

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

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Abstract

In this discussion, we will critically examine the assumptions, design decisions, and programmatic choices that shaped the Space Shuttle program, and consider alternative approaches that might have led to greater success. Key questions include:

- Was the original vision of a low-cost, reusable spacecraft capable of carrying both crew and cargo fundamentally flawed?
- Were segmented Solid Rocket Boosters sufficiently mature for human-rated flight in the 1970s?
- Did the decision to use ceramic thermal protection tiles—rather than more durable refractory metals—undermine the goal of achieving airline-like operations?
- Once it became clear that repeatedly starting and stopping production of the Space Shuttle Main Engines was inefficient and costly, why wasn't an expendable cargo variant pursued?
- What factors contributed to the doubling of the External Tank's cost?
- Why did NASA fail to fully account for or mitigate the destructive effects of unburned hydrogen from SRBs and LOX/LH₂ engines, as highlighted by damage observed on the Mobile Launch Platform during recent Artemis operations?

Nomenclature

• APU	Auxiliary Power Unit
• BTW	By The Way
• CG	Center of Gravity
• ET	External Tank
• KSC	Kennedy Space Center
• LH ₂	Liquid Hydrogen
• LOX	Liquid Oxygen
• MSFC	Marshall Space Flight Center
• MLP	Mobile Launch Platform
• NASA	National Aeronautics and Space Administration

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

- OMS Orbital Maneuvering System
- RCS Reaction Control System
- SRB Solid Rocket Booster
- SOFI Sprayed On Foam Insulation
- SSME Space Shuttle Main Engine, RS-25
- TVC Thrust Vector Control System
- VBAFB Vandenberg Air Force Base

1. Introduction

The Space Shuttle was to be America's "Space Truck" by taking payloads and passengers into Low Earth Orbit at a much lower cost than the Saturn V. In October 1969, at a Space Shuttle symposium held in Washington, George Mueller presented this clearly with his opening remarks: *"The goal we have set for ourselves is the reduction of the present costs of operating in space from the current figure of \$1,000 a pound for a payload delivered in orbit by the Saturn V, down to a level of somewhere between \$20 and \$50 a pound."*¹ At that time, when the 50,000-pound payload was still the standard, Mueller's cost goal represented a cost per flight of \$1 million to \$2.5 million. This was somewhat higher than Lockheed's Max Hunter's estimated cost for a Shuttle Flight as \$350,000 at a flight rate of 95 missions per year, but it would have been a vast improvement from the \$185 million of a Saturn V flight. There was even talk of a Space Hotel by the Hilton family if the cost could get down to \$5/lb.ⁱ

In practice, however, nearly every design and programmatic decision intended to reduce development costs or enhance performance had the opposite effect on operations. Efforts to maximize performance increased system complexity and maintenance requirements, driving up operational costs (i.e., manpower). These higher costs reduced the achievable flight rate, which in turn drove marginal costs even higher. A clear example is the Space Shuttle Main Engine (SSME). Rather than accepting lower performance to enable longer service intervals, the program pushed for maximum specific impulse. As a result, the engines required borescope inspection after every 8-minute flight (BTW: The SSME hydrogen pump is a three-stage centrifugal pump driven by a two-stage hot-gas turbine. It boosts the pressure of the liquid hydrogen from 276 to 6,515 psia and operates at approximately 35,360 rpm with a power of 71,140 hp.)² This level of performance came at the cost of intensive maintenance.

From the outset, the Shuttle design operated with minimal performance margin. Engines routinely ran beyond their original design limits (reflected in ratings of 104% or even 109% thrust), while structural weight was aggressively minimized across the external tank, solid rocket boosters, thermal protection system, and orbiter. This left little room to trade performance for operational simplicity or reduced maintenance. The program prioritized payload capability (more payload to orbit) over process efficiency, effectively locking in high manpower requirements (more manpower on the ground). Compounding this issue, expectations for rapid turnaround were unrealistic. The only prior experience with reusable rocket aircraft—the X-15—required as little as six working days for turnaround and could fly up to three times per month per vehicle. Against this backdrop, NASA's expectation of a 160-hour turnaround for a far more complex system was overly optimistic and ultimately unattainable.

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

2. Space Shuttle Design Lessons Learned

Its official program name was Space Transportation System (STS), taken from a 1969 plan for a system of reusable spacecraft. The cost of operating the Saturn V heavy lift launch vehicle was extreme. The Space Shuttle was supposed to deliver astronauts and satellites and other payloads into Low Earth Orbit at a fraction of the cost while flying 60 missions per year (40 from KSC and 20 from Vandenburg) with only 160 hours on the ground to turn around the vehicle. In reality, over its 30-year operational life, the Shuttle flew just 135 missions, with a peak annual rate of nine launches—far short of the projected 40 per year from Kennedy Space Center alone. Even a brief examination of the design would have suggested that such flight rates were unachievable given the constraints of workforce, facilities, and vehicle complexity. In practice, sustaining even one launch per month proved challenging

Each orbiter was intended to fly up to 100 missions, yet the most flown vehicle, Discovery (OV-103), completed only 39. Opportunities to improve processing efficiency, reduce costs, and enhance safety were limited by management's reluctance to implement significant design changes. This stands in stark contrast to the continuous evolution seen in expendable launch vehicles such as the evolution of very first Thor-Delta rocket in 1960 into the Delta III in 1998.

The Space Shuttle was composed of a reusable orbiter launched with two reusable solid rocket boosters and a disposable external fuel tank. It was to carry up to eight astronauts and up to 65,000 lb of payload into low Earth orbit (LEO). When its mission was complete, the orbiter would reenter the Earth's atmosphere and land like a glider at either the Kennedy Space Center or Edwards Air Force Base. Because the US Air Force was to be a major user of the Space Shuttle, the US Air Force placed requirements for a larger payload bay than NASA intended and for the vehicle to return to launch site during the first orbit (supposedly, to snatch a satellite out of orbit before a hostile nation could react). This return-to-launch-site after 1 orbit capability required the Shuttle to fly 1,100 miles cross range to the east, which resulted in the large wings on the orbiter.

Various shuttle concepts had been explored since the late 1960s. The program formally commenced in 1972, becoming the sole focus of NASA's human spaceflight operations after the Apollo, Skylab, and Apollo–Soyuz programs in 1975. The Shuttle was originally conceived of and presented to the public in 1972 as a 'Space Truck' which would, among other things, be used to build a United States space station in low Earth orbit during the 1980s and then be replaced by a new vehicle by the early 1990s that would get us back to the moon and beyond. The promised new replacement vehicle (SLS) is still under development - now in 2026.

Fundamentally, the Shuttle's design philosophy—launch like a rocket, land like an aircraft, and operate with airline-like efficiency within a 160-hour turn-around schedule — proved to be the single largest management misjudgment error of the entire program. In reality, the vehicle combined the most demanding aspects of both domains without achieving the operational advantages of either. The concept should have been: launch like a rocket, use on orbit as a work platform, land like a rocket on a launch pad at KSC or VBAFB; no runway, no tires, no wheels, no wings and tail, fewer parts, less maintenance, less than 1/3 as many tiles, and no Edwards.

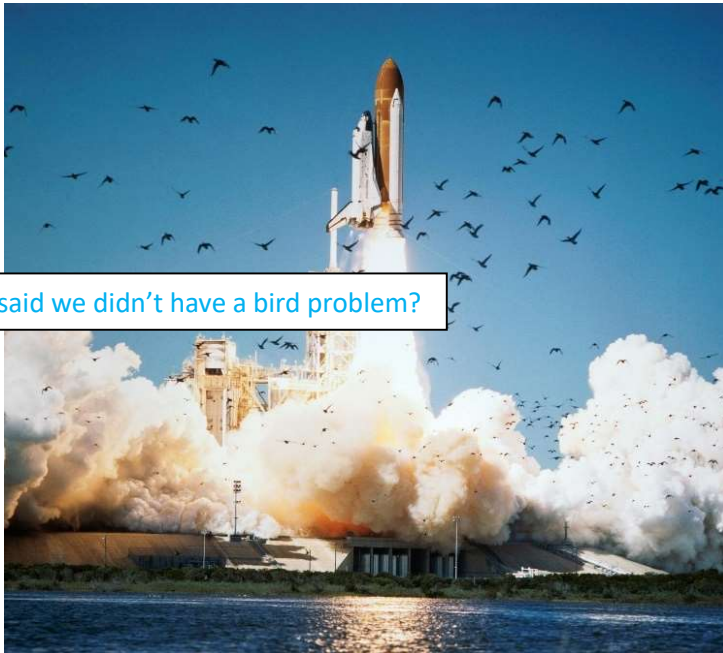
Unfortunately, the Shuttle wasn't designed or operated like an aircraft, but rather it was designed and operated like a top fuel dragster. Much like a top fuel dragster—where engines require complete rebuilds after each 4 second run—the Shuttle's propulsion system demanded intensive post-flight servicing. This approach is fundamentally incompatible with airline-style operations.

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

For a modern aircraft, even the loss of one engine will not result in a total loss of propulsion (which is also true for the Space Shuttle), plus engine failures are incredibly rare. The FAA estimates an engine failure of about one per 375,000 flight hours. In other words, that's one jet engine failure for every ~43 years of continuous flight time³. However, the SSME's were removed after every single launch so the bearings could be inspected by borescope.

The Space Shuttle system's overall failure rate of approximately 2% closely matched predictions made during its design phase—highlighting the accuracy of the engineering analysis, but also the inherent limitations of the design choices. It has been said that engine designers would “*sell their grandmothers*” to get another second of performance (Isp) out of the engines. In the pursuit of maximum performance, the Shuttle sacrificed operational simplicity and cost efficiency. The result was a vehicle that achieved remarkable technical feats, but fell far short of its original promise as a routine, low-cost space transportation system.

2: LESSONS LEARNED ON THE SPACE SHUTTLE DESIGN



Who said we didn't have a bird problem?

1. Passengers and major cargo should never have been put on the same vehicle. A fundamental flaw in the Space Shuttle program was the decision to combine passengers and heavy cargo on a single vehicle. This choice drove the system toward the highest possible safety standards, transforming what could have been a relatively low-cost cargo launcher into an extremely expensive, man-rated system. At the same time, the absence of an expendable cargo variant meant there was no practical way to retire aging hardware other than through attrition or museum display. (Being careful not to design and build vehicles to scrap just to keep production lines in operation.) Compounding this issue, the commitment to full reusability disrupted production stability. Critical components—most notably the Space Shuttle Main Engines (SSMEs)—were not produced continuously, leading to extremely high costs whenever production lines had to be restarted. This reflects a broader management failure: inadequate forecasting of failure rates, launch cadence, shelf life, and hardware lifetime, etc. By mixing cargo and passengers on the same vehicle means a cheap cargo-rated vehicle becomes an expensive man-rated vehicle. If the Space Shuttle didn't have to

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

transport 8 passengers and 65,000 lbs. of cargo at the same time and land like an airplane, the entire vehicle design could have been greatly simplified while having two different vehicles that carry out two different functions.

