions in the space business, unlike many other businesses, carry with them dire consequences for those who err. The willingness to risk life subsequently was not new; rather it had never gone away. After all, anytime you place a man on top of a rocket, fill it with highly volatile fuel, and light the fuse it is enormously risky. The potential for failure is omnipresent. Tom Wolfe, in his classic The Right Stuff chronicles the inherent dangers involved in spaceflight from the early test planes through the Mercury, Gemini and Apollo programs. He vividly explains that it was precisely because America expected to risk human lives that test pilots were chosen as our nation's first astronauts.[197] Commenting later on the loss of the space shuttle *Challenger* astronauts, Apollo Astronaut Michael Collins remarked:

> They [astronauts] know full well the risks of their profession. I can certainly sympathize with the Huntsville mangers who note that flight after flight, the secondary O-rings had remained intact. I might have made the same decision they did.[198]

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[195] Pinkus et al., pp. 312-313.
[196] Edward R. Tufte, Visual and Statistical Thinking: Displays of Evidence for Making Decisions, (Cheshire, Conn., Cheshire Press, 1997), p. 30.
[197] Tom Wolfe, The Right Stuff, (New York, N.Y.: McGraw-Hill, 1979), pp. 76-77.
[198] Collins, p. 236.

It is also important to note that the subsequently much maligned Alan Mulloy followed exactly the process and procedures that had been in place since the beginning of the program. With the *Challenger,* it was not that NASA management was reckless or that they had acquired a new willingness to risk life; more correctly it was that NASA's phenomenal success record up to the point of *Challenger* had lulled many outside the program including the press, and worst of all the American public, into thinking of spaceflight as "routine". Lest we forget, none of the major television networks carried the launch live that day. Space shuttle flights had become "routine". Today, many within NASA will complain that the biggest mistake they made was to let the word "routine" ever surface.[199]

Finally, if Boisjoly was really as convinced prior to the launch as he later claimed to be that NASA was going to kill seven people, didn't he have a moral obligation to warn someone higher up the chain of command? There were dozens of people either in Florida or connected via teleconference that participated in the launch decision. After the fact, many, like Boisjoly claimed they had tried their best. NASA managers, including Arnold Aldrich, the head of the shuttle program, testified that if the depth of the disagreement on launching had been explained to them, they would have recommended a delay. The participants in the NASA and Morton Thiokol teleconferences had the means to call these senior managers, but instead chose to wait and see.

It is difficult when all the facts are in to conclude that management error alone was the root cause of the space shuttle *Challenger* failure. The solid rocket boosters were after all one of several hundred technical issues being reviewed by NASA and its contractor team and not even at the top of the "worry" list. The solid rocket boosters had never before failed and as Tufte argues, the data Boisjoly's presented the night before the launch was far from conclusive.

[199] Interview 23 September 1998 Doyle McDonald, Director, Strategic Planning, NASA's Office of Space Flight, 1989.

3.1.2.5 Hypothesis 5

NASA succumbed to political pressures in launching *Challenger* in spite of the known risks.

This fifth widely accepted hypothesis for the root cause of the accident holds that NASA succumbed to political pressure and decided to launch *Challenger* even though they knew the risks were great. The STS-51L mission had been postponed three times already, and the latest attempt would coincide with President Reagan's State of the Union address that evening. The President planned to mention this first flight into space by a teacher, and the White House maintained close contact with NASA Headquarters on the status of the mission. Although there was no direct interference with the launch decision-making process, there is little doubt that NASA senior management was aware of the level of interest. NASA management was well aware of the O-ring problem, but chose to launch anyway as a direct result of this political pressure. In addition, those preparing the mission itself knew that this would be a highly visible launch or an equally highly visible scrub.

This pressure arose from a shuttle program that had fallen far short of the original promises made by NASA. It was expensive, required a massive work force to operate, and flew far less frequently than originally advertised. Having sold the program on a wildly optimistic rate of a flight a week, NASA was pressed hard to fly just eight times a year. In the early days of the shuttle program, NASA estimated that the shuttle would fly once a week, 50-60 times a year, as access to Earth orbit would become routine and widely available (Figure 3-21).[200] In contrast, the shuttle remained what it really was – a developmental test vehicle. Each vehicle in the fleet required almost one million procedures between launches. Even launching at a fraction of the original estimated rates, the NASA and contractor work force operated at two and sometimes three shifts a day.

[200] Myers, p. 43.

