Scientific Technical Information (STI) I Disclosure
Export Control Rationale

Title of Presentation: Apollo 13 Case Study part 1 & 2
Author/Speaker: Mike Interbartolo

The information is already in the public domain in its entirety through a non-NASA medium and/or through NASA release on NASA websites.

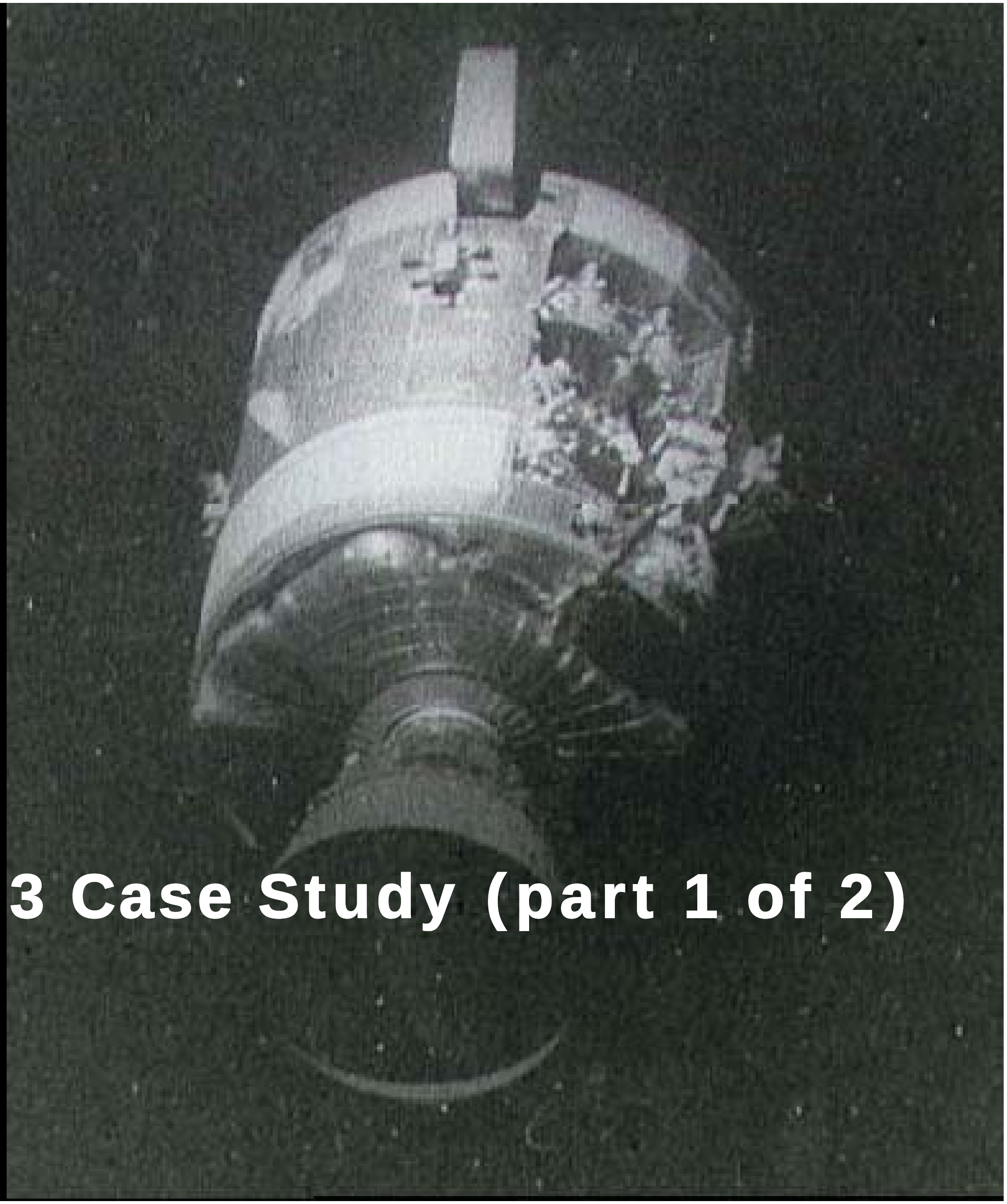
A large percentage of the documents obtained for the library are available to the public at either the NASA History Office's Apollo Lunar Surface Journal (ALSJ), or the NASA Technical Reports Server (NTRS). Here are the URLs for these sites:

http://history.nasa.gov/alsj/frame.html
http://ntrs.nasa.gov/search.jsp

In particular, the Apollo Operations Handbooks were obtained from the former, and the Apollo Experience Reports from the latter. We also obtained a large number of GNC documents from the Virtual AGC site, which is a public non-NASA site with documents largely obtained from the National Archives (NARA-SW):

http://www.ibiblio.org/apollo/

Apollo 13 Case Study (part 1 of 2)



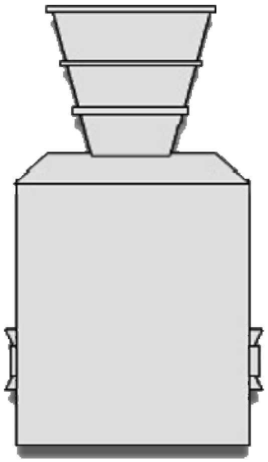
Objectives

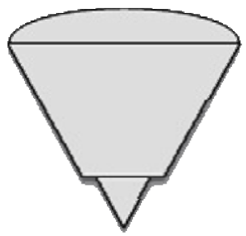
- Describe the Service Module Electrical Power System hardware
- Describe the circumstances which led to the Apollo 13 accident
- Summarize the Mission Control and crew reaction

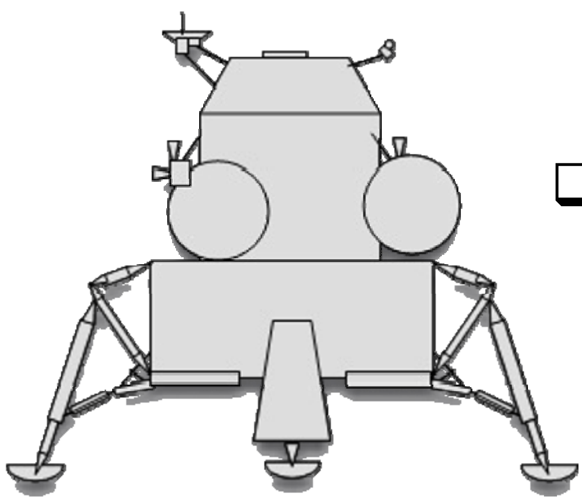
Outline

- This briefing is Part 1 of 2
  - Overview of electrical system hardware
  - Failure chain reconstruction
  - In-flight oxygen tank explosion
  - Immediate MCC reaction
- Part 2 is a separate briefing
  - MCC regains insight
  - Impact to various systems
  - In-flight recovery
  - Entry
  - Post-flight changes and lessons learned

Electrical Power System Overview

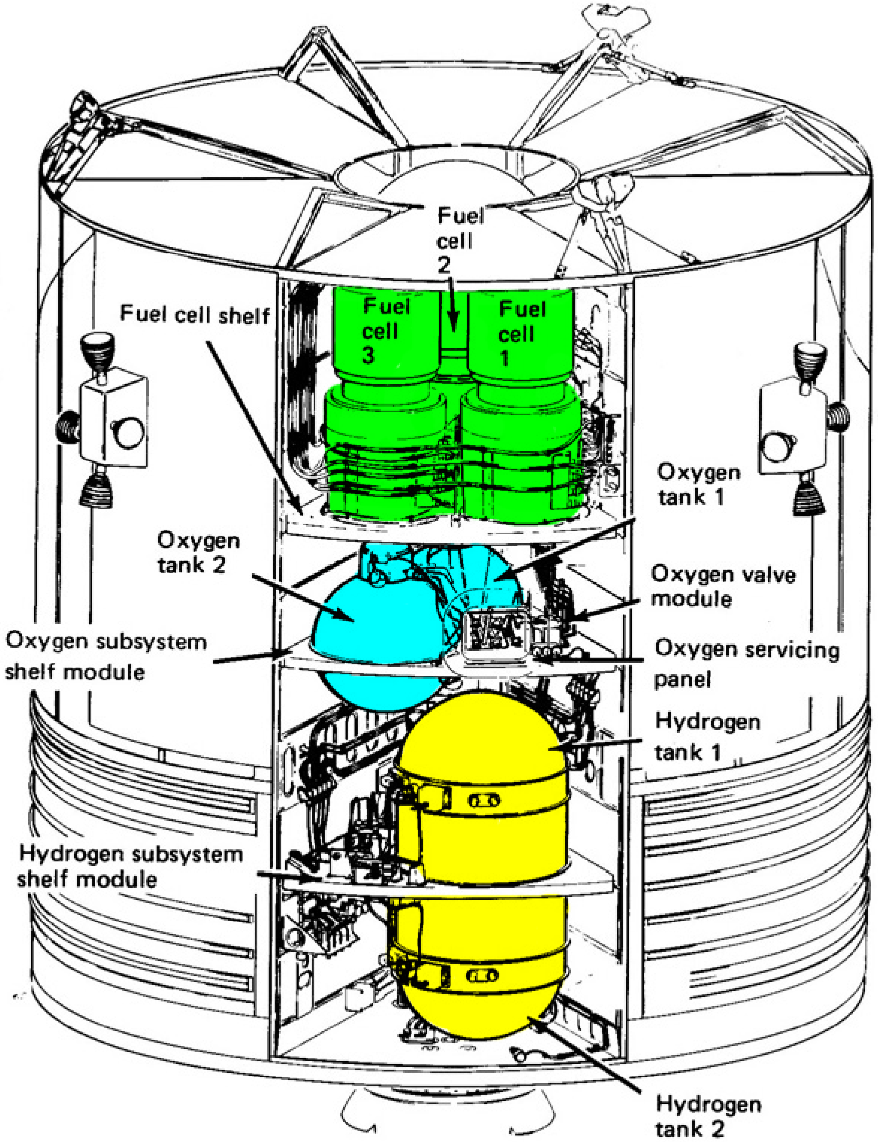






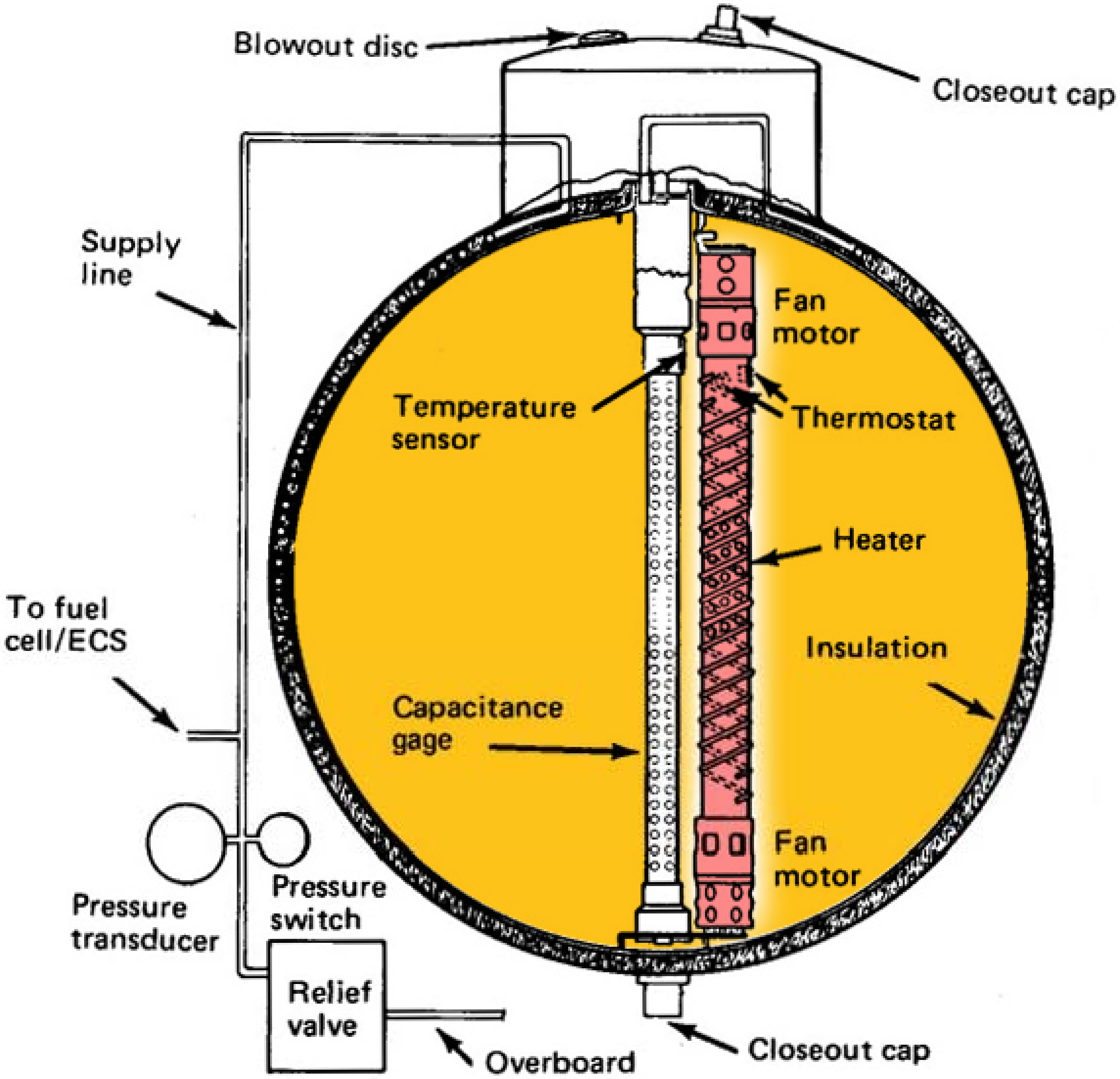
- Service Module
  - Provided majority of power required on the trip
  - Cryogenic H_2 and O_2 tanks fed three fuel cells
- Command Module
  - Rechargeable batteries primarily for entry, also supplement fuel cells for peak loads
  - Powered some heaters and lights on the LM
- Lunar Module
  - Six batteries, normally used only for lunar descent and ascent

