Mishap Lessons for the Moon and Beyond

AR NEXGEN

NASA Quality Leadership Forum (QLF)

March 14, 2024

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Introduction

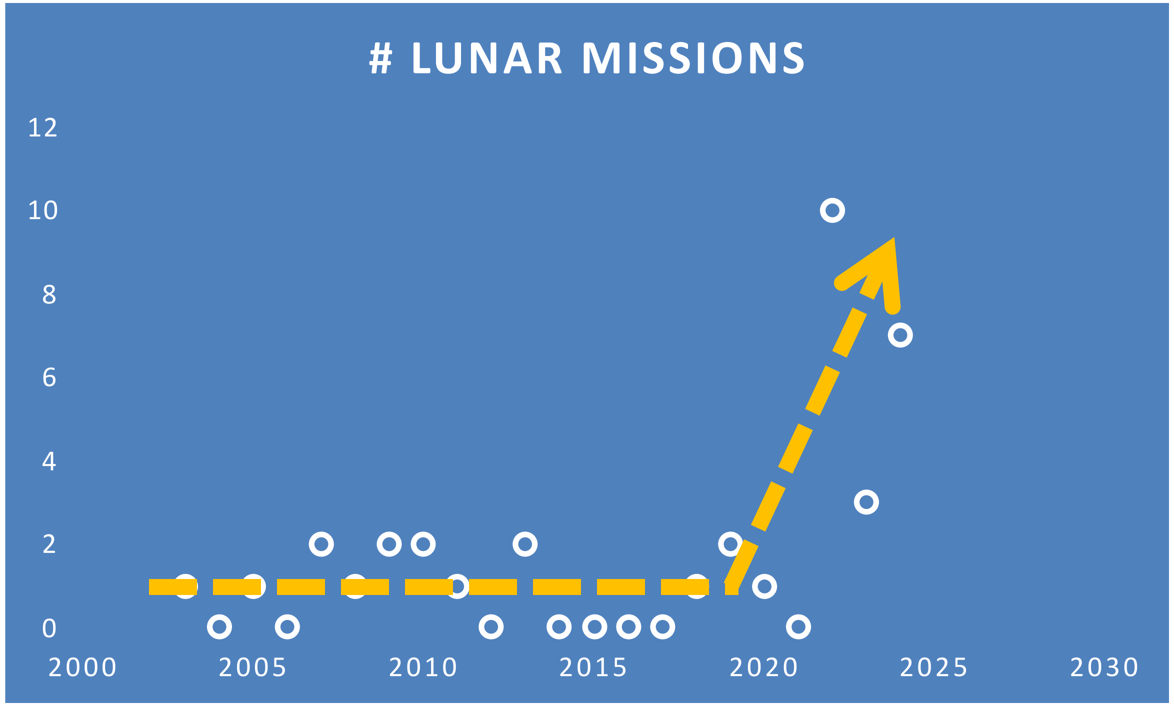
- **Missions to the Moon and beyond have entered a new and exciting phase**
  - Government, private, international
- **Need to develop a way to share lessons from this emerging industry**
  - Critical for both earth and deep space missions
  - Opportunity: sharing lessons from completed moon missions

Missions to the Moon (2004-2024)

Current and Past Missions (31 completed)

- Peregrine Mission 1 - NASA CLPS Lunar Lander (2024)
- IM-1 - NASA CLPS Lunar Lander (2024)
- Chandrayaan 3 - ISRO (Indian) Lunar Lander and Rover (2023)
- SLIM - JAXA (Japan) Lunar Lander (2023)
- Luna 25 - Roscosmos (Russia) Lunar Lander (2023)
- Korea Pathfinder Lunar Orbiter - KARI (South Korea) Lunar Orbiter Mission
- CAPSTONE - NASA Lunar Navigation and Test Orbiter
- LunaH-Map - NASA Lunar Orbiting CubeSat (2022)
- Lunar Ice Cube - NASA Lunar Orbiting CubeSat (2022)
- LunIR - NASA Lunar Flyby and Technology Test CubeSat (2022)
- OMOTENASHI - JAXA (Japan) Lunar Lander CubeSat (2022)
- EQUULEUS - JAXA (Japan) L2 Orbiting Lunar CubeSat (2022)
- Artemis 1 - NASA Lunar Test Flight (2022)
- Hakuto-R M1 - JAXA (Japan) Lunar Lander (2022)
- Lunar Flashlight - NASA Lunar Orbiting CubeSat (2022)
- Chang'e 5 - CNSA (China) Lunar Sample Return Mission (2020)
- Chandrayaan 2 - ISRO (India) Lunar Orbiter, Lander and Rover Mission (2019)
- Beresheet - Space IL and Israeli Aerospace Industries (Israel) Lunar Lander (2019)
- Chang'e 4 - CNSA (China) Lunar Farside Lander (2018)
- Chang'e 3 - CNSA (China) Lunar Lander and Rover (2013)
- LADEE - NASA Lunar Orbiter Dust Environment Mission (2013)
- GRAIL - NASA Lunar Orbiter Mission (2011)
- Chang'e 2 - CNSA Lunar Orbiter Mission (2010)
- ARTEMIS-P1 and ARTEMIS-P2 - NASA Heliophysics/Lunar Orbiter Mission (2010)
- Lunar Reconnaissance Orbiter - NASA Lunar Orbiter Mission (2009)
- LCROSS - NASA Lunar Impactor Mission (2009)
- Chandrayaan-1 - ISRO (India) Lunar Orbiter Mission (2008)
- Chang'e 1 - CAST (China) Lunar Orbiter Mission
- Kaguya (SELENE) - JAXA Lunar Orbiter Mission
- Deep Impact/EPOXI - NASA Mission to Comet Tempel 1 - Lunar Flyby
- SMART 1 - ESA Lunar Orbiter Mission

https://nssdc.gsfc.nasa.gov/planetary/planets/moonpage.html



(*) Planned flights in 2024 included.