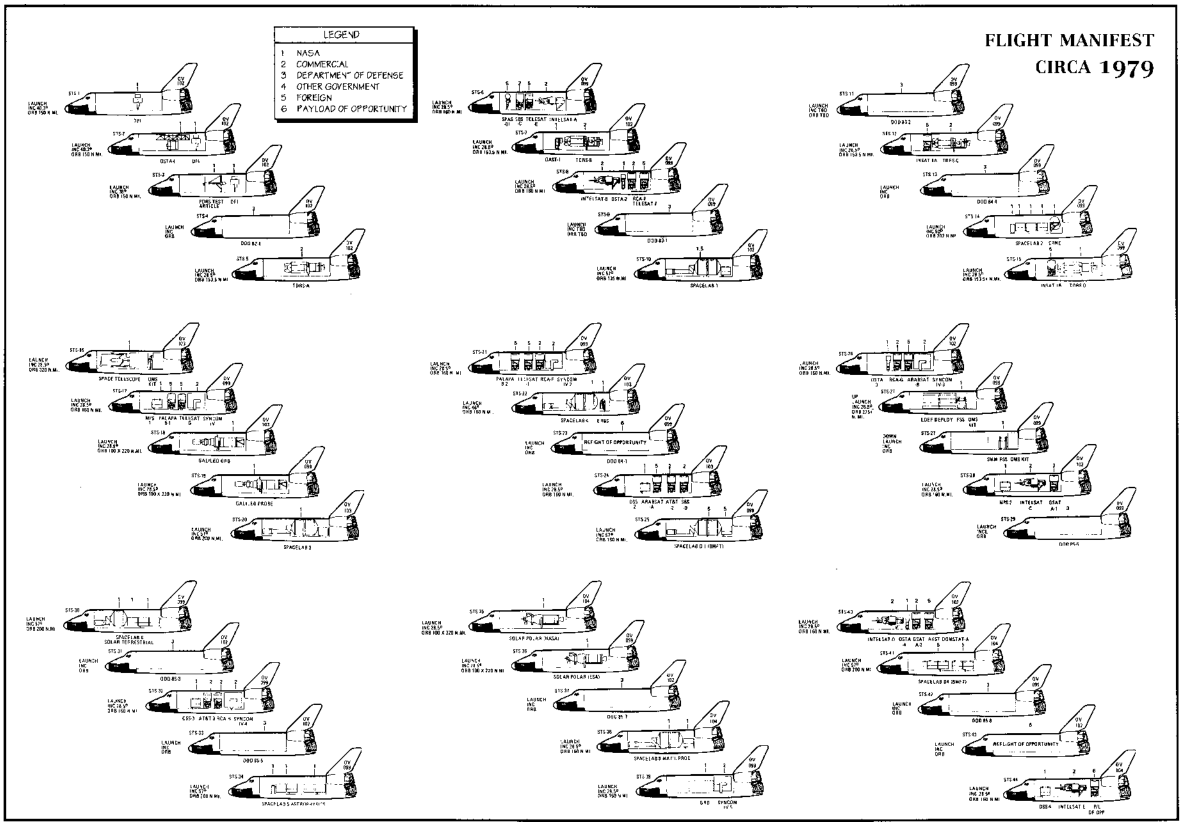

Figure 3-21 - Flight Manifest Circa 1979[201]

NASA was attempting to declare the shuttle an operational program to improve its competitive advantage against conventional rockets. The shuttle flight schedule was extremely erratic. Commercial satellite manufacturers became frustrated as requirements changed and slips in schedules made it difficult for them to commit to providing services for their customers. Many began to look to expendable rockets as a more reliable form of transportation. The European Space Agency recently had introduced the Ariane rocket in direct competition with the shuttle and what remained of the US expendable fleet. Attempting to combat this image of an unreliable system, NASA placed a great deal of emphasis on maintaining the scheduled launch times.

The pressure created for NASA to live up to expectations it had helped create placed huge pressure on the management and the workforce to make good on the promises. The program was

[201] Jenkins, p. 137.

expected to keep schedule even in the face of changing requirements. For example, program managers did not add Gregory Jarvis, the Hughes Company payload specialist, to the Challenger crew until shortly before the Launch Minus 5 Months review.[202] His planned mission activities forced a later revision of the Crew Activity Plan and delayed its release. The processing schedules for the orbiters were being reduced to levels that had never been achieved in the program to date and have not been seen since the return to flight. In fact, this pace was twice as fast as the standard processing template normally employed.

This difficulty in dealing with this executive branch pressure was a manifestation of a larger NASA problem. Contending that NASA's problems were institutional as well as technical or managerial, Romzek and Dubnick argue "the accident was, in part, a manifestation of NASA's efforts to manage the diverse expectations it faces in the American political system."[203] This inability to manage expectations brought about external pressures that translated into internal decisions that prematurely sought to declare the shuttle system operational. The term "operational" was more than just a question of terms. NASA had met no prior promises in the shuttle program. The Air Force was pressuring Congress and the administration to reactivate the Titan and Atlas rocket programs as a backup or a replacement for the shuttle. NASA needed a series of successful launches to quash this disturbing desertion of the shuttle. The effort to declare the space shuttle operational led NASA to set an overly ambitious and unrealistic schedule that eventually led to the *Challenger* failure.

On the morning of January 28, 1986 NASA found itself in a difficult position. It had sold the space shuttle program as capable of launching 50-60 times a year and had succeeded in getting the National Space Policy changed to mandate the shuttle as America's primary launch system. However, here they sat never having launched more than 9 flights in a single year and facing the possibility of having to delay this flight for the fourth time in a little over a month. The Department of Defense was starting to make noise that the shuttle was not capable of meeting its needs and commercial customers were beginning to look overseas to Ariane as a potential means of placing their satellites into space. On top of that, President Reagan was

[202] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, pp. 13-14.
[203] Barbara S. Romzek and Melvin J. Dubnick, "Accountability in the Public Sector: Lessons from the *Challenger* Tragedy," Public Administration Review, May/June 1987, p. 230.

scheduled to deliver his state-of-the-union address that evening and NASA was excited about the favorable press it would receive when he talked warmly about the first teacher in space, Christa McAuliffe. NASA was under tremendous pressure and desperately needed to take advantage of the state-of-the-union if it was to continue to hold the critics at bay much longer. The root cause of the space shuttle *Challenger* failure therefore according to a number of analysts was that NASA succumbed to these political pressures and decided to take its chances with *Challenger* in spite of the risks.

3.1.2.5.1 Flaws with Hypothesis 5 as the Root Cause

This hypothesis, while found in many popular textbooks, probably is the least credible as the "root cause". There is absolutely no evidence that any pressure was applied to NASA. Not only are there no written orders, there has been no testimony to the contrary following the accident. The Presidential Commission charged with investigating *Challenger* stated that:

> …During the Commission's hearings all persons who played key roles in that decision [the decision to launch] were questioned. Each one attested under oath, that there had been no outside intervention or pressure of any kind leading up to the launch.
>
> There were a large number of other persons who were involved to a lesser extent in that that decision, and they were questioned. All of those persons provided the Commission with sworn statements [Twenty-eight Affidavits were submitted to the Commission] that they knew of no outside pressure or intervention.
>
> The Commission and its staff also questioned a large number of other witnesses during the course of the investigation. No evidence was reported to the Commission which indicated that any attempt was ever made by anyone to apply pressure on those making the decision to launch the *Challenger*.
>
> Although there was a total lack of evidence that any outside pressure was ever exerted on those who made the decision to launch 51-L, a few speculative reports persisted.
>
> One rumor was that plans had been made to have a live communication hookup with the 51-L crew during the State of the Union Message. Commission investigators interviewed all of the persons who would have been involved in a hookup if one had been planned, and all stated unequivocally that there was no such plan.

> …The Commission concluded that the decision to launch the *Challenger* was made solely by the appropriate NASA officials without any outside intervention or pressure.[204]

NASA managers and people at the working level have not come forward to cite such pressure. Reinforcing the finding that this pressure is imagined, analysts have noted that the NASA management did not hold any meetings that were not scheduled as part of the normal launch operations. Instead, NASA followed the standard launch process and did not take any shortcuts at any level in its attempt to launch.

Each mission was prepared following a prescribed schedule template. Preparation for the STS-51L mission followed the standard template for space shuttle missions, with initial payloads being assigned in 1984. In the 18 month process that followed, program engineers and operations personnel conducted a series of analyses, developed several mission-specific procedures and documentation that better defined the mission, reconfigured ground systems to control the mission. Many of these activities were dependent on completing prior activities, and this iterative process drove the preparation schedule. The major milestones from this point forward are shown in Figure 3-22.[205]

[204] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, pp. 176-177.
[205] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 12.