Fuel Cells



- ❑ Fuel cells & cryo located in Service Module
- ❑ Cryo O_2 & H_2 stored in tanks (2 each)
- ❑ Fuel cells (3) provided primary power to CSM for duration of flight

Cryo Tank



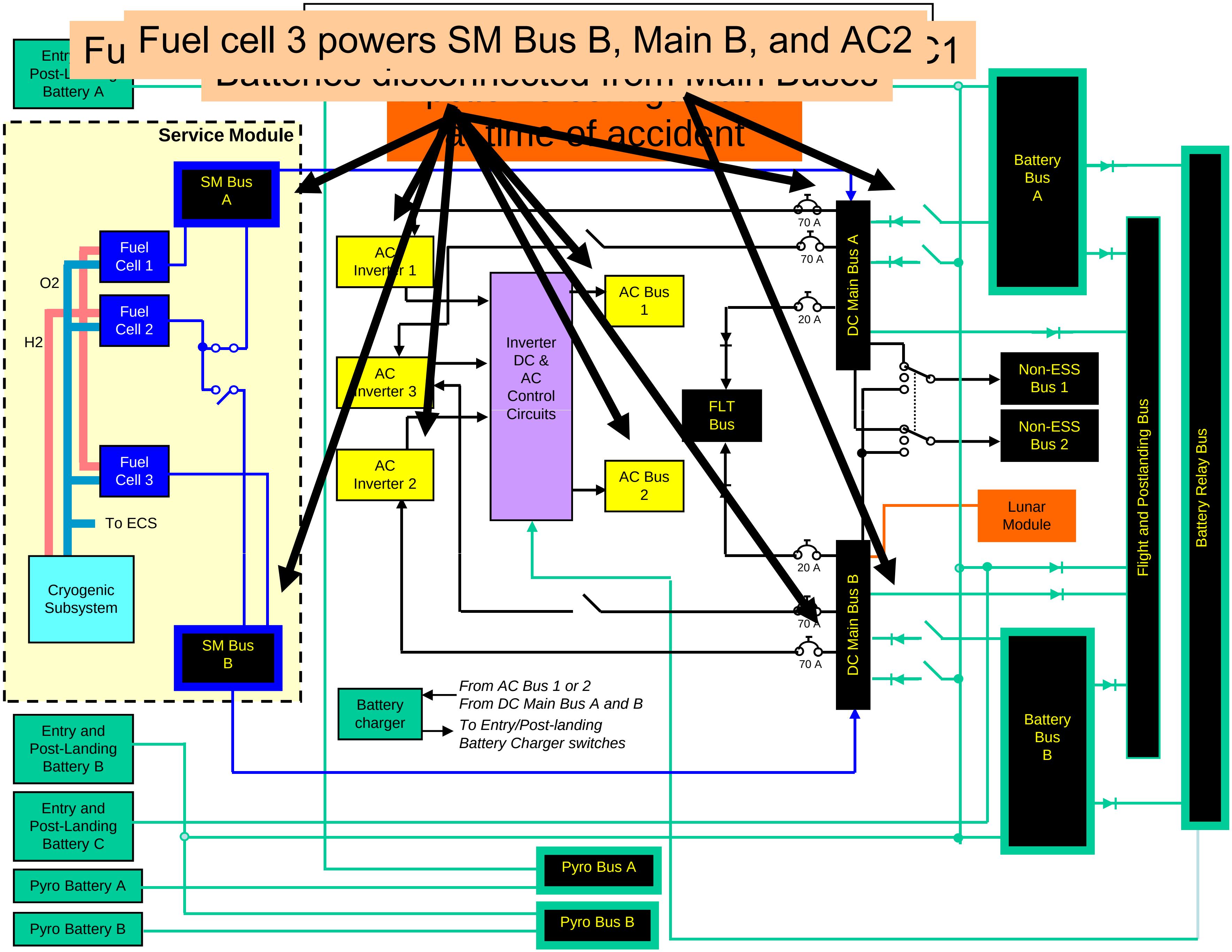
To keep tanks homogeneously mixed, Apollo config had fans to "stir" the tanks

Normally performed periodically throughout the mission

– Mixed tank yields better temperature, pressure, and quantity telemetry readings

– On Apollo 13, crew stirred the tanks several times with no problems prior to the explosion

Fuel cell 3 powers SM Bus B, Main B, and AC2



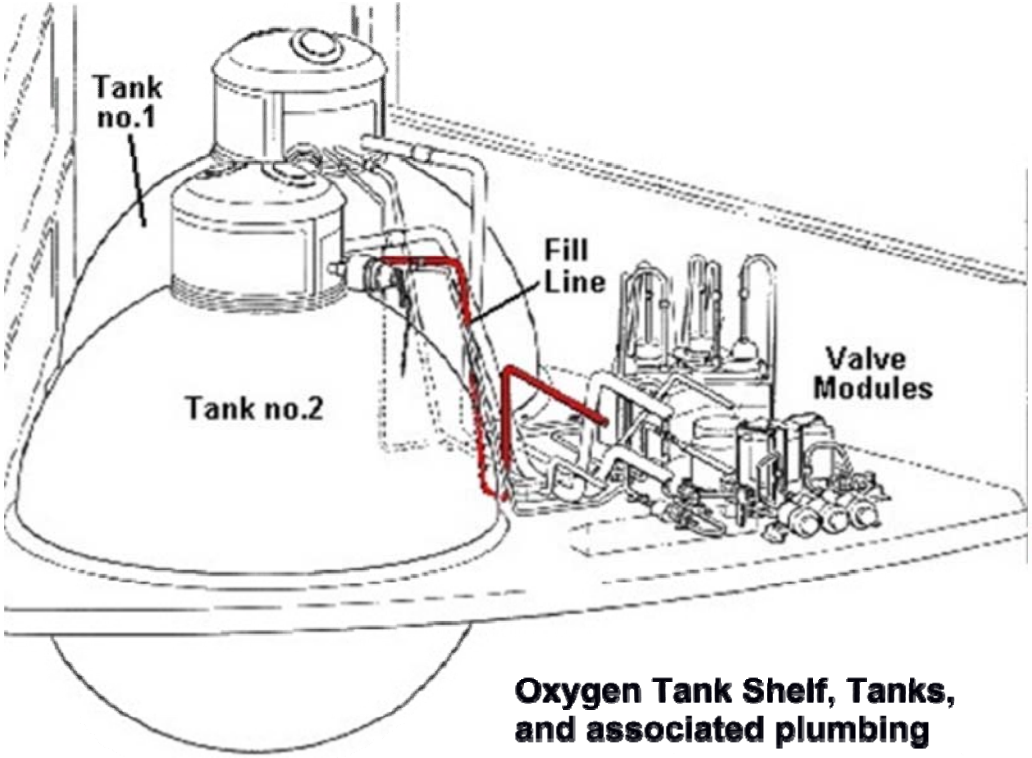
Failure Chain Reconstruction (Part 1)

Fuel cell shelf

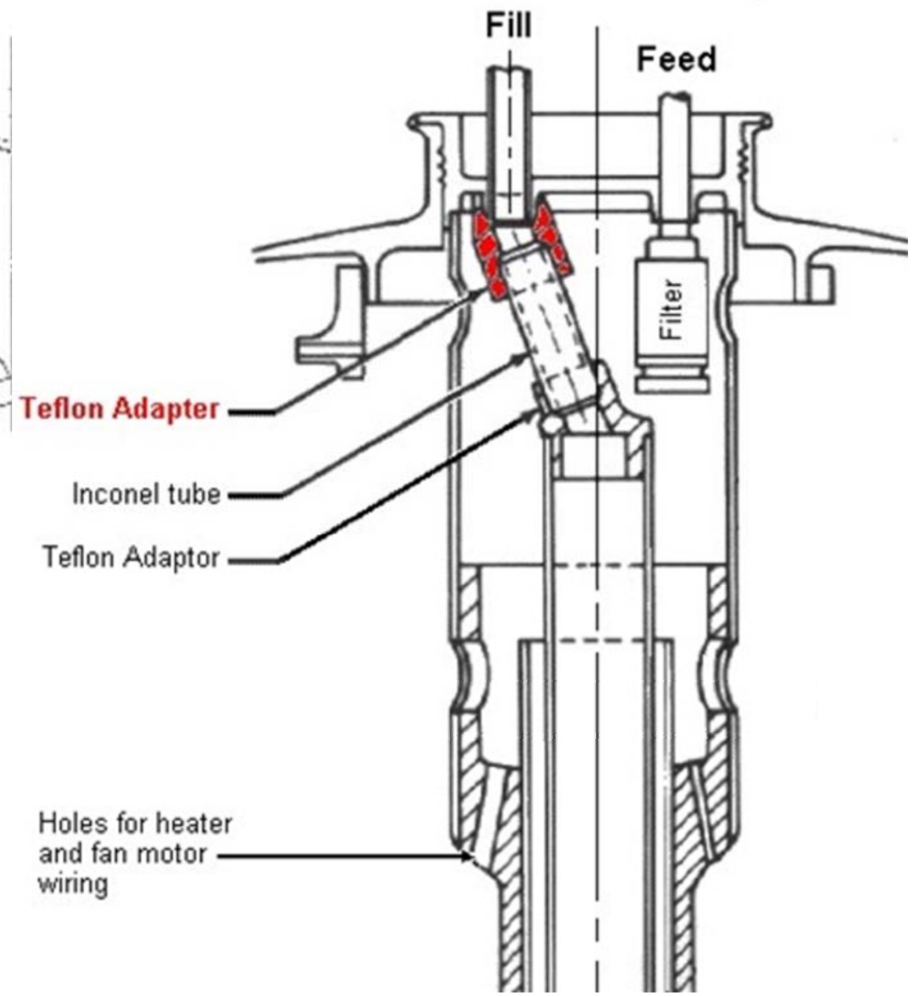
Cryo H2 tanks

- October 1968, North American Rockwell
  - Tank removed from Apollo 10's SM for mods
  - During removal, tank shelf was accidentally dropped 2"
  - Passed all tests, but fill line probably displaced by 0.1"

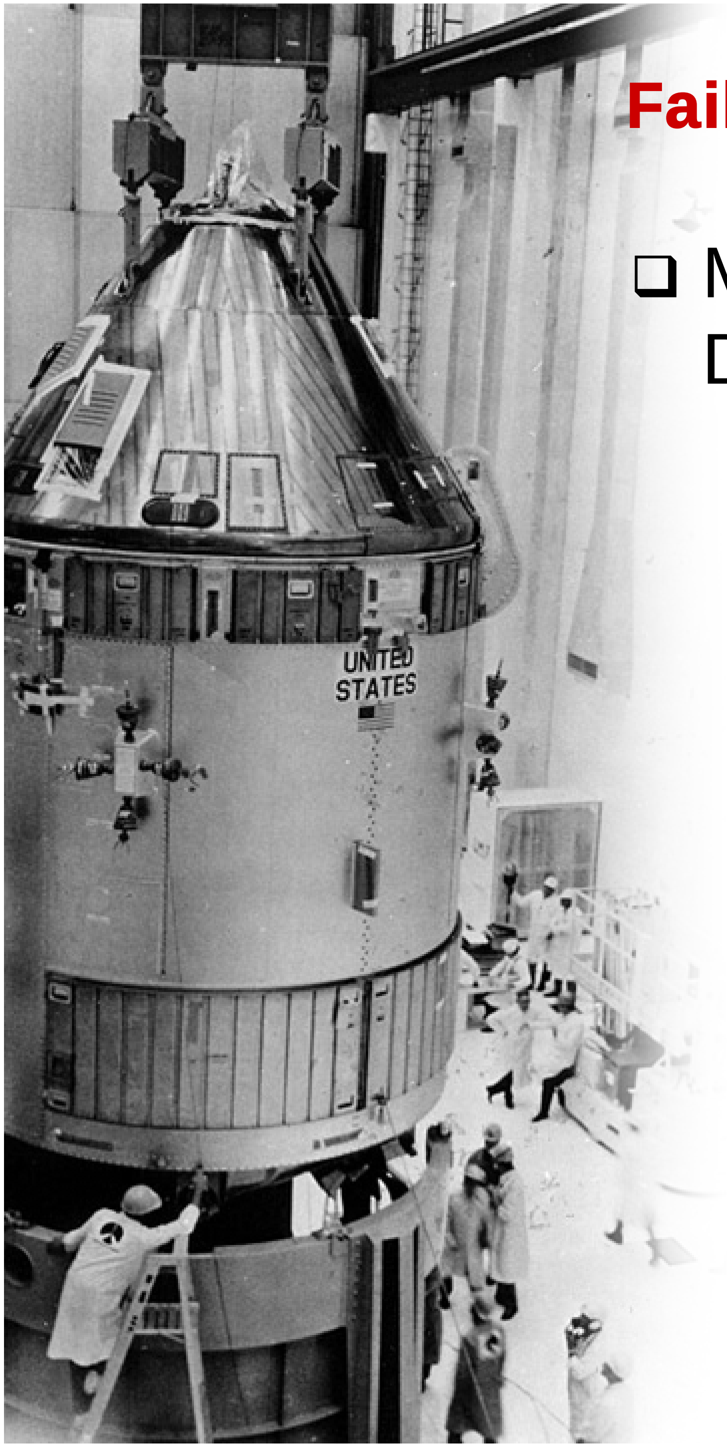
Displaced Fill Line



Oxygen Tank Shelf, Tanks, and associated plumbing



Cross Section of Oxygen Tank's Quantity Probe



Failure Chain Reconstruction (Part 2)

- March 1970, Countdown Demonstration Test at KSC
  - O_2 tank 2 didn't empty as expected
  - Detanking didn't work
  - Discussions suggested a loose fill line
  - Vendor said if tank could be filled, it would be OK in flight
  - Used use tank heaters to boil off remaining O_2, took 8 hrs
  - Would take 45+ hours to replace shelf with O_2 tanks

Failure Chain Reconstruction (Part 3)