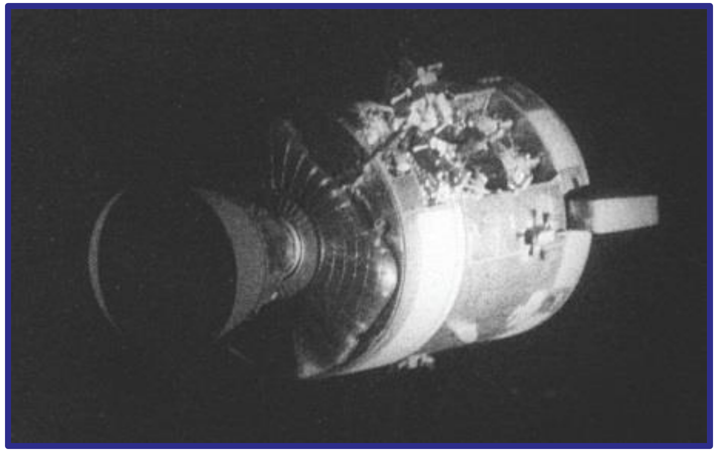
Premise

- **Based on AR NexGen database, majority of mishaps:**
  - Can be traced to preventable root causes
  - Are lost to human error (which will happen)
  - Often repeat

- **Two lunar mission case studies and associated lessons are presented**
  - Examples of lessons to share with current developers

Apollo 13 Oxygen Tank Explosion

(Failure often arrives as the confluence of separate errors.)



Video

Underlying Issue:

Two independent process errors nearly caused a disaster

Problem:

Apollo 13 service module oxygen tank #2 exploded (4/13/1970)

Impact:

Loss of mission and nearly loss of crew

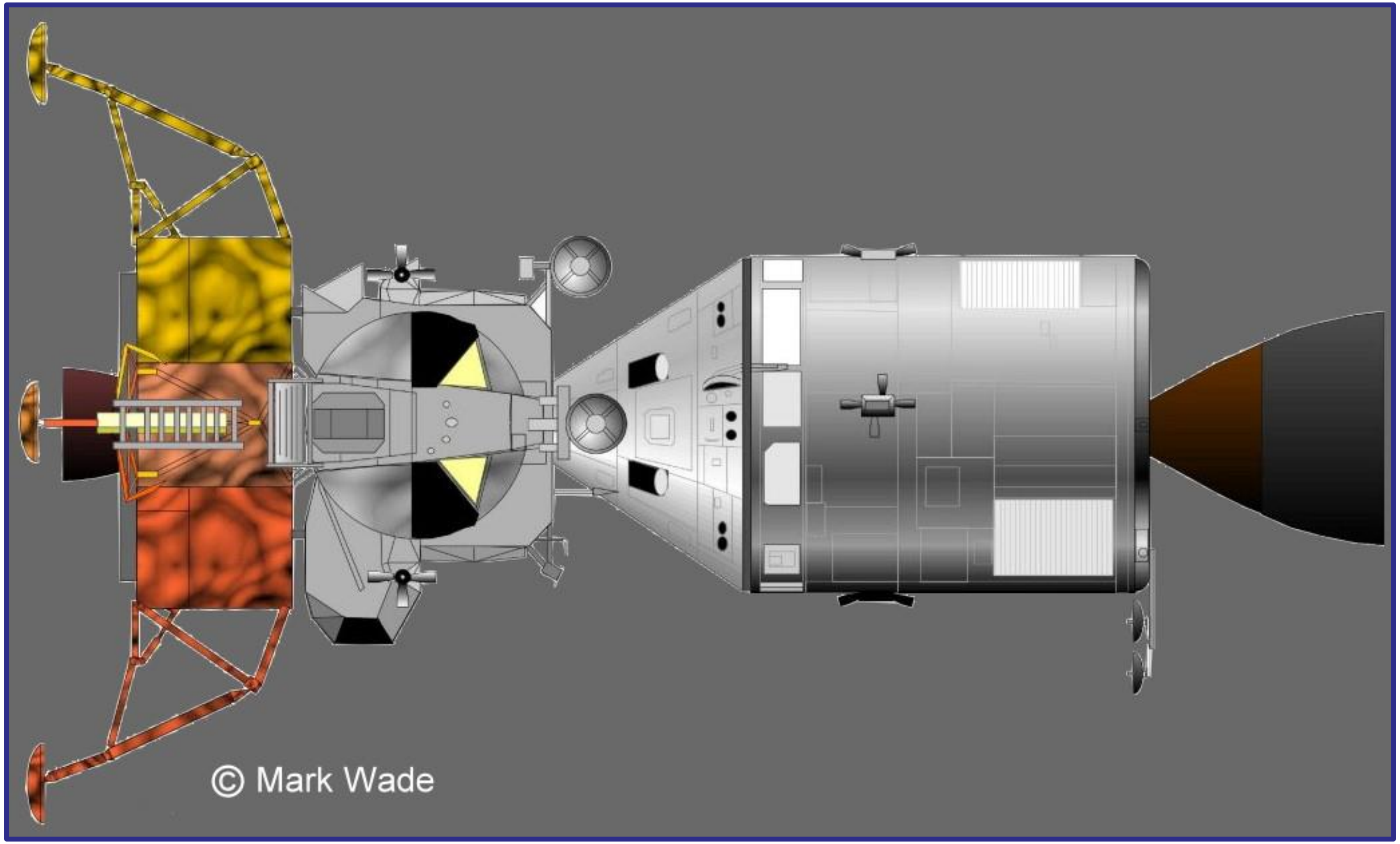
Source: http://history.nasa.gov/ap13rb/ap13index.htm; Apollo 13 Review Board; http://nssdc.gsfc.nasa.gov/planetary/lunar/apollo_13_review_board.txt

Apollo 13 Oxygen Tank Explosion (cont'd)

Why:

- Series of missteps led to damaged wiring in oxygen tank
  - Fill tube design permitted adverse tolerance buildup
  - Tank had been dropped several years earlier
    - Possibly displaced marginally designed fill tube
  - Thermostat circuit operating voltage increased
    - Manufacturer not told and qualification incomplete
  - Non-standard pre-launch procedure caused wire damage

