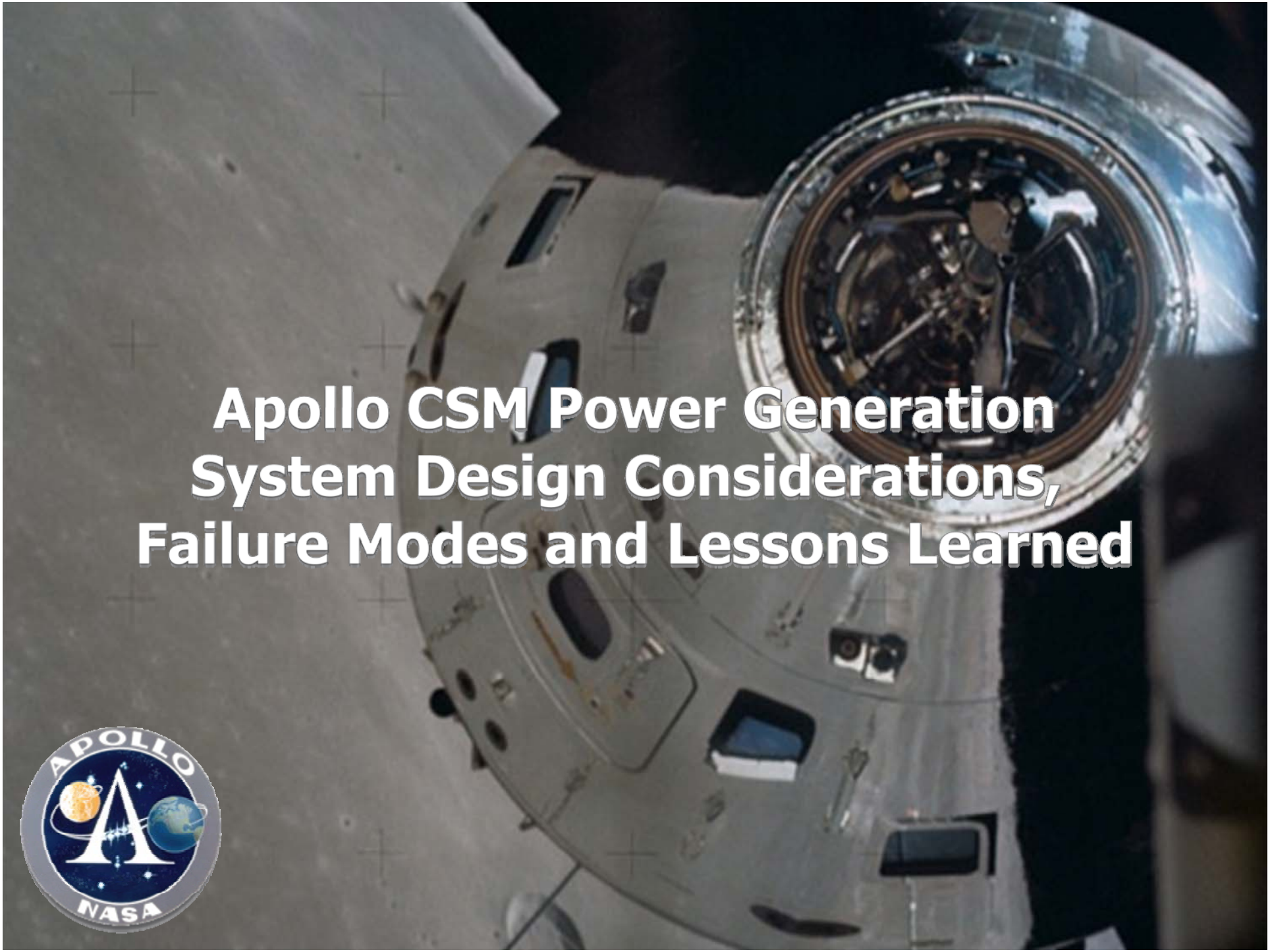
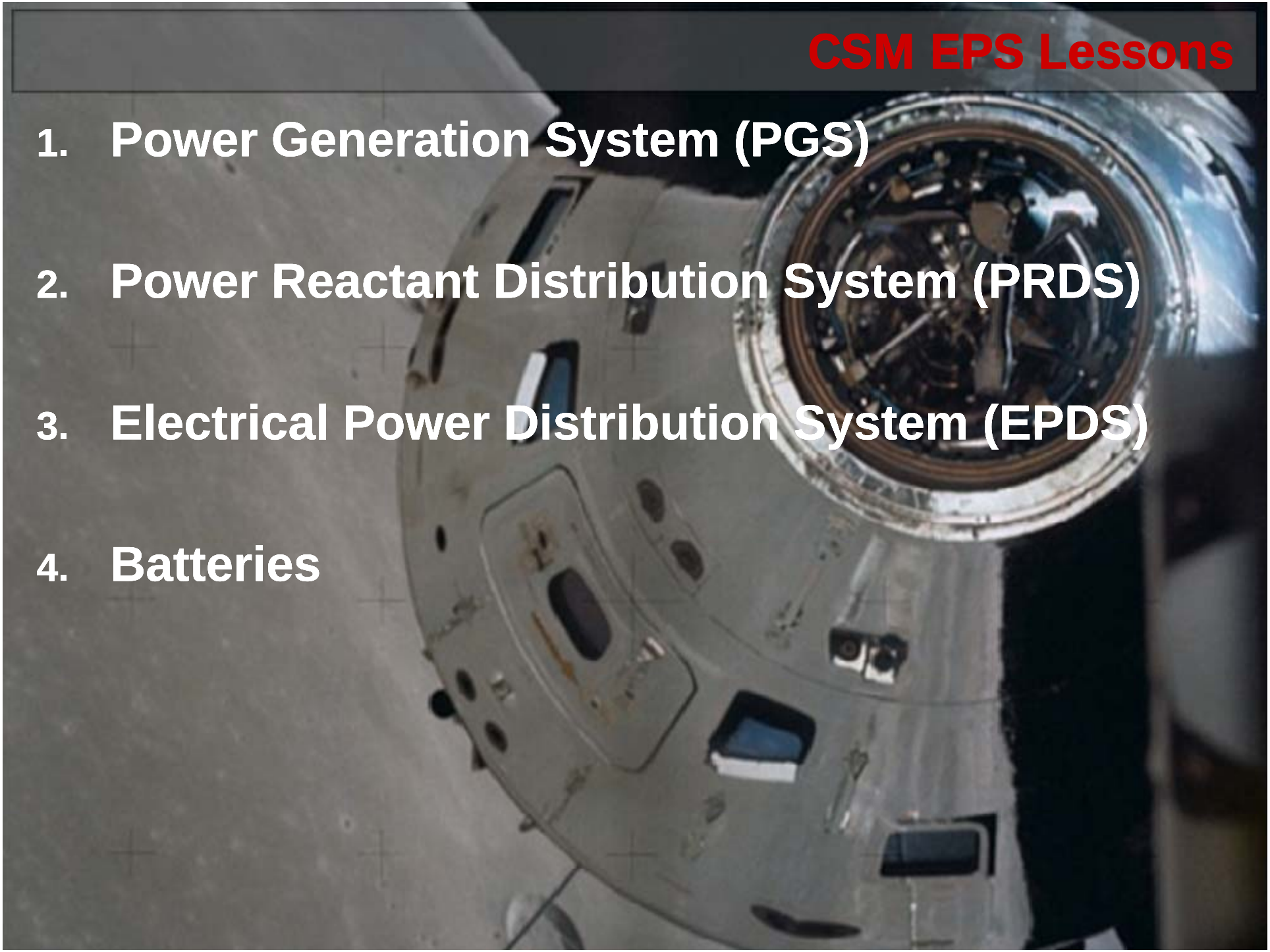
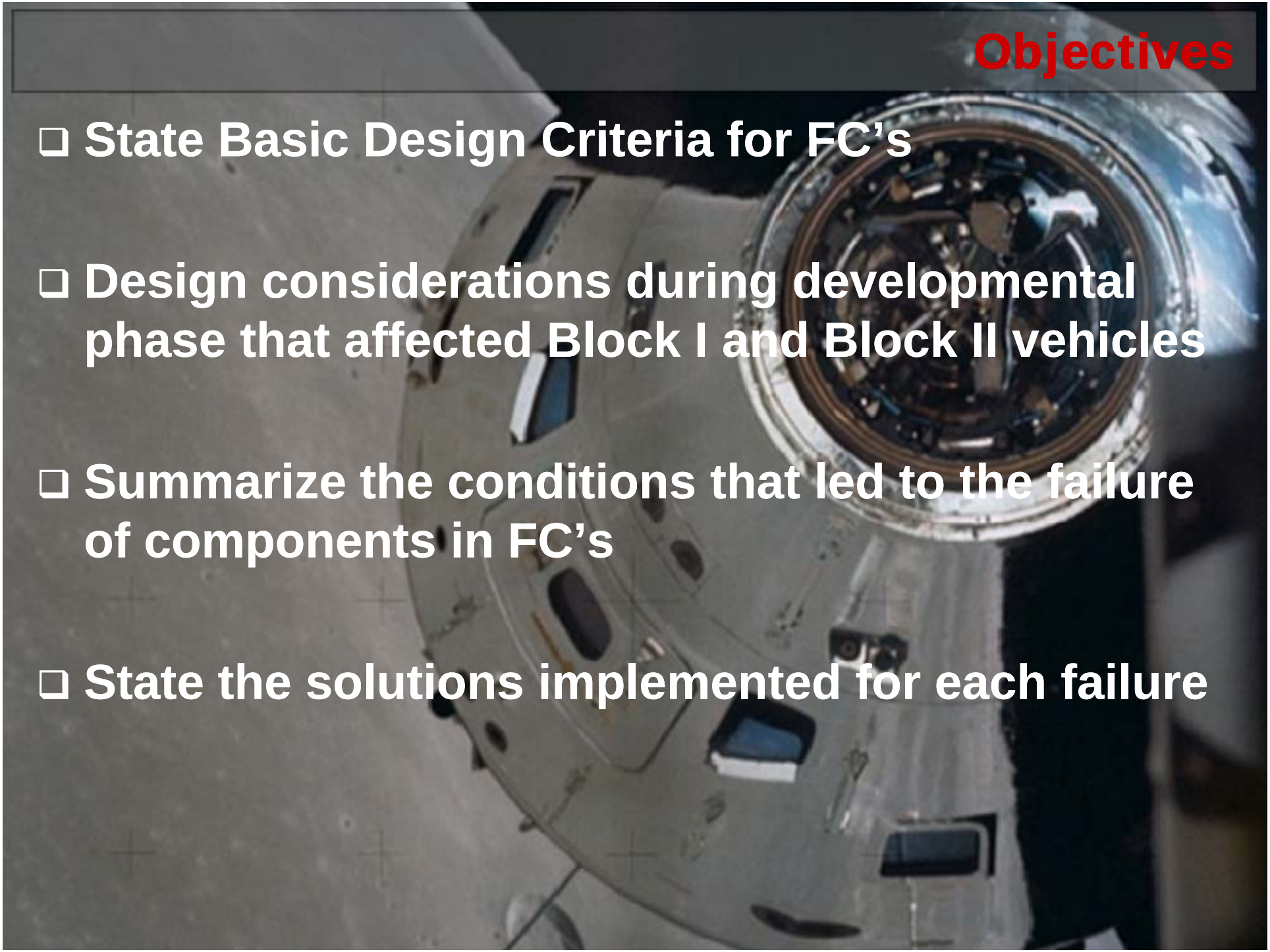