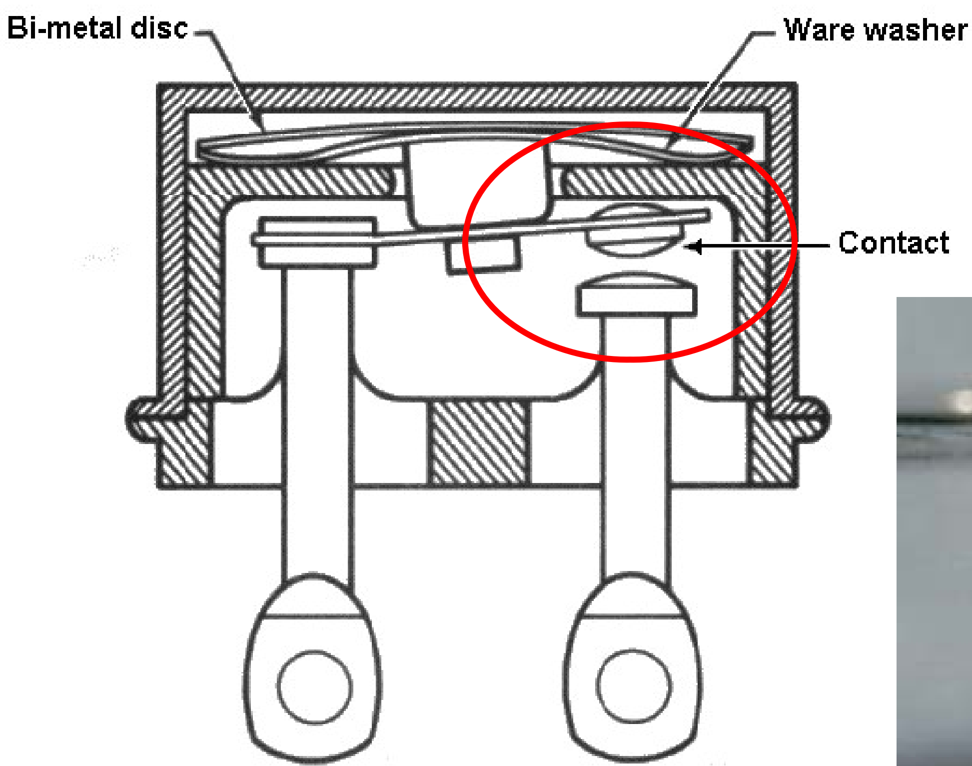
- 12 days before planned launch
  - O_2 tank 2 filled once more, but again needed heaters to empty tank
- Detanking problem considered by Apollo managers
  - Lots of attention paid to **loose fill tube**
  - Very little attention paid to **extended heater operations**
- After extensive consideration given to potential problems, it was decided to leave it as is and proceed with the launch in April 1970

Failure Chain Reconstruction (Part 4)

- Postflight testing showed that heater thermostats did not work properly at 65 volts (KSC GSE power)
  - Originally designed for 28 V, never redesigned to be compatible with 65 V as required in a 1965 spec change
  - Thermostats supposed to cut off at 80° F (27° C), but high voltage welded the relays shut when opened under load
  - Heaters stayed on and temps rose to ~1000° F (538° C) inside the tank
  - Teflon insulation severely damaged
- Loose fill tube by itself wasn't a problem

Heater Relay

- ❑ What happens when you put 65 V through a relay designed to handle 28 V?



Switch Cross Section

NASA photo S70-40850

In Flight

- Mostly unremarkable mission for first two days
  - Launch
  - Earth Parking Orbit
  - Trans-Lunar Injection (02:26 G.E.T.)
  - Trans-Lunar Coast
- MET 46:43, at crew wakeup on FD3
  - Capcom calls the crew: *"The spacecraft is in real good shape as far as we are concerned. We're bored to tears down here."*

Failed O_2 Sensor

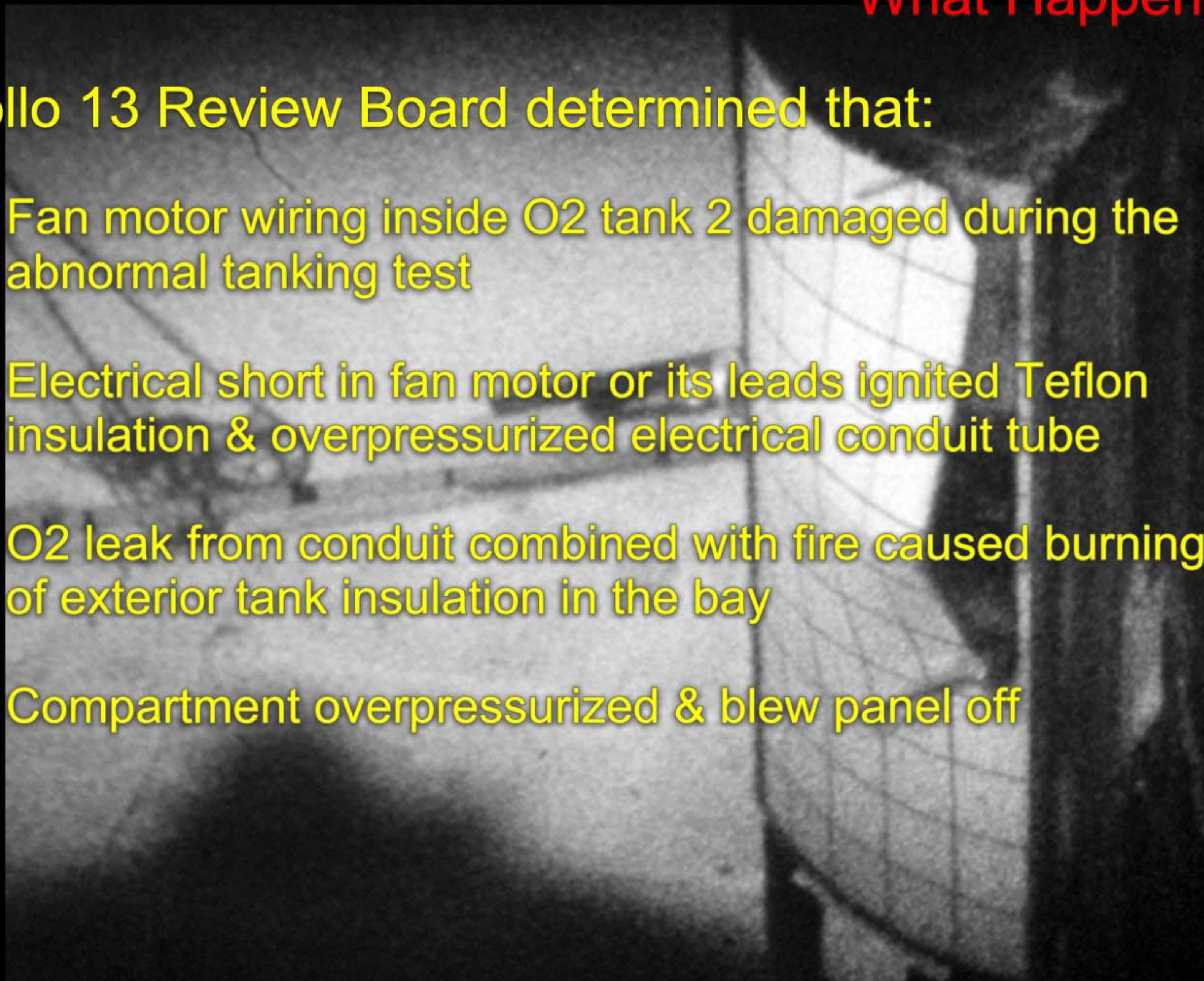
- The O_2 tank 2 quantity sensor failed off-scale high at tank stir #2 at 46:40
  - Scheduled every ~24 hrs
  - Failed quantity sensor caused MCC to request cryo stir more often
  - Apollo 13 Review Board found this to be completely unrelated to the heater problem that caused the accident
- Crew was lucky this sensor failed when it did
  - Had the tanks continued on the normal cycle of every 24 hrs, the stir that caused the explosion would likely have occurred while the LM was on the lunar surface and the CSM was orbiting the Moon

Sequence of Events

46:40	O_2 tank 2 quantity sensor failed off-scale low, resulted in shorter durations between cryo fan cycles
55:52:30 (GET)	Crew got H_2 low pressure indications (part of normal operating cycle). MCC requests that the crew turn fans on
55:53:20	Fans activated, power transient occurs
55:54:53	Crew feels a bang

What Happened ?

Apollo 13 Review Board determined that:



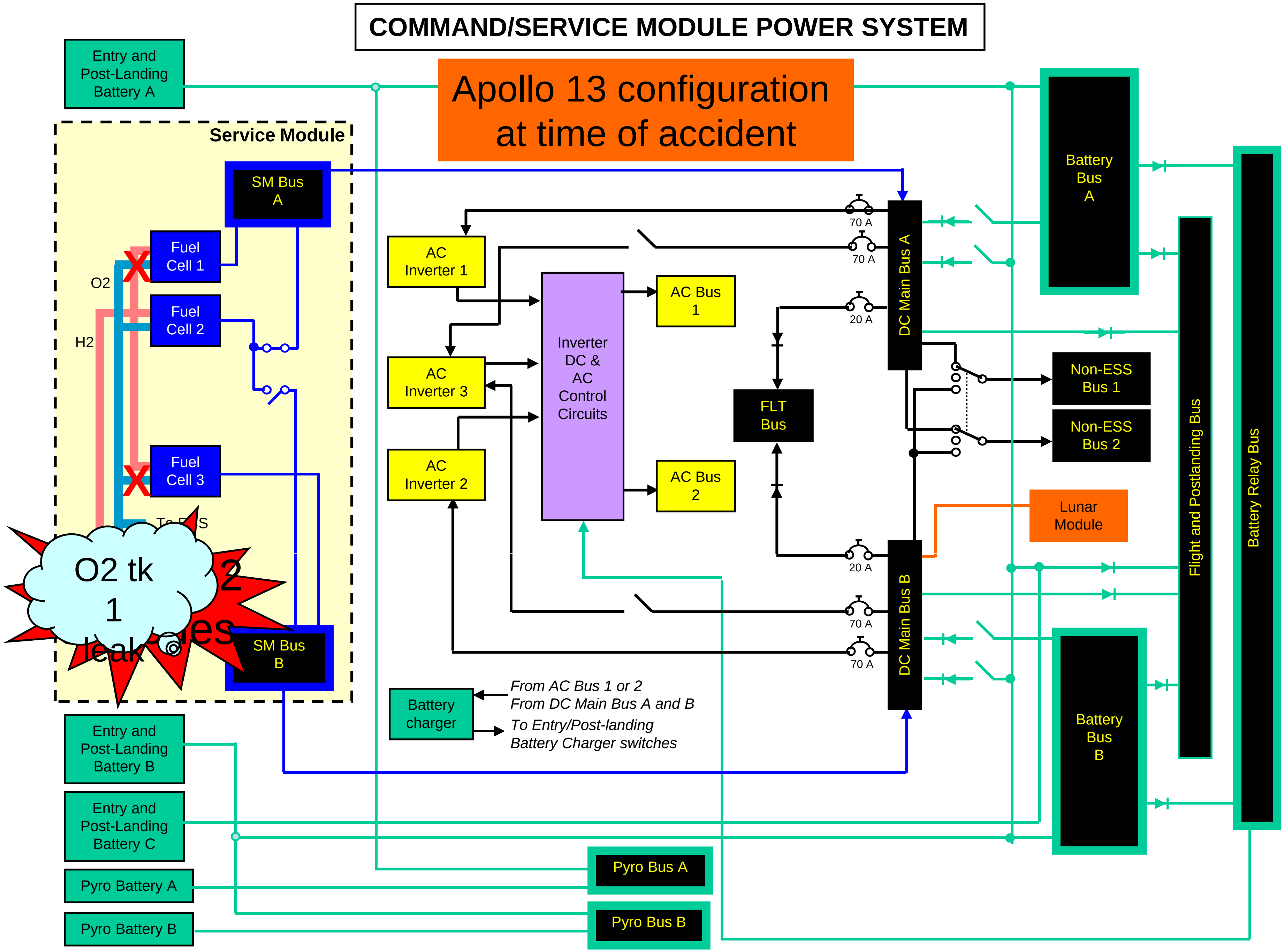
- Fan motor wiring inside O2 tank 2 damaged during the abnormal tanking test
- Electrical short in fan motor or its leads ignited Teflon insulation & overpressurized electrical conduit tube
- O2 leak from conduit combined with fire caused burning of exterior tank insulation in the bay
- Compartment overpressurized & blew panel off

NASA photos S70-41982, S70-41983, & S70-41985 (from post-flight failure recreation testing at Langley)

- Post-flight data reconstruction of time between fan activation (55:53:20) and explosion (55:54:53)
  - Power transients
  - AC & DC voltages drop, currents rise (indicative of a short)
  - O_2 tank 2 pressure rises
  - Sensors fail and/or go erratic
  - Sudden accelerometer activity in X, Y, Z axes
  - 1.8 second loss of data
  - O_2 tank 2 lost pressure and outside panel separated
  - Main Bus B undervolt alarm
  - Crew hears a bang and feels a shudder in spacecraft

Sequence of Events

55:54:53	Crew feels a bang
	1.8 second loss of data from damage to high-gain antenna
55:54:56	Problem shows up in telemetry: ❑ High amps, low volts on main buses (including Main B Undervolt) ❑ O_2 tank 2 sensors all failed ❑ O_2 tank 1 pressure starts steady drop
	❑ Various SM component temps rise a few degrees (from combustion of insulating materials and the leaking O_2 outside of the tank)

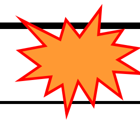


COMMAND/SERVICE MODULE POWER SYSTEM
Apollo 13 configuration at time of accident
Entry and Post-Landing Battery A
Service Module
SM Bus A
Fuel Cell 1
O2
Fuel Cell 2
H2
Fuel Cell 3
O2 tk 2
leak
SM Bus B
AC Inverter 1
AC Inverter 3
AC Inverter 2
Inverter DC & AC Control Circuits
AC Bus 1
AC Bus 2
FLT Bus
70 A
70 A
20 A
20 A
70 A
70 A
DC Main Bus A
DC Main Bus B
Battery Bus A
Battery Bus B
Non-ESS Bus 1
Non-ESS Bus 2
Lunar Module
Flight and Postlanding Bus
Battery Relay Bus
Battery charger
From AC Bus 1 or 2
From DC Main Bus A and B
To Entry/Post-landing Battery Charger switches
Entry and Post-Landing Battery B
Entry and Post-Landing Battery C
Pyro Battery A
Pyro Battery B
Pyro Bus A
Pyro Bus B

“Houston, we’ve had a problem…”

(55 hrs)	dd hh mm ss		
	02 07 55 19	LMP	Okay, Houston - -
	02 07 55 20	CDR	I believe we've had a problem here.
	02 07 55 28	CC	This is Houston. Say again, please.
	02 07 55 35	CDR	Houston, we've had a problem. We've had a MAIN B BUS UNDERVOLT.
	02 07 55 42	CC	Roger. MAIN B UNDERVOLT.
	02 07 55 58	CC	Okay, stand by, 13. We're looking at it.