A more effective architecture would have separated crew and cargo functions:

1. **Passenger Vehicle (Reusable):**

A smaller, simpler orbital vehicle—conceptually similar to modern crew capsules—could have transported crews (and limited cargo) and returned via propulsive landing. Removing the requirement to carry large payloads and land as an aircraft would have significantly reduced system complexity.

2. **Cargo Vehicle (Expendable or Semi-Reusable):**

A Shuttle-derived cargo launcher (often referred to as “Shuttle-C”) using the same boosters, external tank, and engines could have delivered over 100,000 pounds to low Earth orbit. If expendable, this approach would have maintained continuous production lines and avoided costly restarts. Reusability could have been selectively applied where it made economic sense, rather than as a blanket requirement.

2. Solid Rocket Boosters (SRBs)

NASA felt confident in segment SRB based upon their experience with the Titan 3C, 3D, and 3E vehicles. However, the technology for segmented Solid Rocket Motors on a low-cost, man-rated vehicle was not ready in the 1970’s.

Liquid rocket boosters (LRBs), which can be throttled or shut down in an emergency, would have provided greater safety and operational flexibility. Alternatively, monolithic (unsegmented) solid motors could have reduced joint-related risks. These options were ultimately rejected due to performance constraints and aerodynamic loads on the orbiter’s wings, but their exclusion came with significant safety tradeoffs.

3. Main Engine Philosophy

The SSMEs were operated at extremely high performance levels to maximize payload capability. A more conservative approach—lower chamber pressures, reduced turbomachinery speeds, and slightly lower Isp—could have enabled far longer service intervals, potentially approaching airline-like operations.

Accepting reduced engine performance would have required either a smaller orbiter or supplemental propulsion, such as additional LOX/LH2 engines for orbital maneuvering. However, this trade would likely have reduced maintenance demands and overall lifecycle cost.

4. Propellant Choices

Hypergolic fuels are very toxic and cause complete shutdown of other activities during fueling operations while at the pad. Therefore, all hypergolic devices (OMS & RCS) must be eliminated from the vehicle.

1. The hypergolic OMS weigh 69,000 lbs and are very inefficient (have a lower Isp) compared to a LOX-LH2 system. OMS are only operated to boost the Shuttle the last ~35 mph into orbit after the SSME’s are shut-down and the ET is jettisoned; they are also

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

used to deorbit. It would have made much more sense to utilize LOX-LH2 engines (such as RL10 engines developed in the 60's) for OMS and be able to also use the same stored LOX-LH2 for electrical power while in orbit, but there may be a weight penalty.

2. If non-cryogenic propellants must be used instead of hypergolic fueled RCS, nitromethane (used in top fuel dragsters) with a catalyst could have been used as a safe monopropellant thruster;⁴ although this is not a proven system.
 3. The OMS/RCS systems have their own pressurization system using nitrogen gas, which adds another commodity that must be loaded onto the vehicle; although nitrogen is used in several other systems and is safe/easy to load.
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5. Actuators Choices

The longest Shuttle mission was ~17.5 days due to the electrical power consumed which was derived from a limited amount of hydrogen and oxygen for the fuel cells during orbit. Some of the power was used just to keep the hydraulics warm though the Shuttle got plenty of heat from the sun when in orbit. The hydraulic system should have been replaced with electro-mechanical actuators to reduce power consumption on orbit, which would extend time on orbit maybe to the point that a Space Station would not be necessary. Not having wings and landing gear would have also reduced the need to warm hydraulic systems.

6. Recovery Choices

The SRB's landed via parachute in the Atlantic Ocean. Even though they used very large parachutes, the SRB's hit with such force that salt water was found inside 'sealed' hypergolic hydraulic systems. Solution: No navy, stay out of the water and utilize a propulsive return to the launch site to eliminate these issues entirely.

7. Upper Stage Propulsion

Because payload was carried in the same vehicle with passengers, highly efficient upper propulsion stages using LOX-LH2 couldn't be utilized for safety reasons after the Challenger Accident; instead, far less efficient solid propulsion upper stages had to be utilized.

(Solution: A dedicated cargo vehicle would have avoided this limitation. Note that LOX and LH2 will still be needed on the passenger vehicle.)

8. Vehicle Cooling

Cooling the passenger vehicle required a multiple of systems due to the different environments the Orbiter had to operate within. A Freon system was used while the vehicle was in orbit with the payload bay doors open, a steam system was used from the time payload bay doors were closed until the vehicle reached 100,000 ft altitude during deorbit, and a boiling ammonia system was used from 100,000 ft elevation until after landing. A single, much simpler system must be installed in future vehicles, such as a very high-temperature heat pump and steam generator⁵ that can reject heat up to 140°C. On orbit,

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

140°C water would be routed through the payload bay doors like the freon system did, but after the doors are closed, steam would be ejected until landing.

9. Vehicle Ground Connections

100's of cables and fluid lines connects the MLP to the pad that must be connected and verified before every launch and disconnected after every launch or roll-back. This is in addition to the 100's of cables and fluid lines that connect the MLP to the vehicle. This process takes many hours to complete adding to the number days the vehicle spends at the pad. On the other hand, Ariane 5 rockets were typically launched within 24 hours of reaching the pad. ⁶To be fair: Communications between the vehicle / Pad / ground is directly dependent on vehicle design complexity and desired information exchange/control required. Streamlined interfaces and greater automation with automatic verifications—similar to systems used by vehicles like Ariane 5 —could have significantly reduced pad time.

10. Launch constraints

Not having go-around capability was very expensive since it caused many launch scrubs because the Return-To-Launch site and down range sites had to have clear weather to land. (Solution: Launch like a rocket, fly like a rocket, use rocket platform while on orbit, land like a rocket at the launch Pad would have provided far greater operational flexibility and reduced dependence on ideal weather conditions. Otherwise, weather will always be a factor because of Tile-design-and guidance control.

11. Program Management

NASA maintained control of the Space Shuttle during its entire program even though they stated that Earth-to-Orbit transportation would be left to civilian operators. If these lessons had been learned earlier in the program, civilian operators may have taken over the program. Civilian operators could have made additional funding by providing advertising (via overlays on TV feeds, not actually painting on orbiters) and by providing behind-the-scenes visits to the VAB and firing rooms (of course, behind plexiglass windows).

12. Program Management

NASA never realized the Shuttle was a short-term space station that needed to be modified for it to become a long-term space station. Imagine the savings to the agency if the Shuttle could stay in orbit for several months to a year instead of building and maintaining Space Station Freedom.

13. Program Management

Why was the Shuttle program ended? Problems became “within family” and grew in seriousness with time. The Shuttle was always unsafe and grew more unsafe with each flight. We never had a greater understanding of the risks. We just accepted them as normal and continued to fly.

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

3: Shuttle Challenger Disaster

The immediate cause of the Challenger disaster was the failure of the two rubber O-rings that sealed the field joint between the two lower segments of the right-hand solid rocket booster. This failure was contributed to severe cold weather, and a SRB segment seal design that rotated open to provide a path for hot exhaust gas to escape from inside the booster during ignition and lift-off. But the evidence presented herein doesn't support this as the only factor.

January 28, 1986, the Space Shuttle Challenger broke apart 73 seconds into its flight. All seven crew members aboard did not survive. The spacecraft disintegrated 46,000 feet above the Atlantic Ocean, off the coast of Cape Canaveral, Florida, at 11:39 a.m. EST. It was the first fatal accident involving an American spacecraft while in flight.

The two solid rocket boosters (SRBs), built by Morton Thiokol, provided the majority of thrust at liftoff. They were attached to the external tank, and burned for the first two minutes of flight. The cause of the disaster was the failure of the primary and secondary redundant O-ring seals in the AFT field joint of the shuttle's right hand solid rocket booster (SRB). The record-low temperatures on the morning of the launch had stiffened the rubber O-rings, reducing their ability to seal the joints. The Zinc Chromate Putty had also stiffened and did not follow the joint dynamics allowing hot gas to impinge on the O-rings. Shortly after T-O, the seals were breached, and hot pressurized gas from within the SRB leaked through the joint and over a course of 72 seconds burned through the aft attachment strut connecting the SRB rocket to the external LH2 propellant tank (ET), then through the ET's thin skin LH2 tank. The collapse of the ET's internal structures and the rotation of the SRB that followed, moved the shuttle stack, traveling at a speed of Mach 1.92, into a trajectory that allowed aerodynamic forces to tear the orbiter apart. Both SRBs broke away from the now collapsed and failing ET and continued to fly uncontrollably until the range safety officer destroyed them⁷.

Space Shuttle Challenger disaster - Image



Challenger's solid rocket boosters fly uncontrollably after the collapse/breakup of the external tank (ET) separated them from the shuttle stack. The remains of the orbiter and tank leave thin white contrails as they fall toward the ocean and certain death of the crew at water impact.