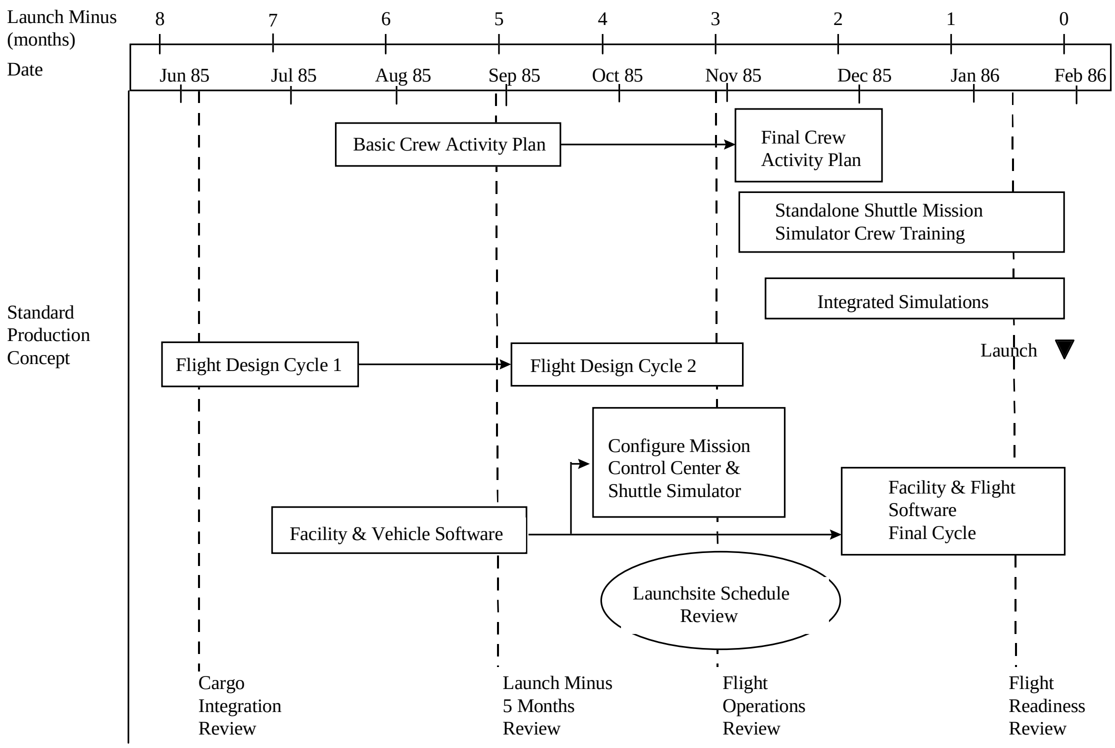

Diagram shows the scheduling of various preparatory milestones in the months that preceded the launching of the Mission 51-L Shuttle.

Figure 3-22 - Major Milestone Summary[206]

The final major review conducted before the launch countdown began was the Flight Readiness Review. This review, conducted on January 15, 1986, provided a forum for all parties, including NASA and contractors, to address any outstanding issues and to certify that the vehicle was ready to fly. The review is preceded by three lower level reviews, structured as shown in Figure 3-23, which consider the detailed engineering and operations issues. Any unresolved issues were then brought to the Flight Readiness Review. In this formal process, each contractor was asked at all four reviews to sign a Certificate of Flight Readiness certifying that their systems are ready to fly. The solid rocket boosters were discussed at the lower level reviews held at Marshall Space Flight Center, with Thiokol and NASA participants signing the Certificate of Flight Readiness. Solid rocket boosters were not discussed at the final Flight Readiness Review.[207]

[206] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 12.
[207] Vaughn, p. 83.

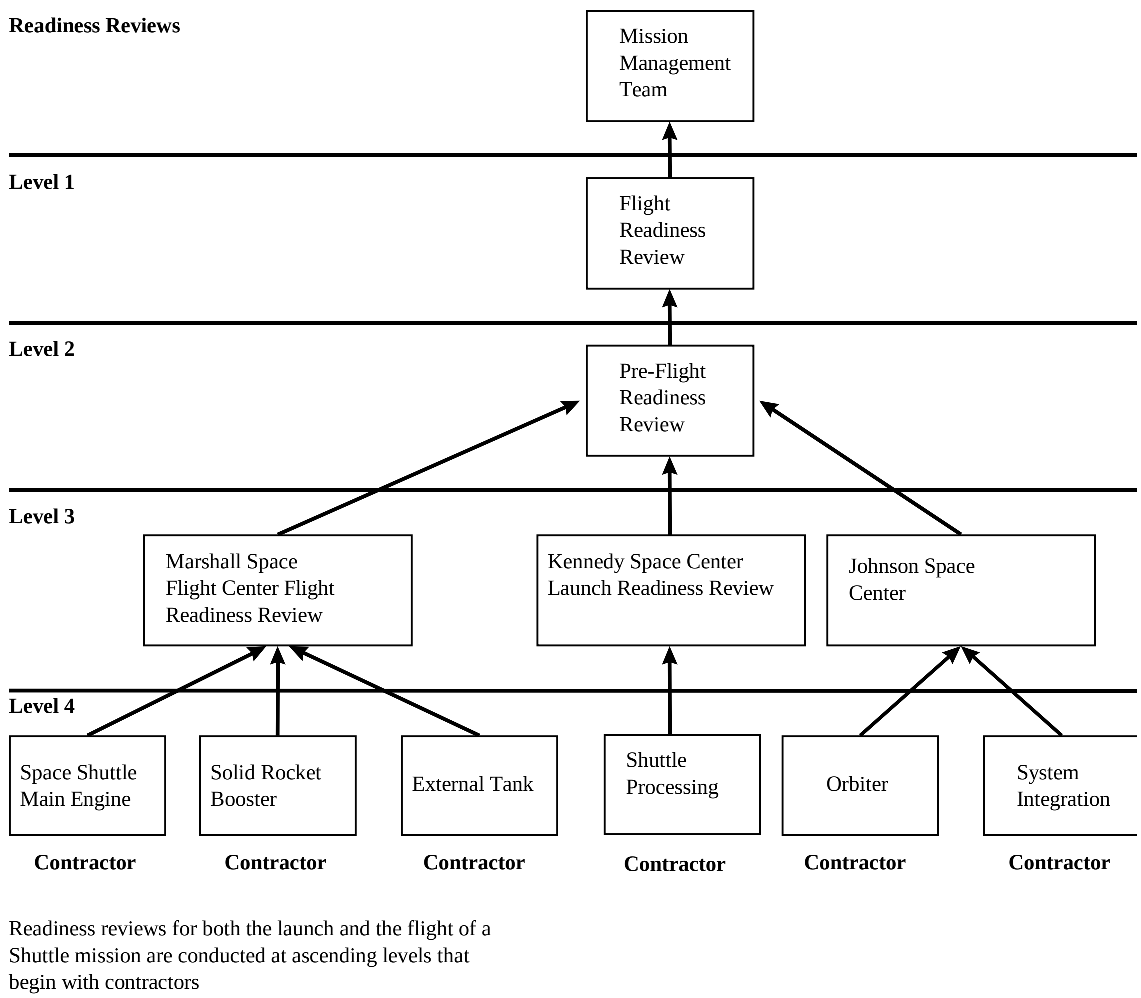

Figure 3-23 - Flight Readiness Review Structure[208]