Apollo CSM Power Generation System Design Considerations, Failure Modes and Lessons Learned



CSM EPS Lessons

1. Power Generation System (PGS)
2. Power Reactant Distribution System (PRDS)
3. Electrical Power Distribution System (EPDS)
4. Batteries



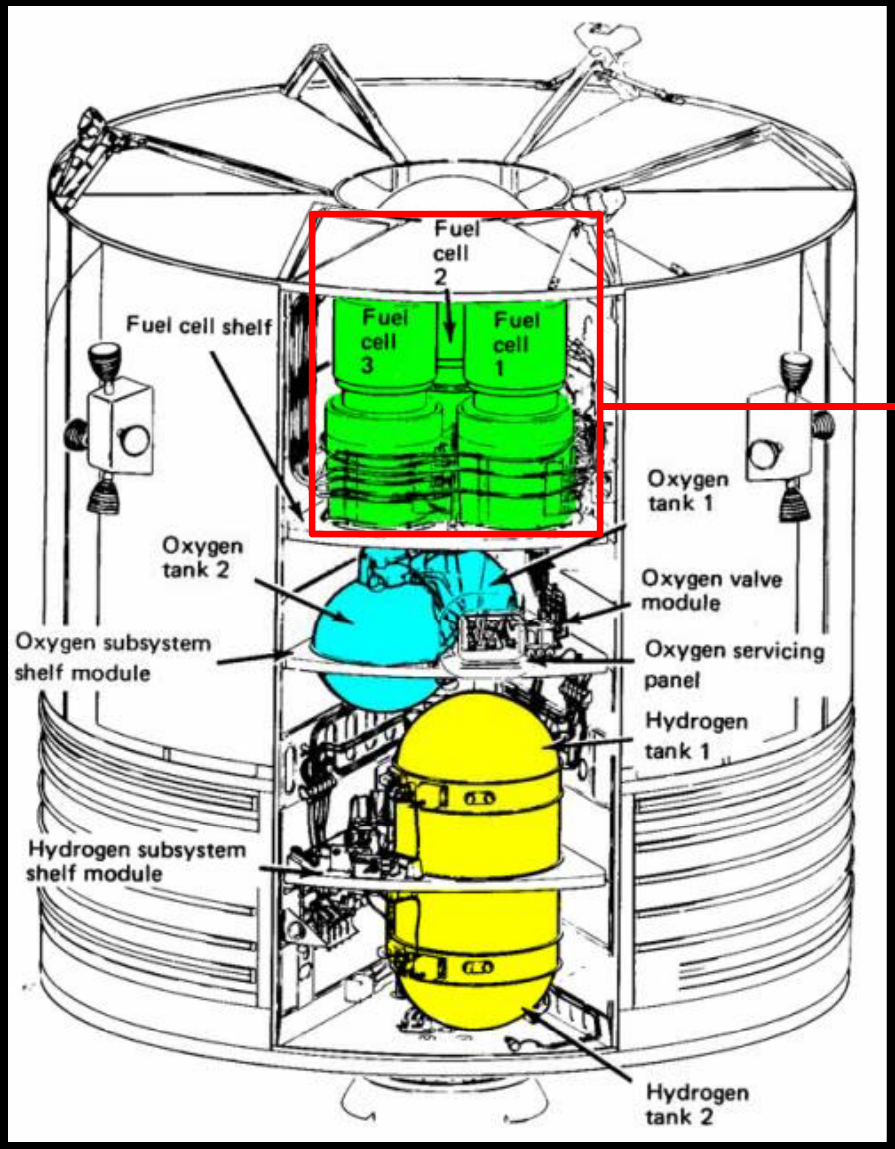
Objectives

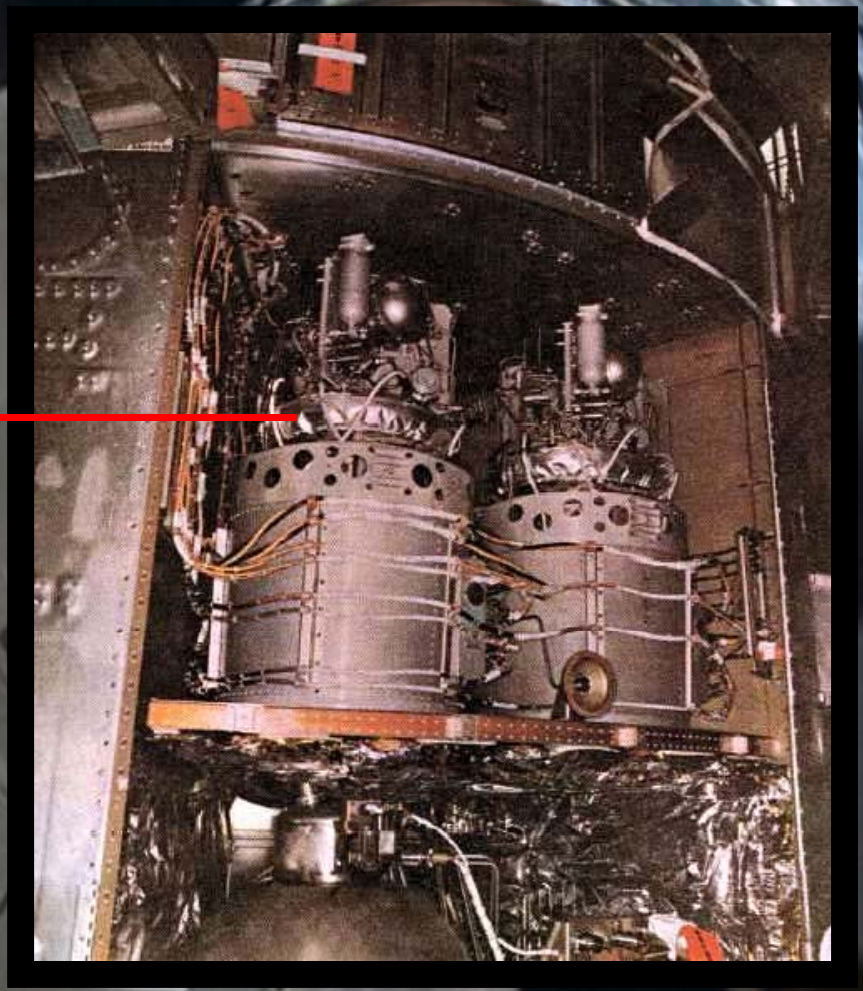
- State Basic Design Criteria for FC's
- Design considerations during developmental phase that affected Block I and Block II vehicles
- Summarize the conditions that led to the failure of components in FC's
- State the solutions implemented for each failure

Overview

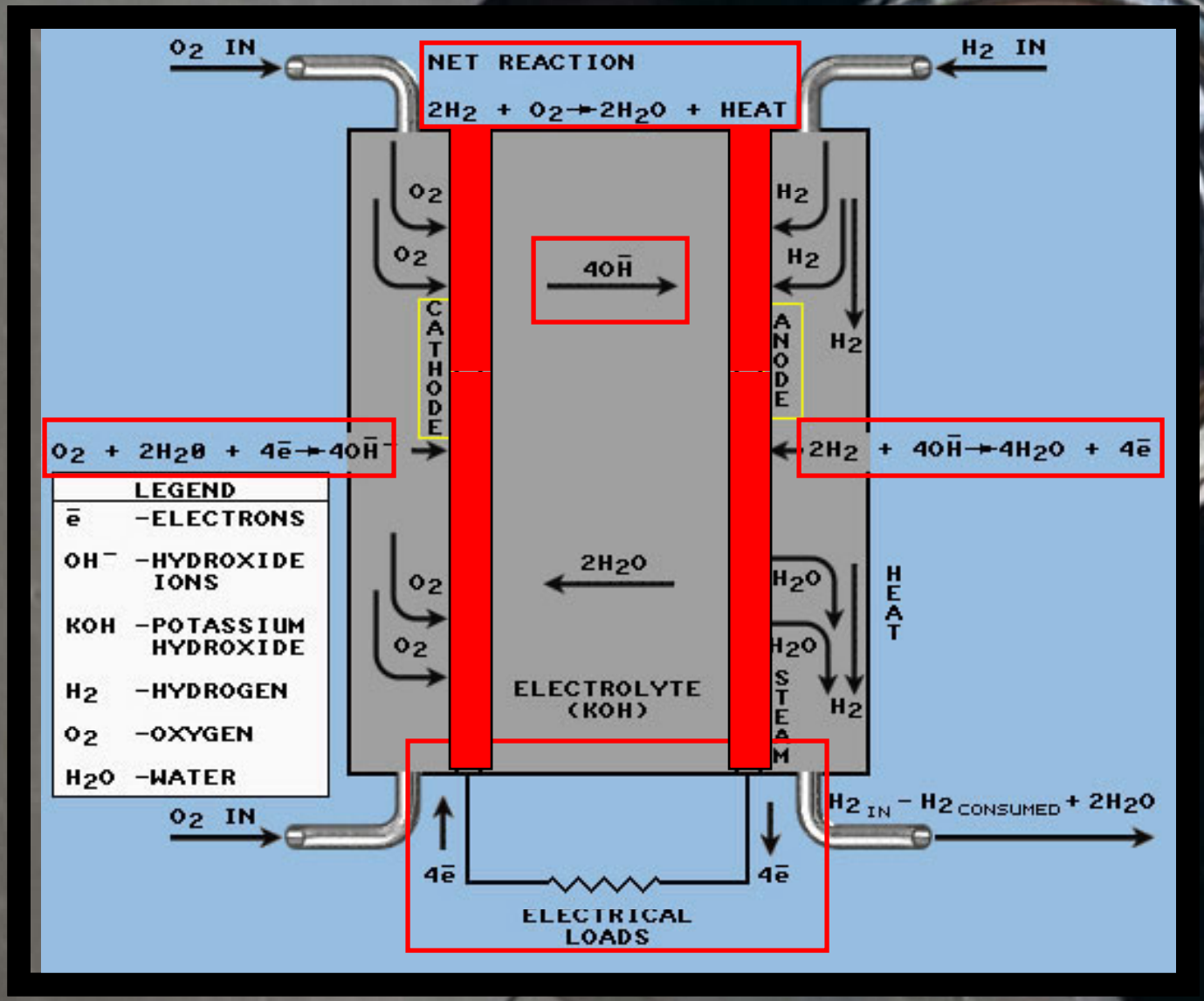
- Location of FC's
- FC Theory and FC Overview
- Design Criteria going into Development Phase
- Design Considerations coming from Development Phase
- Block I Failures and Solutions
- Block II Failures and Solutions
- Lessons Learned

