Description of document:	National Aeronautics and Space Administration (NASA) Selected Apollo & Shuttle Lessons Learned 2014
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Source of document:	FOIA request NASA Headquarters 300 E Street, SW Room 5Q16 Washington, DC 20546 Fax: (202) 358-4332 Email: hq-foia@nasa.gov FOIA.gov

National Aeronautics and Space Administration

Headquarters
Washington, DC 20546-0001

January 12, 2026

Reply to attn. of: Office of Communications
History and Information Services Division

Re: FOIA Tracking Number **26-00032-F-HQ**

This responds to your Freedom of Information Act (FOIA) request to the National Aeronautics and Space Administration (NASA), dated October 25, 2025, and received in this office on October 27, 2025. You seek:

A copy of the SLIDES for each of these NESC Academy (NASA Engineering and Safety Center) videos. The SLIDES are locked on the website so they cannot be viewed by the public.
A copy of the SLIDES and VIDEOs for parts 2 and 3 listed in item 12 below.

1) Lunar Landing
https://nescacademy.nasa.gov/video/427d8334fa41482797cae5cddf7d71a41d

2 and 3) Selected Apollo & Shuttle Lessons Learned ({Parts 1 and Part 2)
https://nescacademy.nasa.gov/video/9edb3c4de48e46d7b66f2a91ace96a171d
https://nescacademy.nasa.gov/video/27784b7aa2ce4c628d77143c86232d621d

(4, 5, 6 and 7) Failure Recovery (Parts 1, 2, 3 and 4)
https://nescacademy.nasa.gov/video/9efbd739aeae4da6b8a80b7370ccff051d
https://nescacademy.nasa.gov/video/4e202def3eb943c99e4ba2744676392c1d
https://nescacademy.nasa.gov/video/9965475c1f2649c4a56aad45cbc553ab1d
https://nescacademy.nasa.gov/video/44323a56200341a198d3911002f0eb211d

8, 9 and 10) Lessons Learned from Fifty Years of Observing Hardware and Human Behavior, Parts 1, 2 and 3
https://nescacademy.nasa.gov/video/c81ccbfd7909415ea72070bbf1c8e38f1d
https://nescacademy.nasa.gov/video/e84a2cc167244d14ac623358f2e9526a1d
https://nescacademy.nasa.gov/video/79e6fd6fc7544b0ba7525f31ed2d866e1d

11) Using TRIZ for Engineering Innovation *https://nescacademy.nasa.gov/video/a42a19ce39a14cd49dfb669e774812b71d*

12) Orion Landing Attenuation: slides for Part 1, Part 2, and Part 3. Copy of the video presentation for Part 2 and Part 3
https://nescacademy.nasa.gov/video/806485bdd20041cda2445409cf5737e21d

In response to your request we conducted a search of NASA's Langley Research Center, Engineering and Safety Center (NESC) using the information from your request. NASA's search began on November 18, 2025 and any records created after this date are not included with this response. That/Those search(es) identified the enclosed records that are responsive to your request. We determined that all **533** pages and 2 videos (Orion Part 2 - 55 minutes, 42 seconds; Orion Part 3 - 47 minutes, 52 seconds) are appropriate for release without excision and copies are enclosed.

Appeal

If you believe this to be an adverse determination, you have the right to appeal my action on your request. Your appeal must be received within 90 days of the date of this response. Please send your appeal to:

Administrator
NASA Headquarters
Executive Secretariat
ATTN: FOIA Appeals
MS 9R17
300 E Street S.W.
Washington, DC 2054

Both the envelope and letter of appeal should be clearly marked, "Appeal under the Freedom of Information Act." You must also include a copy of your initial request, the adverse determination, and any other correspondence with the FOIA office. In order to expedite the appellate process and ensure full consideration of your appeal, your appeal should contain a brief statement of the reasons you believe this initial determination should be reversed. Additional information on submitting an appeal is set forth in the NASA FOIA regulations at 14 C.F.R. § 1206.700.

Assistance and Dispute Resolution Services

If you have any questions, please feel free to contact me at derek.m.moore@nasa.gov. For further assistance and to discuss any aspect of your request you may also contact:

Stephanie Fox
FOIA Public Liaison
Freedom of Information Act Office
NASA Headquarters
300 E Street, S.W., 5P32
Washington D.C. 20546
Phone: 202-358-1553
Email: Stephanie.K.Fox@nasa.gov

Additionally, you may contact the Office of Government Information Services (OGIS) at the National Archives and Records Administration to inquire about the FOIA mediation services it offers. The contact information for OGIS is as follows: Office of Government Information Services, National Archives and Records Administration, 8601 Adelphi Road-OGIS, College Park, Maryland 20740-6001, e-mail at ogis@nara.gov; telephone at 202-741-5770; toll free at 1-877-684-6448; or facsimile at 202-741-5769.