Sequence of Events

55:54:53	Crew feels a bang 
55:55:20	"OK, Houston…I believe we've had a problem here"
55:57:45	Fuel cell 3 fails, taking with it Main B and AC2
55:58	Fuel cell 1 fails
55:58:25	Main A undervolt since it's taking all the load
56:09:07	CDR reports something venting (from O_2 tank 1)

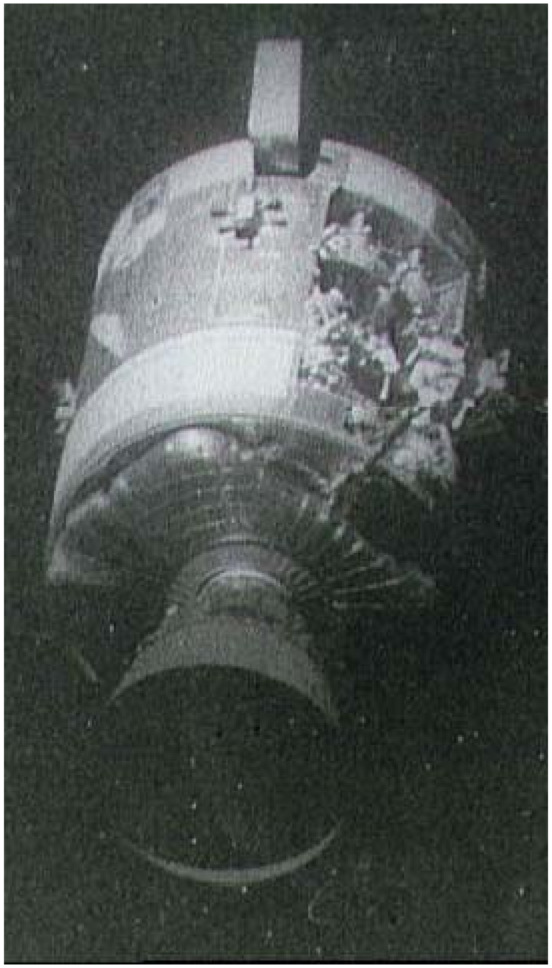
(56 hrs) dd hh mm ss

02 08 09 07	CDR	That's AC, okay. Yes, that's good AC and it looks to me, looking out the hatch, that we are venting something. We are venting something out into the - into space.
02 08 09 22	CC	Roger. We copy your venting.
02 08 09 29	CDR	It's a gas of some sort.

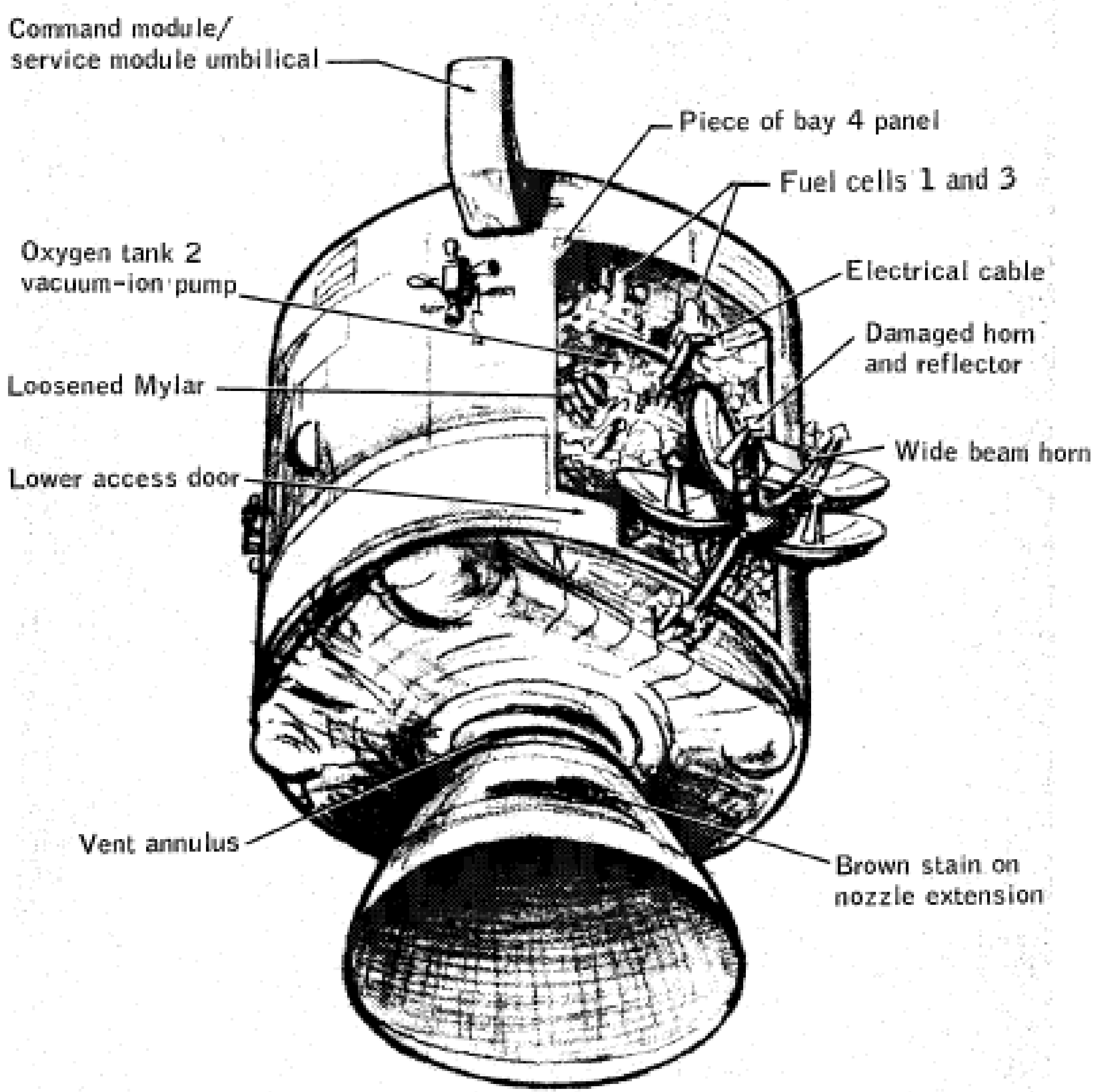
Immediate Damage

- Damage
  - O_2 tank 2 exploded, blowing off a panel cover on the SM, changed spacecraft delta-v by 0.5 fps
  - Panel struck and damaged High-Gain Antenna
  - Explosion shocked several RCS valves closed
  - Explosion shocked fuel cells 1 & 3 reactant valves closed
  - O_2 tank 1 started leaking (would be empty in ~2.5 hrs)
  - Venting produced forces that were eventually counteracted by Automatic Stabilization System
  - Many sensors failed off-scale high or low, or static, so flight controllers not sure they can trust their data