Apollo 13 Command, Service and Lunar Modules

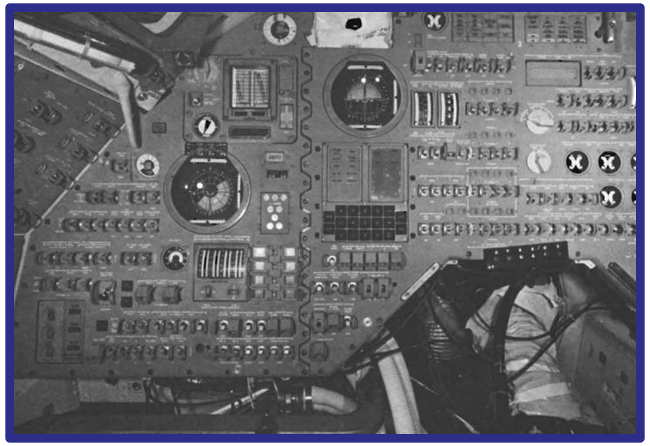


Something's Wrong

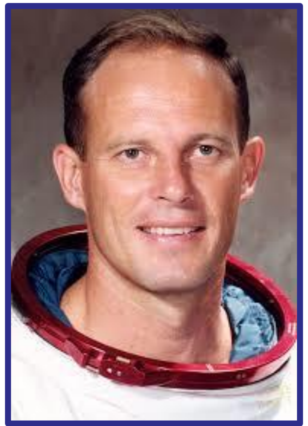
James A. Lovell, Jr.
Commander

John L. Swigert
Command Module Pilot

Fred W. Haise
Lunar Module Pilot

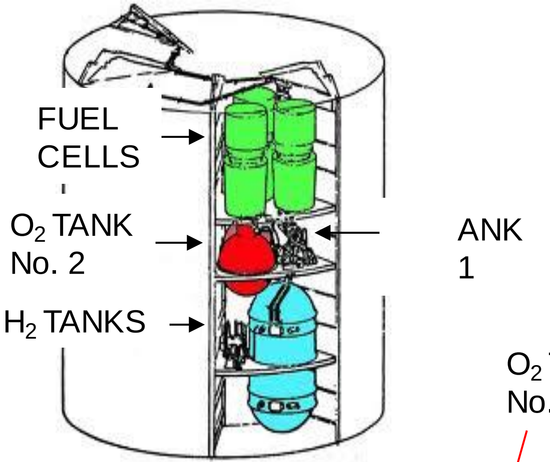


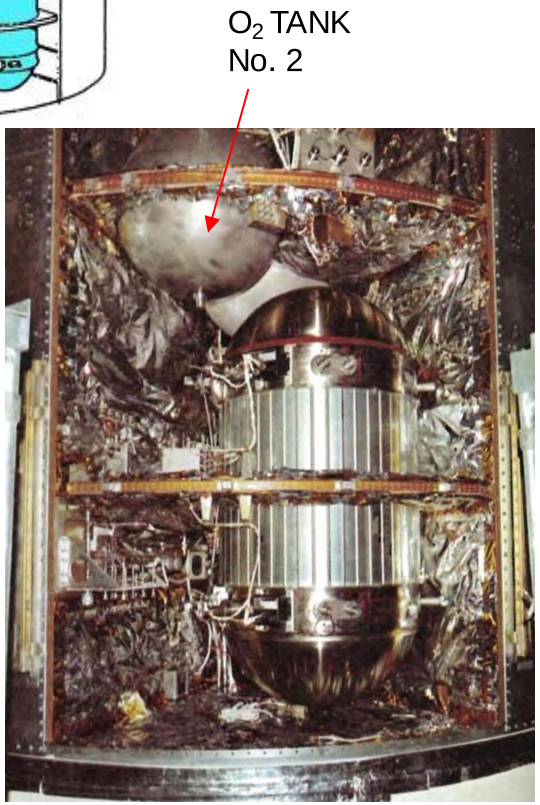
Video

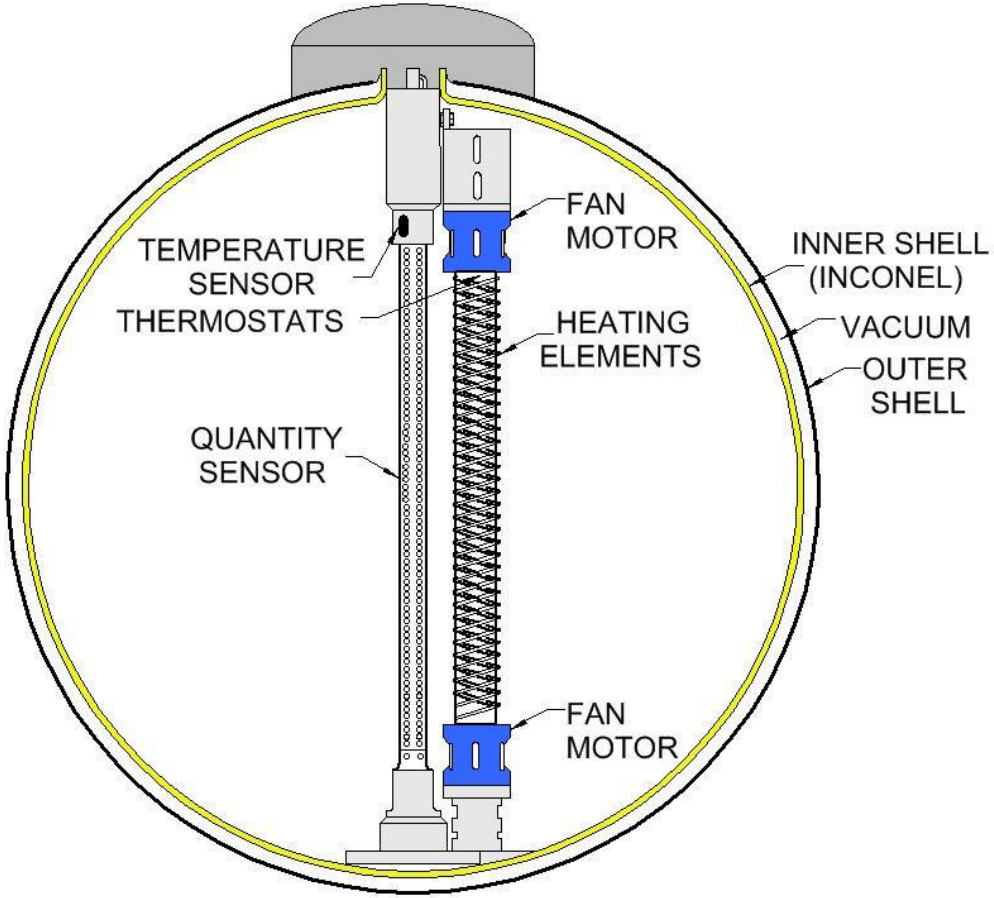


Jack R. Lousma
CapCom

Apollo 13 Service Module Oxygen Tank Installation

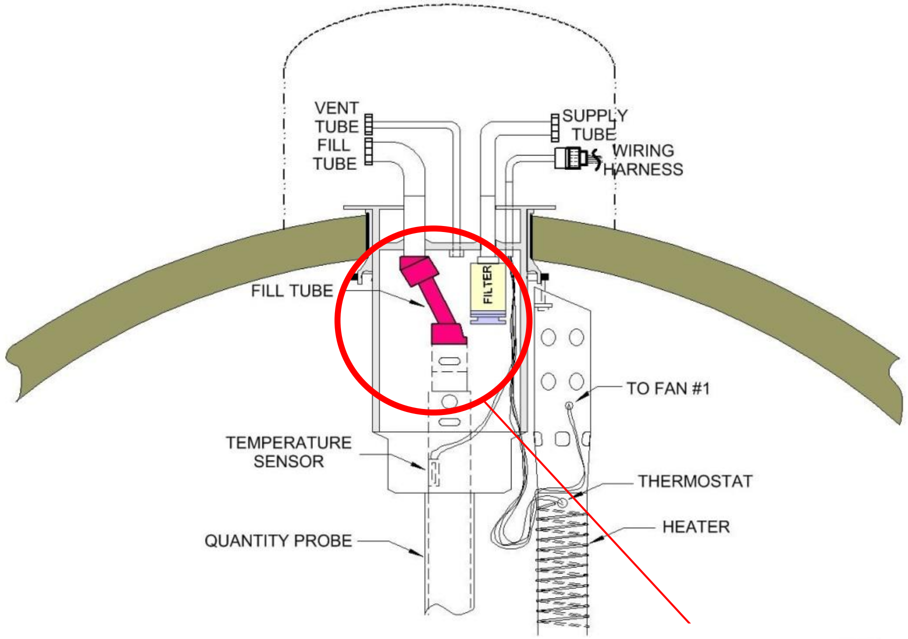