Important: Please note that contacting any agency official including myself, NASA's FOIA Public Liaison, and/or OGIS is not an alternative to filing an administrative appeal and does not stop the 90 day appeal clock.

Sincerely,

Derek Moore

Derek Moore
Government Information Specialist

Lesson 4:
Selected Apollo & Shuttle Lessons Learned (Part 1)

Objectives

- Identify Apollo program pressure vessel failures lessons learned
- Identify Shuttle program thermal protection system failures lessons learned

Lesson 4: Selected Apollo & Shuttle Lessons Learned (Part 1)

- Mr. Bud Castner
- Mr. Glenn Ecord

Introduction

- Materials durability is critical when dealing with pressure vessels
- Pressure vessels store fluids at pressures above atmospheric
  - High stored energy usually involved
  - Hazardous chemicals often involved
- High pressures & hazardous fluids heighten sensitivity to damage modes
  - Stress corrosion cracking
  - Fatigue cracking
  - Embrittlement mechanisms
  - Small defects
  - Others
- Damage modes have potential to cause serious, even catastrophic failures

Apollo Reaction Control System (RCS) Oxidizer Tank Failures

- RCS was propulsion system used to provide spacecraft with maneuvering ability along all 3 axes
- RCS rocket engines used hypergolic propellants
  - Oxidizer: nitrogen tetroxide (N_2O_4)
  - Fuel: Aerozine 50
- RCS oxidizer tank design
  - Material: titanium alloy 6Al-4V (Ti-6Al-4V)
  - Environment: N_2O_4
  - Configuration: cylinder, 12" diam., 18" long, 0.020" thick
  - Usage: 12 total in Command, Service & Lunar Modules

RCS Oxidizer Tank Failures (cont.)

- RCS oxidizer tank exploded in test, January 1965
  - Occurred on 23rd day of 30-day creep test
  - Failure analysis indicated SCC
    - Fingerprint
    - Surface contamination
- 10 additional oxidizer tanks in test, July 1965
  - 4 exploded in first 42 hours
  - 4 others leaked
  - SCC indicated
- All prior experience indicated compatibility
  - Gemini, Lunar Surveyor, Titan missile
  - No contrary historical data
  - Other recent specimen & tank tests verified compatibility
- Confusion reigns
  - Previously compatible system now incompatible
  - Large inventory of tanks already on hand

Investigation Results

- Round robin testing identified problem
  - Tank manufacturer failed everything tested
  - Prime contractor cannot fail specimens or tanks
  - N_2O_4 samples exchanged among test labs
  - Color difference noted in exchanged samples
  - Color difference due to nitric oxide (NO) content
- Supplier of N_2O_4 removed trace amounts of NO starting in June 1964
  - Small change made N_2O_4 highly damaging to titanium
  - No requirement in N_2O_4 specification regarding NO content
  - No clues at start of investigation that NO content mattered
  - Tank manufacturer using new "improved" oxidizer

Damage Mode

Stress Corrosion Cracking

RCS Tank Failure Solutions

- Restored original N_2O_4 chemistry
  - Added back small amount of NO to oxidizer
  - Generated NASA specification requiring 0.5% NO
- Verified fix with many specimen & tank tests
- Tested propellants before each launch

RCS Oxidizer Tank Lessons Learned

- Minor process "improvement" voided all prior compatibility testing
- No such thing as small change
- Safety factors impact durability
  - Low safety factors increase susceptibility to damage modes
  - Low safety factors can change compatibility to incompatibility
- Must establish K_{th} for all fluids that contact tank while pressurized

Apollo Service Propulsion System (SPS) Fuel Tank Failures

- SPS was propulsion system that provided spacecraft with large velocity-change capability
- SPS used same hypergolic propellants as RCS
  - Oxidizer: nitrogen tetroxide (N_2O_4)
  - Fuel: Aerozine 50
- SPS fuel tank design
  - Material: Ti-6Al-4V
  - Environment: Aerozine 50 (methanol used in cold flow test)
  - Configuration: cylinder, 4 ft diam., 14 ft long, 0.055" thick
  - Usage: 2 in Service Module