On the day of the launch there were no critical issues outstanding. Because of the cold weather "the management team directed engineers to assess the possible effects of temperatures on launch. No critical issues were identified to NASA or its contractor management."[209]

The managers making the decision to launch had no doubt that an incorrect decision could lead to disaster. No manager would believe that succumbing to political pressure was better than the alternative. After spending careers in what is essentially flight test, they had seen accidents occur which claimed the lives of the pilots. As a result, they took the responsibility for protecting the flight crew very seriously. This aspect aside, these managers recognized that any

[208] Report of the Presidential Commission on the Space Shuttle *Challenger* Accident, p. 83.

accident would drastically disrupt the shuttle program, perhaps leading to its cancellation. A three shuttle fleet could not meet even the reduced flight schedule. It would cost almost $3 billion to construct a replacement shuttle. The managers knew the complexity of the vehicle and the risk associated with deviating from the planned operations procedures. They would have waited for another day.

3.1.3 The Paradox: Everyone is right and everyone is wrong

Everyone is wrong, but everyone is right. Each of the five major hypotheses discussed has merit. Yes, NASA modified the design of the space shuttle in response to budget pressures. Yes, evidence of groupthink appears in the decisions to continue flights. Yes, the safety system organization could have been a more active participant in the decision making process. Yes, management should have paid more attention to the warnings of its engineers in making the decision to launch. And yes, there was an expectation by senior government officials and the public that this already delayed launch should not be further delayed.

But no, it is difficult to conclude that any of these hypotheses in isolation is the root cause that directly led to the proximate cause which led to the *Challenger* failure. Would the scaled back design still have led directly to a system failure if the safety organization had been more actively involved and management had heeded the warnings of its engineers? If the mission had been a success would we attribute it to groupthink? Would a more actively engaged safety organization really have mattered if the design was flawed and management had ignored its engineers? If the weather had been different that day would we be reading this paper at all? Perhaps Tufte captures the difficulties in contemplating the whole concept of a single root cause when writing about the *Challenger* failure he remarked that:

> Here we encounter diverse and divergent interpretations, as the facts of the accident are reworked into moral narratives. These allegories regularly advance claims for the special relevance of a distinct analytic approach or school of thought: if only the engineers and managers had the skills of field X, the argument implies, this terrible thing would not have happened. Or, further, the insights of X identify the deep causes of the failure. Thus, in management schools, the accident serves as a case study for reflections about groupthink, technical-decision making in the face of political pressure, and bureaucratic failures to communicate. For authors of engineering textbooks and for the

[209] Jenkins, p. 277.

> physicist Richard Feynman, the *Challenger* accident simply confirmed what they already knew: awful consequences result when heroic engineers are ignored by villainous administrators. In the field of statistics, the accident is evoked to demonstrate the importance of risk assessment, data graphs, fitting models to data, and requiring students of engineering to attend classes in statistics. For sociologists, the accident is a symptom of structural history, bureaucracy, and conformity to organizational norms. Taken in small doses, the assorted interpretations of the launch decision are plausible and rarely mutually exclusive. But when all these accounts are considered together, the accident appears overdetermined. It is hard to reconcile the sense of inevitable disaster embodied in the cumulative literature of post-accident hindsight with the experiences of the first 24 shuttle launches, which were distinctly successful.[210]

The classical paradigm presents this dichotomy because it provides no mechanism for determining the relative merit of one hypothesis when compared with another hypotheses. By maintaining the existence of a linear deterministic link from the system failure to its proximate cause to its root cause, the analyst is forced to choose a path to follow, with the others relegated to “the path not taken.”

3.2 The Consequence of the *Challenger* Failure

On January 28, at 11:36 a.m., Eastern Standard Time, with a temperature reading of 36 degrees Fahrenheit at the launch pad, the space shuttle *Challenger* was launched before a worldwide audience. With the first ordinary civilian on board, the interest from the American public was intense. NASA had widely promoted its “Teacher in Space” program and made sure that the video of the launch was available in schools around the world. In addition, the crew of this flight represented a cross section of the nation’s demography, being composed of Caucasian men and women, an African American, and an Asian American. Although the launch was not carried live on the broadcast television channels; it was widely covered by the cable channels and by NASA’s own free television distribution system.

The mission began with the same majesty as the previous 24 launches. The shuttle lifted from the launch pad amid an enormous cloud of steam created by the water deluge on the pad contacting the super-hot exhaust from the shuttle main engines and the solid rocket boosters. Only when reviewing video replays of the launch could the investigators detect anything

[210] Tufte, pp. 17-18.

abnormal. These tapes show that the first puffs of smoke appeared from the solid rocket booster joint at 6.6 seconds into the flight.

At 72 seconds, the shuttle system exploded as the solid rocket booster ruptured the external tank and ripped free of its attachments. The orbiter was lost almost simultaneously. Contrary to most people's understanding of the system failure, the orbiter did not explode. Instead, it was torn apart by the intense aerodynamic pressure it experienced as it turned sideways at an enormous velocity. The internal pressurized cabin housing the seven astronauts separated intact from the over one hundred tons of debris that was the *Challenger* and began a long freefall into the Atlantic Ocean. This ten-mile fall took several minutes and the cabin ruptured upon impact with the water. Debris continued to fall for over 45 minutes.