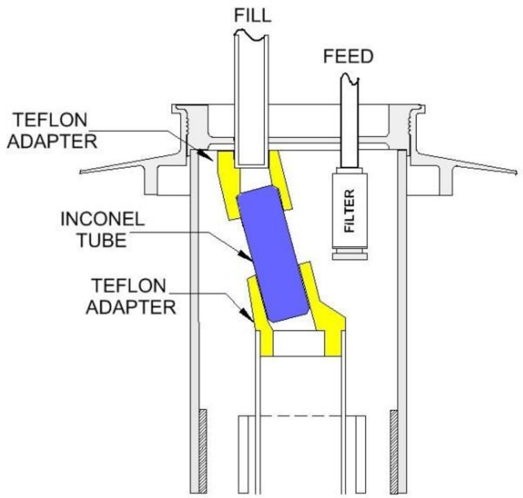


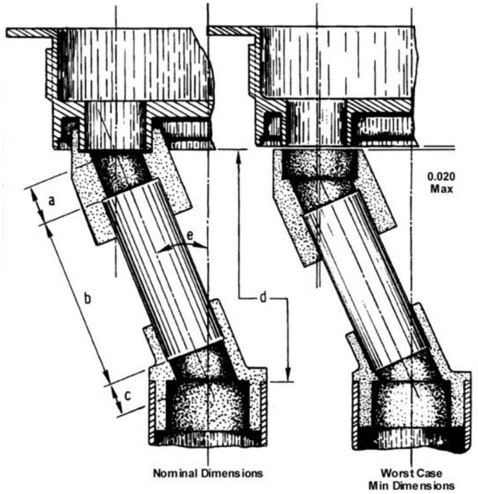
DIAMETER 25 IN (63.5 CM) CAPACITY 330 LB (150 KG) PRESSURE 870-930 PSI (6,000-6,400 KPA)

Apollo 13 Service Module Oxygen Tank Detail



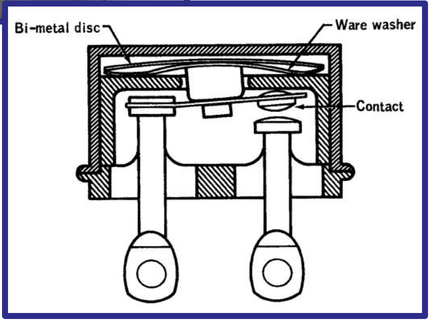
Fill Tube Tolerance Analysis		
Dimension	**Nominal**	**Worst Case Short**
a	0.24” (6 mm)	0.16” (4 mm)
b	1.080” (27 mm)	1.065” (27 mm)
c	0.20” (5 mm)	0.14” (3.6 mm)
d	1.43” (36 mm)	1.45” (37 mm)
e	21 deg	24 deg