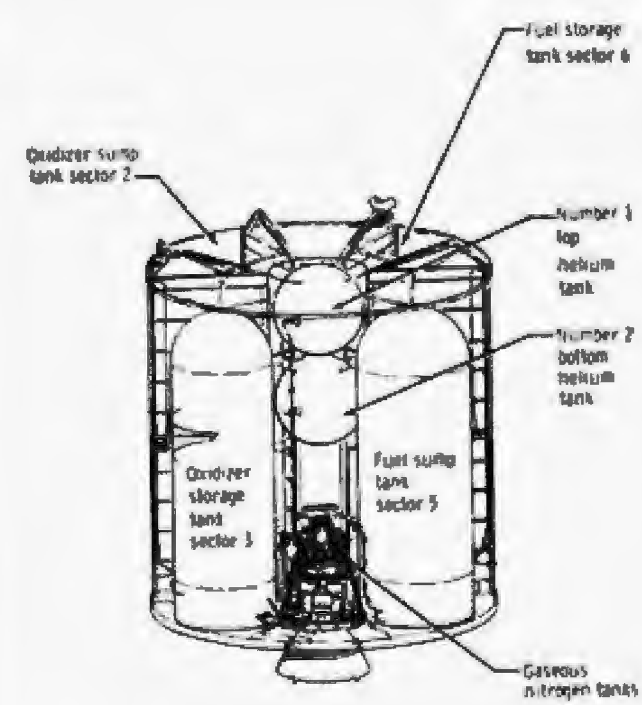
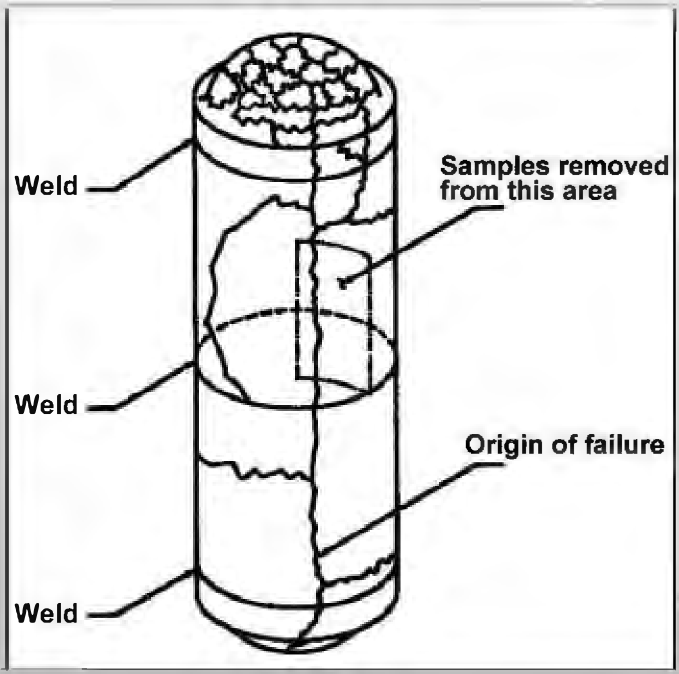


Figure 5. - Service module service propulsion system vessels — Block II.

SPS Fuel Tank Failures (cont.)

- Oct. 1, 1966: SC-101 fuel tank leaked during cold flow test
  - Methanol used in place of Aerozine 50
  - Suspected stress corrosion cracking
  - Weld contamination also suspected
- Additional tank testing instituted to sort out SCC & weld contamination possibilities
  - Tanks to be tested in place
  - Tank considered to be a leaker
- Oct. 25, 1966: SC-017 fuel tank exploded during test
  - Tank installed in Service Module when tank exploded
  - SC-017's Service Module completely destroyed in explosion



Underlying Problem: Methanol

- Methanol used as referee fluid for Aerozine 50 in cold flow test
  - Considered innocuous
  - Less hazardous than fuel
  - Similar specific gravity & flow characteristics to fuel
  - Considered compatible with titanium
- Used reagent-grade methanol in test
  - Anhydrous (low water content)
  - Low-water-content methanol very aggressive to titanium
- Damage mode: stress corrosion cracking

Investigation Results

Constant Load Data

Specimen origin	Number of specimens	Notched	Load, ksi	Test fluid	Time to failure, min	Standard deviation, min	Remarks
SC 101	2	No	120	Air	>4463	-	No failures
SC 101	1	No	130	Methanol	2	-	
SC 101	5	No	140	Methanol	6	1	
SC 101	3	Yes	120	Methanol	9	2	
SC 101	3	Yes	120	Aerozine-50	-	-	Specimens loaded for over 2 weeks with no failure at this writing
SC 101	2	Yes	120	Distilled H_2O	>2565	-	No failures

Shows extreme stress corrosion sensitivity of anhydrous methanol compared to fuel & distilled water