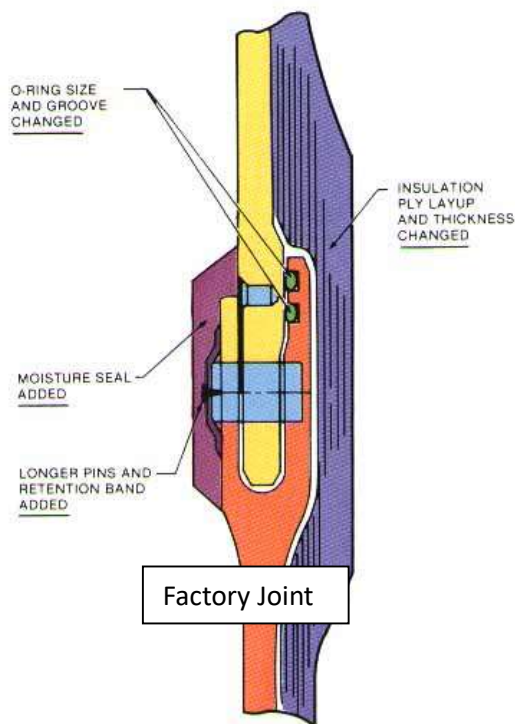
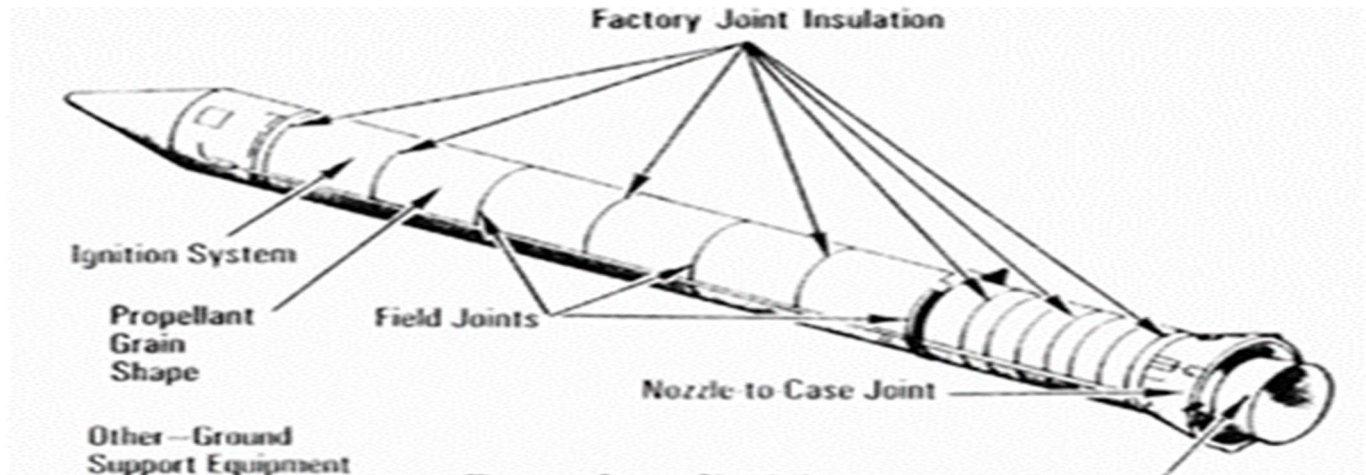
The Space Shuttle's Solid Rocket Booster problem began with the faulty design of its field joint including O-rings and increased as both NASA and contractor management first failed to recognize it as a problem, then

failed to fix it, and finally treated it as an acceptable flight risk. Costs were the primary concern

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

of NASA's selection board, particularly those incurred early in the program. Thiokol's three competitors were Aerojet Solid Propulsion Co., Lockheed Propulsion Co. and United Technologies. The Source Evaluation Board on the proposals rated Thiokol **fourth** under the design, development and verification factor, **second** under the manufacturing, refurbishment and product support factor and **first** under the management factor.⁸ Despite its lower technical ranking, Thiokol was selected, reflecting the program's prioritization of cost and managerial factors over design robustness.

3a: SRB JOINTS



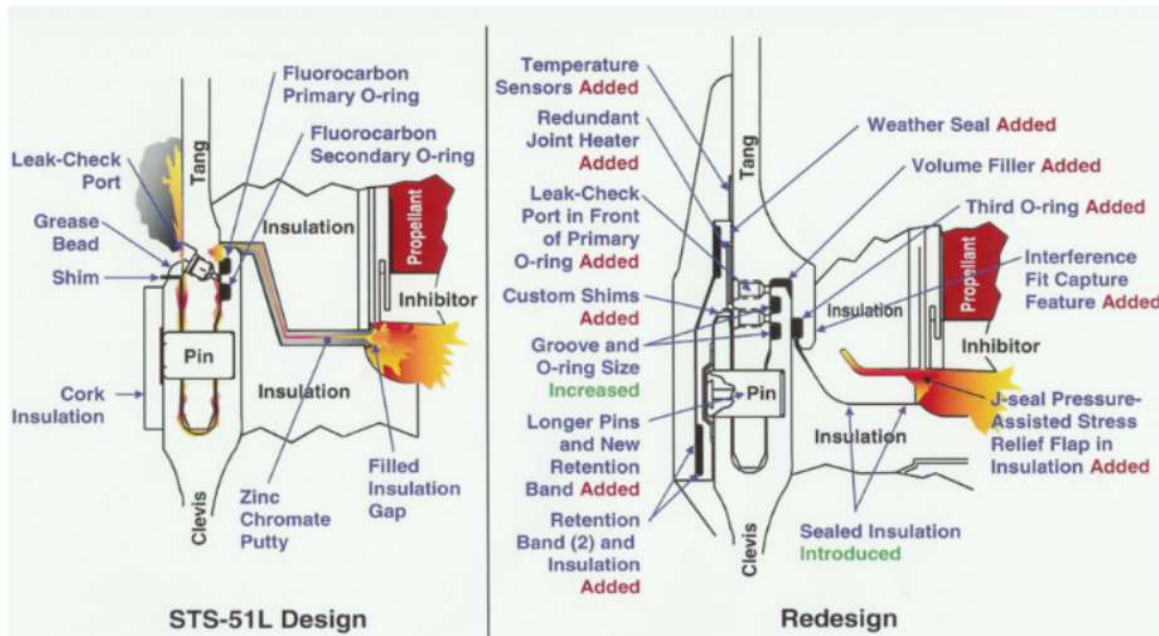
Each SRB was constructed in eight cylindrical segments and put together in pairs at the factory in Utah and transported by rail to KSC. The resulting 4 paired motor segments were assembled in the Vehicle Assembly Building at KSC with three tang-and-clevis **FIELD JOINTS**. In this design, the tang (a protruding flange) of the upper segment fit into the clevis (a U-shaped receptacle) of the lower segment. Each field joint was sealed with two ~20-foot (6 meter) diameter Viton-rubber O-rings around the circumference of the SRB and had a cross-section diameter of 0.280 inches (7.1 mm). The O-rings were required to contain the hot (5,630°F), high-pressure (1,000 psi) gases produced by the burning solid propellant. The two O-rings were configured to create a double bore seal. The upper and lower segment interfacing sidewall insulation were coated with a thin layer of Zinc Chromate putty to aid in sealing. It is important to distinguish these **FIELD JOINTS** from the **FACTORY JOINTS**, which connected segment pairs during initial manufacturing.

Factory joints incorporated continuous insulation across the joint and included thicker insulation layers, making them inherently more robust. Although the metal case geometry was identical for both joint types, the field joints lacked the same level of integrated insulation protection. During

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

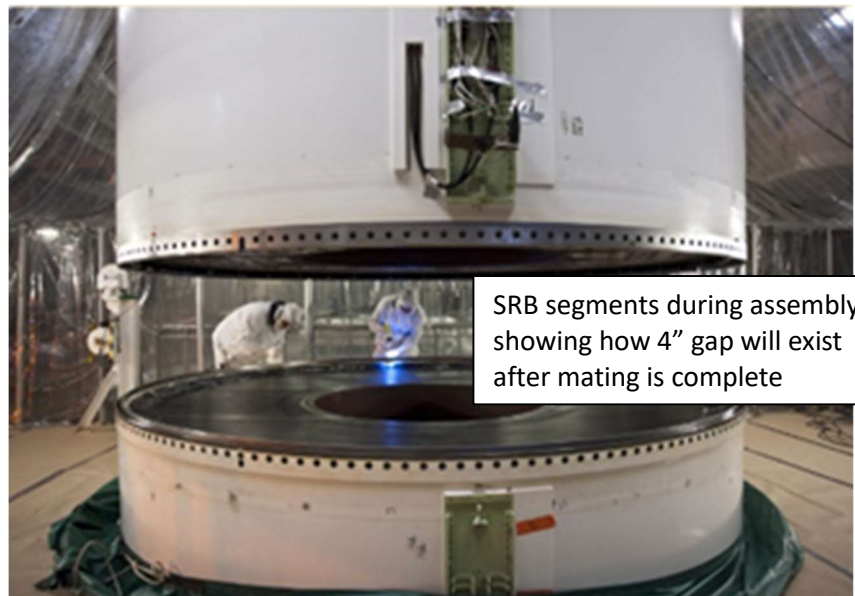
leak check pressure decay test, the secondary O-ring would be seated properly in the correct direction, however the primary O-ring would be seated in the direction opposite to motor pressurization. During the first 0.6 second after ignition, it was believed that the internal combustion gases would cause the primary O-ring to move to the correct position and seat⁹. This assumption proved to be a critical vulnerability. It relied on rapid and reliable O-ring movement under dynamic conditions—precisely the condition most susceptible to degradation from temperature, material stiffness, and joint deformation during ignition.

FIELD JOINT COMPARISON



3b: Space Shuttle Field Joints

Space Shuttle SRB field joints were assembled at KSC with joint hardware exposed to gases during combustion and were more susceptible to failure. There were 7 factory joints. Three field installed joints were of more concern than seven factory joints. When the segments are assembled, there is still a 4" gap between the segments; so flames and pressure quickly impact the joints soon after booster ignition.



LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

3c: O-Ring Concern

The original SRB field joint design consisted of a tang-and-clevis interface. The upper end of the lower segment formed a deep U-shaped cavity (the clevis), while the lower end of the upper segment extended into a tang that fit within this cavity. Two parallel grooves along the inner surface of the clevis housed approximately 20-foot (6-meter) diameter Viton O-rings, which were intended to seal the gap and prevent hot combustion gases from escaping the joint. It has been suggested—notably by Allan J. McDonald—that this configuration allowed water to accumulate in the bottom of the clevis, potentially freezing and contributing to joint rotation during launch¹⁰. However, this claim is not supported by physical evidence. The large external grease bead applied along the exposed clevis leg remained intact through ascent, ocean impact, and tow-back to Hangar AF, only being removed during post-recovery pressure washing. This indicates that water intrusion and freezing within the joint were not primary contributors to joint behavior.