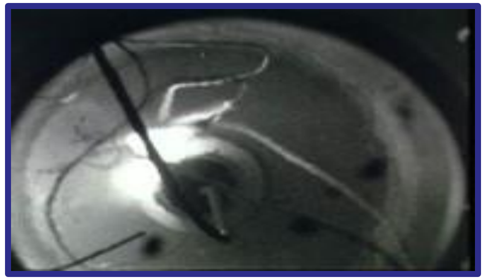
Apollo 13 Post Flight Testing

Thermostat Welded Closed



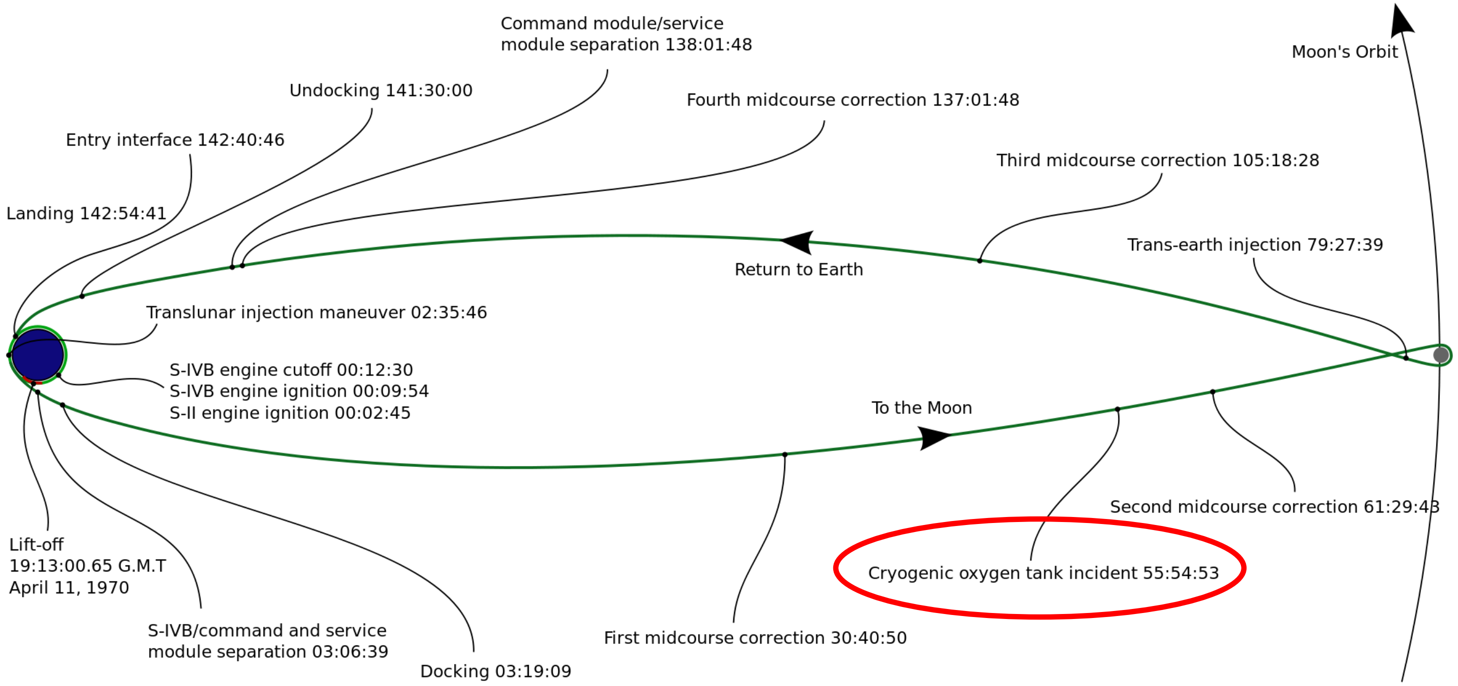
Fan Motor Wire Damage Heater Test

Teflon Burning in Supercritical Oxygen



Vacuum Service Module Panel Separation Test

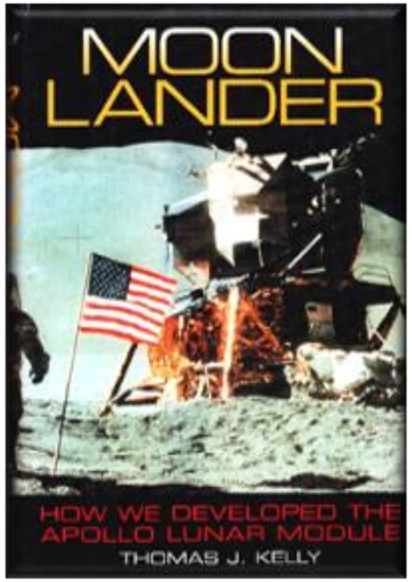
Coming Home



Command module/service module separation 138:01:48
Moon's Orbit
Undocking 141:30:00
Fourth midcourse correction 137:01:48
Entry interface 142:40:46
Third midcourse correction 105:18:28
Landing 142:54:41
Trans-earth injection 79:27:39
Return to Earth
Translunar injection maneuver 02:35:46
S-IVB engine cutoff 00:12:30
S-IVB engine ignition 00:09:54
S-II engine ignition 00:02:45
To the Moon
Second midcourse correction 61:29:43
Lift-off
19:13:00.65 G.M.T
April 11, 1970
Cryogenic oxygen tank incident 55:54:53
S-IVB/command and service module separation 03:06:39
First midcourse correction 30:40:50
Docking 03:19:09

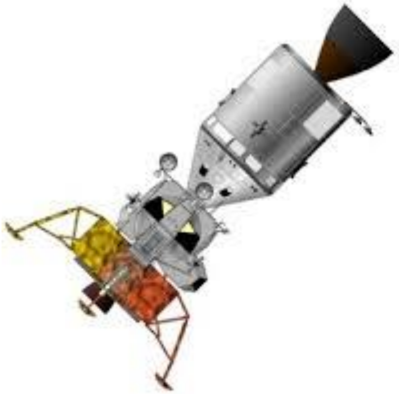
A “What if ?” Culture Produced Life Saving Measures on Apollo 13

***What if* the CSM becomes uninhabitable?**



Design the LM as a lifeboat utilizing its propulsion, guidance and control, life support, and other systems to return the crew to the vicinity of the Earth’s atmosphere for reentry in the CSM.

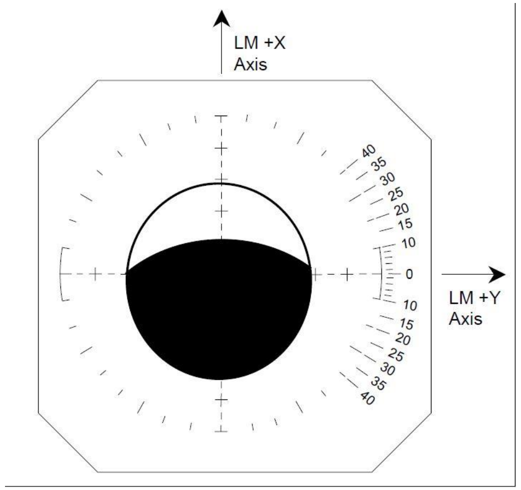
***What if* the SPS is damaged. Can the LM Descent Engine be used in its place”?**



Descent Engine firing while attached to CSM demonstrated on Apollo 9.

***What if* the CSM guidance system couldn’t be used and the stars were not viewable for normal sextant operation. How would a course correction maneuver be performed?**

Use the sextant in a mode that uses the Sun and Earth as references.
Demonstrated by Jim Lovell on Apollo 8



Successful High Performing Organizations are Obsessed With the Prospect of Failure!