3.2.1 The Aftermath

Almost instantly, NASA began to execute contingency plans for dealing with the accident. These plans were in place for each mission and had been practiced as part of the never-ending preparations for maintaining mission safety. Each member of the operations team at Kennedy Space Center and in the mission control center in Houston had specific instructions to follow for a wide variety of contingencies ranging from a premature return to the launch site to the complete loss of the vehicle. The primary rule in any of these cases was to protect civilians on the ground from harm. The launch complex is near Orlando and an off course rocket could pose a risk to the city. When the *Challenger* exploded, not all components were destroyed by the failure. An Air Force safety officer used radio commands to destroy the solid rocket boosters that were still flying erratically through the sky.[211]

Officials at the Kennedy Space Center froze the launch processing systems to preserve the data and instituted rescue procedures in the event the crew had survived. At this point, no one knew what had caused the system failure and NASA took every effort to preserve all data for future analysis. The computer systems were downloaded to storage and all papers associated with the mission impounded. High seas hampered rescue efforts, as did the risk to searchers from debris that continued to fall into the impact zone.

[211] Jenkins, p. 279.

The shuttle mission control team also halted their systems and began an intensive effort to review their data for any clues to the accident. When it had been confirmed that the vehicle was lost the flight director, Jay Greene, ordered his team to pull out the associated emergency procedures. All screens on the video-tracking monitors were frozen while flight controllers copied down everything they saw. Also, they completed flight control logs that documented everything they had seen up to the explosion. With this done, the team immediately began to sift through the data downlinked from the shuttle to identify any anomalous behavior.

In Washington, D.C. President Reagan was busy preparing his State of the Union address scheduled for later that evening when he was interrupted when Vice President Bush informed him that "the shuttle has exploded." Initially, the President planned to go forward with his address, but chose instead to delay it for one week while the nation mourned the deaths of the crew. That evening, President Reagan gave a brief televised address in which he expressed the nations' grief and paid tribute to the seven astronauts who died in the explosion. He also promised a prompt investigation into the cause of the accident. [212]

Nine days later, on February 6, William P. Rogers was sworn in as the chairman of the Presidential Commission on the Space Shuttle *Challenger* Accident. Exactly four months later, on June 6, the commission delivered its final report. It contained nine recommendations for improving the nation's human space flight program. The recommendations included items on system design, management, safety, flight rate, and maintenance. President Reagan concurred with all of these recommendations and directed NASA to prepare a plan for implementing them. The shuttle fleet was grounded while NASA worked on the recommendations of the Presidential Commission.

This report became the basic text for understanding the accident and its recommendations, implemented in total, guided the nation's recovery.[213] They may be summarized as follows:

> I. The Solid Rocket Motor joint and seal must be changed. This could be a new design eliminating the joint or a redesign of the current joint and seal. No design

[212] Magnuson, p. 29
[213] See the Report of the Presidential Commission on the Space Shuttle *Challenger* Accident.

options should be prematurely excluded because of schedule, cost or reliance on existing hardware.

II. The Shuttle Program Management Structure should be reviewed. A redefinition of the Program Manager's responsibility is essential. This redefinition should give the Program Manager the requisite authority for all ongoing Shuttle operations. Program funding and all Shuttle Program work at the centers should be placed clearly under the Program Manager's authority. NASA should establish an Shuttle Safety Advisory Panel reporting to the Shuttle Program Manager.

III. NASA and its primary Shuttle contractors should review all critical items and hazard analyses. This review should identify those items that must be improved prior to flight to ensure mission success and safety of flight.

IV. NASA should establish an Office of Safety, Reliability, and Quality Assurance to be headed by an Associate Administrator, reporting directly to the NASA Administrator. It should have direct authority for safety, reliability, and quality assurance throughout the agency.

V. The Commission found that the Marshall Space Flight Center project managers failed to provide full and timely information bearing on the safety of flight to other vital elements of the Shuttle program management. NASA should take energetic steps to eliminate this tendency whether by changes in personnel, organization, indoctrination or all three.

VI. NASA must take steps to improve landing safety by improving Shuttle landing systems and establish specific conditions for landing at the Kennedy Space Center.

VII. NASA should make all efforts to provide a crew escape system for use during controlled gliding flight and make every effort to increase the range of flight under emergency conditions.

VIII. The nation's reliance on a single launch capability should be avoided in the future. NASA must establish a flight rate that is consistent with its resources.

IX. Installation, test, and maintenance procedures must be especially rigorous for Space Shuttle items designated Criticality 1. [Items which have no redundancy and, if fail, would result in catastrophic failure.] NASA should establish a system for analyzing and reporting performance trends of such items.

One year later, in June 1987, NASA's responded, in its report to the President, recommendation by recommendation on the steps taken and included a summary of the agency's preparations for returning to flight.[214] NASA responded to the recommendations through technical and management changes. It redesigned the solid rocket boosters to conform to the Commission's report. The shuttle program management was revamped. The agency reviewed all hazards from the "bottoms up" as it was described by the NASA Administrator, Adm. Richard Truly, himself a former astronaut. An Office of Safety, Reliability, and Quality Assurance was established. NASA revised criteria for landing the shuttle and improved orbiter systems such as brakes and tires. A new abort mode was introduced which allowed the shuttle to cross the Atlantic to land in Europe and Africa. The shuttle was modified to allow the crew to bail out of a gliding orbiter and parachute to safety. Finally, NASA introduced a new safety program designed to ensure that no problem could be dropped from sight or allowed to languish unchallenged in the complex shuttle management process.[215]

The National Space Policy was significantly changed to restrict who and what could fly onboard the Space shuttle. In a complete reversal from previous policy promoting the shuttle as the National Space Transportation System, no longer would the shuttle fly commercial satellites. Its uses were restricted to activities that required human intervention, the unique capabilities of the shuttle, or to support national security. Commercial payloads could be flown if they met either of the first two requirements. For example, a pharmaceutical company could test prototype drugs in the shuttle mid-deck or a commercial research platform could be retrieved for return to Earth. Commercial satellite manufacturers scrambled to redesign satellites specifically made to fit into the shuttle payload bay. The launch slots were limited and many companies turned to the European Ariane for launches.

In another reversal, the National Space Policy that mandated that the space shuttle would be America's sole launch vehicle was rewritten to promote the use of expendable launch vehicles. When previously arguing to make the shuttle the country's primary vehicle, NASA had asserted that the expendable launch industry was sufficiently mature to compete in the market without government support. They made comparisons to the airplane industry that was growing

[214] National Aeronautics and Space Administration, Report to the President: Implementation of the Presidential Commission on the Space Shuttle *Challenger* Accident, June 1987.
[215] See Appendix F

without government subsidy. Now the policy gave government assistance to improve rocket technology and to develop the next generation of launch vehicles.

Following the *Challenger* accident, the nation sought instead to reduce its reliance on single systems, such as the shuttle, by promoting the expendable rocket industry. NASA worked with other government users of launch services, the commercial satellite providers, and the rocket industry to accurately estimate the demand for launches in the next several years. NASA modified its planning to utilize a “mixed fleet” of vehicles that gave the agency the ability to continue to launch should a particular type of rocket develop problems.