SPS Tank Failure Solutions

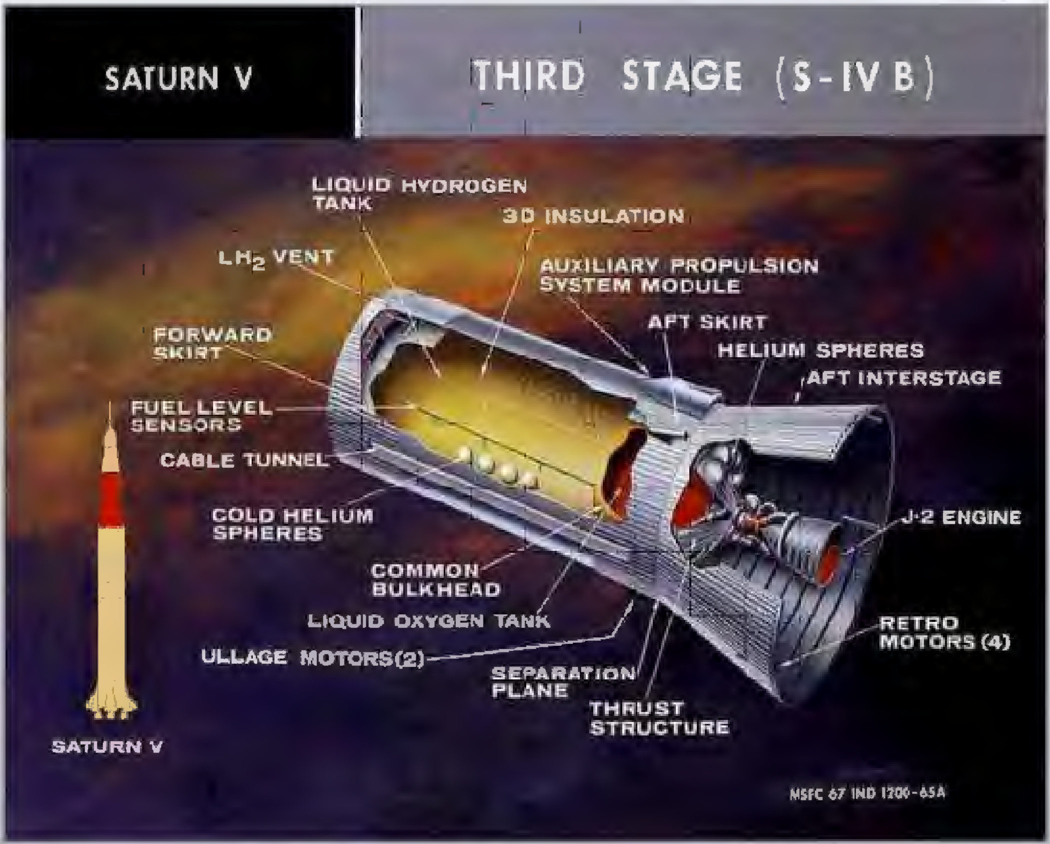
- Stopped using methanol as referee fluid
- Scrapped all tanks that had been through cold flow test
- Applied fracture mechanics methodology to all pressure vessels in remainder of Apollo Program
  - Proof-test logic principally used
    - Many tanks already in inventory
    - Low number of cycles involved
  - Measured fracture toughness, fatigue & environmental crack growth properties of all tank materials
    - Parent, weld & HAZ
    - Measured K_{th} of actual flight propellants before each lunar mission

SPS Tank Lessons Learned

- Small chemical changes can have profound effect on durability
- Even environments considered innocuous cause stress corrosion
- Must establish K_{th} for all fluids used as pressurants

S-IVB Helium Pressurization Tank Failure

- Helium tanks pressurized S-IVB LOX & LH_2 tanks
- Helium tank design
  - Material: Ti-6Al-4V
  - Configuration: spherical, 27" diam., 0.333" thick
  - Usage: 12 per S-IVB stage
- S-IVB stage
  - Third stage of *Saturn V*
  - 20 ft diam. × 40 ft long
  - LOX/ LH_2 propellants
- S-IVB 503 stage was scheduled for *Apollo 8* (1st manned circumlunar mission)



S-IVB Helium Pressurization Tank Failure (cont.)

- Static firing part of S-IVB stage acceptance test
- Began simulated launch countdown Jan. 20, 1967
- Without warning, S-IVB exploded in enormous fireball
  - Occurred at T_0–11 seconds
  - Stage completely destroyed
  - Static firing test stand substantially damaged
  - 300-ft fireball observed
  - Offsite damage reported 12 miles away
- Observers saw flashes in aft skirt region prior to explosion
- Subsequently determined helium tank exploded first
  - Found helium tank halves in debris
  - Brittle fracture along weld fusion line

S-IVB Helium Pressurization Tank Failure (cont.)

Explosion destroyed entire S-IVB stage & severely damaged static firing test stand

Underlying Problem

- Tank welded with wrong weld wire
  - Commercially pure (CP) titanium weld wire used
  - One spool of CP wire was mislabeled/misshelved
  - Specification called for titanium 6Al-4V weld wire
- Wrong wire resulted in low alloy content in the weld
  - Much lower hydrogen solubility in weld
  - Hydrogen diffused to weld via a stress gradient
  - Hydrogen precipitated as titanium hydride needles at fusion line
  - Over time sustained load cracking occurred
- Very-low-alloy content resulted from multipass weld
  - 10–12 passes required
  - Each pass further diluted weld deposit