Apollo 13 Oxygen Tank Explosion
LESSONS

The best teams can make mistakes, including lapses in critical processes

Independent errors can combine to produce serious consequences; for Apollo 13:	Bad design (flawed or omitted tolerance stack-up analysis)
	Bad process (design change not re-qualified)

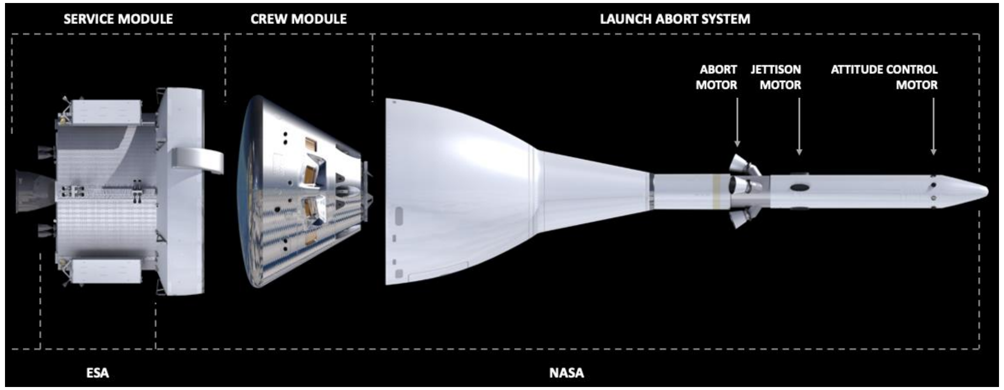
Apollo 13 Oxygen Tank Explosion (concluded)

LESSONS

Among the many detailed lessons to be learned are:	
	Approved changes need a closed loop way of getting to all involved parties
	Non-standard procedures need especially rigorous and formal discipline
	Instrumentation ranges should have margin beyond expected operating limits
Even time-proven processes can have undetected vulnerabilities	Assume they exist and continuously look for them

A "What if ?" culture can produce life saving measures!

Orion Testing Program: Readiness for Moon Missions



Underlying Goal:

Integrated Flight & Ground Testing

Approach:

Heritage Systems & TLYF in Multiple Test Programs

Impact:

Artemis I was hugely successful

ORION SPACECRAFT DETAILS

PERFORMANCE

Crew	**4**
Mission Duration	**21 Days x 4 Crew**
Translational Delta V	**3,550 ft/s (1,100 m/s)**
Regenerable Electrical Power	**11 kW**
Co-Manifested Payload Capability	**10.0 t**
Lunar Payload Return	**220 lb (100 kg)**

Regenerable Air Revitalization

Redundant Return Engine Capability

Return to Earth Capability Without Communications

ORION SPACECRAFT
(W/DOCKING CAPABILITY)

Gross Liftoff Mass	***78,000 lb (35,000 kg)***
Trans-Lunar Injection	*58,500 lb (27,000 kg)*
Crew Module Landed	*20,500 lb (9,300 kg)*
Useable Propellant	*19,000 lb (8,600 kg)*

CREW ACCOMODATIONS

Habitable volume	**316 ft^3 *(9 m^3)***

Waste Management System

Galley

Crew Exercise Device

Radiation Tolerance

MMOD Protection

Unpressurized Crew Survival Capabilities

NASA Testing "Doctrine"

Test-test-test is the first choice for system validation

Know what you build, test what you build, test what you fly, test like you fly

Successful projects make testing a very high priority!

Orion Flight Tests

Major Features

- Maximum Use of Heritage Systems
  - Apollo, Shuttle, Space Station, ATV
- Flight Testing Emphasis
  - Exploration Flight Test-1 (High earth orbit to demonstrate CM space-worthiness, heat shield, and recovery systems) 2014√
  - Pad/Ascent Abort Flight Tests 2010 & 2019 √
  - Artemis I (SLS L/V, Uncrewed, Lunar Orbit, long duration flight testing all major systems except life support) 2022 √
  - Artemis II (SLS L/V Crewed. Lunar Orbit) 2025
  - Artemis III (SLS L/V, Crewed, Lunar Landing) 2026

