



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)

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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





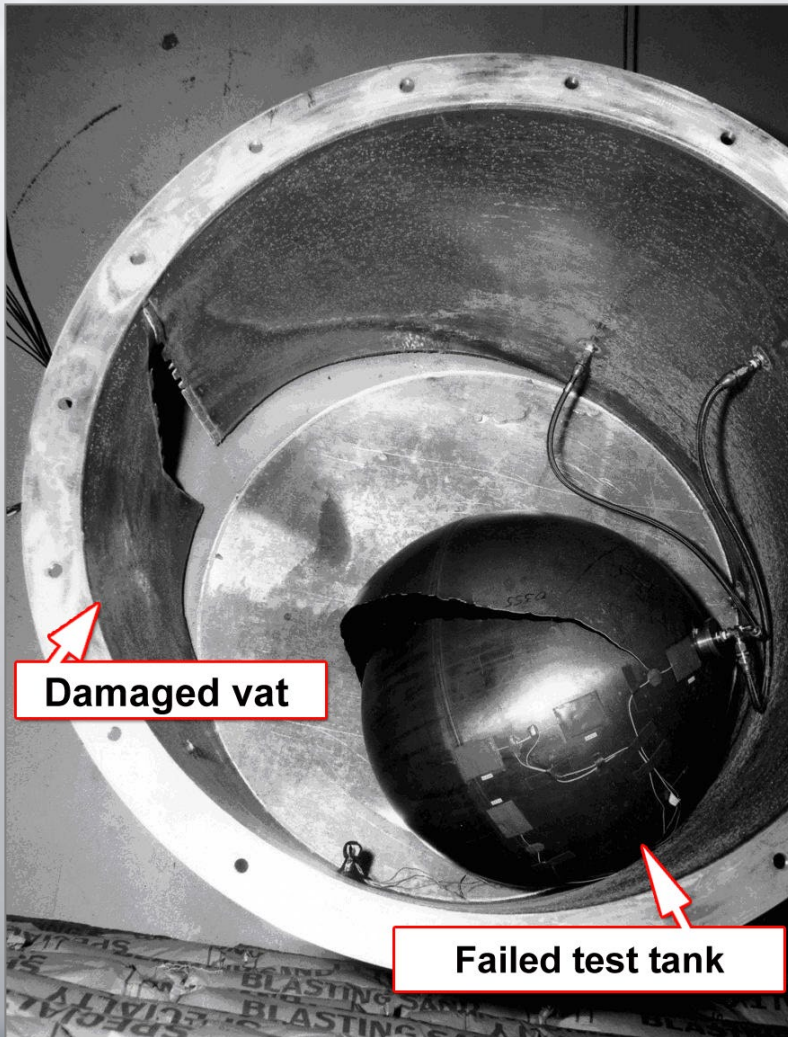
Experimental “Ardeformed™” Stainless Steel Tanks