Wrong Weld Wire

Titanium hydride needles

S-IVB Tank Failure Solution

- Remove all helium tanks welded with CP weld wire
  - 5 on S-IVB 503 stage
  - 4 found on other stages
- Spacecraft 6Al-4V tanks implicated by problem
  - Welded on purpose with CP weld wire
  - JSC cut up many tanks looking for hydrides
  - No hydrides were found
    - Hydride problem peculiar to thick multipass welds
    - Spacecraft 6Al-4V tanks were thin-walled single/double pass welds

S-IVB Tank Lessons Learned

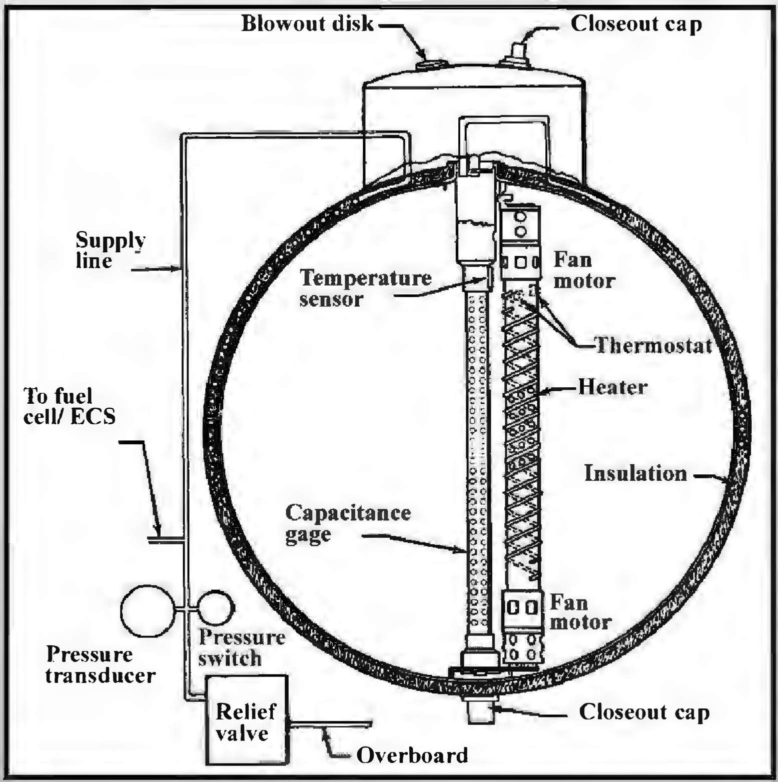
- Mislabeled weld wire, i.e., human error is a fact of life
- Verify weld wire composition at start & stop of welding process

Apollo 13 Oxygen Tank Failure

- *Apollo 13* lifted off April 11, 1970, at 13:13 pm CST
  - 00:00:00 GET
  - 00:12:40 GET—Reached Earth orbit
  - 02:41:47 GET—Translunar injection
  - 05:59:59 GET—S-IVB maneuver for lunar impact
  - 55:54:20 GET—Oxygen tank explosion (200,000 miles from Earth)
  - 77:27:39 GET—Pericynthion
  - 77:56:40 GET—S-IVB impacts lunar surface
  - 138:02:06 GET—Service Module jettisoned
  - 141:30:02 GET—Lunar Module jettisoned
  - 142:40:47 GET—Entry interface
- *Apollo 13* landed April 17, 1970, at 12:08 pm CST
  - 142:54:00 GET

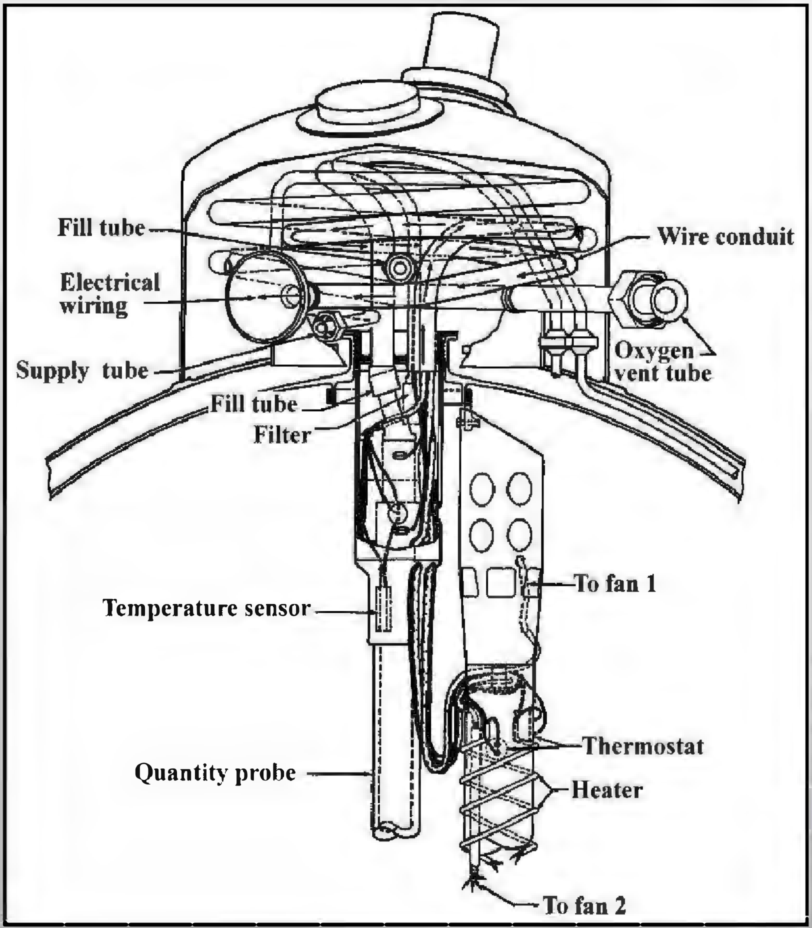
Apollo 13 Oxygen Tank Failure (cont.)