In all of this activity which followed the loss of the *Challenger*, the efforts were focused on the accident itself and on preventing its reoccurrence. The analysts, within and outside the space industry, discussed the accident and how it affected America’s goals in space almost to the point of futility. An exhaustive search of the literature found no analysts who dispute that the proximate consequence of the *Challenger* system failure was the loss of the shuttle and its crew. Consistent with the classical paradigm, most analysts ventured no further than the proximate consequence when discussing *Challenger*.

Others, such as Perrow, contend that this represents the entire set of consequences, so it is not necessary to continue looking. In his view, the shuttle had few other consequences. No one except the shuttle crew had been killed and the loss of the vehicle did not endanger others and would have no life-threatening effect on those remote in space and time from the site of the explosion. The continuation of the shuttle program in the aftermath of this system failure was unlikely to introduce any new risks to mankind that extended by this localized risk to the vehicle and crew.

3.2.2 In Search of the Ultimate Consequence

The remaining analysts incorporate the proximate consequence in discussing the “ultimate” consequence. They recognize that without the proximate consequence, no further consequences would exist, but are not content with stopping at this point. Instead, they use the proximate consequence as the linear link to the ultimate consequence that defines the final impact of the system failure. As with the cause literature, the writers agree that there is an ultimate consequence, but cannot agree on the definition of this consequence.

Instead, analysts discuss a number of ultimate consequences. Some of these are positive and others are negative. For example, some analysts believe that the *Challenger* failure prevented the nation from continuing down the disastrous path of relying completely on one launch system. In this way, the consequences were positive. Other analysts bemoaned the set back to science as scientific research was set back years and experiments had to await reflight or be modified for expendable rockets. These experiments already had endured the years-long safety review process required to launch on the shuttle. As the shuttle flight rate estimates were steadily reduced, the anticipated launch dates slipped. After the shuttle, resumed flight, experiments proposed as part of a junior high school competition were eventually flown with the same student now pursuing a graduate degree. As Baker comments:

> The fate of the shuttle has resulted in the loss of 38 years from the science projects… which are only the more prominent of many programmes now abandoned or frustrated.[216]

A number of analysts focused on the loss of America's competitive advantage in the space launch market even as the demand for launches were increasing. Prior to the accident, the United States was the world leader in this lucrative market. However, before the accident the National Space Policy had dictated that payloads be moved to the shuttle. Expendable rocket manufacturers struggled to position themselves in the commercial market after operating for decades with the federal government as their largest customer. Without this base of revenue, the manufacturers were forced to resize their production facilities for the smaller market, disrupting operations and making fewer rockets for sale. These difficulties and the disappointing lack of a reliable shuttle schedule and flight rate generated a backlog of payloads "waiting for a ride."

By placing all its eggs in one basket, the space shuttle, the nation watched the excess launch demand move abroad. The space policy announced by President Reagan on July 4, 1992 did not provide for any support for the manufacturers of expendable rocket attempting to adjust their production from government to commercial use. The satellite manufacturers could not wait and looked elsewhere for more dependable transportation. When the *Challenger* failure

[216] Baker, p. 57.

occurred, the shift to other sources became a stampede. The U.S. had lost its ability to accelerate expendable launch vehicle production and could only stand by as a spectator. As Williamson states, the consequence was far reaching:

> Because of the spectacular and tragic 1986 failure of *Challenger*, as well as the lack of a commercial US launch industry, Arianespace has emerged as the present and foreseeable world leader in providing commercial space launch services.[217]

The impact of the commercial satellite launch delays had a domino effect on the entire industry and on the users of the services from the satellites. With a limited supply of rockets and the Department of Defense having priority for national security purposes, commercial satellites were bumped and had to wait for a slot on an expendable launch vehicle. Making matters worse, at the time of the accident many new ventures were being developed which relied on the shuttle's unique capabilities. For example, the US government was planning to turn the Landsat Earth observation program over to a private operator, Eosat. This group had selected a new generation of satellites over the venerable Tiros model. The new satellite could not be launched on an expendable rocket because of size and weight.[218]

In addition, the users of commercial satellites lost large amounts of revenue because of their inability to provide services.[219] The now global communications revolution was in its infancy in 1985. The Internet was still a Department of Defense research network managed by a few universities and government research installations. Many of those planning to take advantage of the satellites to be launched from the shuttle had made commitments to satellite providers. These providers no longer could deliver; delaying the deployment of space-based communications networks and increasing overall costs to consumers.

The national defense posture was weakened by the inability to launch defense satellites. Before the *Challenger* explosion, the Department of Defense recognized that it had no back-up plan should the shuttle fleet be grounded for extended periods of time. Confronting a national security mission where satellites had to be launched on demand according to world political

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[217] Ray A. Williamson, "The USA and international competition in space transportation," Space Policy, Vo. 3, May 1987, p. 117.
[218] Ramon Lopez, "Impact of *Challenger* Loss: Future Shuttle flights ties to presidential probe findings," Space Markets, Spring 1986, p. 44.
[219] Lopez, pp. 42-43.

conditions, they began to develop a "complementary expendable launch vehicle" fleet to supplement NASA's shuttle. It was a classic case of too little too late, as Lopez writes:

> None of these expendable rockets can meet all the US military needs. Defense Secretary Caspar Weinberger has said the *Challenger* loss will 'have a serious impact' on Defense Department programs. "We'll do the best we can on other vehicles… But a lot of them were configured for the size and capacity of a Shuttle."[220]

The loss of the *Challenger* left a permanently weakened NASA**.** NASA could not meet its flight commitments and projects dragged on far after their scheduled completion dates. Project costs increased for assembly and storage facilities had to be kept operating. Biddle argues that this was the result of NASA's policy of making the shuttle NASA's only launcher and its subsequent overreliance on the shuttle.[221] He further contends that "extinction [of the human space flight program] is the consequence" of any policy that depends too much the shuttle.[222]

NASA's image was permanently tarnished. NASA had been the agency for which no challenge was too great. Going to the Moon within a decade had seemed impossible, but this team had done it six times. In Apollo 13, the one mission encountering an emergency, the agency's operations team performed a miracle in bringing the crew back alive. This "can do" attitude was celebrated within the agency and NASA saw the space shuttle as the vehicle representing a new age in space flight. The loss of the *Challenger*, coupled with the revelations that NASA did not have all of the answers to how the accident occurred, led many to believe that the agency had been lost as well.[223]

The morale of NASA's work force hit an all time low. Many employees felt that they were, in some undefined way, responsible for the failure. These people worked with the astronauts and took pride in keeping them safe. The team had put millions of hours into identifying and eliminating hazards to the vehicle so that it might fly safely, but somehow it had failed. In addition, many employees were unprepared for the loss of public confidence in NASA.