- 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





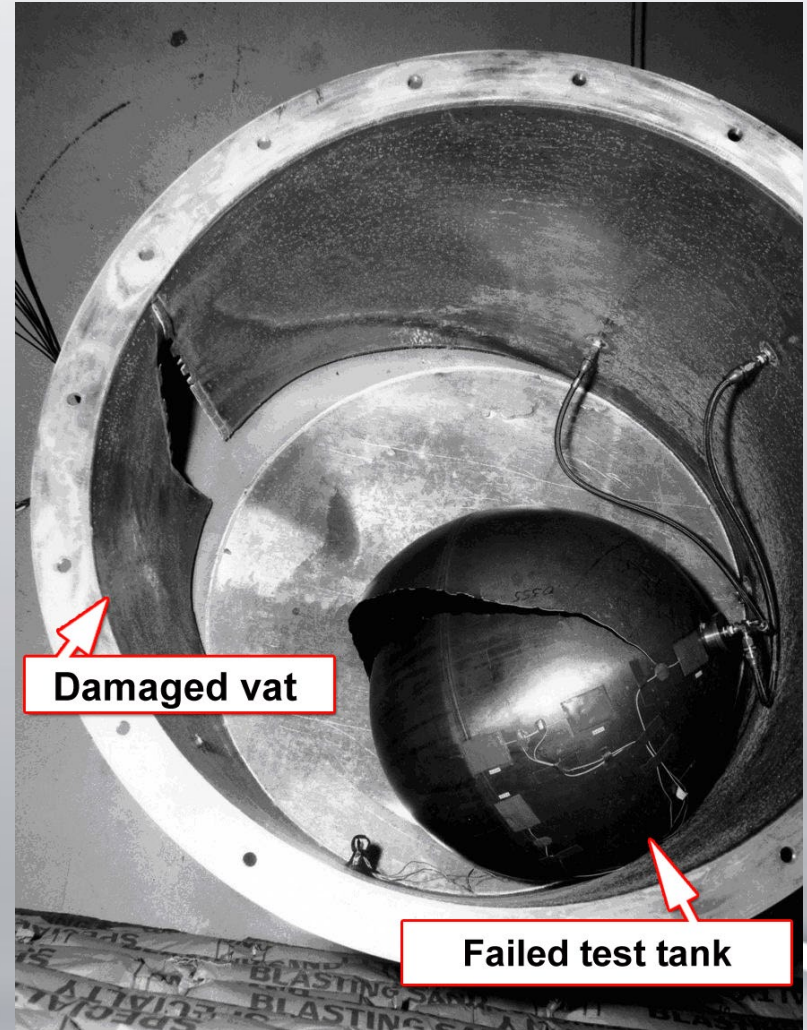
Underlying Problems

- 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



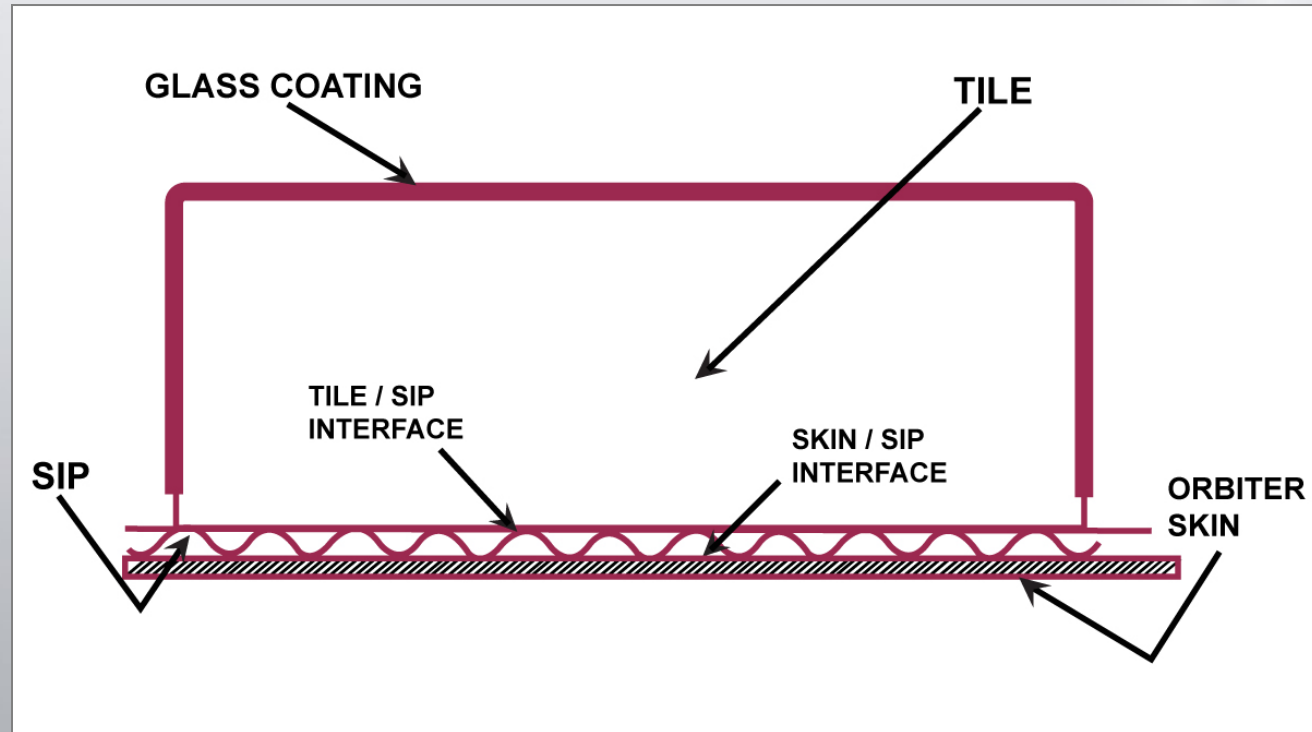
Tile system structure

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



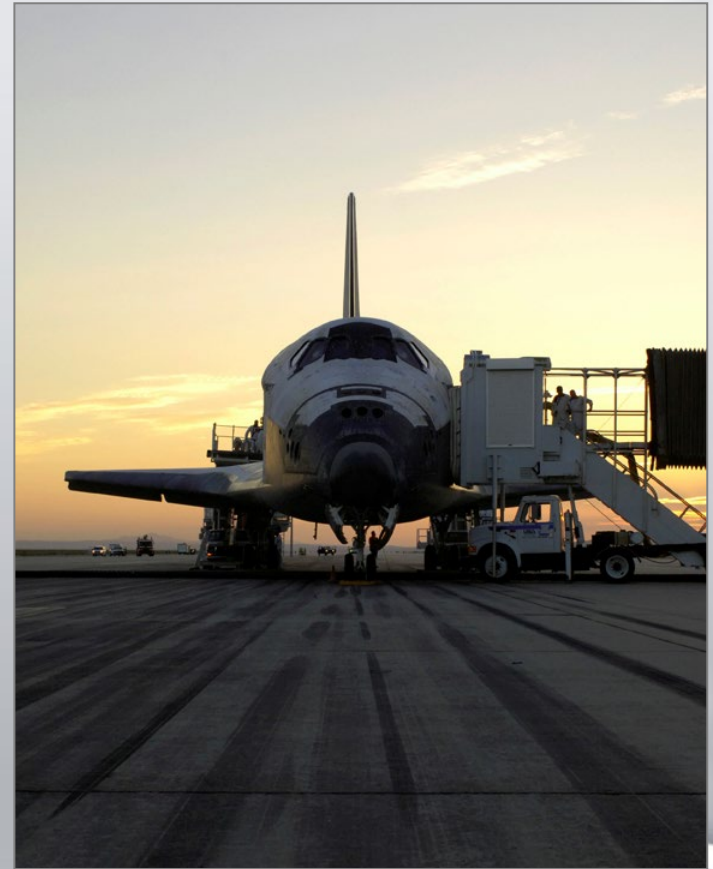
TPS Tile Loss Lessons Learned