- Supercritical oxygen tanks provided breathing oxygen to CM & reactant oxygen to fuel cells for electrical power
- Oxygen tank design
  - Material: Inconel 718
  - Configuration: spherical, 25" diam. × 0.060" thick
  - Usage: 2 in Service Module
- Internal components—2 tube assemblies
  - Quantity gauge/fill tube
  - Heating element/stirring fans



Underlying Problems

- Tank contained:
  - Pure-oxygen environment
  - Flammable materials
  - Ignition sources
- Thermostatic switches underpowered
- Switches not tested under power
- Tank dropped in manufacturing
- Could not detank after CDDT
- Improvised detanking procedure
  - No test/verification
  - Very high internal temperature occurred
  - Wire insulation severely degraded



Cause of Accident

- Not single cause but combination of mistakes & deficient, unforgiving design
- Nature is unforgiving
  - Does not read our papers
  - Patient & the ultimate judge
- Combination of mistakes
  - Higher-power (65 VDC) switches required in Block II tanks not incorporated
  - Switches never cycled under load in qualification or acceptance test
  - Tank dropped during manufacturing
    - Bolt not removed
    - Handling fixture broke
    - Tank shelf dropped
    - Fill tube jarred loose
  - Tank #2 cannot detank per procedure at KSC after CDDT
  - KSC improvised new detanking procedure
    - No test & verification

Cause of Accident (cont.)

- Improvised detanking procedure required prolonged heating of tank contents
  - Thermostatic switches set at 80 °F
    - Prolonged heating requires switches to open
    - First time ever with 65 VDC
  - 28 VDC switches opening with 65 VDC power applied weld shut
    - Opening arc persists too long
    - Contacts melt & bridge 0.015" gap
  - Power to heating element on for 8 hours
    - Temperature near heating element 1,000 °F
    - Teflon insulation on nearby wires severely degraded

PM 4-20, 4-21

Explosion Sequence of Events

- KSC-improvised detanking procedure created hazardous condition in tank 2
- Cryogen-stirring fans turned on (7th time) at 55:54:20 GET
  - Bare wire exposed by degraded insulation shorted
  - Teflon wire insulation ignited
- Rapidly rising temperature & pressure inside tank caused rupture of electrical conduit in tank dome area
  - Explosive release of high-pressure oxygen into Service Module electrical compartment
  - Extensive damage in compartment defeats all redundancies of 2 oxygen tanks & 3 fuel cells
  - Overpressure blows exterior panel off Service Module fuel cell compartment
- Primary source of breathing oxygen & power generation lost

Apollo 13 Oxygen Tank Solutions

- Major tank redesign
  - Removed all wiring & motors from contact with oxygen
  - Minimize use of flammable materials inside tank
- Some felt installing correctly rated switch would be sufficient
- Implemented rigorous requalification test program
- Revised KSC prelaunch anomaly resolution procedure
- Reassessed all subsystems & responsible organizations

Apollo 13 Lessons Learned

- Failures not necessarily due to single cause
- Qualification testing is space industry gold standard
- Margin between success & failure can be very narrow
- Randomness of event can make difference between success & failure
- Even cryogenic oxygen environments can be flammability hazards

Summary

- RCS oxidizer tank failure demonstrated that:
  - Any change is important
  - Qualification testing is extremely important
  - Safety factors impact durability
  - Engineers must establish K_{th} for all fluids
- SPS fuel tank failure:
  - Reinforced lessons learned in RCS oxidizer tank: small chemical changes & otherwise innocuous fluids can cause stress corrosion cracking
  - Led to adopting fracture mechanics methodology for pressure vessels in remainder of Apollo program

Summary (cont.)