Video – Artemis I Mission
https://www.youtube.com/watch?v=jrDv0OdMt5s

Shuttle OMEs

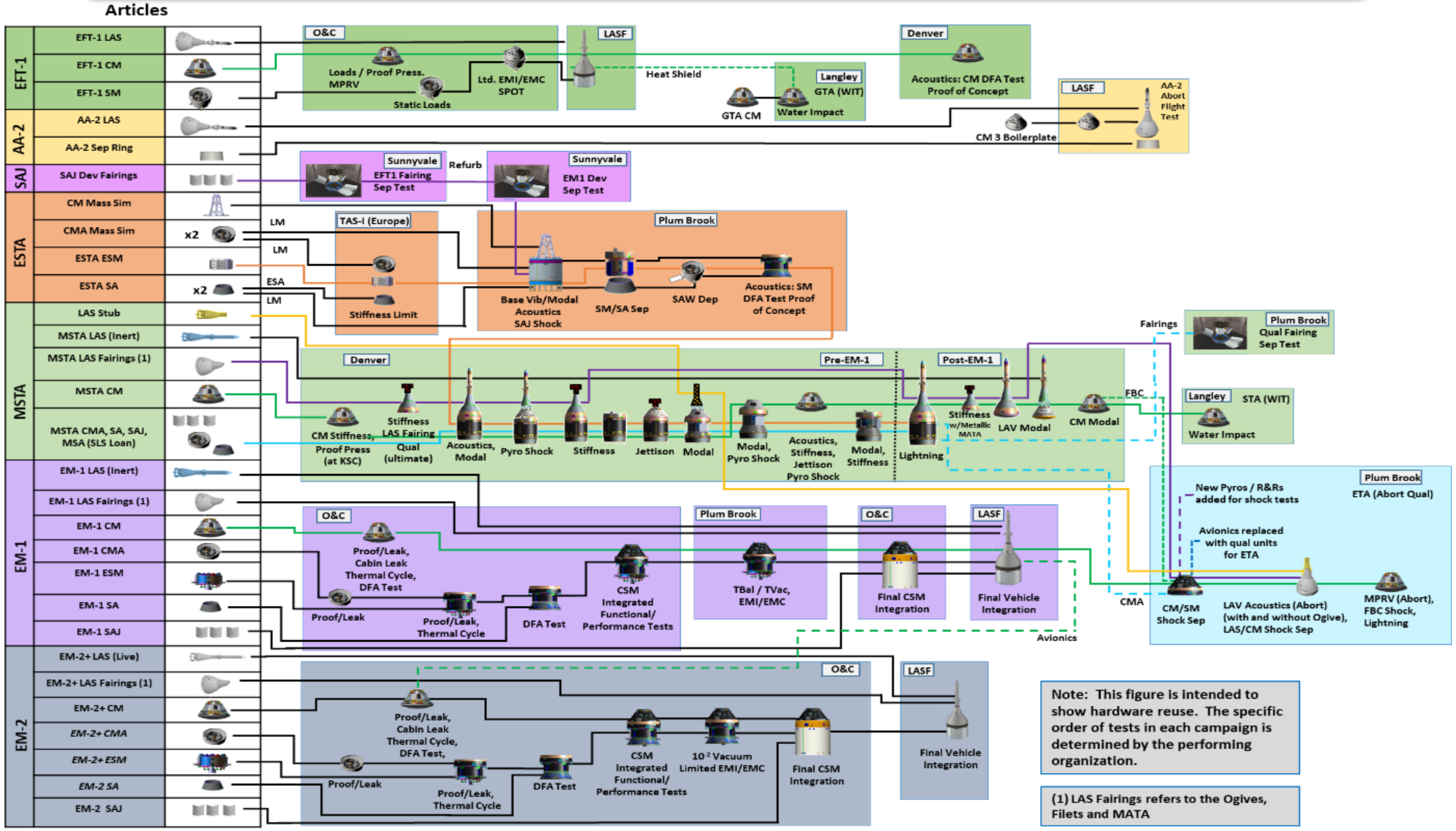
ATV to ISS

EFT-1

AA-2

Orion Development

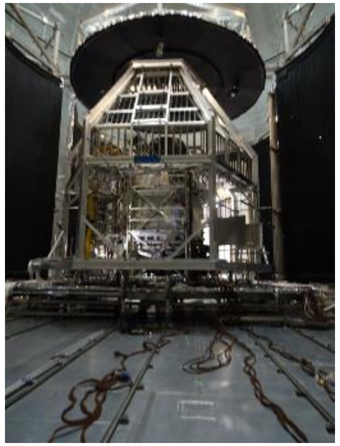
Major Features: Integrated Flight & Ground Testing- Hardware Rich



Orion Spacecraft Development

Major Features (cont'd) – Extensive Environmental Testing

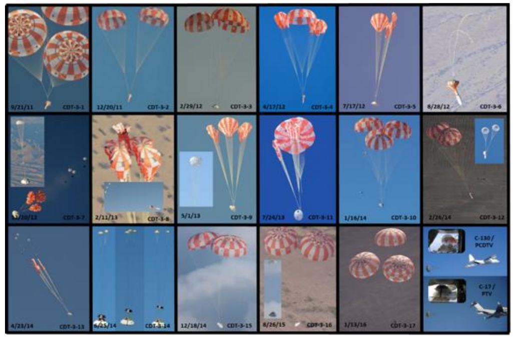
Thermal Vacuum: 816 Hours



Aerosciences: 61 Wind Tunnel Tests

Structural/Acoustic: 34 Tests

Parachute: 47 Tests

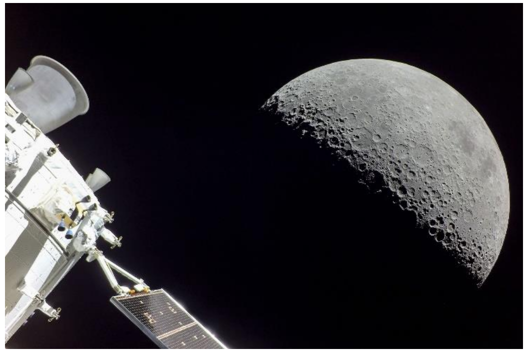


Orion European Service Module: Propulsion System Development Testing

Propulsion Qualification Module

OMS-E Hot Fire

ESM Propulsion Video



Artemis I Flight

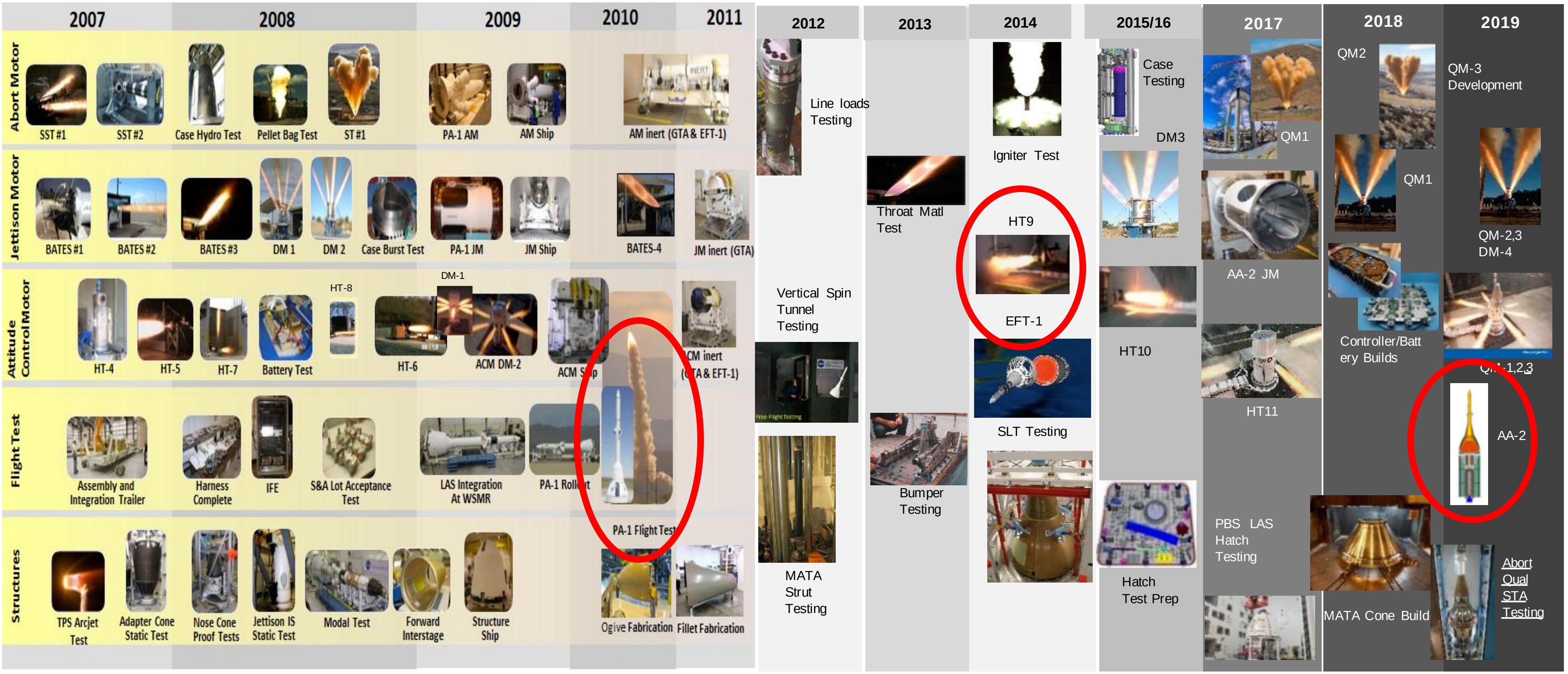
Testing begins at the engine level and proceeds through subsystem-level qualification hot fire tests