Alkaline Fuel Cell Location





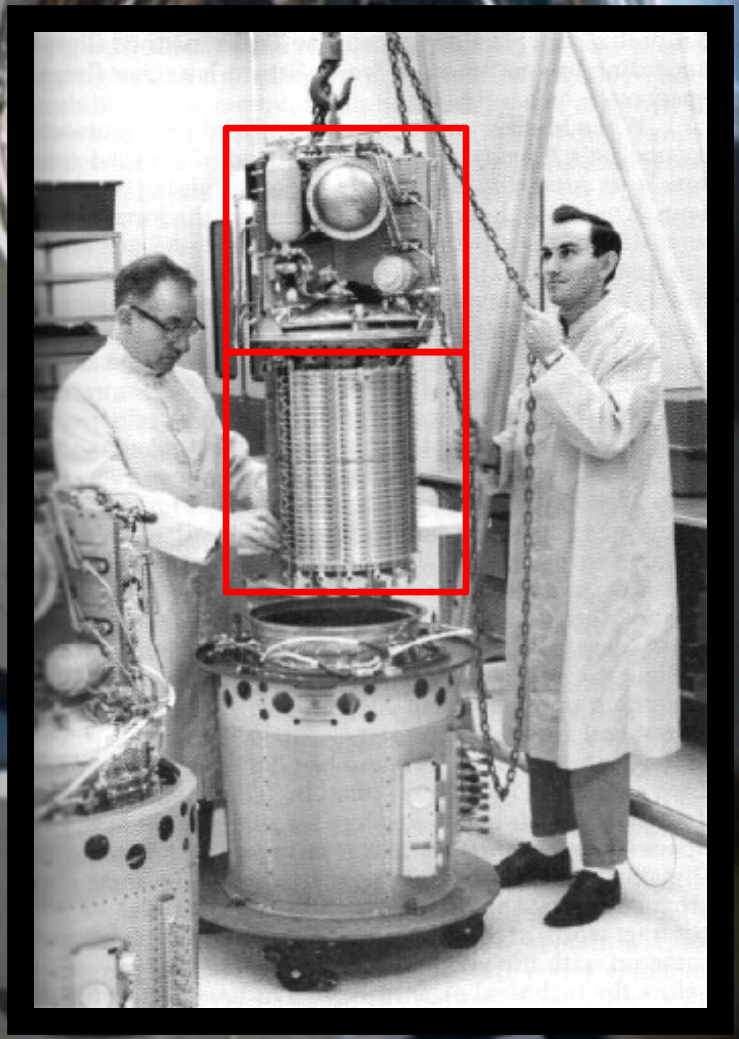
Alkaline Fuel Cell Theory



Alkaline Fuel Cell Overview

- FC's produce DC electrical power over a normal range of 563 to 1420 (W) at a voltage of 27 to 31 (V).

1. Energy Conversion Section
2. Reactant-Control Section
3. Thermal-Control Section
4. Water-Removal Section



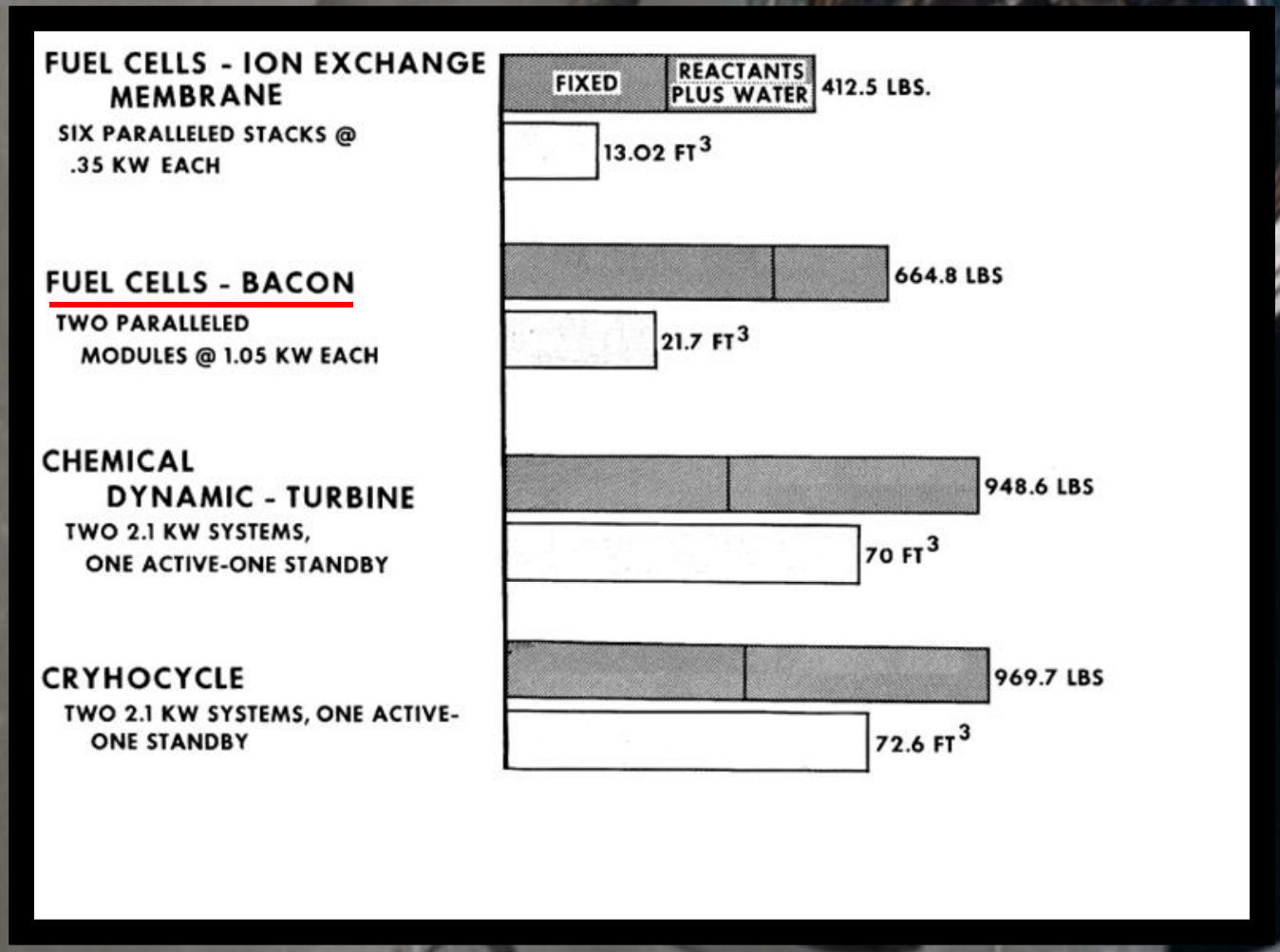
Design Criteria

- **Criteria:**
  - **“Shall be designed to supply, regulate, and distribute all electrical power required by CSM for mission requirements, and LEM during checkout and monitoring.”**
- **System had to possess adequate mission flexibility**
  - **No constraints imposed on launch dates**
  - **Had to be operationally adaptable to changing requirements for successive missions without a subsequent requirement for design changes**
- **High reliability and safety that were consistent with system weight**
  - **Factors affecting reliability, such as multiple starts, were to be avoided, and simplicity of design was desired**