- S-IVB helium tank failure emphasized:
  - Importance of verification of correct material usage
  - Ever-present possibility of human error
- *Apollo 13* oxygen tank incident reiterated:
  - Risks of oxygen-rich environments
  - Importance of ‘test as you fly, fly as you test’ practice

Lesson 10:
Selected Apollo & Shuttle Lessons Learned (Part 2)

Objectives

- Identify additional pressure vessel failures (not covered in Part 1) from Apollo era & lessons learned
- Identify 2 Shuttle program thermal protection system (TPS) failures & lessons learned

Lesson 10:
Selected Apollo & Shuttle Lessons Learned (Part 2)

- Mr. Bud Castner
- Mr. Glenn Ecord

Introduction

- 4 Apollo-era pressure vessel failures were discussed in Lesson 4
  - RCS oxidizer tank
  - SPS fuel tank
  - S-IVB helium tank
  - *Apollo 13* oxygen tank
- 2 additional pressure vessel failures & 2 tile problems also provide valuable lessons about materials durability

Experimental “Ardeformed™” Stainless Steel Tanks

- Built by ARDE Corporation
- New materials concept
- New manufacturing method
- Made from cryoformed 301-type stainless steel

1st ARDE Stainless Steel Tank Failure

- Failure during volumetric expansion test
  - Proof pressure was 1,337 psi
  - Tank exploded unexpectedly at 1,160 psi

Underlying Problems

- New tank material
- First stainless steel tank was filled with water
- Tank immersed in protective aluminum vat, also filled with water
- Bottom of tank touched inside of vat
- Contact created galvanic cell
- Started localized corrosion process
- Released hydrogen
- Cryoformed 301 CRES sensitive to hydrogen

1st ARDE Tank Solution

- Barrier placed inside vat
- Tank placed on nonconductive pad
- No contact between vat & tank
- No galvanic cell
- Damage mode eliminated

2nd ARDE Tank Failure

- Tank exploded during a pressure hold at 1,337 psi
- Tank immersed in water with galvanic barrier during test
- Strain gages applied to tank prior to hold test & then waterproofed
- Waterproof coating attacked cryoformed steel when strain gages applied, causing localized cracking
- Stress corrosion proceeded at tips of induced cracking, growing until critical flaw size (onset of unstable crack growth fracture) was reached

ARDE Tank Lessons Learned

- New materials may act in an unanticipated manner during testing
- Hydrostatic tests can be very dangerous
  - Energy released testing with liquid is < energy released testing with gas
  - Ullage at top of tank must be avoided
  - Be aware of possible hydrogen embrittlement or stress corrosion potentials
- Keep open mind when doing failure analyses
  - Do not jump to conclusions; new & unexpected damage modes can be expected—especially with new materials
  - Look for all related data that can be found
  - Do not presume you know what happened & try to design failure investigation to prove that assumption
  - Verify events & data before making them factor in investigation

Impact on Future

- Pressure tests must be conducted remotely
- Be aware of what environment might do to material
- Be aware that cryogenically formed tanks may react differently than regular stainless steel tanks

Cryoformed stainless steel tank

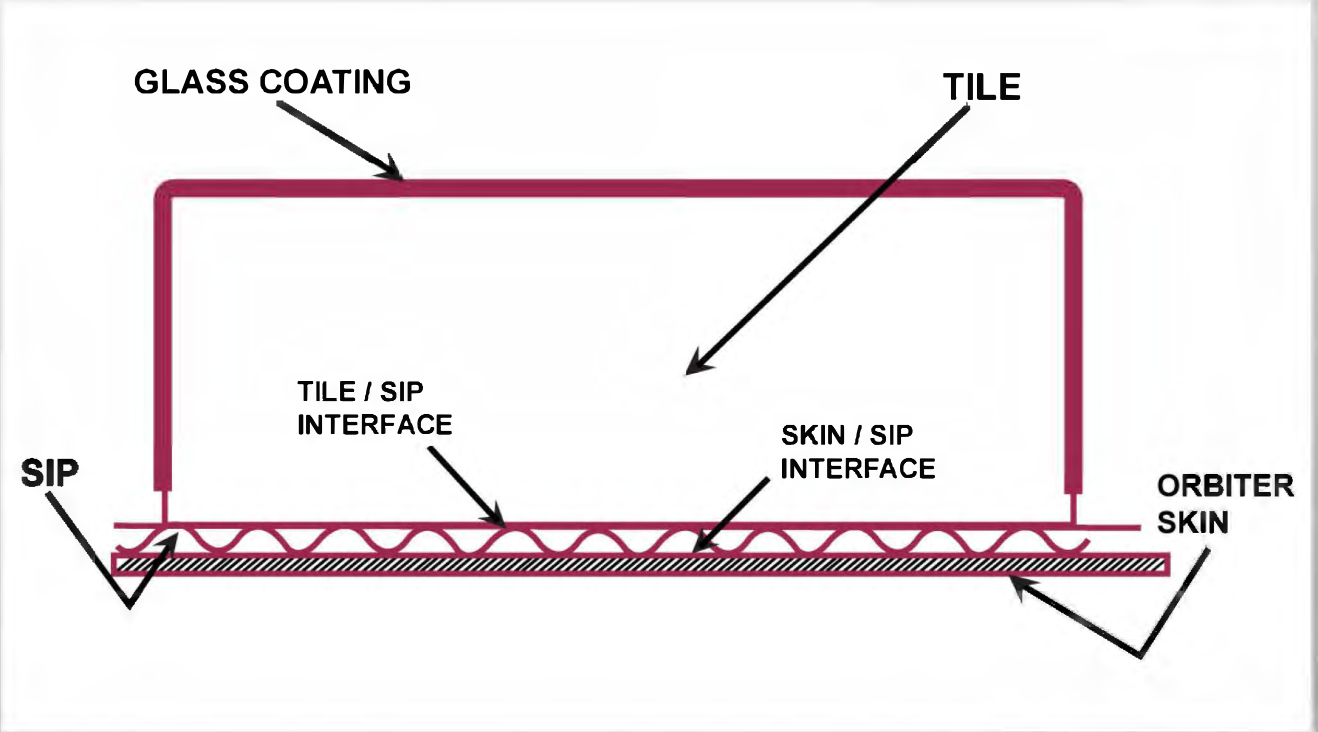
Space Shuttle Thermal Protection System (TPS) Failures