A 1977 test showed that up to 0.052 inches (1.3 mm) of joint rotation occurred during the simulated internal pressure of a launch. Joint rotation, which occurred when the tang and clevis bent away from each other, reduced the compression on the O-rings, which weakened their sealing capability and increased the possibility for combustion gases to reach, erode, and breach the O-rings¹¹. NASA engineers suggested that the field joints should be redesigned to include shims around the joints, but they received no response¹². In 1980, the NASA Verification / Certification Committee requested further tests on joint integrity to include testing in the temperature range of 40 to 90 °F (4 to 32°C) and with only a single O-ring installed¹³. The O-rings were certified down to 40 °F. The NASA program managers decided that their current level of testing was sufficient to support the current level of O-ring damage being observed on the flight elements which was considered to be acceptable and within family. Further testing was deemed not to be required. One of the biggest failures of the program was the inability to test the SRB's in the vertical position. Thiokol engineer, Howard McIntosh, SRB contractor, stated that tests conducted with the DMSRBs in the horizontal position were not valid for O-ring seating and temperature verification¹⁴. According to Allan McDonald, *“One of the biggest failures of the program was the inability to test the SRB's in the vertical position.”* This statement is a direct quote but is totally incorrect. Vertical testing of both scale and full size SRM components was possible and could have been performed. Management decided that the extra effort was not necessary and that horizontal testing, including full scale DMSRB testing, was adequate.

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

The following table¹⁵ shows gas blow-by occurred even when the joint temperature was above 75° F. Thus, proving that temperature can only be considered a contributing factor in having O-ring failures.

Flight or Motor	Date	(Solid Rocket Booster)	Joint/O-Ring	Pressure (psi)		Notes	Erosion	Blow-by	Joint Temp °F
				Field	Nozzle				
STS 51-L	1/28/1986			200	200				31
STS 61-B	11/26/1985	(Left)	Nozzle/Primary	200	200		1	1	76
STS 51-B	4/29/1985	(Left)	Nozzle/Primary	200	100		1	1	75
STS 41-D	8/30/1984	(Left)	Nozzle/Primary	200	100		1	1	70
STS 51-G	6/17/1985	(Right)	Nozzle/Primary	200	200	5	1	1	70
STS 51-G	6/17/1985	(Left)	Nozzle/Primary	200	200		1	1	70
STS 51-C	1/24/1985	(Right)	Center Field/Primary	200	100		1	1	53
STS 51-C	1/24/1985	(Left)	Forward Field/Primary	200	100		1	1	53
DM-6	10/25/1984	-	Inner Gasket/Primary	NA	NA		1	1	52
STS 61-A	10/30/1985	(Left)	Aft Field/Primary	200	200			1	75
STS 61-A	10/30/1985	(Left)	Center Field/Primary	200	200			1	75
STS 41-D	8/30/1984	(Right)	Igniter/Primary	NA	NA			1	70
STS 51-G	6/17/1985	(Left)	Igniter/Primary	NA	NA			1	70
STS 51-D	4/12/1985	(Right)	Igniter/Primary	NA	NA			1	67
STS 51-D	4/12/1985	(Left)	Igniter/Primary	NA	NA			1	67
STS 41-C	4/6/1984	(Right)	Igniter/Primary	NA	NA			1	63
STS 61-C	1/12/1986	(Left)	Nozzle/Primary	200	200			1	58
STS 51-C	1/24/1985	(Right)	Nozzle/Primary	200	100			1	53
STS 51-C	1/24/1985	(Left)	Nozzle/Primary	200	100			1	53
STS 51-I	8/27/1985	(Left)	Nozzle/Primary	200	200	7	1		76
STS 61-B	11/26/1985	(Right)	Nozzle/Primary	200	200		1		76
STS 51-B	4/29/1985	(Right)	Nozzle/Primary	200	100		1		75
STS 51-B	4/29/1985	(Left)	Nozzle/Primary	200	100		1		75
STS 61-A	10/30/1985	(Right)	Nozzle/Primary	200	200		1		75
STS-2	11/12/1981	(Right)	Aft Field/Primary	50	50		1		70
STS 41-D	8/30/1984	(Right)	Forward Field/Primary	200	100		1		70
STS-6	4/4/1983	(Right)	Nozzle/Primary	50	50	1	1		67
STS-6	4/4/1983	(Left)	Nozzle/Primary	50	50	1	1		67
STS 51-D	4/12/1985	(Right)	Nozzle/Primary	200	200		1		67
STS 51-D	4/12/1985	(Left)	Nozzle/Primary	200	200		1		67
STS 41-C	4/6/1984	(Right)	Nozzle/Primary	200	100		1		63
STS 41-C	4/6/1984	(Left)	Aft Field/Primary	200	100	3	1		63
DM-7	5/9/1985		Nozzle/Primary	NA	NA		1		61
QM-4	3/21/1983	-	Nozzle/Primary	NA	NA		1		60
STS 61-C	1/12/1986	(Right)	Nozzle/Primary	200	200		1		58
STS 61-C	1/12/1986	(Left)	Aft Field/Primary	200	200		1		58
STS 41-B	2/3/1984	(Right)	Nozzle/Primary	200	100		1		57
STS 41-B	2/3/1984	(Left)	Forward Field/Primary	200	100		1		57
STS 51-C	1/24/1985	(Right)	Center Field/Secondary	200	100	4	1		53

O-ring erosion occurred on all but one (STS-51-J) of the Space Shuttle flights in 1985. To correct the issues with O-ring erosion, engineers at Morton Thiokol, led by Allan McDonald and Roger Boisjoly, proposed a redesigned field joint that introduced a metal lip (shim) to limit movement in the joint. They also recommended adding a spacer to provide additional thermal protection and using an O-ring with a larger cross section.¹⁶

It is truly bewildering that the Program would take a massive, massive chance on using the largest Solid Rocket Boosters ever built for the first flight of a manned Space Shuttle but

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

insisted on keeping the ultra-toxic and operations intensive hypergolic fueled OMS, RCS, and APU systems just because they had experience with those propellants. Although size of the SRB was not the real issue, the risk was using a solid rocket over which we had very little control, could not shut down, and could not get away from if something went wrong.

3d: Lessons Learned From Challenger Accident:

Some of the following insights draw on the work of former Morton-Thiokol, Inc., Program Manager's (Allan J. McDonald), "*Truth, Lies, and O-Rings: Inside the Space Shuttle Challenger Disaster*".

1. The Space Shuttle was to be "an all-weather capable vehicle" (later changed due to orbiter tiles) therefore the ambient temperature requirement for all elements was set by NASA's multi-center Shuttle 1st Level Managers (one of which is a co-author on this paper, Russ Rhodes) who originally set the minimum flight temperature of 28 degrees Fahrenheit and a high of 95 degrees Fahrenheit. Later these temperature limits were adjusted by the Launch Commit Criteria (LCC) to 36 degrees Fahrenheit to 97 degrees Fahrenheit at the time of launch.
 - a) NASA MSFC and the SRB contractor didn't verify/certify that they were working according to the same temperature requirements. NASA MSFC was fully aware of the vehicle launch temperatures. SRB contractor built the SRB's with a minimum flight temperature of 40 degrees (which was never the correct temperature requirement of 28°F); even though KSC can experience temperatures less than 40 degrees in January. According to McDonald, Thiokol management actually thought the minimum launch temperature was 53 deg F¹⁷. This directly led to the controversy surrounding the Go-No-Go decision the night before the Space Shuttle Challenger accident. As a recent example of low temperatures at the Cape, on 18 January 2018, Canaveral temperatures stayed below 40 deg for 10 hours, hitting a low of 30 deg; cold temperatures of 30 deg such as experienced during the Challenger Accident (that sometimes lasts 3 or 4 days) should have been expected. There was absolutely no reason for Thiokol to be calling for "No Go" the night before Challenger, unless they also wanted to admit that they didn't build the SRB's per LCC.
2. There should have been extreme condition static tests on flight hardware.
 - a) The SRB's should have been tested at 10 degrees beyond flight limits in the flight configuration, i.e., the SRB in the vertical position. This means a static test conducted at 18 deg F and at 105 deg F in order satisfy the temperature limits set during joint design of 28 and 95°F.
 - b) Additional extreme temperature and humidity tests should have been conducted until reliable data and conclusions could have been developed.
3. Due to lack of Lesson #2, Contractor management didn't have enough data points and were extrapolating to the point that NASA management didn't believe them. Also, the contractor inexplicably didn't think about cold temperatures at the launch site until the night before a launch in January, even though winter happens every year, even in Florida. Contractor could have easily inquired the previous July that 'their SRB's can't fly in less than 53°F and does it ever get colder than that in Florida'. At which point, NASA would have sought another SRB contractor.