Development Phase

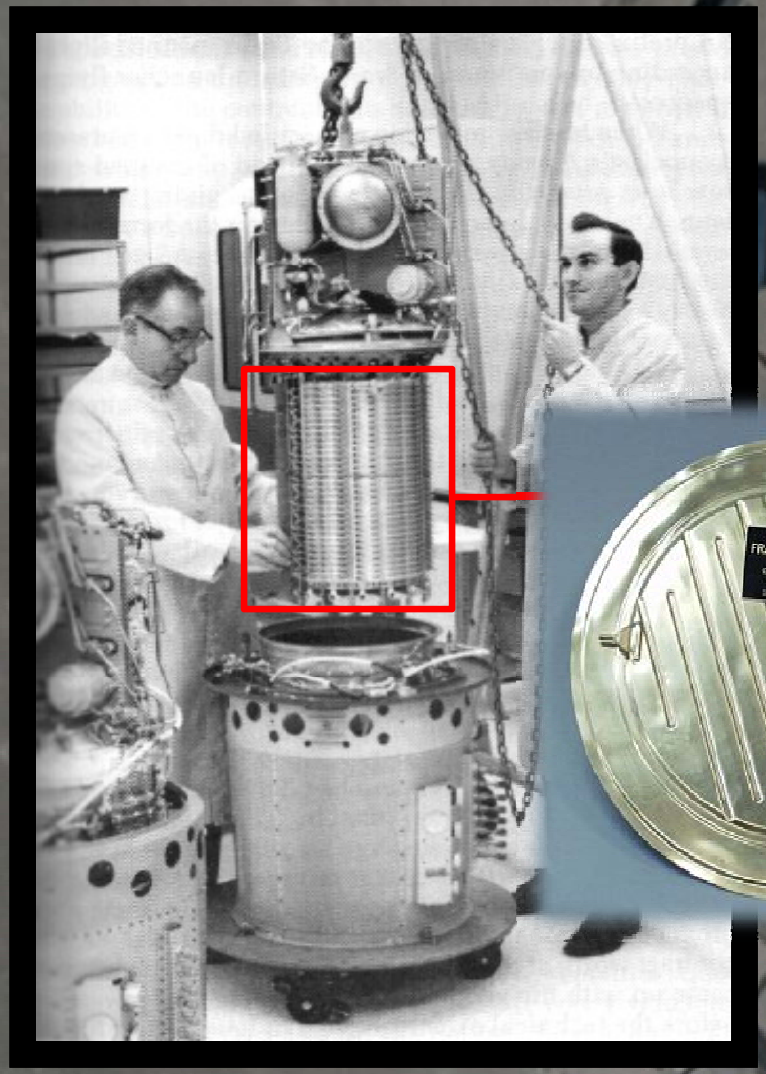
Development Phase

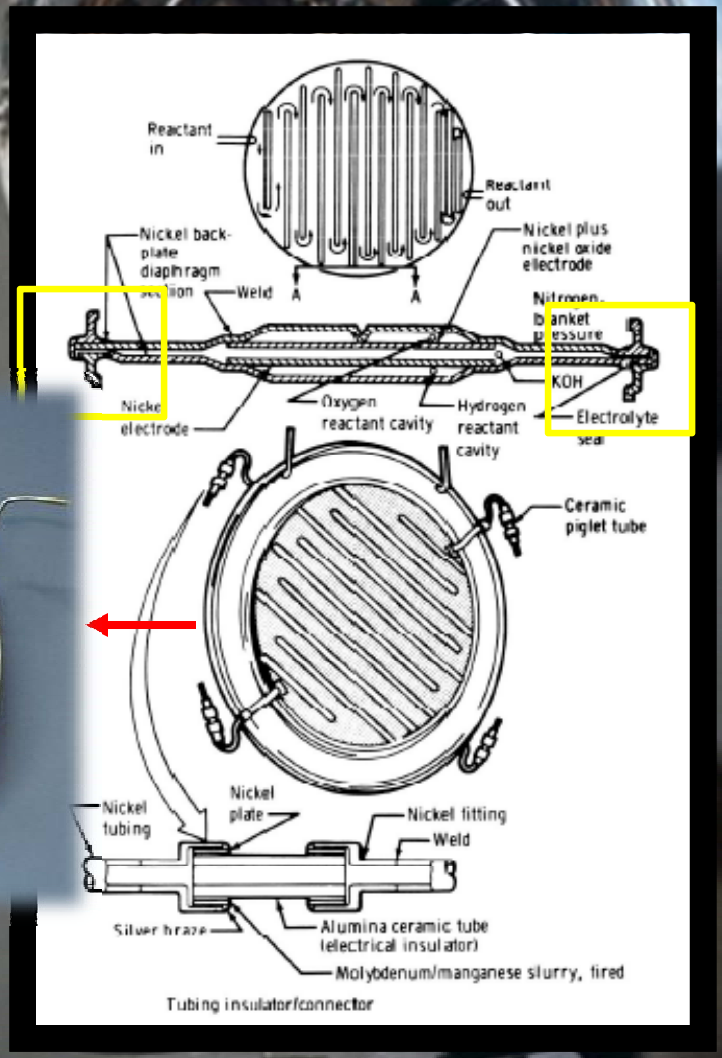
- Concept for 1.5 (kW) FC came from the Gemini program
  - Gemini program utilized Ion Exchange Membrane (IEM) FC



Electrolyte Seal

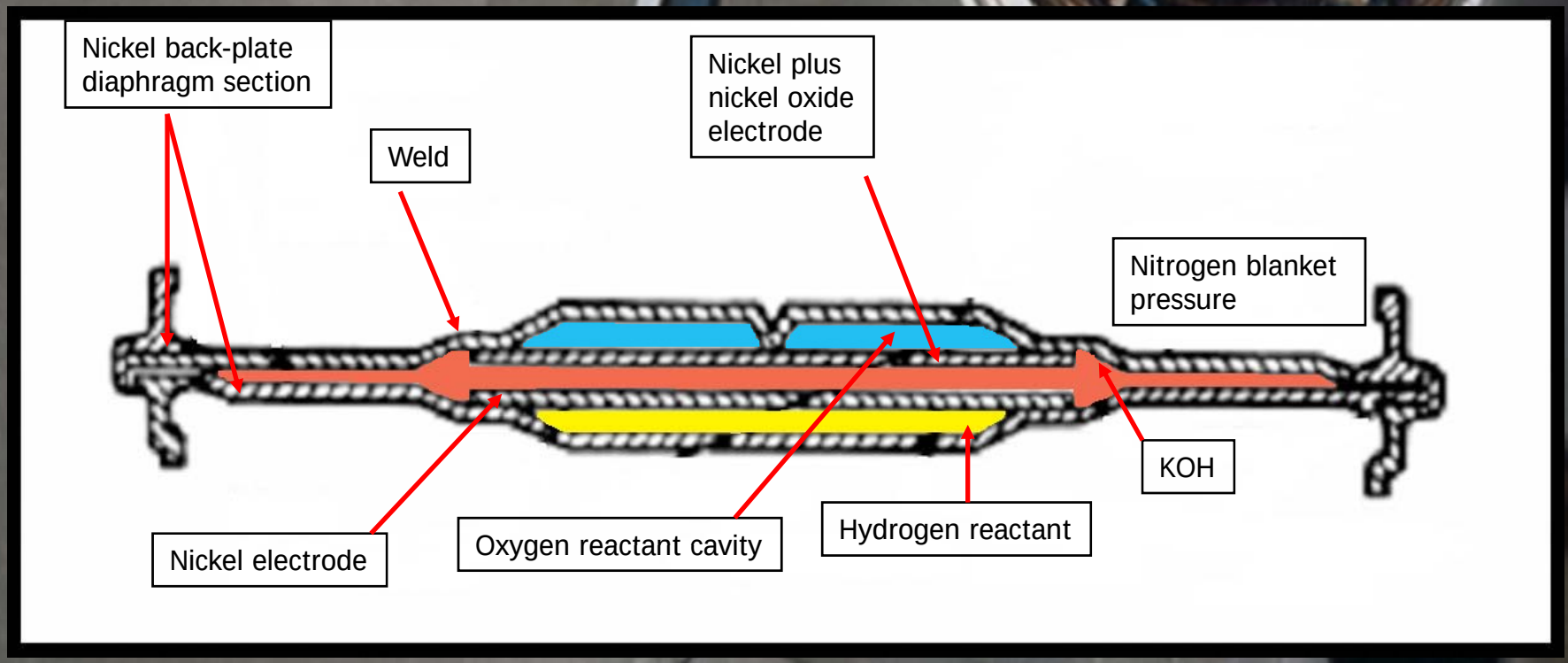
- Leakage of electrolyte at the periphery of the unit cell





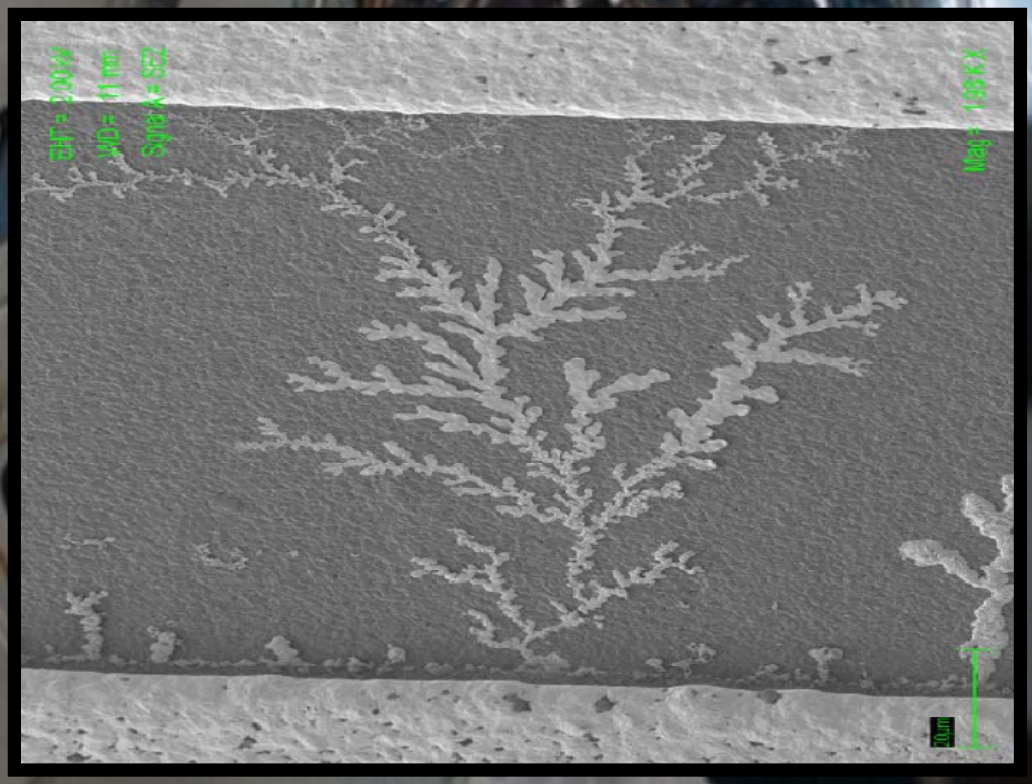
Cell Flooding

- If either hydrogen or oxygen gas pressure is more than 2.5 (psi) below or 10.5 (psi) above the electrolyte pressure, a breakdown of the liquid/gas interface was possible