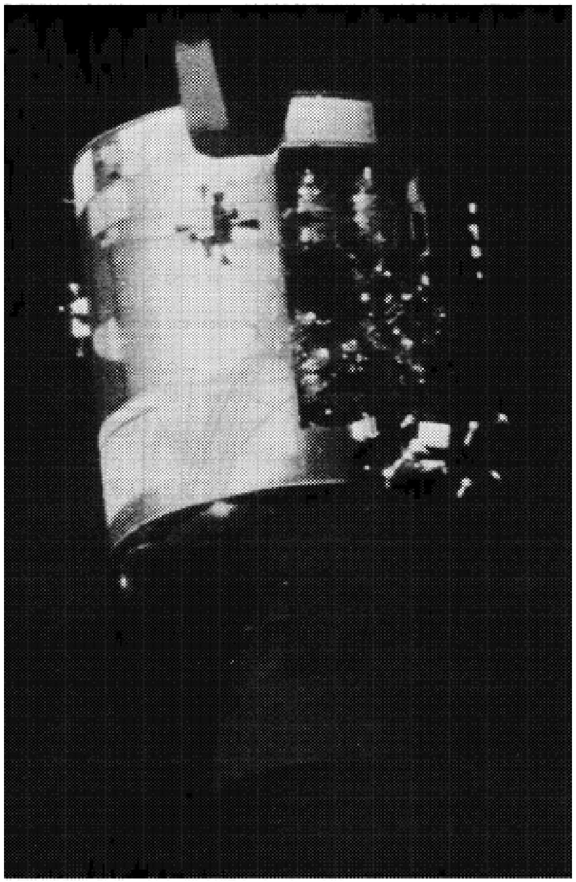
Apollo 13 SM Damage



NASA photo AS13-59-8500

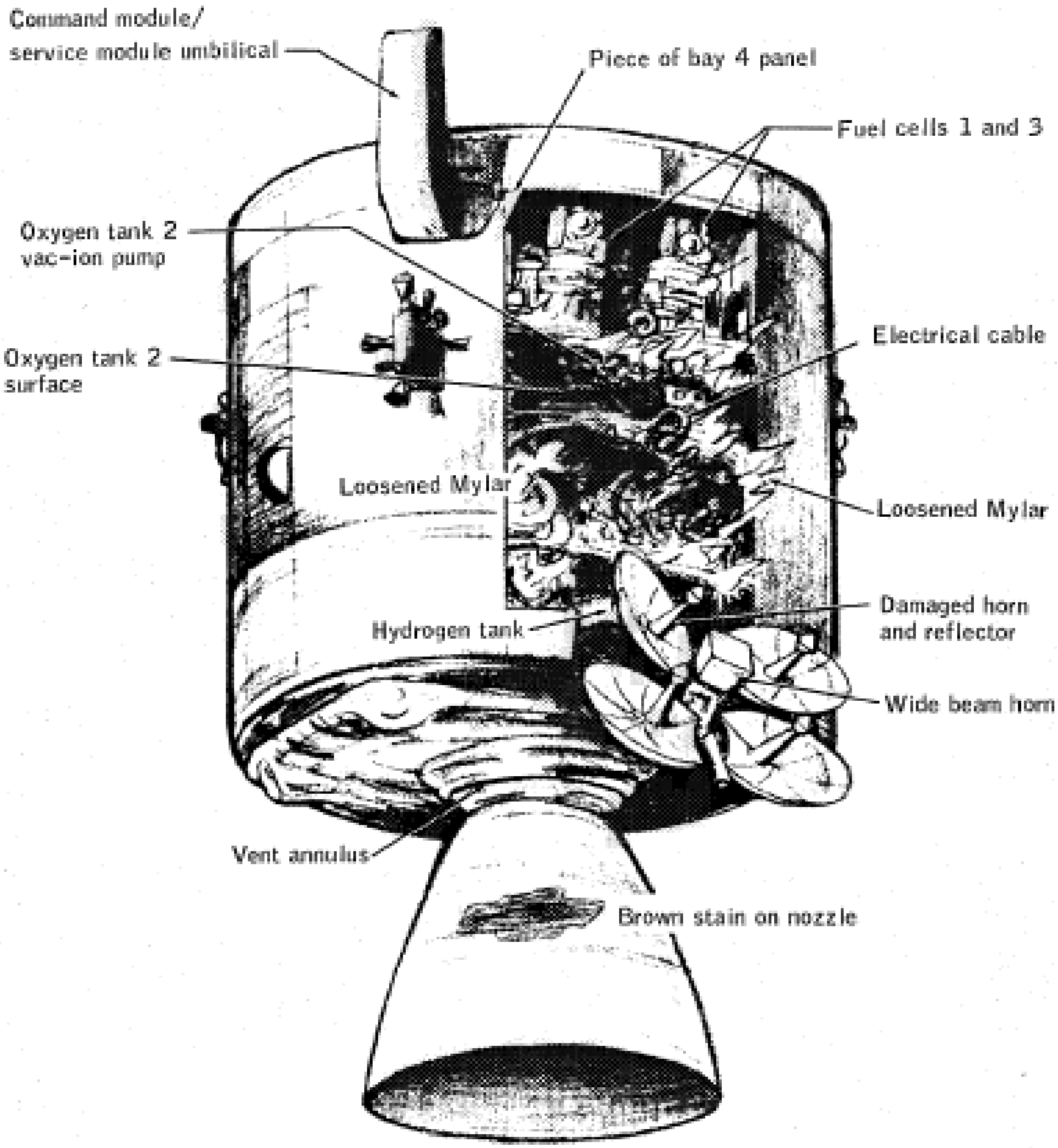


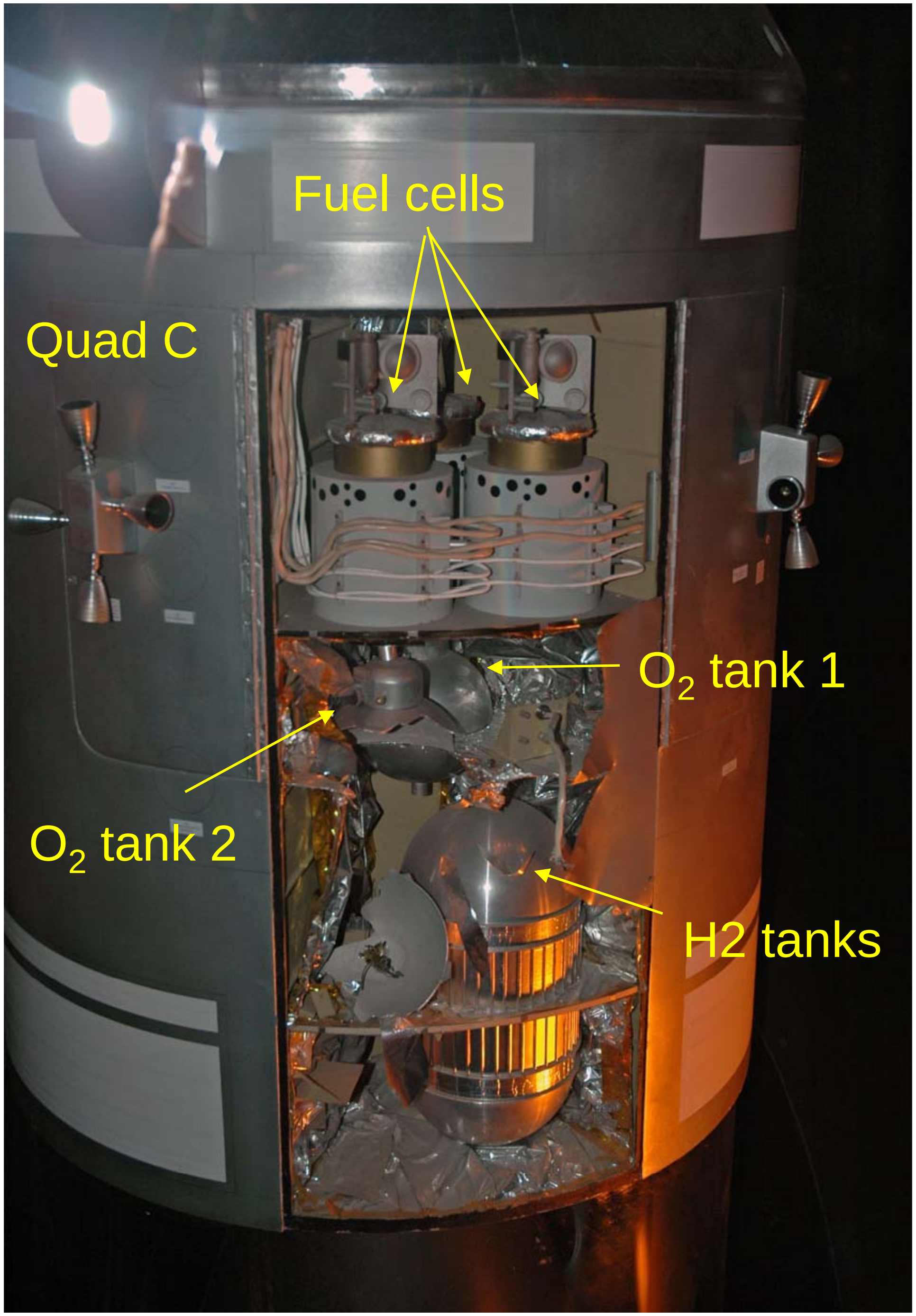
Apollo 13 SM Damage (Cont'd)



(a) Onboard camera view.

Figure 4-18.- 70-mm color film frame 8464.





Damage Reconstruction

- Model on display at the Kansas Cosmosphere

Original photo courtesy Linden Sims,

Originally retrieved from http://www.ninfinger.org/~sven/models/vault2006/A13_damage_model.jpg

Uncertainty in MCC

- ❑ Main B undervolt, CM computer rebooted
- ❑ Five RCS valves closed, “random” thruster firings, attitude excursions
- ❑ Inconsistent fuel cell/cryo readings – instrumentation?
- ❑ Loss of fuel cells 1 and 3

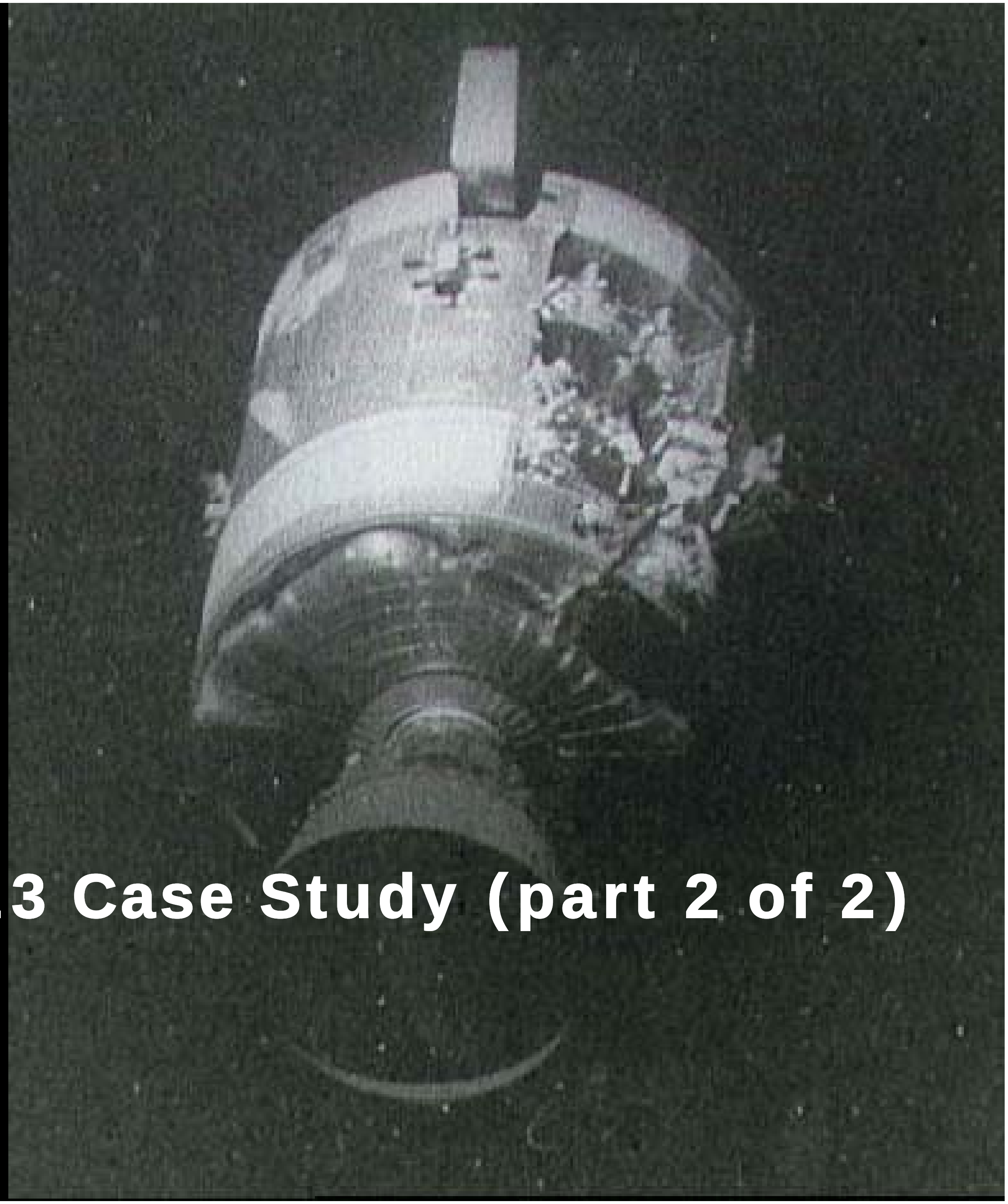
NASA photo AP13-S70-35638

End of Part 1

- In part 2, we will:
  - Discuss the Mission Control and crew reaction to the accident
  - Discuss the impacts of the explosion to the various systems
  - Discuss the changes made to future Apollo spacecraft and the lessons learned

For More Information

- Report of the Apollo 13 Review Board
  - Panel 1, Spacecraft Incident Investigation, Vol. 1: Anomaly Investigation, 06/70
  - Appendix B, Report of Mission Events Panel, 06/70
- Mission Operations Report
  - NASA-MSC Internal Report, Apollo 13, 4/28/70
- Apollo 13 Mission Report
  - MSC-02680 with PCN-1, 5/70
- Apollo Mission Familiarization for Constellation Personnel
  - Apollo Wiki



Apollo 13 Case Study (part 2 of 2)

Objectives

- In this lesson, we will:
  - Discuss the Mission Control and crew reaction to the accident
  - Discuss the impacts of the explosion to the various systems
  - Discuss the lessons learned and changes made for subsequent flights

Outline

- Previously, in Part 1:
  - Overview of electrical system hardware
  - Failure chain reconstruction
  - In-flight oxygen tank explosion
  - Immediate MCC reaction
- This is Part 2
  - MCC regains insight
  - Impact to various systems
  - In-flight recovery
  - Entry
  - Post-flight changes and lessons learned

Uncertainty in MCC

- Main B undervolt, CM computer rebooted
- Five RCS valves closed, “random” thruster firings, attitude excursions
- Inconsistent fuel cell/cryo readings – instrumentation?
- Loss of fuel cells 1 and 3

NASA photo AP13-S70-35638

MCC Regains Insight

- At first, suspected instrumentation
  - Sort out false readings from true ones
  - Some readings lost due to loss of Main B
- Realized O_2 tank 2 lost when sensor power swapped to Main A and they could see real data
- Realized fuel cells 1 and 3 are down for good, and O_2 tank 1 is leaking
- Took about an hour to get full story
  - Will lose all CSM power in less than 90 minutes
  - “Several hundred man-days” of post-flight data analysis to reconstruct the problem and sequence of events

Post-incident Sequence of Events

55:55	Crew feels a bang	
56:00	MCC begins directing troubleshooting on fuel cells, cryo, and electrical buses after fuel cells 1 and 3 fail	0:05 since explosion
56:14	Crew reports something venting from SM	0:19
56:15	Start emergency powerdown	0:20
56:41	Flight Director orders team to start working on power/traj profile for flight back to Earth	0:46
57:32	Automatic stability control regained (though always had manual control)	1:38
57:40	LM powered up (with 15 min of fuel cell 2 left)	1:46
58:04	Entry Battery A activated, fuel cell 2 deactivated	2:10
58:34	Attitude control handed from CSM to LM	2:39
58:40	CSM completely powered down	2:45

Immediate Problems

- SM will run out of power in ~2.5 hours, need to power up LM
  - State Vector, attitude control, course-correction burns
- Venting forces from the O_2 tank putting motion on the stack, but RCS subsystem is not fully operative

Longer-Term Problems

- LM designed for 2 men for 2 days, needed to stretch consumables to 3 men for 4 days
- Consumables management
  - Stretch LM battery power to last for a return trip
  - Stretch water supply
  - Stretch LiOH supply for CO_2 removal from air
  - O_2 for breathing not a concern, they'd run out of the other consumables first
- Replan maneuvers to return crew ASAP
- Procedures and checklists for entry

Electrical Issues

- When Main A undervolted, crew connected Entry battery A to Main Bus A
  - Prevented total loss of power to CSM
  - Battery taken offline for recharging when powerdown completed (battery A down to ~50%)
- Faced with imminent loss of all CSM electrical power, LM required as “lifeboat”
- Need to charge CM batteries from LM
  - Umbilical usually used to power LM from CM
  - Procedure was non-standard and not in the checklists
- Will motor-driven switches work in low temps?

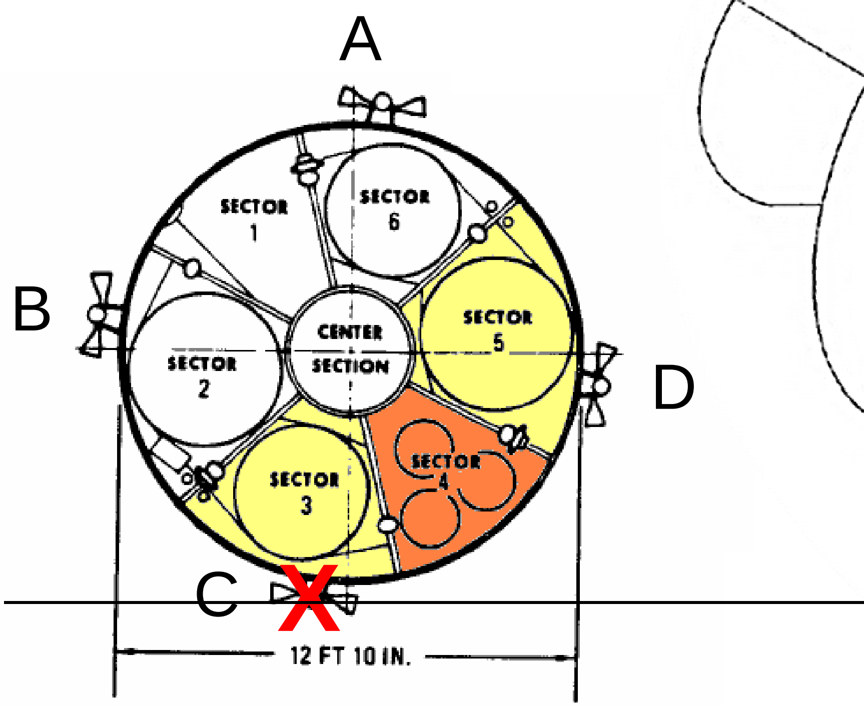
LM as a Lifeboat

- Idea for using the full LM as a lifeboat had been suggested but never worked in a simulation
  - Pre-mission work with LM systems and CSM systems in minimum power configurations contributed greatly to the ability to provide suitable systems configurations
- MCC modified existing LM powerup procedures in real-time
  - Aligned LM inertial platform manually
  - Revised powerdown procedures to reduce loads to ~20%
  - Contingency plans also developed in case of battery problem