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

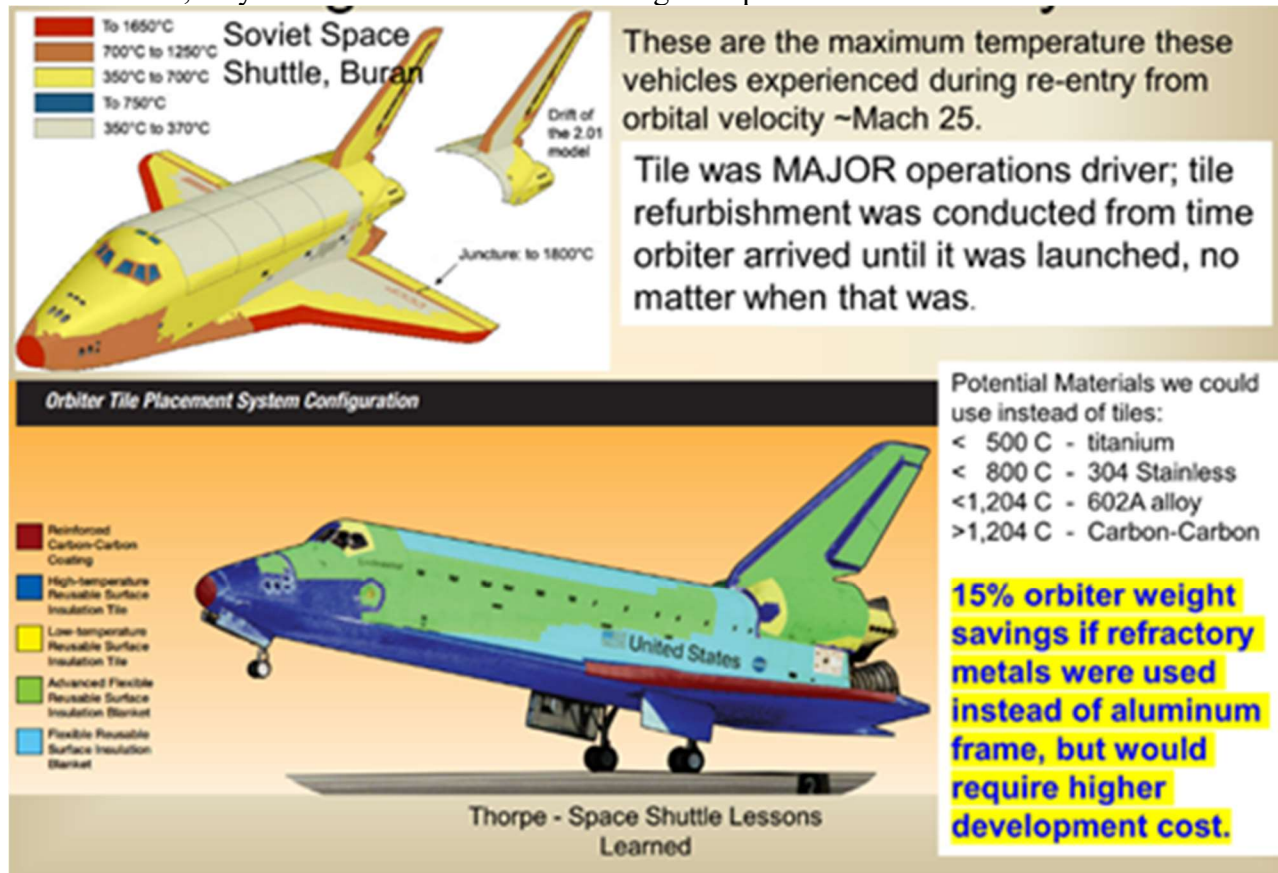
4. The contractor did not understand the science behind the sealing hardware. According to TMI management, *the SRM joint pressure decay test would properly seat the secondary O-ring in the groove, but could force the primary O-ring in the incorrect direction. This means high pressure, combustion gases would have to seat the primary O-ring in the groove in the first 0.6 seconds or gases could get by both O-rings.* Requiring hot, high pressure, combustion gases to seat a Crit 1 component (not Crit 1R - redundant component) in the first fraction of a second is an extremely haphazardous design. Also, at the time of the accident, TMI management suspected the failure was caused by the Nozzle – to – Case seal and not the Field Joint Seal¹⁸. The nozzle to case O-ring always leaked too and was considered the number one concern. It was never corrected and NASA justified not correcting the design by declaring it ‘within family’.
5. 7 of the 8 Field Joints did not leak during the ill-fated Challenger Mission which saw the same temperature and use environment.
6. NASA didn’t award a \$1B⁺ fixed contract to TMI for 66 boosters, but instead was seeking a second (cost plus) supplier. McDonald claims, *“This action or in-action by NASA ended up pulling engineering resources from Thiokol, who could have been investigating all of the O-ring blowby incidents before the Challenger accident”*¹⁹. (We don’t understand this quote. Where did the engineering resources go, what were they doing, who was paying them?)
7. McDonald also claims:
 - a) that even if there were no problem with the SRB O-rings,
 - b) the massive amount of ice on the facility and MLP could have caused considerable damage to the Shuttle Challenger tile.
 - c) Plus, the 17 mph winds and 30 ft waves had caused the SRB recovery ships to go into survival mode, which placed them out of position to recover the boosters and parachutes²⁰.
 - d) These three problems should have persuaded NASA to scrub or at least postponed the launch until warmer temperatures that fateful afternoon; since it was 47 °F by 5PM²¹.However, NASA KSC did postpone launch for over three hours until the ambient temperature reached the LCC requirement of 36°F. There was no visible or instrumented indication that the vehicle was not ready to launch. There was no ice on the vehicle.
8. During the morning of the Challenger Accident, temperatures were measured all over the vehicle. The coldest temperature was on the Right Hand Lower SRB Strut at 17 °F. All other surface temperatures were warmer, including the SRB surfaces. After Challenger, Field Joint heaters were installed and used on every launch to ensure joint and O-ring temperatures met minimums regardless of ambient temperatures. The heaters were usually turned on at the start of cryo loading which totally neglected the effect of propellant cold soak on the joints.

4: THERMAL PROTECTION SYSTEM

The Space Shuttle had an extremely fragile thermal protection system which was comprised of silica ceramic. There are multiple resources on the internet that can provide the exact details and locations of the plethora of materials that formed the thermal protection system for the Space Shuttle Orbiter and it makes no sense to repeat that information here.

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

Unlike nearly all other design decisions when it came to the Space Shuttle where performance out weighed costs, the use of ceramic tiles ADDED 15% MORE WEIGHT to the Space Shuttle than the use of refractory metals. If it didn't make sense to build the Blackbird (SR71) frame out of aluminum, why would it make sense to building the Space Shuttle frame out of aluminum?



The Space Shuttle Thermal Protection System includes²²:

- Felt Reusable Surface Insulation (FRSI) blankets: ~532.1 kg (1,173 lbs)
 - Low-Temperature Reusable Surface Insulation (LRSI) tiles: ~1,014.2 kg (2,236 lbs)
 - High-Temperature Reusable Surface Insulation (HRSI) tiles: ~4,412.6 kg (9,728 lbs)
 - Reinforced Carbon-Carbon (RCC) panels: ~1,697.3 kg (3,742 lbs)
 - Miscellaneous components: ~918.5 kg (2,025 lbs)
- Total: 8,575 kg (18,900 lbs)**

When combined with the 4,800 lb of foam on the ET (there to protect ice/frost from striking the tile), the **tile has a weight penalty of 23,700 lbs!**

But there was readily available high temperature materials available during the 70's that could have been used instead of these operational intensive materials, such as:

- High strength, high temperature steel could have been used for the frame of the Space Shuttle instead of aluminum with its much lower operating temperature.
- 602A nickel alloy²³ could have replaced all the 20,548 black High-temperature reusable surface insulation (HRSI) tiles that could withstand 2,300 deg F.

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

- 304 Stainless steel²⁴ could have replaced Low-temperature Reusable Surface Insulation (LRSI) tiles and is much cheaper than 602A alloy, but has the same density.
- And lightweight titanium could have replaced Flexible Insulation Blankets/Advanced Flexible Reusable Insulation (FIB/AFRSI).

The problem with using the refractory metals was they added development costs.

The Shuttle Tile was cheaper to develop than a refractory metal skin, but the tile was an operational nightmare requiring constant repair the entire time the Orbiter was on the ground. The Shuttle Tile was so fragile that it could even be damaged by ice from the cryogenically cooled External Tank resulting in the ET having very heavy foam on it. The foam only weighed 2 lb/ft³ (~4,800 lbs); we just used too much of it and it was carried with the ET 99.8% of the way into orbit. This is to be contrasted with the Saturn V's first stage which didn't have any insulation on its LOX tank; ice is actually a good insulator. Videos that show the launch of a Saturn V will be remembered for all of the ice falling from the LOX tank; but, when it got to the end of its flight, there was no ice on the stage, and it gained all of that weight savings by eliminating any SOFI insulation.

After the Challenger Accident, \$5B in funding was available for a new shuttle. That would have been an excellent time to replace the tile with refractory materials. Instead the replacement orbiter, Endeavor, was designed exactly like the other 4 with extremely fragile tile that prevented the Shuttle program from ever completing its objective of launching every 2 weeks.

4a: Lessons Learned On Ceramic Tile As TPS

1. Tile maintenance was a major driver of operational cost—second only to the crew/cargo integration issue. Tile was continuously worked on the entire time the Orbiter was on the ground, no matter how long that was.
2. Weight of the tile, blankets, & foam amounted to 23,700 lb that was carried into orbit. Shuttle should have been constructed from high temperature steel & covered with refractory metals.
3. Tile was easily damaged by ice from the ET (resulting in tremendous work on the ET foam to make sure it didn't produce any ice/frost), exhaust from the SRB thrusters, and acoustic noise during launch.
4. The leading edge of Carbon-Carbon panels may have been weakened by the corrosive effects of oxygen during deorbit, leading to the panels losing strength and the loss of the Orbiter Columbia from a strike by foam.

5: SPACE SHUTTLE MAIN ENGINES

The Space Shuttle Main Engine (SSME) was initially planned for 100 starts and a 10-hour life, representing a twentyfold improvement over the engine of the X-15. This long life would be essential for a low-cost shuttle, by reducing the number of costly engine overhauls and eliminating downtime due to engine changeouts and major maintenance. An X-15 engine demanded major maintenance after 30 minutes of operation; it thus had a long life between overhauls, for at full thrust an X-15 would burn a complete load of propellant in less than 90 seconds. By 1969, the total operating time for a single RL-10 test engine exceeded that of 50 shuttle missions, while a thrust chamber / turbopumps, received a series of test firings that

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

totaled more than 11 hours. The engines of Apollo showed similar life. The F-1 was rated for 20 starts and 2250 seconds in total duration. Yet by replacing the liquid-oxygen pump impeller and the turbine manifold at 3500 seconds, test engines achieved as many as 60 starts and total durations of 5000 to 6000 seconds. The J-2 had a test engine running for 103 starts and 6.5 hours, without overhaul²⁵.

SSME requirements, however, were far more demanding because it was to operate at much higher pressures. The chamber pressures of the F-1 and J-2 were modest by SSME standards: 763 and 982 psi, respectively. At full power, SSME chamber pressure is 3280 psi. Preburners, which fed the main combustion chamber operated at 5500 psi. In turn, these preburners received propellants from the turbopumps, whose pump discharge pressures had to be higher than the preburner: as much as 8000 psi.²⁶ As a result, maintenance of the SSME would be far more intense than what NASA had experienced with the X-15 or Saturn rocket engines. This intense maintenance preserved the life of the engine, but at a severe cost to Operations, which resulted in lower flight rate and higher costs per pound to orbit.

5a: Start-Stop Engine Production

Start-stop production lines are extremely expensive to implement.

The next three charts show the cost of LOX/LH2 engines at various levels of production.

The first chart shows cost of a reusable SSME (a.k.a., RS-25 engine) during the initial production of the engine in 1983. Each engine costs \$33.2M in 1983\$ as a result of 161,000 man-hours.