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[220] Lopez, pp. 42-43.
[221] Biddle, p. 32.
[222] Biddle, p. 32.
[223] T.A. Heppenheimer, "Lost in Space: What Went Wrong with NASA?" American Heritage, Vo. 43, Nov. 1992, pp. 60-72.

They did not expect to be vilified as unethical or careless workers who treated their responsibilities lightly. As a consequence, many employees were afraid to pass data up the chain of command that might come back to haunt them. Michael Brody remarked that:

> Watching the agency's fortunes decline, employees have tended to act like cowed bureaucrats. The result: an organization in which the flow of vital information up and down was as flawed as the now notorious O-rings…[224]

NASA managers became risk averse as well. With memories of the shuttle program managers testifying before the Presidential Commission, managers grew hesitant to certify that a system was safe.[225] The previous assertion that it was as safe as they could make it would no longer serve. Collins captures this sentiment well:

> NASA simply cannot guarantee 100% safety. If it tries it will never fly again. If this period of grounding drags on too long, more and more engineers will conjure up more and more objections or improvements. Top management may become afraid to ignore any warnings, no matter how ill founded. The safety profession seems to attract more than its share of zealots and it takes an experienced gutsy leader to know when their precautions are becoming excessive… When it is grounded NASA is just another bureaucracy, and we have plenty of those already. [226]

With the *Challenger* accident, Americans realized that human space flight involved inherent dangers. Although NASA made no secret that space flight involved systems that released enormous amounts of energy, the risks were not widely known by most citizens. This naiveté was the result of over two decades of successful missions. Wainright comments that, "As time passed, a kind of public innocence developed, a denial of reality, of the unchanging realities of experimental flight…"[227] Now they were forced to realize that such efforts are hard and dangerous, not easy and routine. As Furniss writes, " Above all… *Challenger*'s epitaph will be that the tragedy brought the space business very much down to Earth and back to reality." [228]

Contrary to conventional thought public support for the space shuttle program actually increased.[229] Before the accident, the program had receded into the background of news to most

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[224] Michael Body, "NASA's Challenge: Ending Isolation at the Top," Fortune, 12 May 1986, p. 26.
[225] Collins, p. 239.
[226] Collins, p. 239.
[227] Louden Wainwright, "After 25 Years, An End to Innocence," Life, March 1986, p. 15.
[228] Tim Furniss, "Space Comes Down to Earth," Space, Sept-Nov., 1986, p. 41.
[229] John D. Miller, "The Challenger Accident and Public Opinion: Attitudes Toward the Space Programme in the USA." Space Policy. Vol. 3, May 1987, pp. 122-140.

Americans. Although the missions were mentioned in broadcasts, they were no longer the lead story. After the *Challenger* accident, people indicated that the accident should not prevent the nation from moving forward in exploring space. In President Reagan's speech to the nation on the day of the accident, he summarized this spirit:

> I know it's hard to understand that sometimes painful things like this happen. It's all part of the process of exploration and discovery, it's all part of taking a chance and expanding man's horizons.[230]

Responding to the Presidential commission, NASA made a number of organizational changes.[231] In what has been called a "quiet revolution… in the upper ranks of NASA management", the agency promoted astronauts into senior positions.[232] Captain Robert Crippen, the pilot of the first shuttle mission, led the management overhaul itself. Rear Admiral Richard Truly served as the Associate Administrator for Space Flight and Dr. Sally Ride as the Associate Administrator for the Office of Exploration. Paul Weitz became the Deputy Director for the Johnson Space Center. When all positions were filled, current or former astronauts (Figure3-24) held 10 senior positions.

Astronaut	Position	Location
Rear Admiral Richard Truly	Associate Administrator for Space Flight	NASA Headquarters
Dr. Sally Ride	Acting Assistant Administrator, Office of Exploration	NASA Headquarters
Captain Rick Hauck	Associate Administrator for External Affairs (August 1986-January 1987)	NASA Headquarters
Colonel Fred Gregory	Chief, Operational Safety Branch Office	NASA Headquarters
Captain Robert Crippen	Deputy Director, NSTS Operations	Kennedy Space Center
Paul Weitz	Deputy Director	Johnson Space Center
John Young	Special Assistant to the Director for Engineering, Operations, and Safety	Johnson Space Center
Lt. Colonel James Adamson	Assistant Manager for Engineering Integration, NSTS Program Office	Johnson Space Center
Colonel Charles Bolden	Chief, Safety Division	Johnson Space Center
Colonel Brewster Shaw	Chairman, Orbiter Modification Team	Johnson Space Center
Colonel Bryan O'Connor	Assistant Manager for Operations, NSTS Program Office, Chm., Flight Safety Panel	Johnson Space Center

Figure 3-24 - Astronauts in Management[233]

[230] Magnuson, p. 29.
[231] See Appendix G
[232] David L. Chandler, "Astronauts Gain Clout in 'Revitalized'," The Boston Globe, p. 1.
[233] NASA, Report to the President on the Implementation of the Recommendations of the Presidential Commission on the Space Shuttle Challenger Accident, p.32.

The safety function of the program was separated out from the operational functions. NASA created an Office of Safety, Reliability, Maintainability, and Quality Assurance at NASA Headquarters. This office was responsible directing and implementing the agency-wide safety program. It provided independent technical reviews of all NASA programs and projects to ensure that the programs were properly identifying and controlling risk. Astronaut Colonel Fred Gregory managed the Operational Safety branch of this new organization. The new office also had functional management responsibility for all safety offices at the NASA field centers. George Rodney, the new director for the Office of Safety, Reliability, Maintainability, and Quality Assurance at NASA Headquarters, responding to inquires about this new organization, concluded that this was a step that should have been taken prior to *Challenger* and that, “There were not as clear-cut lines of authority last year as there should have been.”[234]

Overall management of the shuttle program was taken away from the Johnson Space Center and moved to NASA Headquarters in Washington D.C. Now, the shuttle program was the responsibility of the Director, National Space Transportation System, NSTS, reporting directly to the Associate Administrator for Space Flight. The most senior managers in the shuttle program at Johnson Space Center, Kennedy Space Center, and Marshall Space Flight Center became Headquarters employees reporting to the Director, NSTS. Budget authority for the shuttle program was transferred to the new director. Each field center now was to develop budget requests that were submitted to the director for any activities involving the program. NASA also re-established an Office of Space Flight Management Council composed of the Director, NSTS, and the center directors of the four centers involved in human space flight. This council, which had been discontinued, provided a forum for establishing strategic direction for the program.