- 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

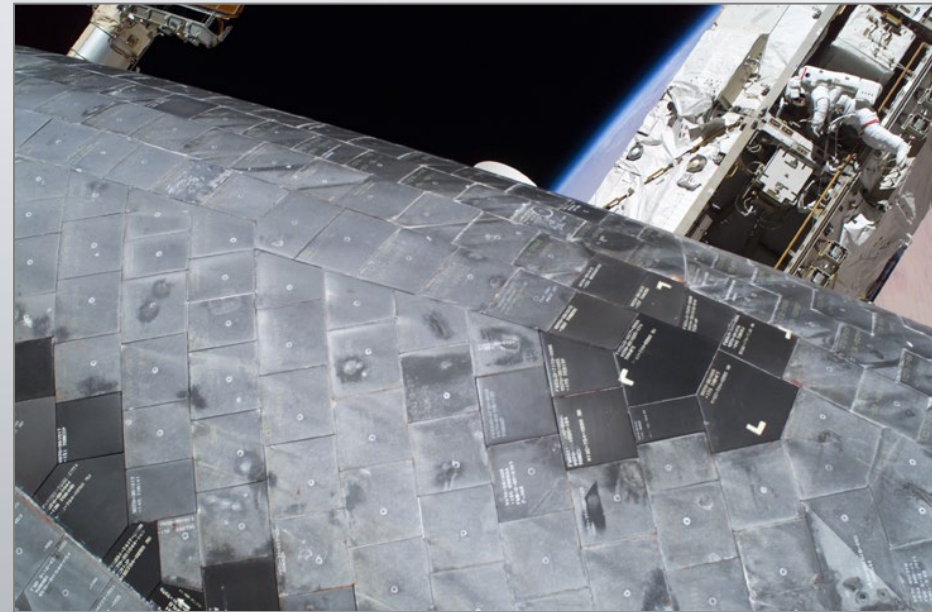
- Installation of tiles preceded completion of dynamic TPS testing
- Repair method not certified for dynamic performance
- During vibration testing, many tile surface repairs fell out
- Launch vibration might cause loss of tile repairs needed for reentry protection





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