Rockwell International Corporation
Canoga Park, California

Letter 83RC05720

- SSME COST MODEL -
COST BY MAJOR COMPONENT IN FISCAL YEAR 1983 DOLLARS

Index Family	Hardware Component	FABRICATION & SUPPORT		Cost	MATERIAL		SUBCONTRACT Includes Rockwell G&A	Total Cost per Unit
		Fab & Assy Hours	Rate per Fab Hr. (1) Rate/hour		P.O. Value Adjusted to FY'83 Dollars	Total Mat'l Unit Cost @ 1.50(2)		
009	Powerhead Ducts	1,726	AA \$115.20	\$ 198,800	\$ 56,828	\$ 85,200		\$ 284,000
054	ASI Injector Assy	474	J 115.23	54,600	1,229	1,800		\$6,400
047	Main Injector	9,946	G 111.85	1,112,500	306,066	462,100		1,574,600
059	Heat Exchanger	3,000	L 113.40	340,200	55,055	82,600		422,800
051	Preburner Injector (Fuel)	3,178	IA 113.46	360,600	56,973	85,400		446,000
	Preburner Injector (Oxidizer)	2,119	IB 113.46	240,400	25,596	38,400		278,800
083	Preburner Chamber (Fuel)	2,215	IC 113.46	251,300	12,914	19,400		270,700
	Preburner Chamber (Oxidizer)	2,118	ID 113.46	240,300	12,914	19,400		259,700
057	Hot Gas Manifold	6,547	Q 111.18	727,900	253,245	379,900		1,107,800
145	Powerhead Assembly of	2,610	M 114.83	299,700	-	-		299,700
044	Nozzle Assy & Insulation	24,312	H 111.80	2,718,100	1,015,210	1,522,800		4,240,900
042	Chamber Body Assy (MCC)	15,629	F 110.29	1,723,700	221,616	332,400	\$8,841,100	2,056,100
091	Controller	-	T -	-	-	-		\$841,100
056	Spark Igniter	2,302	PA 113.73	261,800	35,868	53,800		315,600
086	Flight Instrumentation	-	PB -	-	235,042	352,600		352,600
086	Electrical Harness	1,914	PC 113.73	217,700	40,727	61,100		278,800
088	Flowmeters	47	PD 113.73	5,300	17,379	26,100		31,400
018	Flex Ducts	6,791	AB 115.20	782,300	1,498,270	2,244,400		3,026,700
017	Rigid Ducts	4,271	AC 116.20	492,000	73,804	110,700		602,700
011	Static Seals	-	EA -	-	34,901	52,500		52,500
011	Global Bearing	-	KB -	-	37,719	56,600		56,600
171	Other Valves	1,389	O 116.11	161,300	263,492	395,200		556,500
093	Hydraulic Actuation System	-	S -	-	-	-	993,800	993,800
160	Main Propellant Valve Assy	1,137	N 112.16	127,400	274,843	412,300		539,700
135	High Pressure Oxidizer Pump Assy	19,576	E 114.16	2,234,800	252,489	378,700		2,613,500
131	Low Pressure Oxidizer Pump Assy	1,737	D 116.73	202,400	83,334	125,000		327,400
125	High Pressure Fuel Pump Assy	24,429	C 114.69	2,801,800	270,260	405,400		3,207,200
121	Low Pressure Fuel Pump Assy	4,736	B 115.29	546,000	89,074	133,600		679,600
006	System Installation Details	3,676	AD 115.20	423,500	159,818	239,700		663,200
007	System Line Assy's	9,604	AE 115.20	1,106,400	34,512	51,800		1,158,200
204	Engine Assembly	5,190	R 114.83	596,000	-	-		596,000
TOTAL UNIT VALUE		160,673 Hrs.	\$113.44 (Weighted)	\$18,226,800	\$5,419,256	\$8,128,900	\$8,834,900	\$33,190,600
Powerhead Assy Complete		33,933	V	\$3,826,300	\$ 782,820	\$1,174,200		\$ 5,000,500
HGM Assy Complete		19,177	W	\$2,160,700	\$ 416,697	\$ 625,100		\$ 2,785,800

(1) The rates per fab hour for the various component groups are calculated as presented in the cost breakdowns (Enclosure 3) using the SSME forward pricing factors (Enclosure 2).
(2) The material factor of \$1.50 per base material dollar is the same for all components. The development for this factor is presented on the last page. Enclosure 3.

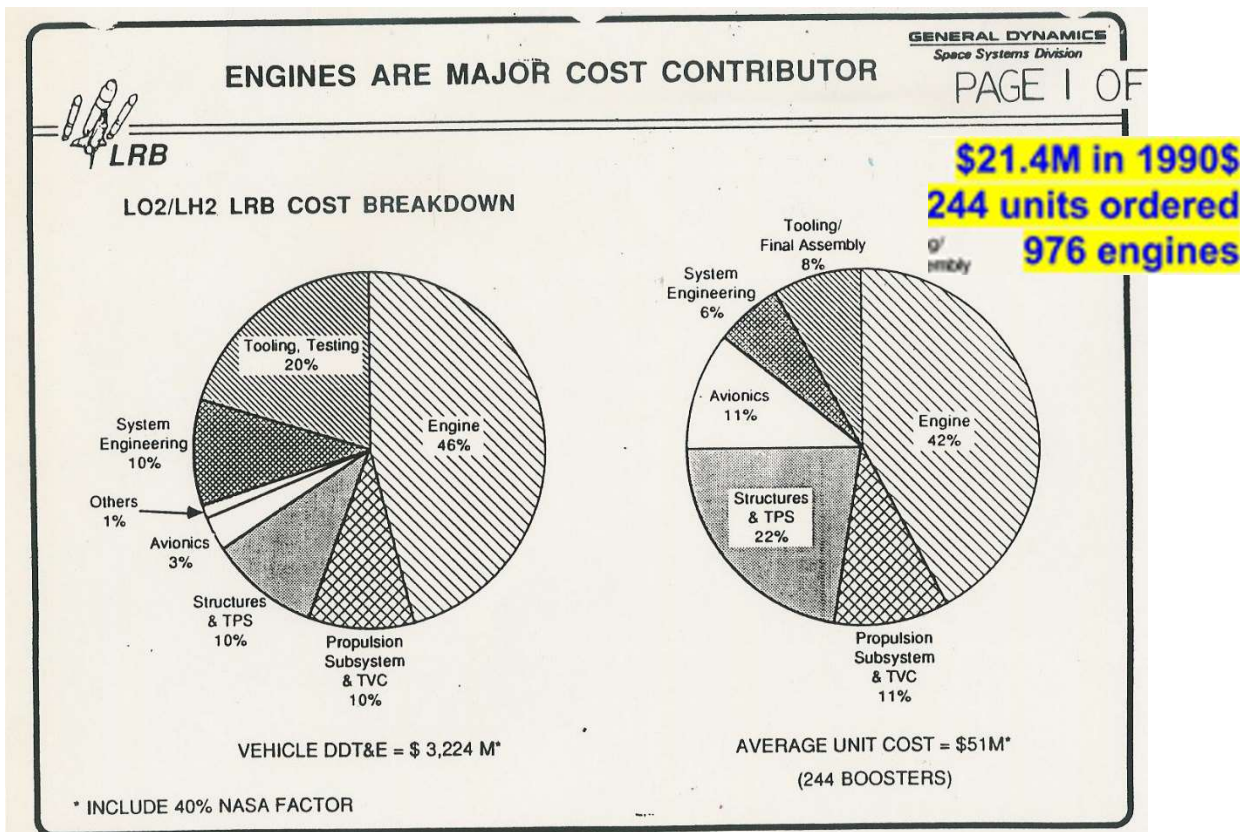
LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

The next chart²⁷ illustrates the cost profile of an expendable SSME (RS-25). Remarkably, approximately \$1.6 billion is required simply to reestablish production capability before a single engine is built. Despite this substantial upfront investment, NASA has procured only a limited quantity—on the order of a few dozen engines—after which production is again scheduled to cease. \$1.79B for 18 expendable engines amounts to \$100M each in 2020\$. The \$33.2M reusable SSME in 1983 would only cost \$87.5M in 2020\$, so even accounting for inflation and not adding the cost to restart the production line, the cost of each expendable RS-25 in 2020 is still more expensive than the cost of a reusable engine in 1983.

During the Liquid Rocket Booster (LRB) studies, engines were identified as a primary cost driver,

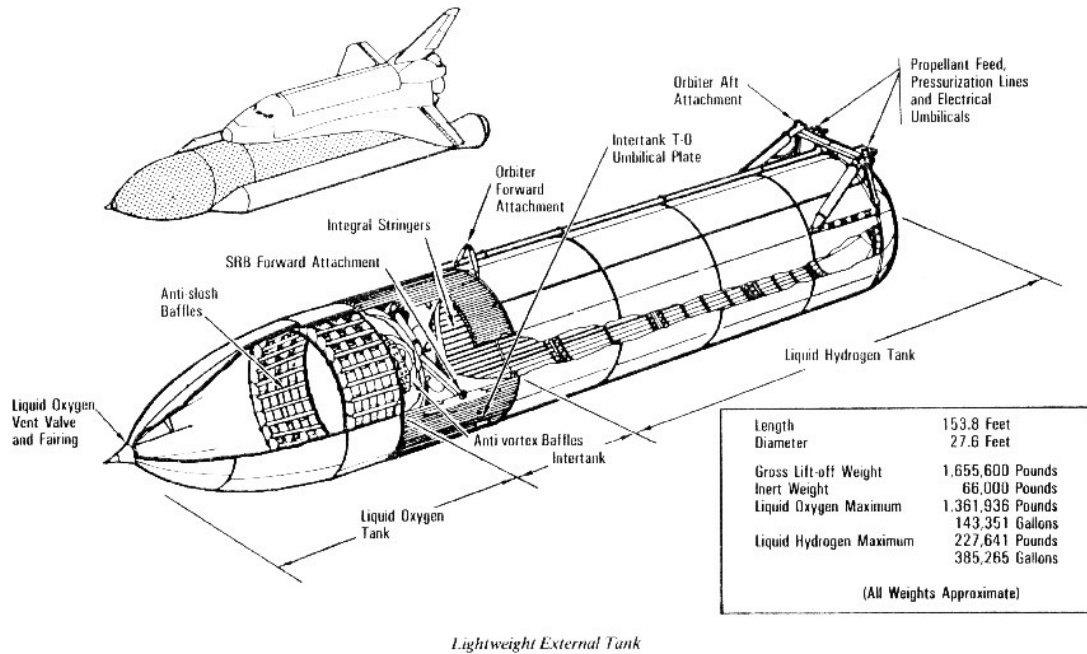
accounting for nearly 50% of total booster cost. However, the analysis also showed that with sustained, high-rate production—on the order of hundreds of engines—the unit cost could be reduced dramatically. In one such scenario, with nearly 1,000 engines produced, the estimated cost per engine dropped to approximately \$21.4 million in 1990 dollars. As a comparison, it is reported that SpaceX can build their Raptor engines for less than \$1M each.