SM RCS Propulsion Issues

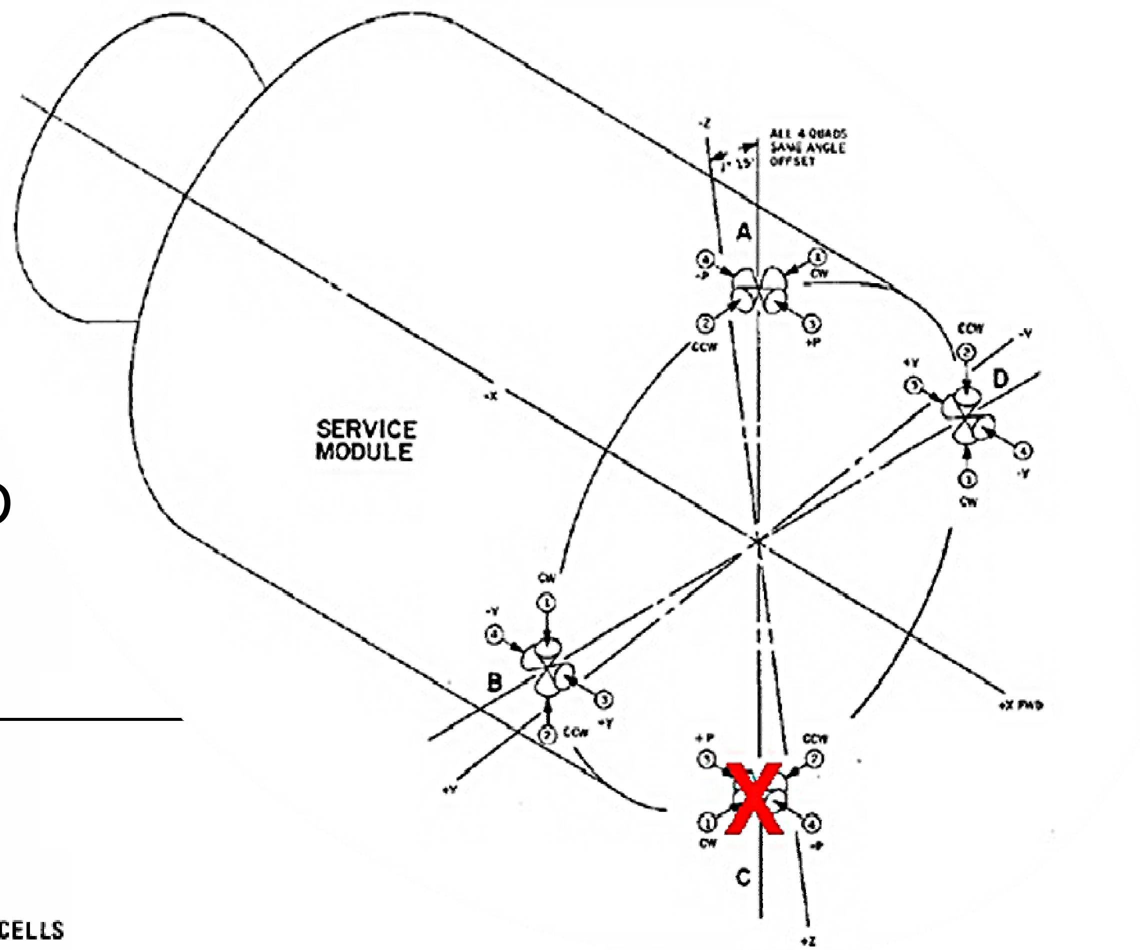
- Explosion knocked out Quad C, other valves
  - Venting giving rates in –Pitch and –Roll axes
- Pitch control lost with combo of Main B and Quad C
- Manual attitude control using thruster emergency valves on MCC call
- Auto control regained when thrusters reconfigured to use Main A power
- Loss of fuel cell power: all SM thrusters inoperative
  - New procedure for CM/SM separation for entry required

SM Propulsion



SECTOR 2 } SERVICE PROPULSION SUBSYSTEM
SECTOR 3 } OXIDIZER TANKS
SECTOR 4 OXYGEN TANKS, HYDROGEN TANKS, FUEL CELLS
SECTOR 5 } SERVICE PROPULSION SUBSYSTEM
SECTOR 6 } FUEL TANKS

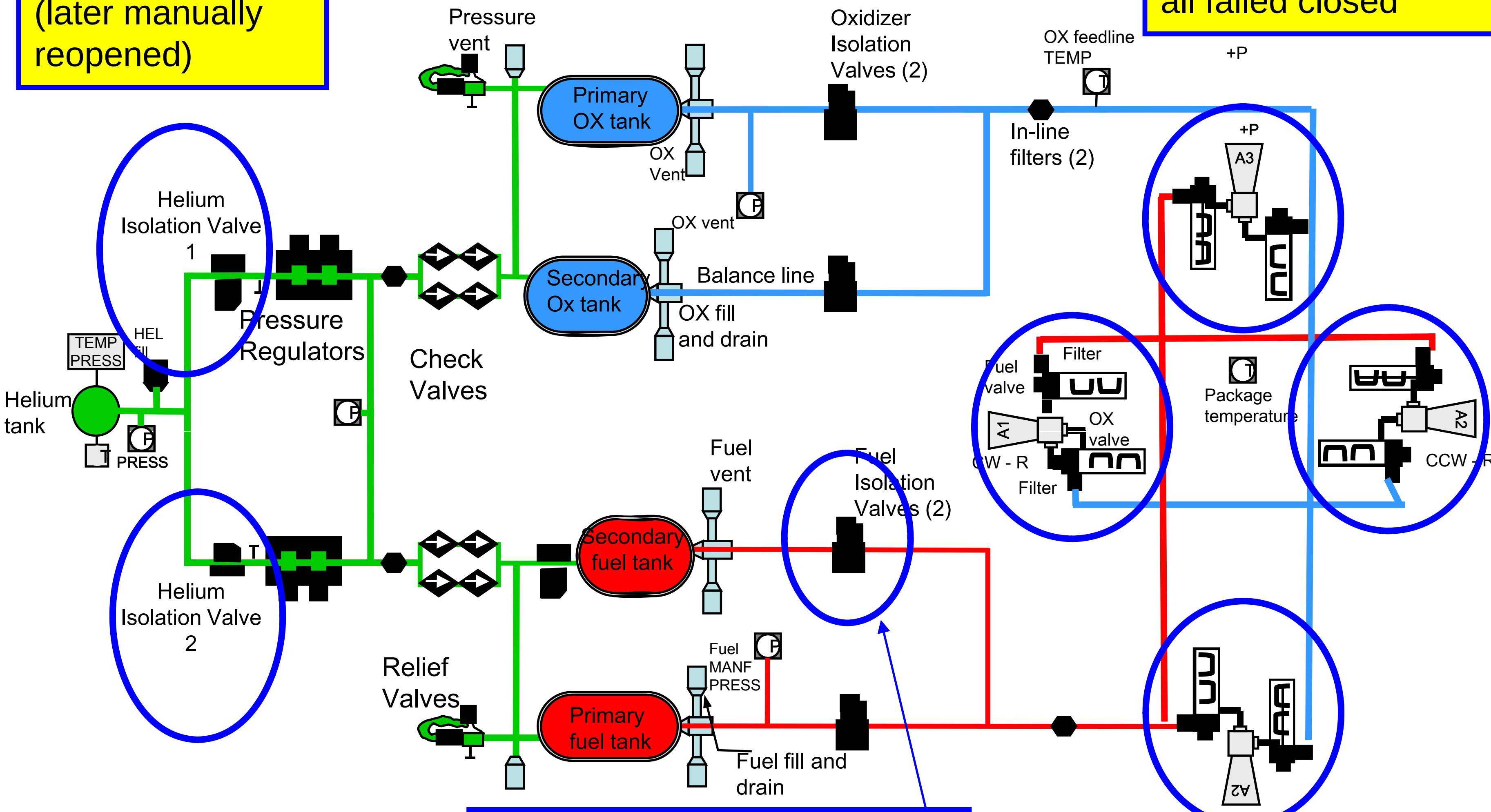
CENTER SECTION - SERVICE PROPULSION ENGINE AND HELIUM TANKS



SM RCS

Quads B&D: Helium isols shocked closed (later manually reopened)

Quad C: inlet valves all failed closed



Quads A&C: Secondary fuel isols shocked closed

Communications Issues

- Panel impacted the SM high-gain antenna, damaged one of the four dishes required for narrow-beam mode
- Loss of data for 1.8 seconds
- Ratty comm until the LM comm system powered up
- SIVB S-band beacon on same frequency as LM S-band
  - MCC drove the SIVB slightly off frequency to allow lock onto LM carrier

GNC Issues

- Danger of gimbal lock due to RCS problems
- Powerup of LM to get state vector and inertial platform alignment from CM before it failed
- Attitude control with off-nominal weight/CG
  - LM not designed to be used with the CSM attached at the top
- Difficulty in using stars as alignment reference
  - O_2 and debris cloud obscured views out the windows

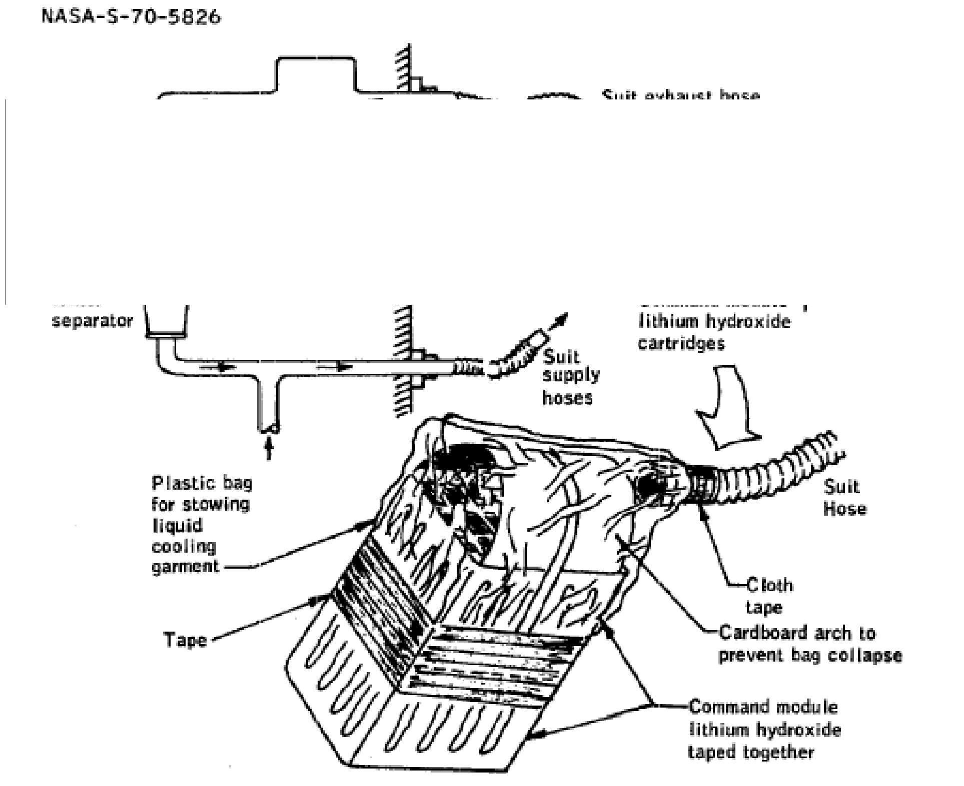
Life Support Issues

- Square LiOH cans from CM (to remove CO_2) not compatible with round LiOH slots in LM
  - Only 53 hrs of capability with LM alone, needed another 85 hrs
  - In-flight maintenance (IFM) to adapt the LM cans using plastic Flight Data File covers, plastic bags, and lots of gray tape
- Some O_2 left in CM surge tank and repress tanks
  - Normally used to repress the cabin after venting
- Powerdowns also reduce heat loads, so less water required for cooling

How to fit a square peg into a round hole?

LM LiOH can CM LiOH can

LiOH Removal Tool



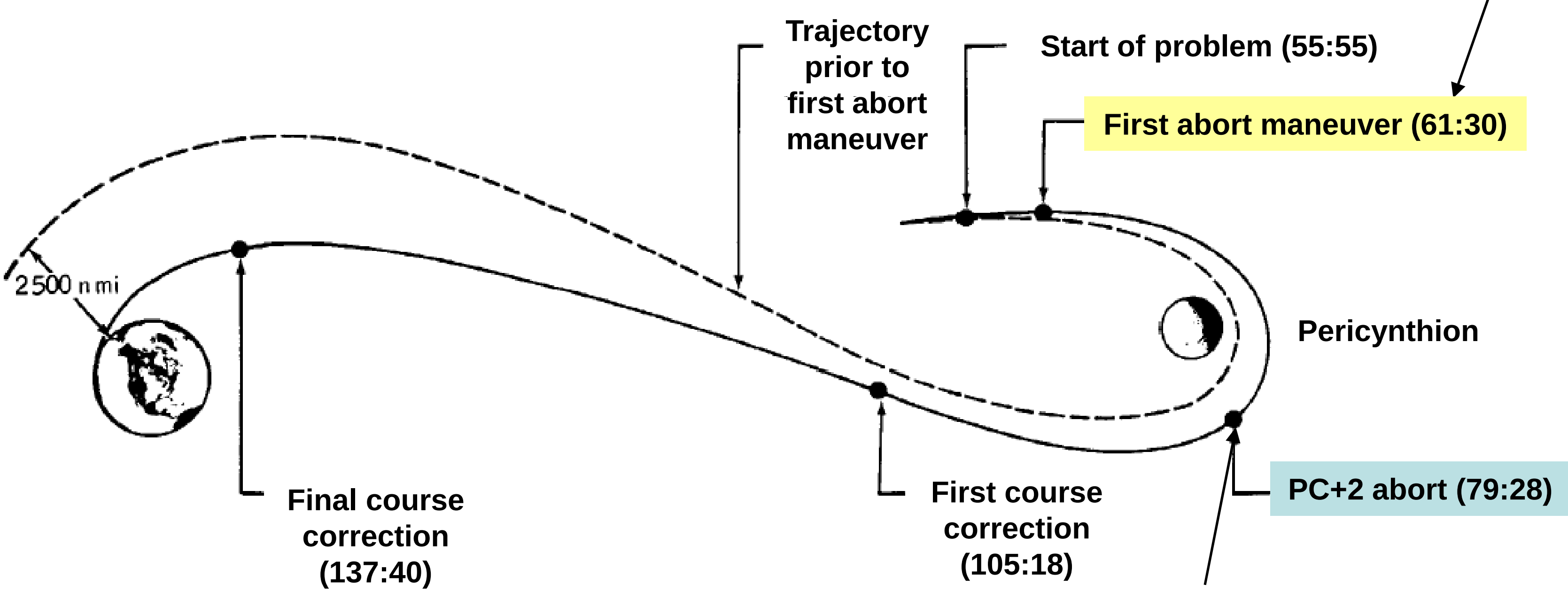
NASA photo AS13-62-8929

Trajectory Issues

- After situation stabilized, MCC replanned trajectory to get crew home soonest – how and when to burn?
  - Direct Abort: quicker, but uses much more propellant, required SM jettison to lower weight
  - Circumlunar Abort: slower, but saves propellant
- Used LM Descent Propulsion System (DPS) instead of SPS due to high power usage and uncertain nature of SM structure