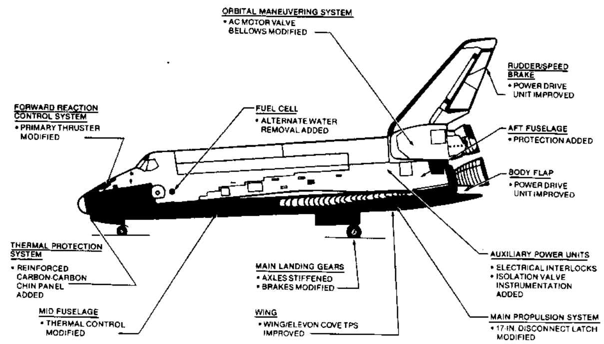
The agency also took advantage of the suspension in shuttle flights to improve a number of the shuttle and support systems to make them safer (Figure 3-25). The space shuttle main engines were modified to eliminate a number of hazards and to improve the margin of safety in critical components. The shuttle landing gear was strengthened to lower the risk of a problem

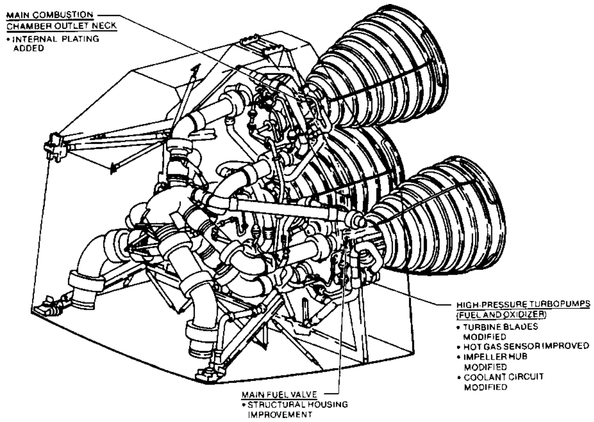
[234] Chandler, p. 1.

when landing on the relatively confined runway at the Kennedy Space Center. The now familiar drag chute was added to slow the orbiter during landing and help prevent overshooting the end of runway. Also, NASA revalidated the databases that supported shuttle operations. For example, simulators were used to revalidate the flight rules, which determine whether a mission is cut short due to problems.

Responding to charges that the safety systems did not adequately track known problems, the problem reporting system was completely overhauled. The agency established the System Integrity Assurance Program. This program established clear responsibilities for the managers in each shuttle program organization. It also included a management information system that supplied everyone in the program access to problem-related data. This program compliance assurance and status system increased visibility into critical problem data and allowed managers to monitor for trends that could signify the existence of a larger problem. Using this system, the program safety offices could independently assess problems and provide reports to both the program managers and to the safety managers at NASA Headquarters.

Shuttle Element	Prime Contractor	Independent Review Contractor
Orbiter	Rockwell International, Space Transportation Systems Division	McDonnell Douglas Astronautics Company, Houston Division
External tank	Martin Marietta, Michoud Aerospace Division	Rockwell International, Space Transportation Systems Division
Solid rocket motor	Morton Thiokol, Inc., Wasatch Operations	Martin Marietta, Denver Aerospace Division
Solid rocket booster	United Technologies Corp., United Space Boosters, Inc	Martin Marietta, Denver Aerospace Division
Space Shuttle main engine	Rockwell International, Rocketdyne Division	Martin Marietta, Denver Aerospace Division





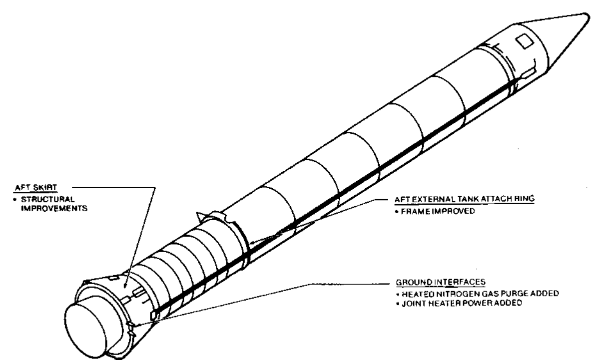


Figure 3-25 - Examples of Technical Changes Made to the System[235]

Although the volume of the consequence literature is far smaller than that of the cause literature, there are similarities. First, all of the analysts are correct in stating that these are the consequences of the system failure. However, each ultimate consequence is discussed in isolation. Depending on the sphere of interest of the analyst, the consequences are considered as they affect a particular discipline. Although other competing consequences may be acknowledged, there is no attempt to integrate them or discuss their relationships.

Second, all analysts assume that the proximate consequence moves directly to the ultimate consequence in a linear deterministic fashion. As if preordained, events unfold step-by-step in an unalterable journey to a particular consequence. Consequently, analysts do not discuss

[235] NASA, Report to the President on the Implementation of the Recommendations of the Presidential Commission on the Space Shuttle Challenger Accident, pp.88-91.

whether any actions taken after the failure might have modified or eliminated the ultimate consequence. For example,

- What would have happened had NASA responded more rapidly with its own investigation and a Presidential Commission never been formed in the first place?
- What would have happened if NASA had not chosen to ground the fleet for almost 3 years, but had gone ahead with the next scheduled flight?
- What would have happened had NASA not so readily agreed with all of the Presidential Commission recommendations?
- What would have happened if NASA had done a better job of preparing Congress and the American Public about the dangers of space flight and the probability of a catastrophic system failure to the space shuttle system?

Finally, a comprehensive review of over 100 books and journal articles written prior to *Challenger* reveals only three authors who acknowledge the fact the consequences of a system failure would be severe and far reaching**.**[236] Even more surprising, however, is that those who were astute enough to recognize the possibility of a system failure do so in non-space related journals. This complete absence is startling, as certainly space industry officials were aware of the risks of the complicated space shuttle System.

Ominously, one of the few to recognize the potential fallout of a space shuttle failure and call for preparations in advance of that day, Harry Stine, warned

> There is a definite, finite probability that one of the four NASA Space Shuttle Orbiters is going to go prang…This is the Big One, the loss of the entire Orbiter along with two to seven people aboard; the total wipe-out of 25% of the USA's manned space capability;. When the shuttle prangs, it will be the media event of the decade.[237]

What a shame that America and NASA, in particular, did not heed Stine's warning and better prepare for such a day.

[236] See Appendix H.
[237] Harry G. Stine, "The Sky is Going to Fall," Analog, August 1983, pp. 74-77.