- NASA ordered total of 24 **expendable** RS-25 engines:
- \$1.79 billion - 18 additional RS-25 engines in 2020
- **\$1.16 billion** - 6 new RS-25 engines in 2015
- **\$1.6 billion** to start getting its production line ready for new RS-25 engines
- Total contract value for 24 RS-25 engines - **~\$4.55 billion. = \$189.6M per expendable engine**



LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

6: EXTERNAL TANK



The design, production, and operation of the Space Shuttle External Tank (ET) were marked by numerous incremental issues that collectively provide important lessons learned. The two Solid Rocket Boosters (SRBs) were attached to the ET via a horizontal thrust beam located within the intertank structure, along with three aft attachment struts that maintained proper alignment along the tank. During the **Space Shuttle Challenger disaster**, a breach in the right-hand SRB produced a plume of hot gases that burned through one of these aft struts. The resulting structural failure allowed the SRB to pivot into the liquid oxygen (LOX) tank, leading to the rapid disintegration of the entire vehicle.

The ET itself underwent several weight-reduction evolutions over the course of the Shuttle program:

- **Standard Weight Tank (SWT):**
Used on the first seven missions, the SWT had a dry weight of approximately 77,000 pounds. This figure excludes about 600 pounds of external paint (applied on the first three missions) and an additional 400-pound anti-geyser line used during early flights.
- **Lightweight Tank (LWT):**
Introduced on STS-8 and used through STS-107, the LWT reduced weight to approximately 66,000 pounds. This reduction was achieved by eliminating portions of longitudinal stiffeners in the liquid hydrogen tank, reducing the number of stiffener rings, modifying major structural frames, and selectively thinning tank walls through improved machining. Thermal protection system (TPS) weight was also reduced.
- **Super Lightweight Tank (SLWT):**
First flown in 1998, the SLWT further reduced weight to approximately 58,500 pounds.

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

This was accomplished by replacing the traditional 2219 aluminum-copper alloy with a higher-strength, but more expensive, aluminum-lithium alloy (Al 2195).

While these design changes successfully improved performance by reducing mass, they also introduced cost and manufacturing complexity tradeoffs.

The cost of the LWT ranged from \$38.1M as shown from ET-41 in the April 1988 DD Form 250 below to \$50.6M for ET-55 in the June 1992 receipt. ET-94 was built at a cost of \$75M and delivered to California Science Center museum in May 2015²⁸.

TERMINAL INSPECTION AND RECEIVING REPORT		NASS-33708		1 1	
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4. PART NUMBER 10860		5. REGISTERED BY		6. CODE 1AP43	
7. Martin Marietta Manned Space Systems Post Office Box 29304 New Orleans, LA 70189		8. Procurement Office George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812		9. CODE 1BF52	
10. SHIPPER FROM (See Block 9)		11. PAYMENT WILL BE MADE BY		12. CODE 1BF52	
13. SHIPPER TO Michoud Assembly Facility National Aeronautics and Space Administration New Orleans, Louisiana 70189 Attention: Mr. J. W. Hill, SA39		14. For Contract NAS10-10900		15. CODE 1	
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43. 1-ET S/W1 & Data Pkg.		44. 1-ET S/W1 & Data Pkg.		45. 1-ET S/W1 & Data Pkg.	
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49. 1-ET S/W1 & Data Pkg.		50. 1-ET S/W1 & Data Pkg.		51. 1-ET S/W1 & Data Pkg.	
52. 1-ET S/W1 & Data Pkg.		53. 1-ET S/W1 & Data Pkg.		54. 1-ET S/W1 & Data Pkg.	
55. 1-ET S/W1 & Data Pkg.		56. 1-ET S/W1 & Data Pkg.		57. 1-ET S/W1 & Data Pkg.	
58. 1-ET S/W1 & Data Pkg.		59. 1-ET S/W1 & Data Pkg.		60. 1-ET S/W1 & Data Pkg.	
61. 1-ET S/W1 & Data Pkg.		62. 1-ET S/W1 & Data Pkg.		63. 1-ET S/W1 & Data Pkg.	
64. 1-ET S/W1 & Data Pkg.		65. 1-ET S/W1 & Data Pkg.		66. 1-ET S/W1 & Data Pkg.	
67. 1-ET S/W1 & Data Pkg.		68. 1-ET S/W1 & Data Pkg.		69. 1-ET S/W1 & Data Pkg.	
70. 1-ET S/W1 & Data Pkg.		71. 1-ET S/W1 & Data Pkg.		72. 1-ET S/W1 & Data Pkg.	
73. 1-ET S/W1 & Data Pkg.		74. 1-ET S/W1 & Data Pkg.		75. 1-ET S/W1 & Data Pkg.	
76. 1-ET S/W1 & Data Pkg.		77. 1-ET S/W1 & Data Pkg.		78. 1-ET S/W1 & Data Pkg.	
79. 1-ET S/W1 & Data Pkg.		80. 1-ET S/W1 & Data Pkg.		81. 1-ET S/W1 & Data Pkg.	
82. 1-ET S/W1 & Data Pkg.		83. 1-ET S/W1 & Data Pkg.		84. 1-ET S/W1 & Data Pkg.	
85. 1-ET S/W1 & Data Pkg.		86. 1-ET S/W1 & Data Pkg.		87. 1-ET S/W1 & Data Pkg.	
88. 1-ET S/W1 & Data Pkg.		89. 1-ET S/W1 & Data Pkg.		90. 1-ET S/W1 & Data Pkg.	
91. 1-ET S/W1 & Data Pkg.		92. 1-ET S/W1 & Data Pkg.		93. 1-ET S/W1 & Data Pkg.	
94. 1-ET S/W1 & Data Pkg.		95. 1-ET S/W1 & Data Pkg.		96. 1-ET S/W1 & Data Pkg.	
97. 1-ET S/W1 & Data Pkg.		98. 1-ET S/W1 & Data Pkg.		99. 1-ET S/W1 & Data Pkg.	
100. 1-ET S/W1 & Data Pkg.		101. 1-ET S/W1 & Data Pkg.		102. 1-ET S/W1 & Data Pkg.	

6a: Lessons Learned From The Space Shuttle ET:

- Cost vs. Performance Tradeoffs:** The use of aluminium-lithium alloy added \$20M to the cost of the ET for a savings of 7,500 lbs or \$2,666 per lb to orbit. However, SpaceX Falcon 9 Block 5 can place 40,800 lb into LEO at a cost of \$50M²⁹ or \$1,225 per lb to LEO for the entire launch vehicle. This highlights a key lesson: incremental performance gains through advanced materials can come at disproportionately high cost, particularly when applied to only one component of a larger system.
- Foam Insulation: Weight, Risk, and Operational Burden:** The use of foam insulation added considerable weight to the ET (4,800 lbs) and was a source of one costly roll-back when woodpeckers pecked holes in the foam. Hail damage also caused a roll-back. If ice/frost accumulation from ambient temperatures is such an issue, why didn't they blow hot, dry air up between the ET and Orbiter, which would have also blown away any accumulation of hydrogen gases? This was tried at VBAFB with jet engines, but it would only prevent ice from forming on the orbiter side of the LH2 tank. When the Shuttle

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

experienced hydrogen leaks in 1990's, they built such a blower on top of the MLP to disperse the GH₂ at a cost of \$100M, but removed it before it became operational. The blower was inadequate and in the path of the body flap at lift off. Nonetheless, the correct solution for the Shuttle vehicle would be to design, build, and operate the correct sized blower and eliminate all foam from the External Tank. It is unclear why the SLS Core Stage has foam on it; may be a good opportunity to implement the blower.

3. **Over-Application of Insulation:** Why was the entire intertank covered in foam? It's understandable that the bottom portion that was near the LH₂ tank or the top portion that was near the LOX tank, but there was many feet of the intertank where there was no cryogenic reason to insulate the tank. As it turns out, the entire ET was spray foamed in one continuous spiral wrap top to bottom at 1 RPM. The spray machine could not be turned on and off for this small an area without creating many close out problems. The first layer of foam was hand sprayed and sanded smooth so that the final coat could be automatically machined sprayed. To make matters worse, the intertank was covered with two layers of foam, which at one point required over 10,000 holes be drilled into them at KSC to relieve any pressure build-up between the foam layers. The blowing agent for the foam was changed to eliminate this problem, but wouldn't a better solution be to put a diverter so this foam was never added to the intertank?
4. **Ground Umbilical Carrier Plate (GUCP):** The GUCP served as a critical interface between ground systems and the ET, connecting the gaseous hydrogen vent line along with purge and instrumentation systems. Derived from earlier Saturn V hardware, it functioned as a T-0 umbilical. Late in the program, the GUCP became increasingly sensitive to installation and alignment during quick disconnect (QD) operations. These issues were largely attributed to design creep and "recertification by similarity," often performed by less experienced engineers without full historical context.

Lesson Learned: Diversify your knowledge base. Everyone can't know everything. Most people soon forget what they have learned particularly if they don't use it often.



LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

7: SOUND SUPPRESSION SYSTEM



The Sound Suppression System (SSS) was designed to mitigate the intense acoustic energy generated by the Space Shuttle's main engines and solid rocket boosters during launch. This system was crucial in protecting the Shuttle, its payloads, and facilities from damage caused by sound waves. The SSS consisted of 6 nozzles, 12 feet high, known as "rainbirds," which released 300,000 US gallons of water in only 41 seconds onto the launch platform and into the SRB/MLP exhaust hole. An additional six water nozzles surrounded each SRB nozzle.

7a - Free Hydrogen Detonation – Part 1:

Because of the lack of understanding of the interaction between the SRB exhaust with the ground system and its impact on the orbiter during the first Shuttle launch, the SRB exhaust shock wave caused damage to the orbiter at liftoff³⁰. The SRB exhaust gases detonated in the Mobile Launcher and created a pressure wave from the SRB/MLP exhaust hole that caused considerable movement of the entire orbiter and bent a strut in the forward end of the orbiter. The program did not determine the true cause of this pressure wave but instead, determined that 12 inches of water would suppress this pressure wave. Therefore, the program's corrective action would require the placement of thirty water bags containing 12-24 inches of water be placed in the MLP SRB exhaust holes to mitigate the pressure wave from escaping from the top of the MLP. There was a pressure transducer in the MLP that recorded a pressure in excess of 25 psi (maximum range of transducer), but SRB engineering group would not accept this reading as valid, therefore the range of the transducer was never changed to try to determine the real pressure that was occurring in the MLP.