Dendrite Formation

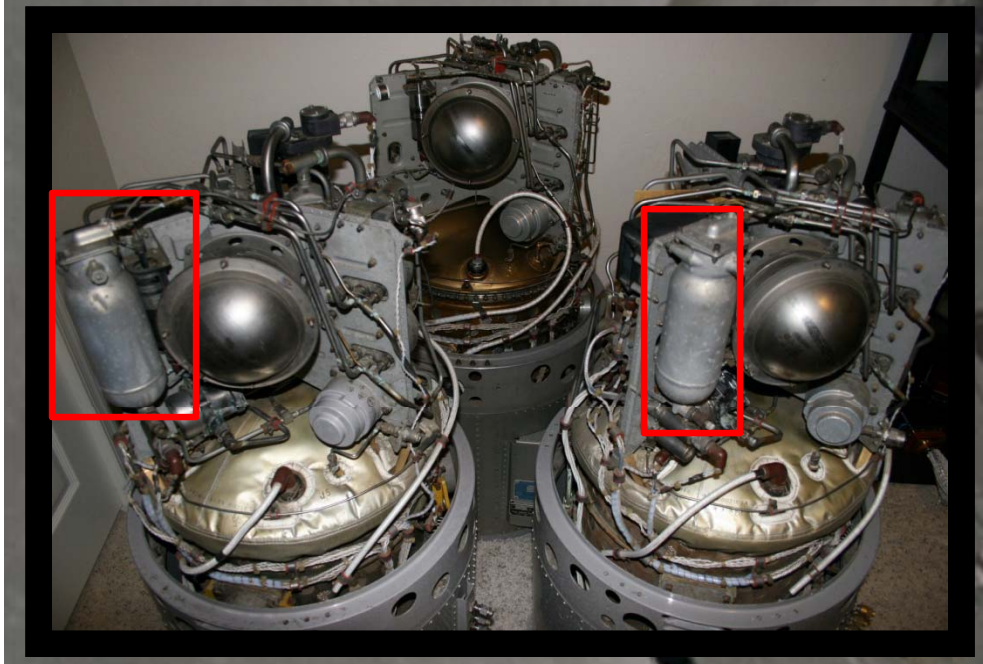
- FC shorted out internally during shutdown

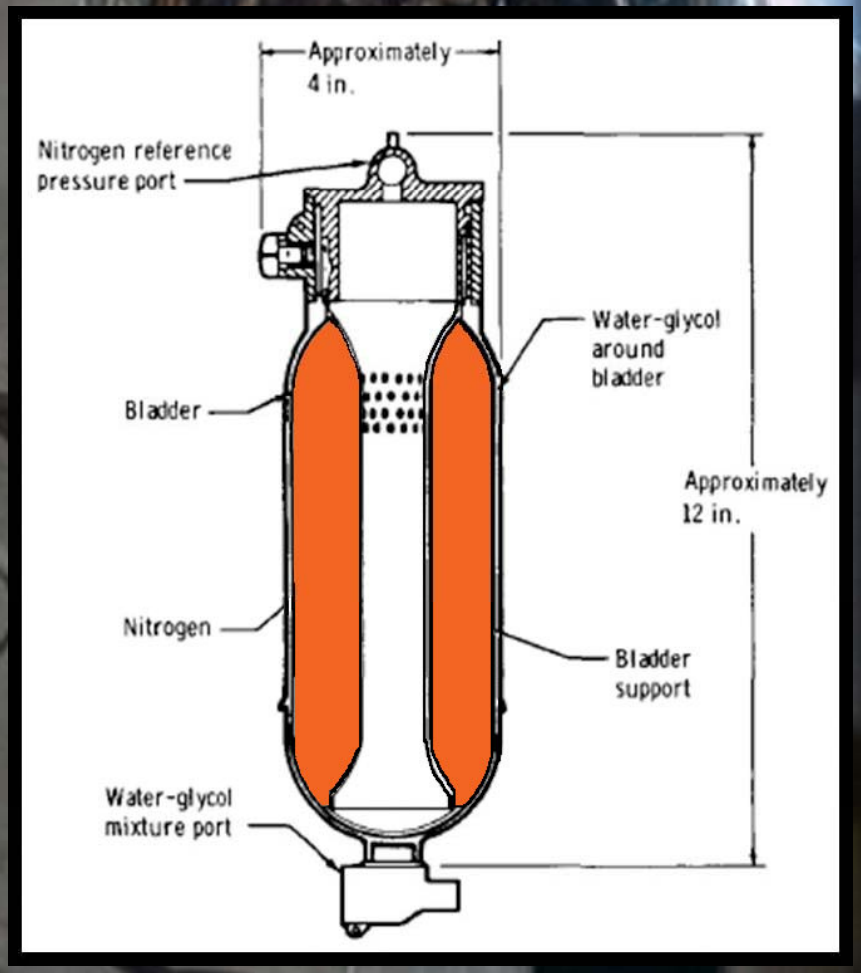


Silver dendrite experiment from Goddard Space Flight Center

Accumulator

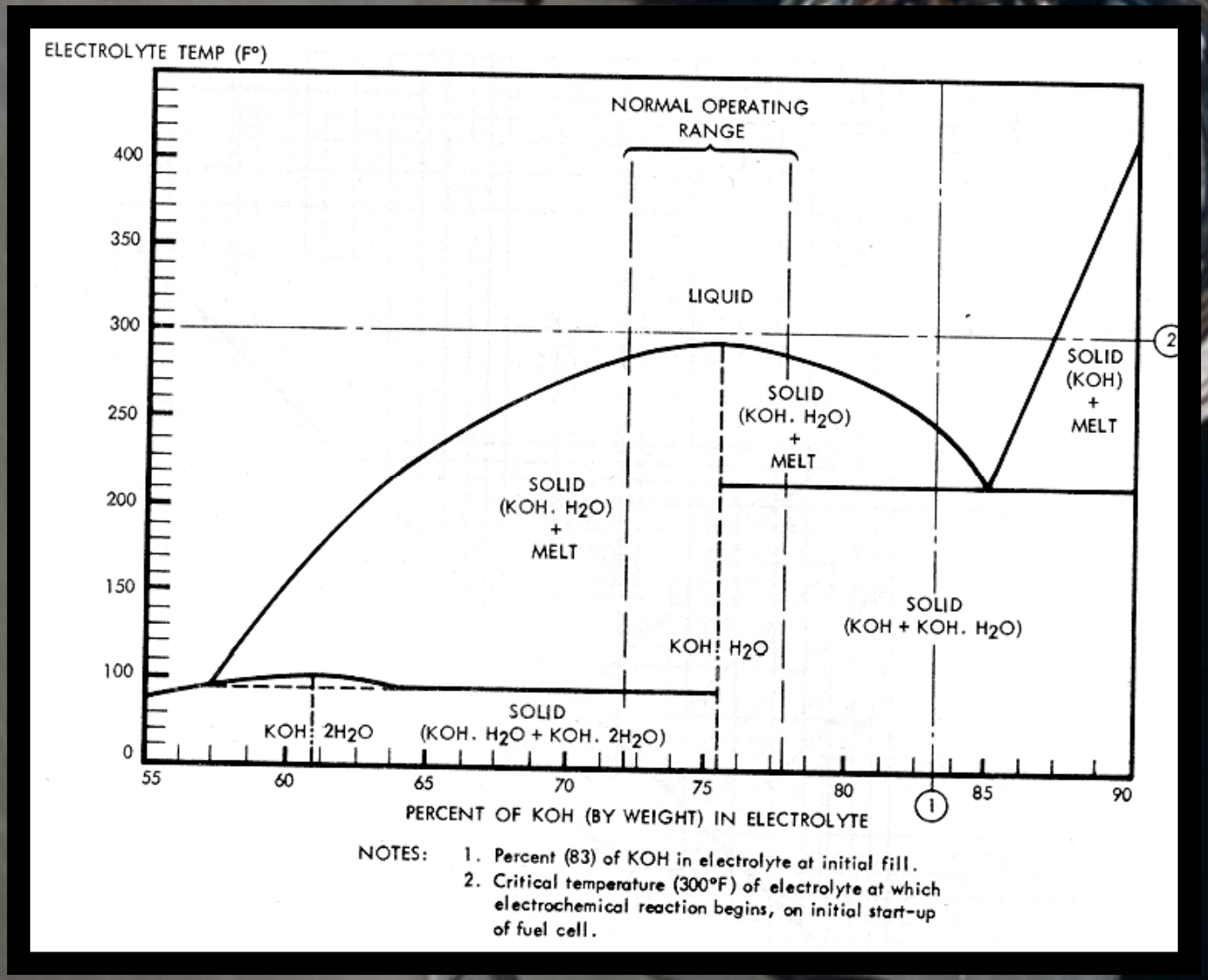
- Size was insufficient to function as a pressure control device for total temp range of FC