- TPS protects Space Shuttle from:
  - Heat during reentry
  - Hazards of space
- TPS tiles are blocks of fibrous silica
  - Soft porous structure
  - Not strong structure

Tile system structure

Orbiter Tiles Fall Off During 1st 747 Aircraft Ferry Flight

- May 1979—Several tiles fell off Orbiter when it was ferried by 747 aircraft to Kennedy Space Center
- Tiles vital to protection of Orbiter during reentry



Underlying Problem

- Tiles were glued to Orbiter skin with room-temperature vulcanizing (RTV) silicon adhesive & Nomex strain isolation pad (SIP)
  - SIP “needling” caused localized stress concentrations along bondline interface with tiles
  - Concentrations resulted in low bond strength
- Original tests of bond strength conducted on small (2"×2") flatwise tensile specimens, not full-sized tiles
- Dynamic testing had not been started

TPS Tile Loss Initial Solution

- Massive proof testing effort
  - Conduct acoustic emission test on each tile
  - Replace any tiles that come off
  - Test took 3 hrs/tile
  - Space Shuttle has ~6,000 tiles
- Testing not reliable enough or fast enough—stopped before complete

TPS Tile Loss Final Solution

- Densification of tile's bottom surface:
  - Eliminated voids
  - Exposed denser, stronger surface to RTV at bond
  - Allowed stress concentrations to be "neutralized" & not a performance factor
- 2 densification methods developed:
  - LUDOX process, which added silica to tile surface
  - Tetraethylorthosilicate (TEOS) process, which also added silica to tile surface

TPS Tile Loss Lessons Learned

- Important to demonstrate durability of new materials, new designs & their combinations before proceeding with assembly
- Once assembled, problems can cause delays & disruptions
- Testing should be completed on representative hardware, not just small samples

Tile Coating Repairs Fail During Vibration Testing

- TPS tiles coated with thin film of borosilicate glass
- Coating prevents tiles from absorbing water
- Coating easily damaged
- Initial repair method only certified for thermal environments

Underlying Problem

- Installation of tiles preceded completion of dynamic TPS testing
- Repair method not certified for dynamic performance

- During vibration testing, many tile surface repairs fell out
- Launch vibration might cause loss of tile repairs needed for reentry protection

Environment Aggravated Situation

- Tile material very soft & lightweight
- Repair material very hard & heavy
- During dynamic movement, hard repair material damaged surrounding soft tile material
- Repair popped out

TPS Vibration Solution

- Use TEOS & tile material to make repair "nugget"
- Densify repair area to reduce density gradient between tile material & repair material
- Method became standard for tile repair
- More than 100,000 repairs done

TPS Lessons Learned

- Very risky to start vehicle assembly for flight before all testing is completed
  - Quick fixes not always possible
  - Do as much work up front as possible
- Dual approaches with resolutions of specific issues of concern can be valuable for:
  - Maintaining schedules
  - Making needed design changes

Summary

- Materials durability & damage modes are strongly influenced by new materials & new applications
- Low safety factors (low margins) make materials more sensitive to environments & damage modes
  - Bring out unknowns
  - Invite unpredictable problems
- New materials are often rushed into use & pushed to their assumed limits
- New designs are often rushed into manufacturing of flight hardware before testing is completed

Summary (cont.)

- Unexpected problems/failures are especially true of new materials, high-strength materials & new material combinations & applications
- Embrace your technical problems
  - They indicate something is wrong
  - Source of many valuable lessons
  - Focus of new designs is often about avoiding past failures