Orbital Maneuvering System Engine (OMS-E)

Original Shuttle Qual for 100x missions:	>15,000 seconds of cumulative on-time
Combined Shuttle operations:	>90,000 seconds of cumulative on-time
Additional Orion qualification tests:	>800 seconds of cumulative on-time

Orion Spacecraft Development: LAS

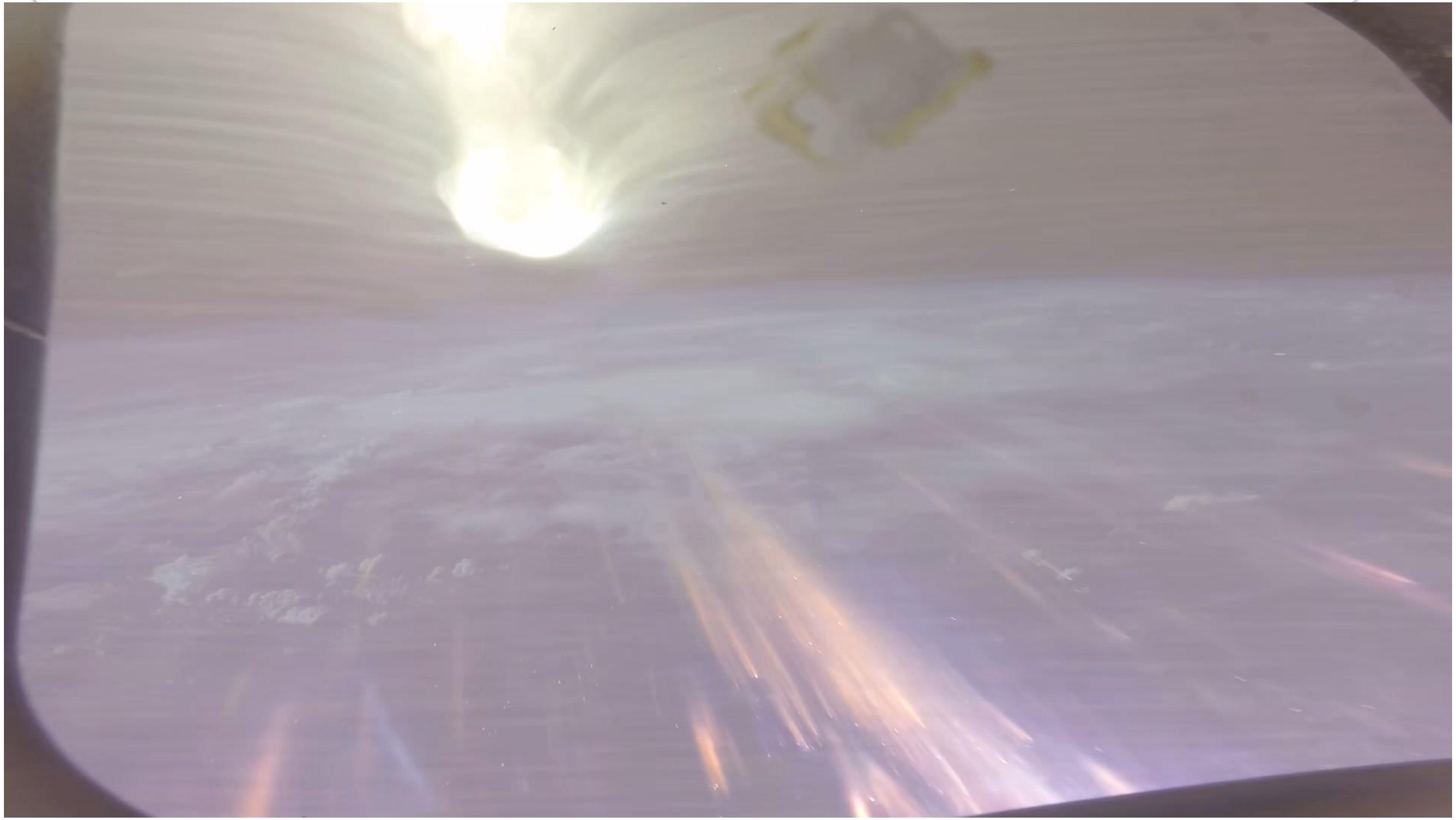
Major Features (concluded) – Launch Abort System (LAS) Development



Mission Needs Drive Design & Testing

Artemis I: Orion Reentry

First Full Test of the Orion Heat Shield



The Cost of Testing

Easy for you to say – “they” always cut it back for budget reasons!

What to do? → Start off right → Define “right” test program

Then, consider backing off as you <u>reasonably</u> can in the clear light of day by, for example:

- **Considering alternative (lower cost) test approaches (90% data @ 60% cost)**
- **Easing some requirements, e.g. performance**
- **Adding margins, or redundancy**
- **Judiciously using “test anchored” simulations**
- **Focusing on interfaces, or areas historically problematic**
- **Using Probabilistic Risk Assessment (PRA) derived relative risks as a guide**
- **<u>Appropriately</u> using heritage, qualified systems**
- **Depending on the judgment of experienced, senior engineers**

Orion Testing Program (concluded)

LESSONS

Successful programs like Orion have been anchored in testing	Thorough, well-vetted test plan a must Testing is the first choice method of verification
Successful programs like Orion include robust modeling	Plan and protect budgets to validate modeling with testing, and vice versa

Nearly every test reveals something unexpected

↓

Test, Model, Test!

↓

Test like you fly and fly like you test

Conclusion

- **Past planetary mission lessons exist and these lessons still apply today**
  - Most have preventable, human based root causes
- **The Orion Program is a great example of a successful, hardware rich, testing campaign**
  - Each test, ground or flight, success or failures, reveals new understandings
- **Need to develop a way to share lessons based on the tremendous growth and experiences from lunar missions**
  - Government, private, international
  - NASA SMA community is a leader in this area … next steps?

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MISSION

Our mission is to leverage the vital lessons learned by generations of NASA and ODOT engineers to strengthen the skills of today's explorers.

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Excellence Through Experience