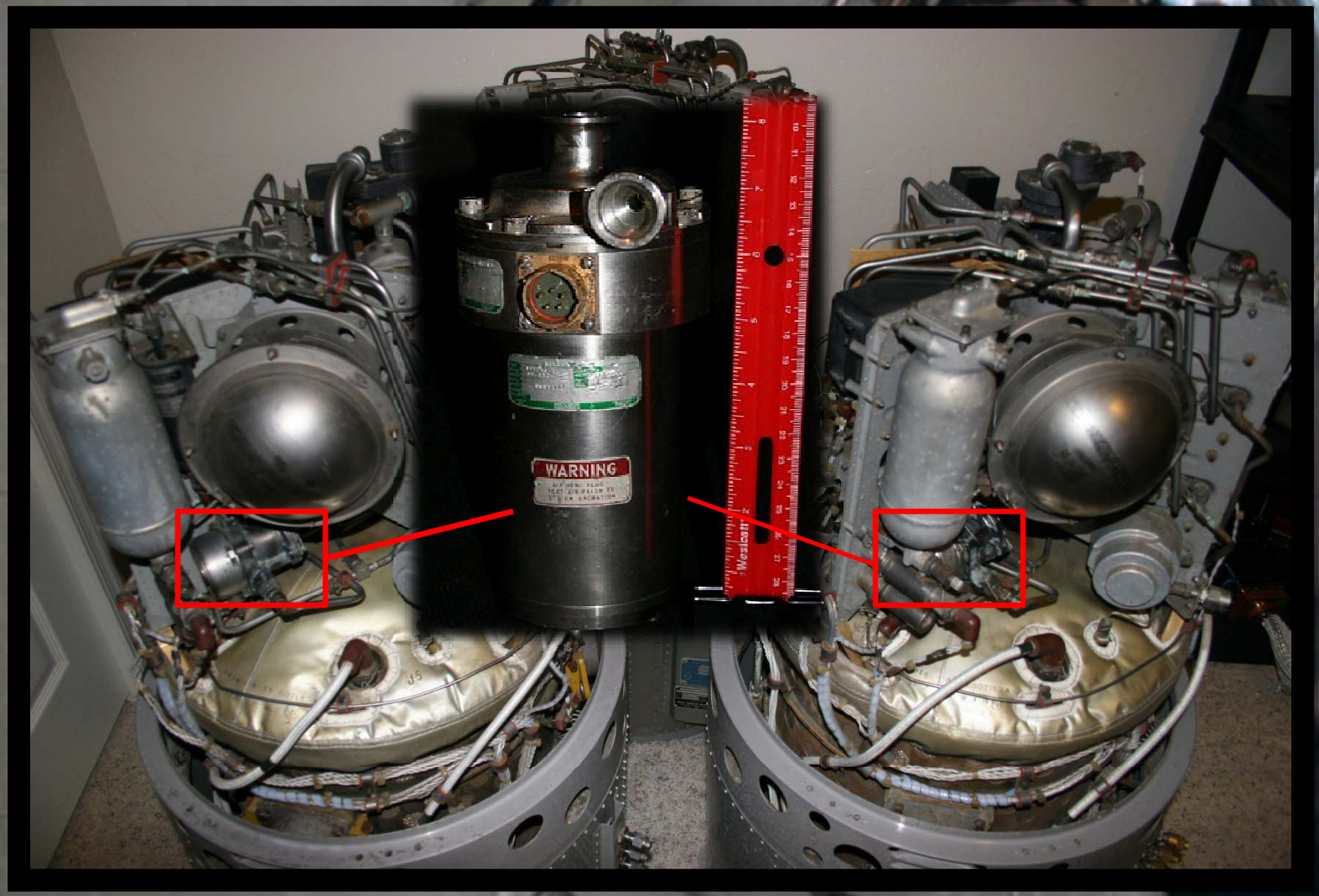
Cell Separation

- Occurrence of cold popping

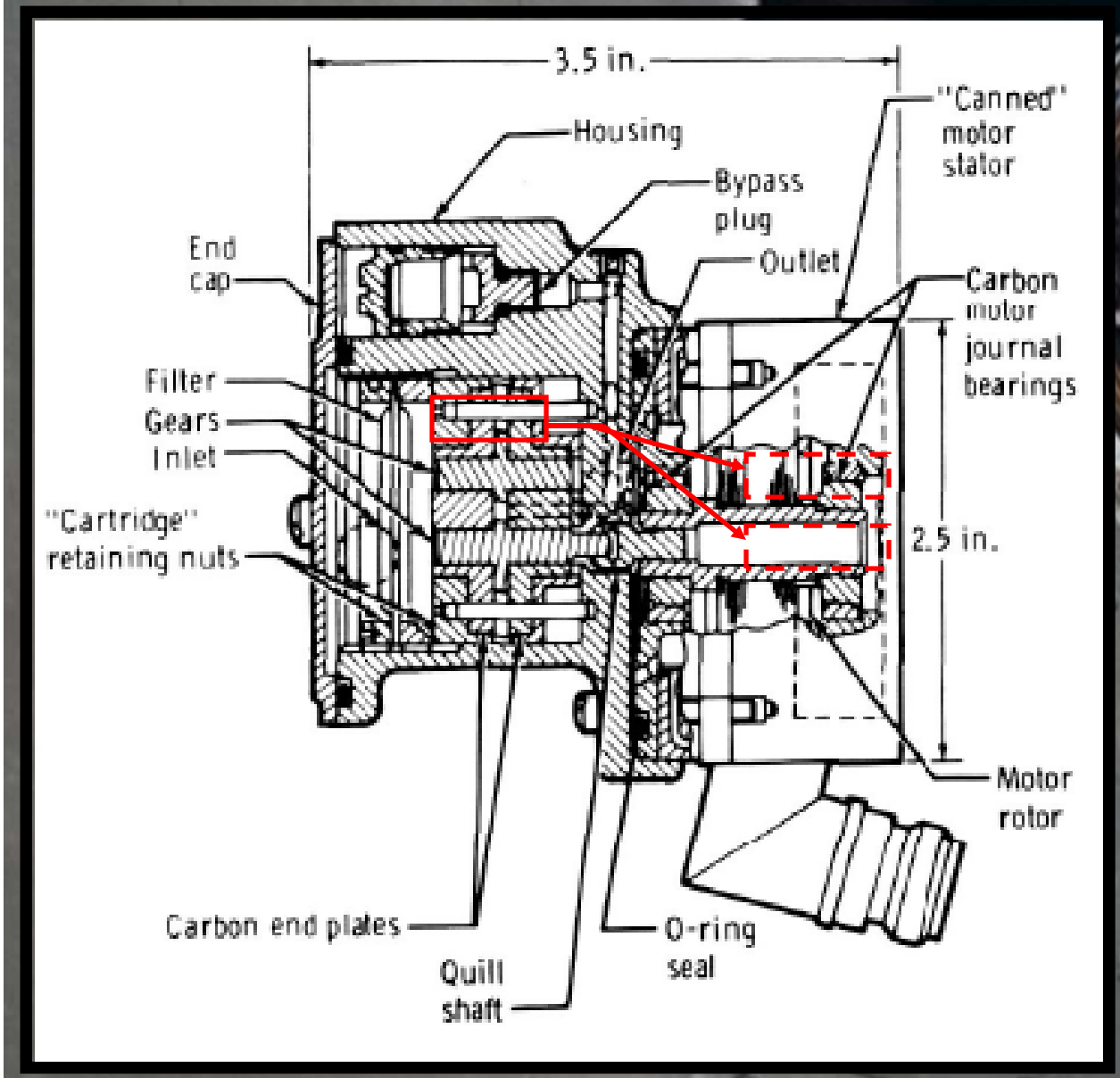


Water-Glycol Pump

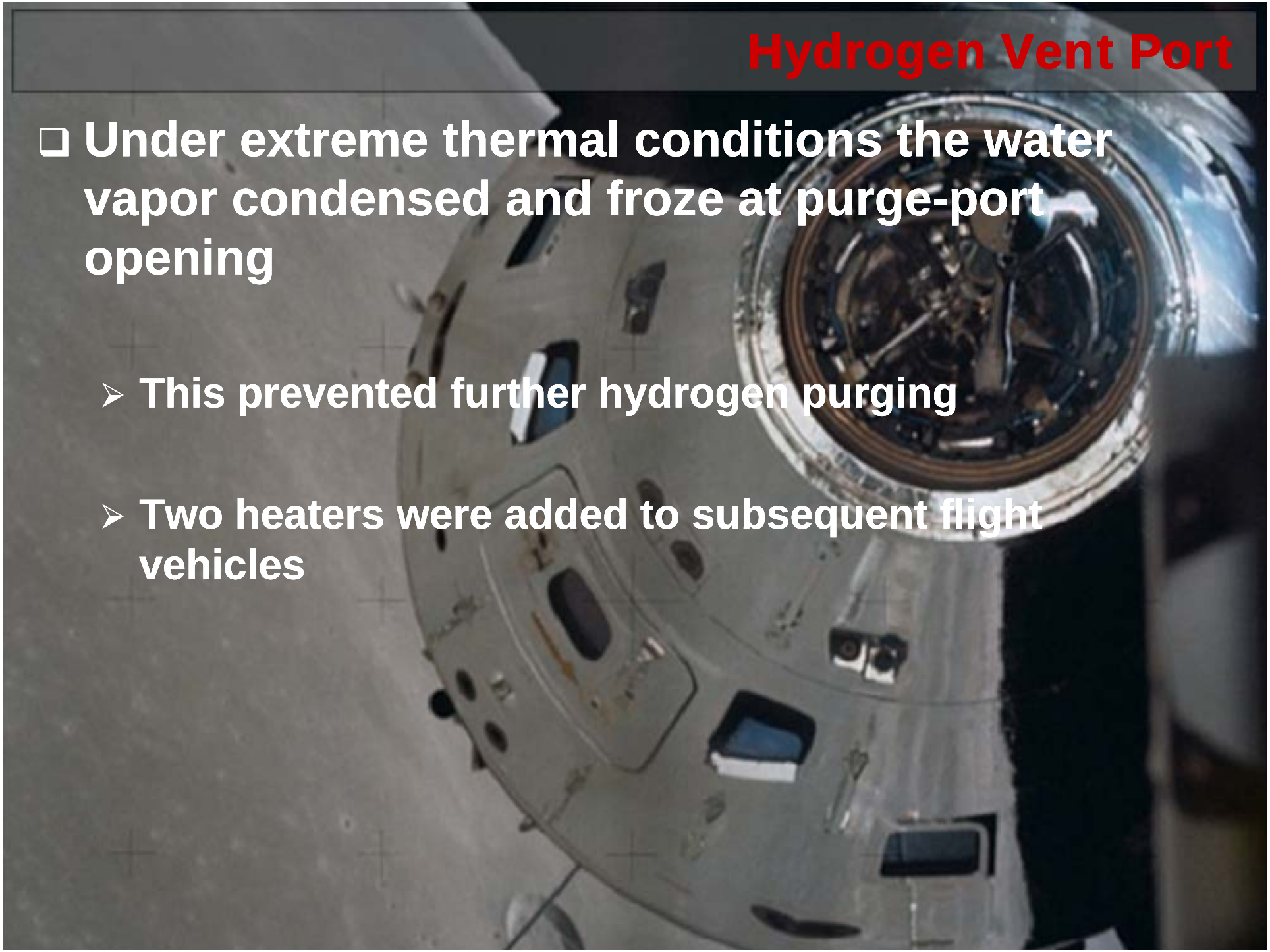
- Leakage and failure to start



Water-Glycol Pump, cont'd



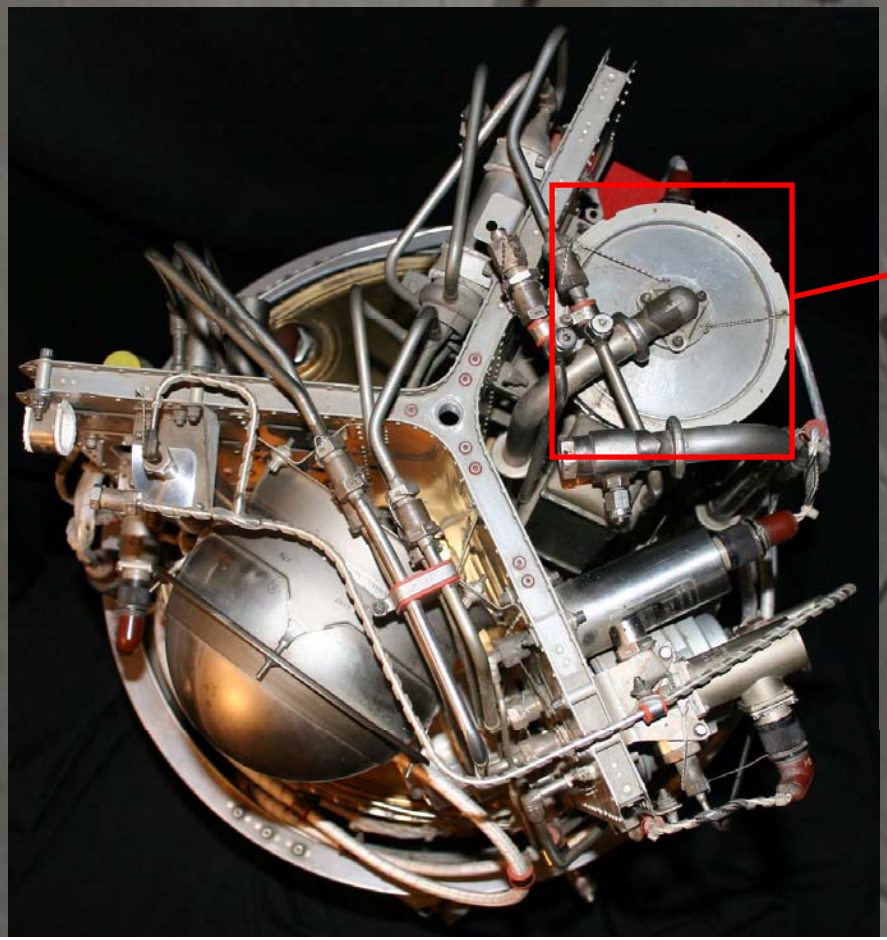
Hydrogen Vent Port



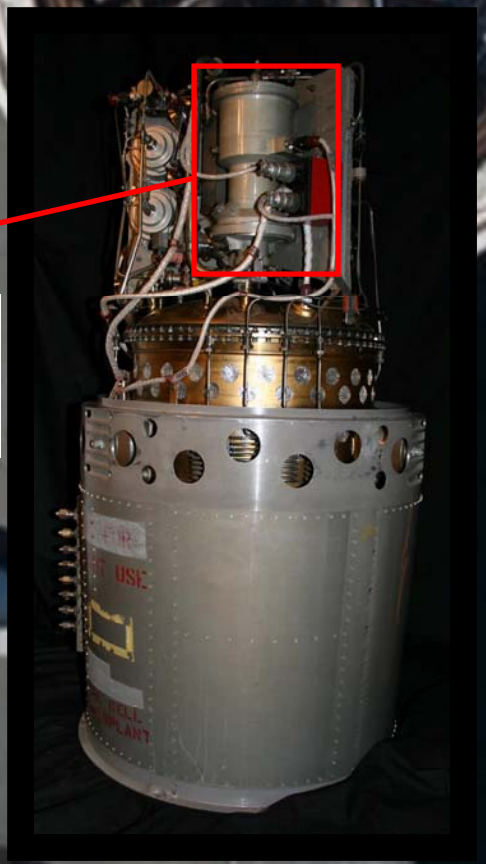
- Under extreme thermal conditions the water vapor condensed and froze at purge-port opening
  - This prevented further hydrogen purging
  - Two heaters were added to subsequent flight vehicles

Hydrogen Pump/Separator

- Because the hydrogen was saturated with water vapor, several electrical problems were encountered until a satisfactory waterproofing epoxy insulation was found