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

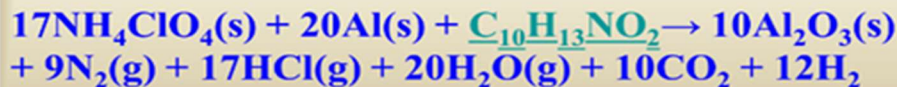
Image: To reduce effects of H₂ detonation on the Orbiter sound suppression water bags were installed in the SRB flame holes before every launch.



In the process of building the Shuttle launch capability at the Vandenberg Air Force Base in California, it was

#2: SRB propellant produces free Hydrogen that detonates

% of chemicals	PROPELLANTS	Chemical Formula	Weight (lbs.)
69.60%	ammonium perchlorate (oxidizer)	NH ₄ ClO ₄ (s)	765,600
16.00%	aluminum (fuel)	Al(s)	176,000
12.04%	polybutadiene acrylonitrile (PBAN) polymer (rubber binder & secondary fuel)	COOCH ₂ - CH - OH	132,440
1.96%	epoxy curing agent (1.96%)		21,560
0.40%	iron oxide (a catalyst)	Fe ₂ O ₃	4,400
% of chemicals	COMBUSTION PRODUCTS	Chemical Formula	Weight (lbs.)
37.70%	Aluminum Oxide	Al ₂ O ₃ (s)	414,700
22.80%	Hydrochloride Acid	HCl(g)	250,800
16.20%	Carbon Dioxide	CO ₂	178,200
13.50%	Steam	H ₂ O(g)	148,500
9.20%	Nitrogen gas	N ₂ (g)	101,200
0.90%	Free Hydrogen gas	H ₂	9,900
0.40%	iron oxide (a catalyst)	Fe ₂ O ₃	4,400



Thorpe - Space Shuttle Lessons Learned

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discovered they had an unsolved issue that the program had not recognized. The Shuttle program was planning to use the Vandenberg Space Launch Complex 6 (SLC-6) that was an unfinished launch pad that originally was to support the Manned Orbiting Laboratory (MOL program). Unfortunately, it contained a closed exhaust for the orbiter

and the SRBs. In trying to arrive at a solution to the orbiter closed duct, it was pointed out by a JSC contractor engineer that the SRB exhaust was 52% fuel rich (27% hydrogen). This new insight created a need to better understand what was really taking place in this SRB exhaust. Measurements were taken in the exhaust cloud segments from 8.6 min until 2 hrs and 8 min after launch. HCl concentration ions ranged from 17.5 ppm to 0.9 ppm and a relative humidity from 86 percent to less than 10 percent. Particle concentrations ranged from 330 pg/m³ to 375 ug/m³³¹. Under ideal stoichiometric conditions, the SRB would consume all oxygen within the motor and exhaust free hydrogen. The only source of oxygen is air entrainment into the exhaust as it leaves the SRB. With the aid of an exhaust plume expert contractor using a JANTIF classified computer code, it was determined that this distance would be approximately 35 feet or in the middle of the MLP. Hydrogen in excess of 19.5% could cause a detonation only in the presence of proper mix of O₂. Pressure from this detonation have not been determined, but it could be in excess of 1,000 psi.

SSME's were also dumping H₂ into flame trench

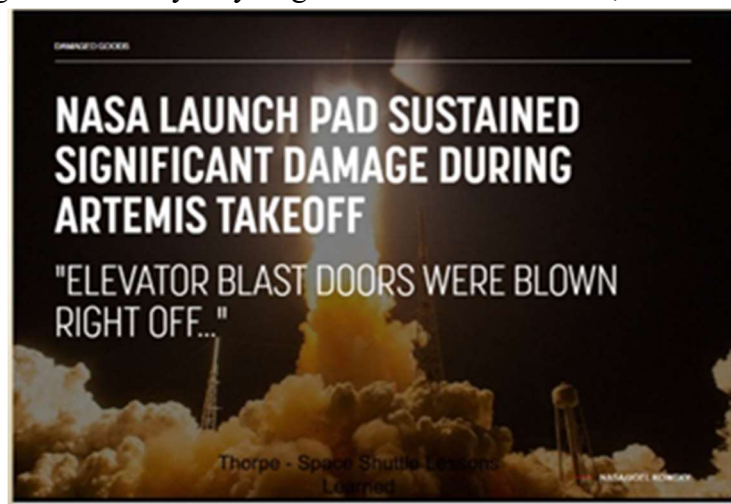


- Each SSME's (RS-25 engines) produced 418,000 lb of thrust on flowrate of 1,134.26 lb/sec.
- 6.03:1 oxidizer to fuel ratio
 - 161.3 lb/sec of LH₂
 - 972.9 lb/sec of LOX
- But stoichiometric for LOX-LH₂ is 8:1, so 972.9 lb/sec of LOX only burns 121.6 lb/sec of LH₂ meaning: **~120 lb/sec of free hydrogen dumped / 3 engines**

Space Shuttle Lessons Learned 7

7b - Free Hydrogen Detonation – Part 2:

NASA moved on to the SLS program with SRB's that added an additional segment or about 25% more free hydrogen in the exhaust. The first launch experienced major damage to the Mobile Launching Pad (MLP). The complete redesign of the exhaust holes may be a contributing factor. The engineers are in denial that this damage is caused by a hydrogen detonation. However, the only way to avoid this MLP damage would be to stop the entrainment of oxygen until the exhaust plume passes through the MLP. NASA still did not take into account the available free hydrogen by the four SSME's (not 3) and larger SRBs resulting in damage to launch pad (MLP). The SLS mega rocket is powered, in part, by four RS-25 engines, firing simultaneously to produce as much as 2 million pounds of combined thrust. The agency will use the Artemis missions to establish a long-term presence on the moon while preparing technologies and capabilities needed to send humans to Mars. Qualification testing of the rocket engines is performed without the presence of hydrogen rich Solid Rocket Booster exhaust which may be caused by an explosive condition at the launch pad, ie, explosive environment where detonation of the fuel rich liquid core exhaust combined with fuel rich solid booster motor and entrained air.



LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

8: Flight Center Funding

The true marginal cost of Space Shuttle flights may have been overstated due to accounting practices. Development and infrastructure expenses—such as launch pad upgrades, MLP work, and astronaut training—were charged directly to the Shuttle program, inflating per-flight cost estimates.

Following the Shuttle program's conclusion and the cancellation of Constellation, funding levels at NASA's flight centers remained relatively constant, despite the absence of an active flight program of similar scale. Personnel were largely retained and reassigned to ongoing and future projects, but funding was not clearly restructured into distinct categories.

This raises an important question: should operational flight costs be more clearly separated from ongoing research and development expenditures?

NASA must keep the Flight Centers engaged in the development of new flight hardware, new technology, new probes, and new designs without charging to the flight vehicle. Why not set aside independent research funding for each center to provide greater transparency so that the true marginal cost per flight is established?

CONCLUSION

The Space Shuttle was envisioned as a “space truck” that would dramatically reduce the cost of access to orbit. In practice, this goal was not achieved. Operational constraints, design trade-offs, and management decisions limited the Shuttle's ability to reach its full economic and operational potential. Although the Shuttle demonstrated remarkable versatility, it was never utilized as a long-duration orbital platform. The longest mission lasted just over 17 days 15 hours³². A truly great Shuttle design would have allowed the vehicle to stay in orbit for over a year with a lab/habitat module in its payload bay or where multiple orbiters could dock together and allow crews to stay in orbit indefinitely; such a vehicle would have eliminated the need for a Space Station at tremendous savings to NASA.

Primary Factors Limiting Cost Efficiency

1. Thermal Protection System and Foam Insulation

The Shuttle relied on over 13,000 pounds of fragile ceramic tiles, along with thousands of pounds of foam insulation on the external tank. These added significant weight and maintenance burden, severely limiting flight rate. The inability to achieve high launch cadence was a major factor in failing to meet cost targets.

2. Air Force Requirements and Vehicle Design

Requirements for a larger payload bay and return-to-launch-site capability drove the addition of large wings and landing gear. These features increased weight and complexity, constraining future upgrades such as larger tanks or alternative booster configurations.

3. Engine Operating Margins

The Space Shuttle Main Engines (SSMEs) were routinely operated at performance levels exceeding their original design limits (up to 109%). This necessitated extensive inspection and refurbishment after each flight, increasing operational costs. A larger overall system with reduced engine stress might have improved reliability and lowered maintenance demands.

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

Additional Lessons Learned

1. **Challenger Launch Decision-Making**
The Challenger accident highlighted discrepancies in launch commit criteria and a lack of testing under extreme conditions. Clear, enforced standards and real-world validation testing are critical.
 2. **SRB Joint Design**
The reliance on O-ring sealing under dynamic conditions, including rotation and delayed seating, introduced unacceptable risk. Improved sealing strategies and gap mitigation should have been implemented.
 3. **Facility Utilization**
The Vehicle Assembly Building (VAB) was underutilized during the Shuttle era compared to Apollo. Alternative facilities for SRB stacking could have improved safety and workforce efficiency.
 4. **Configuration Variability**
Each Shuttle mission involved hardware and software differences, increasing operational complexity and cost.
 5. **Incomplete Knowledge Transfer**
Some lessons from the Shuttle era—particularly regarding exhaust plume chemistry and pad interactions—do not appear to be fully reflected in current launch system designs.
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Key Strategic Takeaways

1. **Prioritize Practical Engineering Over Novelty**
Proven materials and designs should not be overlooked in favor of more complex or fragile technologies.
2. **Design for Modularity and Evolution**
Launch systems should be adaptable, supporting incremental upgrades and diverse mission profiles.
3. **Separate Operations from R&D Funding**
Clear financial boundaries improve accountability and cost transparency.
4. **Operate Within Practical Performance Limits**
Avoid pushing systems beyond sustainable margins at the expense of reliability and cost.
5. **Optimize Exhaust Flow Management**
Reducing back pressure and allowing efficient exhaust expansion can improve both performance and infrastructure longevity.
6. **Reevaluate SRB Reliability Factors**
Temperature alone is insufficient to explain O-ring failures; a deeper understanding is required before future human-rated use.
7. **Align Vehicle Design with Operational Reality**
Aircraft-like vehicles without aircraft-like operations create economic inefficiencies.
8. **Reconsider Winged Orbital Vehicles**
Wings introduce mass and complexity that may not be justified for most space missions.
9. **Modernize Recovery Approaches**
Reducing reliance on ocean recovery could improve turnaround time and cost.

Embrace Full Reusability Philosophy

Launch, live in, land, refurbish, and relaunch the same vehicle to maximize efficiency and sustainability.

LESSONS LEARNED from the SPACE SHUTTLE PROGRAM

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