Trajectory Burns

~38 fps burn to get into a free-return trajectory with an Indian Ocean splashdown at 152:00 GET

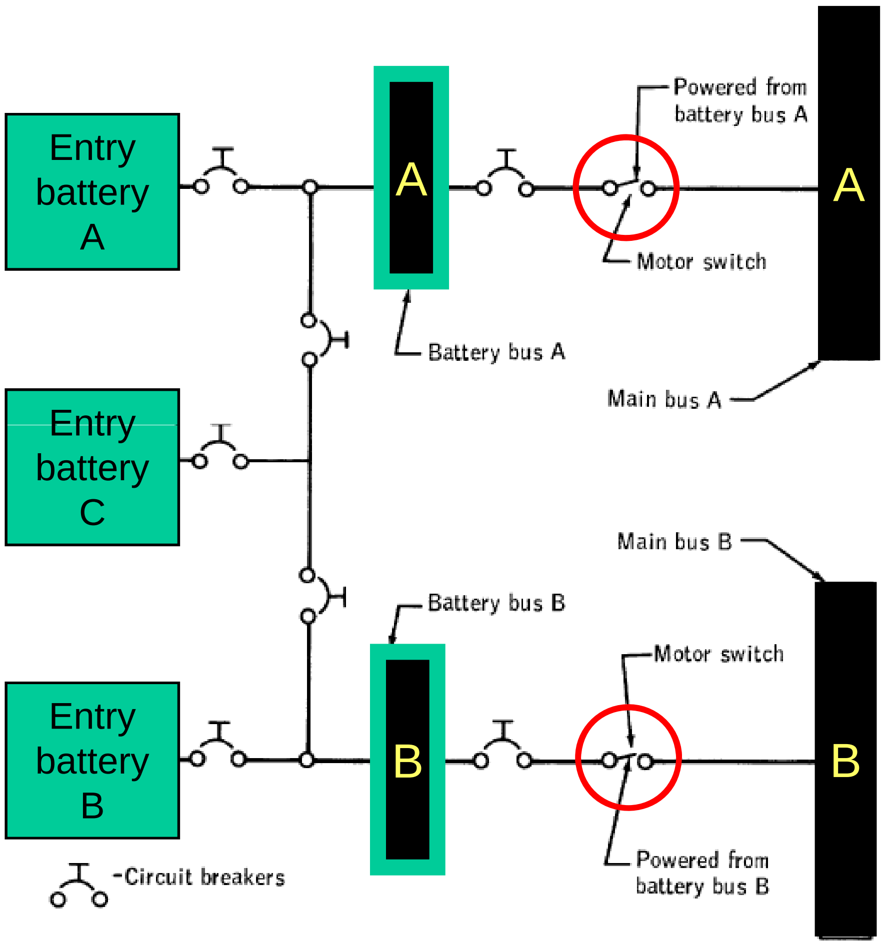


Pericynthion + 2 hrs (PC+2), ~890 fps burn to shorten return time with a Pacific Ocean splashdown (prime recovery site) at 142:53 GET

CSM Structural Issues

- Structural issues drove trajectory replan options
  - If they jettisoned the SM early in order to get a bigger burn, questions of exposure of CM heat shield to cold for extended duration
  - Health of SPS questionable/unknown, so decided to use LM Descent Propulsion System (DPS) for burns instead
- Issues with cold temperatures and condensation
  - Will motor-driven switches work?
  - Will condensation cause shorts?

Condensation Issues



- Cold temperatures led to significant moisture condensation
- Close switches early, use circuit breakers as controller
- Insulation and blankets put in place after Apollo 1 likely prevented water-triggered short circuits

Post-Incident Sequence of Events

55:55	Crew reports a bang
58:40	CSM completely powered down
61:30	Mid-course correction burn to establish free-return trajectory
69:30	MCC had final consumables plan: stay powered up until PC+2 burn, then power down PGNS
79:28	PC+2 burn to speed up return to 142 hrs GET (was 152 hrs)
82:37	LM powered down to 12 amps
94:19	Motor-driven switch test: make sure motors close relays, then use circuit breakers for power connections
101:38	CSM powered up for 10 min for data gathering
105:18	Mid-course correction to lower perigee at Earth capture
112:11	CM battery recharge start
127:00	Entry procedures read up to crew
133:24	LM powered up early for crew due to extra margin

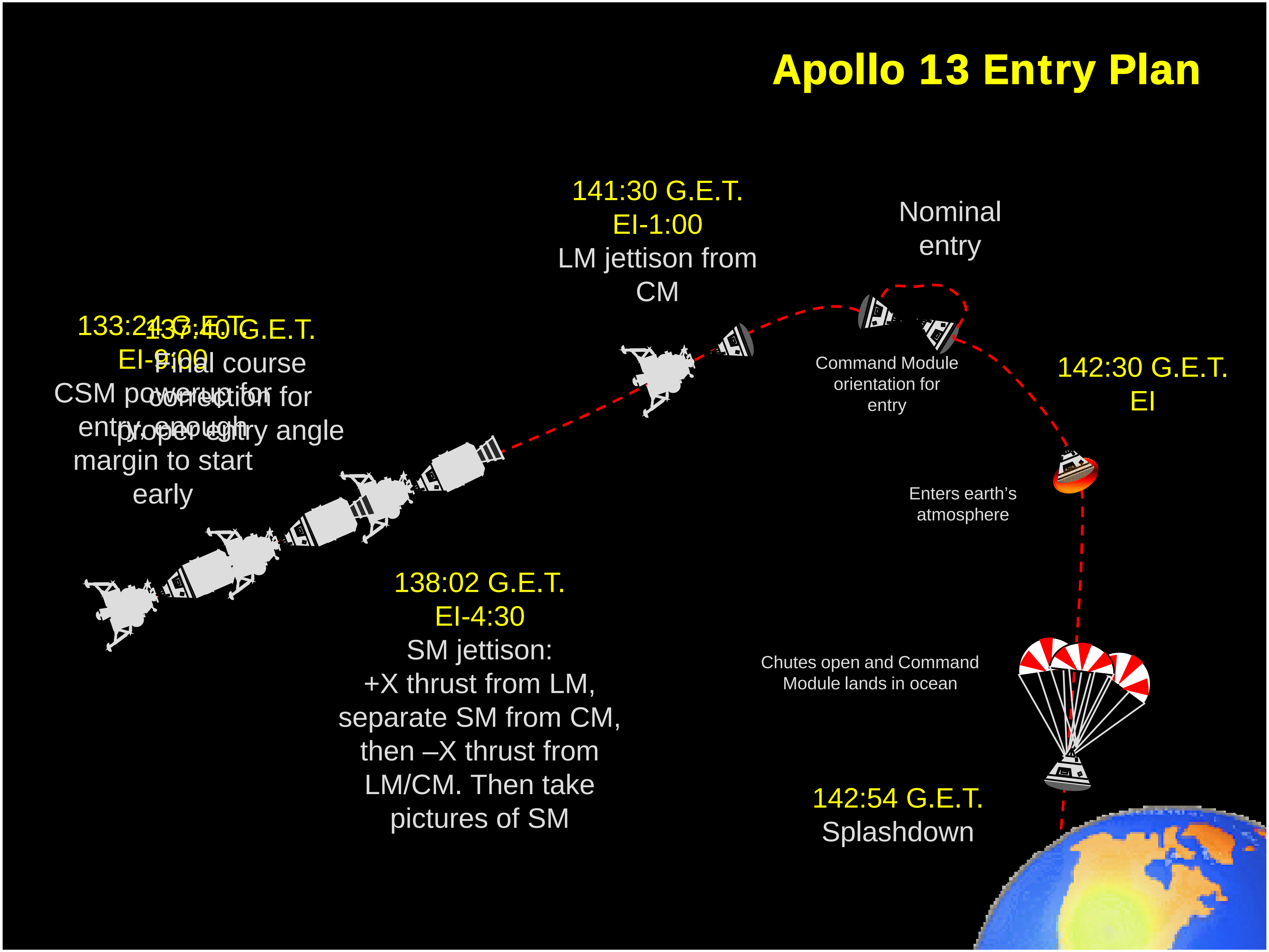
Final Margins

- Needed to get down to 24 amps and 3.5 lb H_2O per day
  - Powerdowns predicted to be 17 amps, 2.7 lbs H_2O
  - Actual usage was 12 amps and 2.5-2.8 lbs H_2O
- MCC allowed crew higher electrical and water usage rate towards the end of the mission once it was determined that they had hours of margin
- Margins at LM jettison:

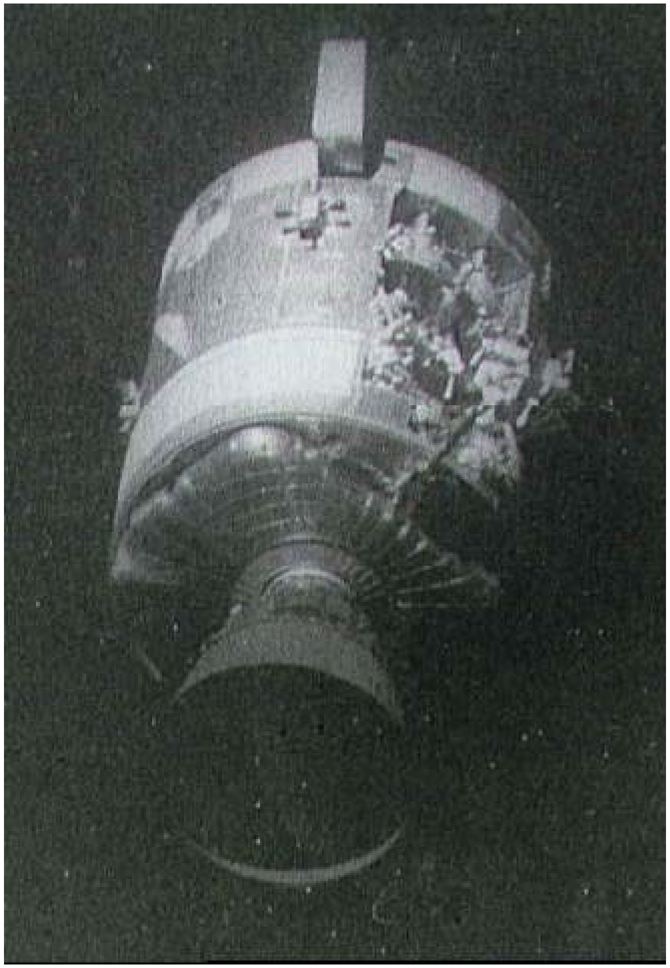
Power	189.6 amp-hrs	~4.5 hrs
Water	28 lbs	~5.5 hrs
Oxygen	28.5 lbs	~124 hrs
LiOH	LM stockpile	~150 hrs

MCC Planning

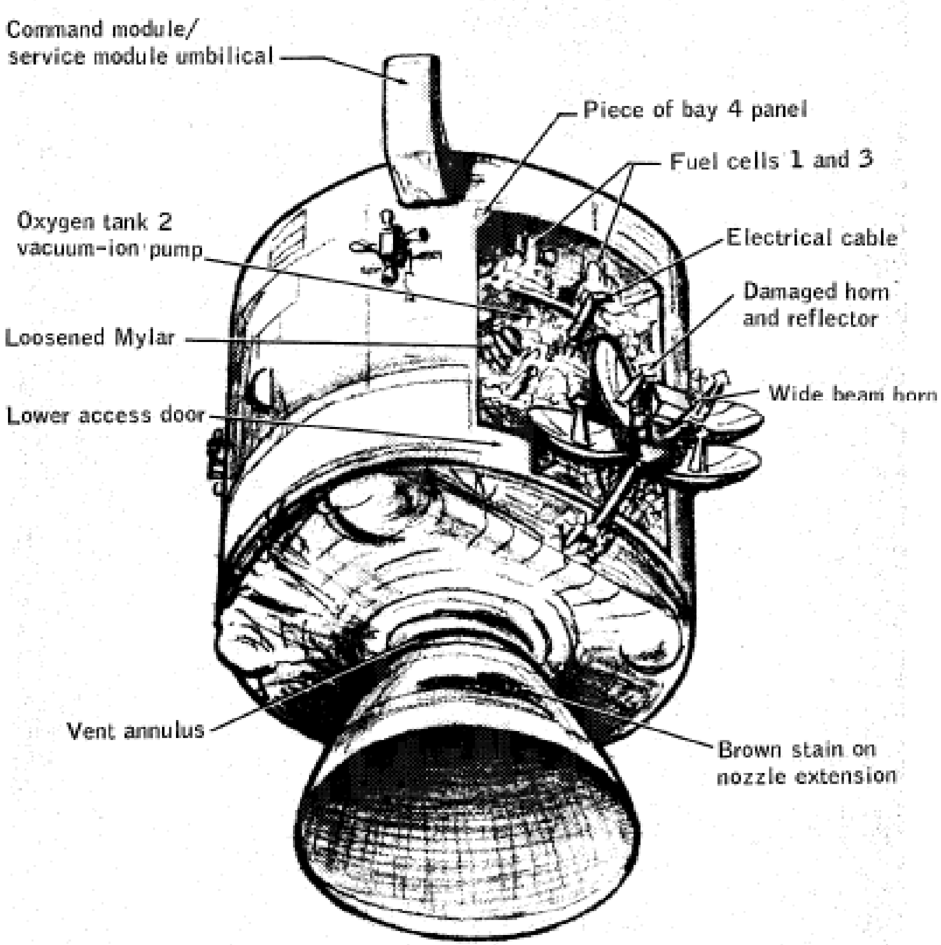
- MCC had initial set of course correction and entry procedures within 12 hrs of accident
  - Modified and evaluated in simulators in Houston and KSC by backup crews
    - Practical, safe, efficient, adequate, and timely
  - Trajectory evaluations of contingency conditions for LM and SM separation conducted and documented prior to the mission by mission-planning personnel at MSC
  - Most of the LM/SM jettison steps extracted from other procedures which had been developed, tested, and simulated earlier
  - Final procedures read to crew 24 hrs before entry, after 2 days of planning and evaluation


Apollo 13 Entry Plan
133:21 G.E.T.
EI-9:00
CSM powerup for entry: enough margin to start early
137:40 G.E.T.
Final course correction for proper entry angle
141:30 G.E.T.
EI-1:00
LM jettison from CM
Nominal entry
Command Module orientation for entry
142:30 G.E.T.
EI
Enters earth's atmosphere
138:02 G.E.T.
EI-4:30
SM jettison:
+X thrust from LM, separate SM from CM, then –X thrust from LM/CM. Then take pictures of SM
Chutes open and Command Module lands in ocean
142:54 G.E.T.
Splashdown

- Crew took photos/video of the SM after jettison, the first time anyone had seen the damage.



NASA photo AS13-59-8500



Root Cause of Accident

- Heater voltage specs changed but nobody noticed
  - Original specs (1962): use 28 VDC as in the CM
  - Revised specs (1965): be compatible with up to 65 VDC as at KSC
  - Wiring changed to handle higher voltage, but vendor didn't change the heaters to be compatible with 65 VDC
  - Discrepancy overlooked by Beech (tank vendor), Rockwell (prime contractor), and NASA
  - Qual and acceptance testing not performed under load, only opened during special detanking

Contributing Factors

- "Improvised" detanking procedures
  - Tank hadn't been qualified for those conditions, although procedures didn't violate operation specs at KSC or Beech
  - Standard procedures at Beech but not KSC
- Tank temperature meter pegged off-scale high at 100° F (38° C)
  - Impossible on the ground to realize that temps were too high
- During detanking, nobody monitored heater current readings to make sure they shut off when expected
  - Only that they came on when expected

Error Chain

- Like most error chains, if any of the items below were different, there would have been no accident on Apollo 13
  - Heater relay never modified for higher voltage [1965]
  - Tank dropped 2 inches and displaced fill line [1968]
  - Decision to drain the tank with heaters (8 hrs) instead of replacing it (45 hrs) [1970]
  - Heaters left on to drain the tank
  - Nobody monitored heater to make sure it came off
  - Temperature meter didn't show proper range
  - Insufficient attention paid to fact that heater stayed on for so long

Lessons Learned 1

- O_2 tank design was inadequate and conducive to explosive failure.
  - Reduce the amount of combustible material in the tank and reduce the potential ignition sources within the tank
- Modified system should undergo rigorous requalification testing with particular attention to potential operational problems

- C&W system had flaws
  - It locked out alarms that should have been made
    - Example: H_2 tank pressure low indication (which drove the tank stir in the first place) inhibited the O_2 tank pressure alarms
  - It didn't annunciate some that should have been
    - Example: MCC didn't realize that O_2 reactant valves to the fuel cells were closed because sensors only indicated when both O_2 and H_2 were closed, not just one
  - It annunciated some because the limits were too tight
    - Example: Cryo H_2 C&W limits were too close to the actual heater limits, and alarms went off when not needed
  - Would not have changed outcome, but would have improved MCC situational awareness

Lessons Learned 3

- Consumables and emergency equipment in the LM and the CM should be reviewed to determine whether steps should be taken to enhance their potential for use in a "lifeboat" mode
  - Example: incompatible LiOH cartridges between the LM and CM
- It is not practical to develop, simulate, and practice procedures for use in every possible contingency.
  - However, simulations provide MCC with cases where they can learn to adapt existing procedures and philosophy instead of having to create new ones from scratch

Lessons Learned 4

- Whenever significant anomalies occur in critical subsystems during final preparation for launch, standard procedures should require a presentation of all prior anomalies on that particular piece of equipment, including those which have previously been corrected or explained.
- Critical decisions involving the flightworthiness of subsystems should require the presence and full participation of an expert who is intimately familiar with the details of that subsystem.

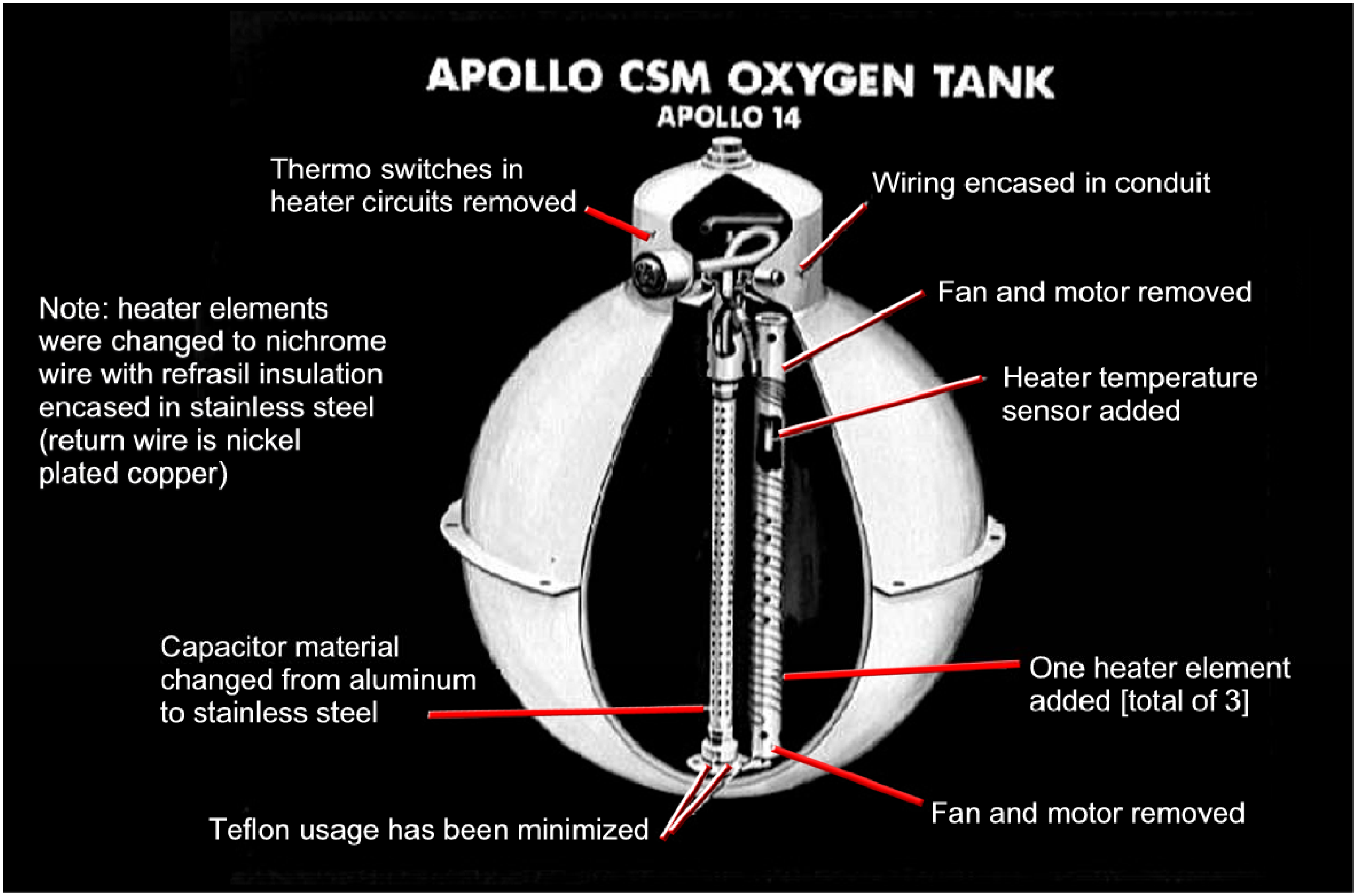
Lessons Have Been Learned

- Shuttle and ISS veterans will recognize many of these lessons as the way things are currently done
  - Flight Techniques Panels
  - Joint Operations Panels
  - Flight Readiness Reviews
  - Mission Control Flight Rules

Post-Flight Changes

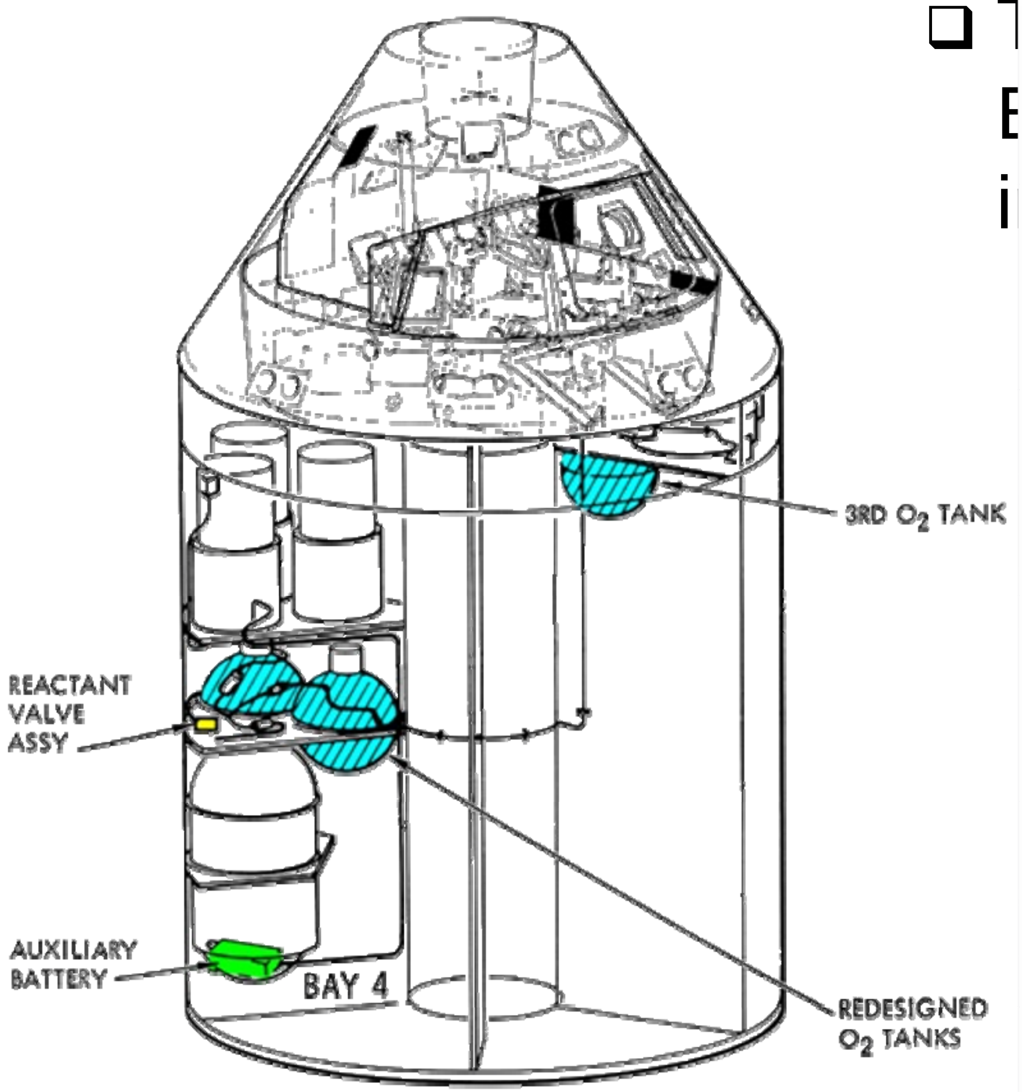
- Redesign of O_2 tank system
- Upgraded Fuel Cell instrumentation
- Updated Caution & Warning
- Third O_2 tank added to Apollo 14
- Added extra LM and SM batteries
- Added circuit protection on power transfer cable

Redesigned Oxygen Tank



NASA photo S71-16745

Battery Upgrades for Apollo 14



- Two LM Descent Batteries @ 12 kWh installed
  - SM "Auxiliary Battery", could connect to CM Main Buses via fuel cell 2 distribution
  - LM "Lunar Battery", 5th Descent stage battery
  - To be utilized in a similar situation on the way back from the mooon

Board Findings

- “It was found that the accident was not the result of a chance malfunction in a statistical sense, but rather resulted from an unusual combination of mistakes, coupled with a somewhat deficient and unforgiving design.”
- “The accident is judged to have been nearly catastrophic. Only outstanding performance on the part of the crew, Mission Control, and other members of the team which supported the operations successfully returned the crew to Earth.”

For More Information

- Report of the Apollo 13 Review Board
  - Panel 1, Spacecraft Incident Investigation, Vol. 1: Anomaly Investigation, 06/70
  - Appendix B, Report of Mission Events Panel, 06/70
- Mission Operations Report
  - NASA-MSC Internal Report, Apollo 13, 4/28/70
- Apollo 13 Mission Report
  - MSC-02680 with PCN-1, 5/70
- Apollo Mission Familiarization for Constellation Personnel
  - Apollo Wiki