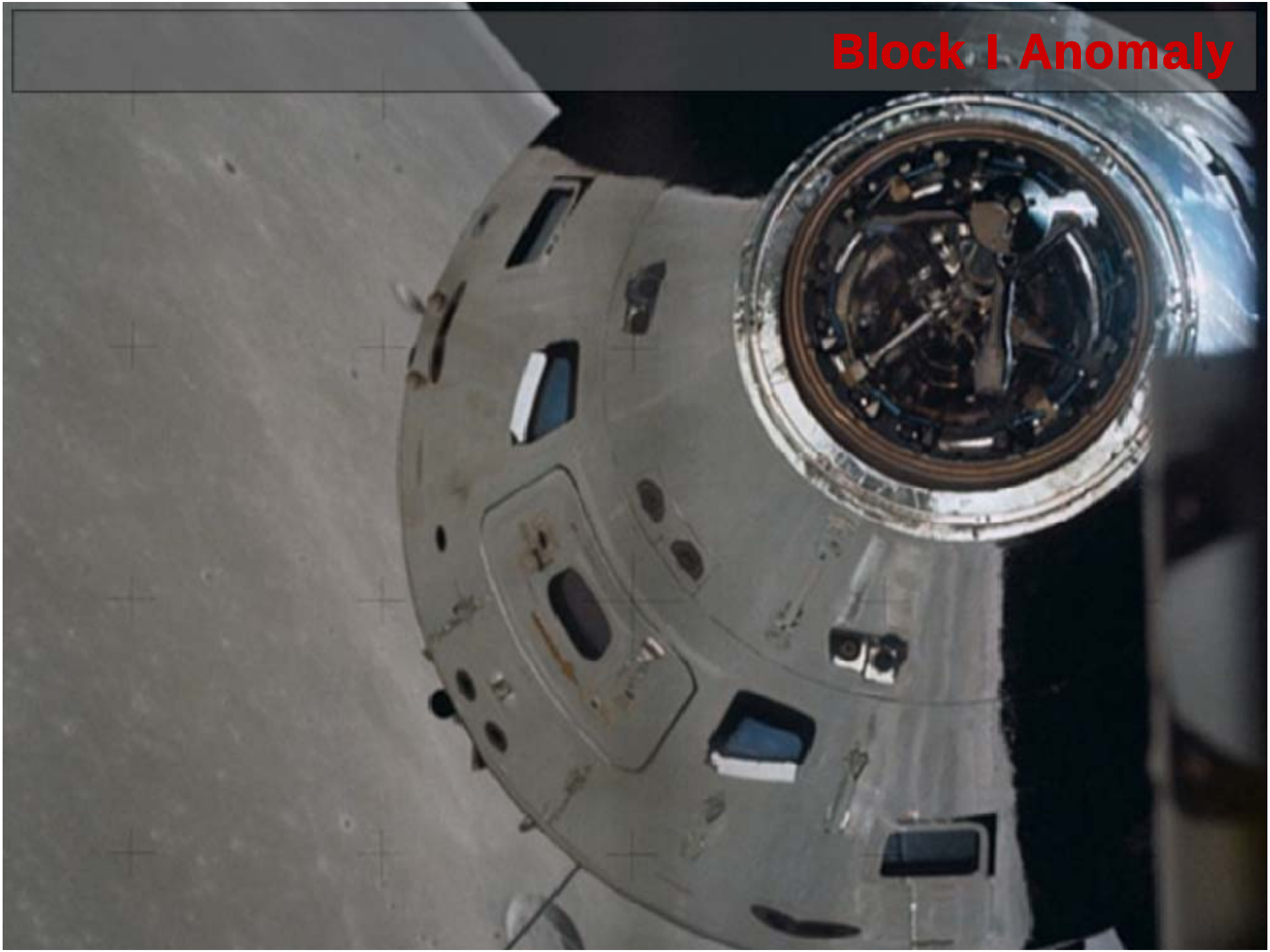


TOP VIEW



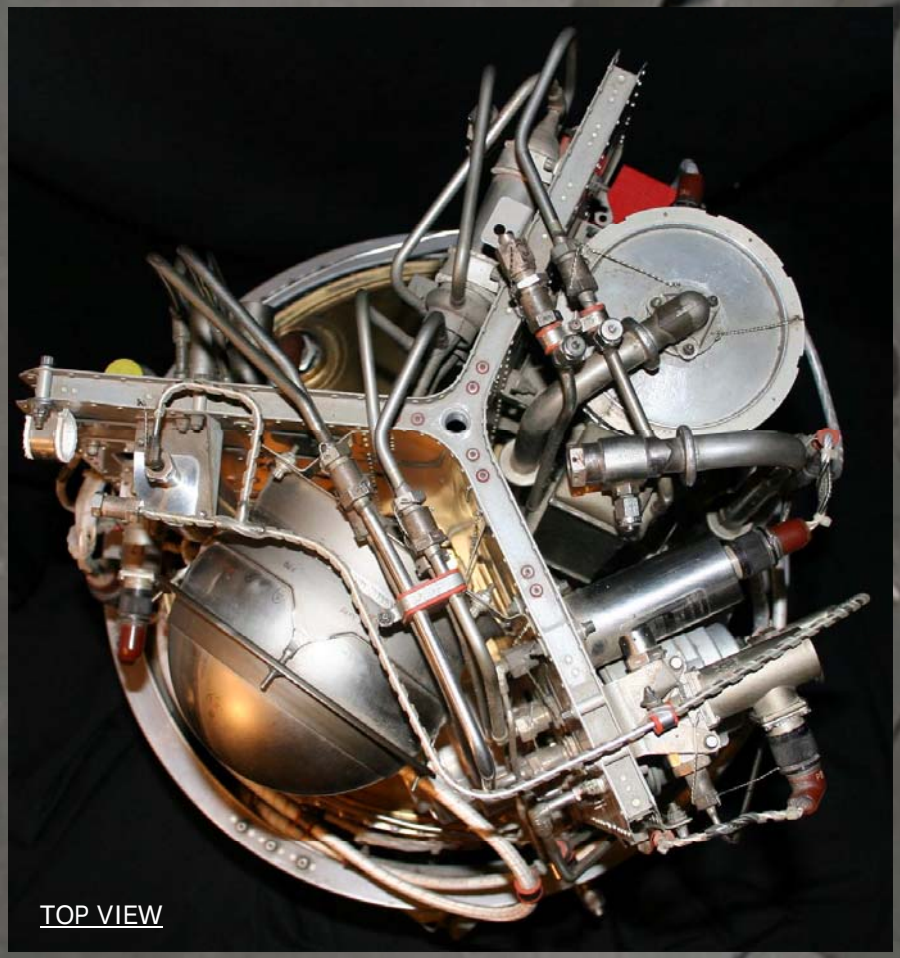
BACK VIEW

Block I Anomaly

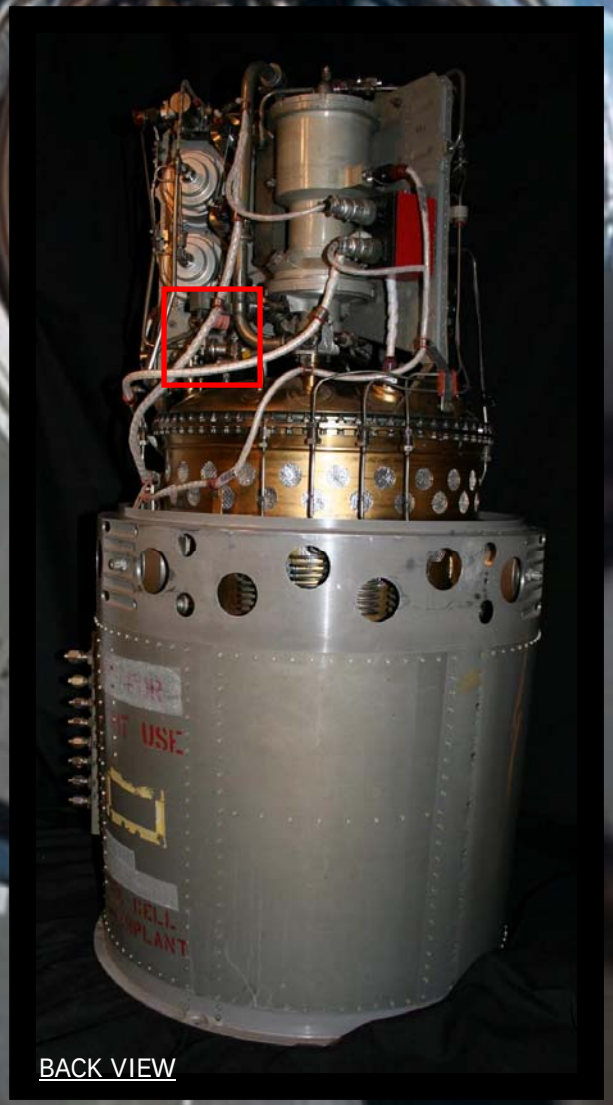


Secondary Coolant Loop

- Cooling capacity of the secondary coolant loop was reduced

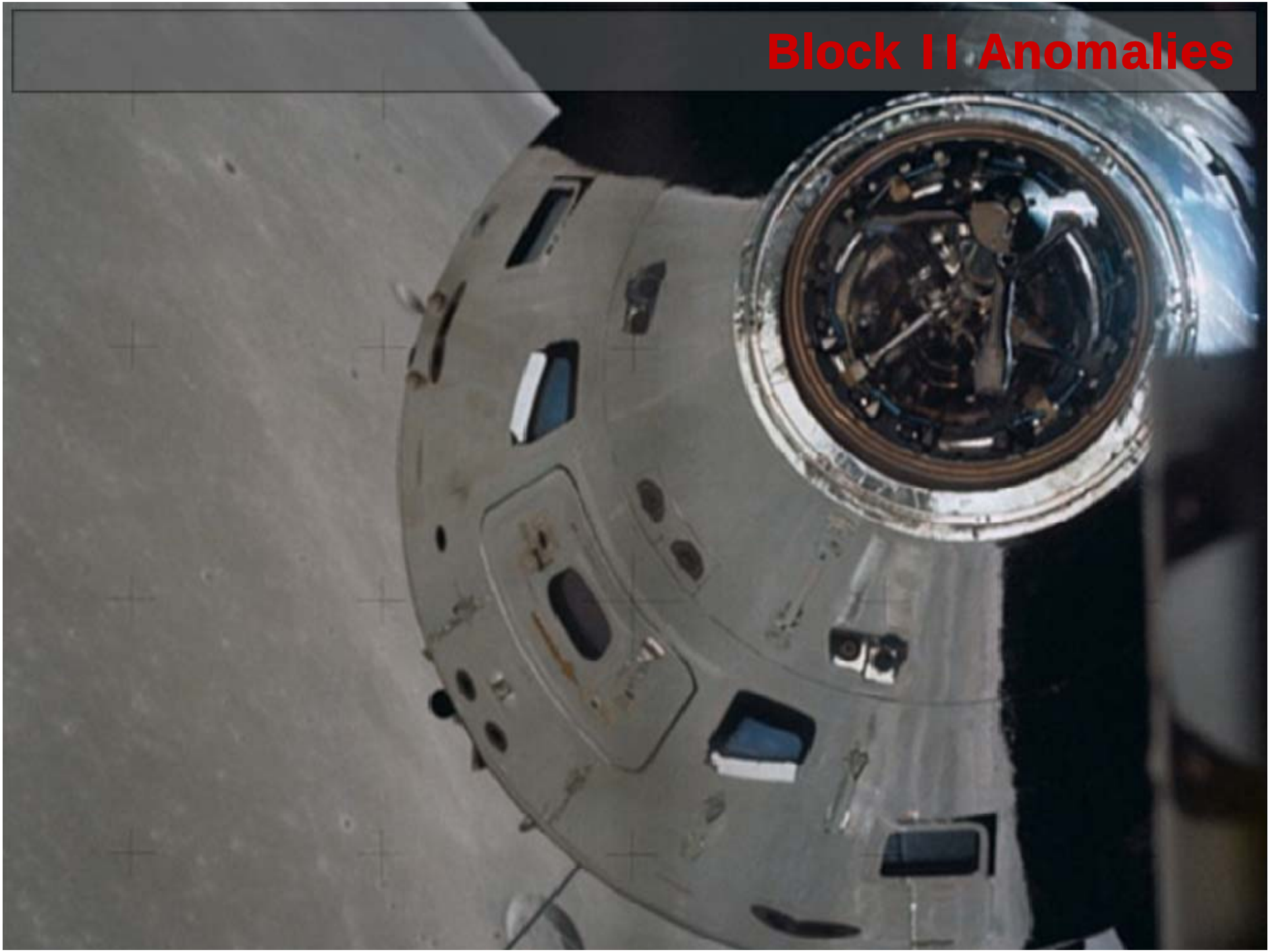


TOP VIEW

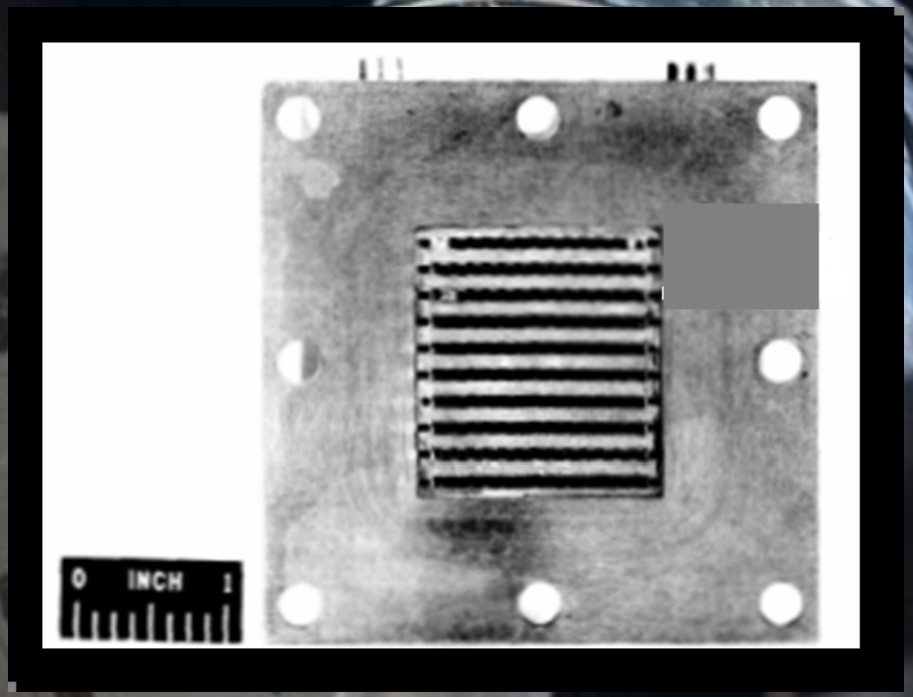


BACK VIEW

Block II Anomalies

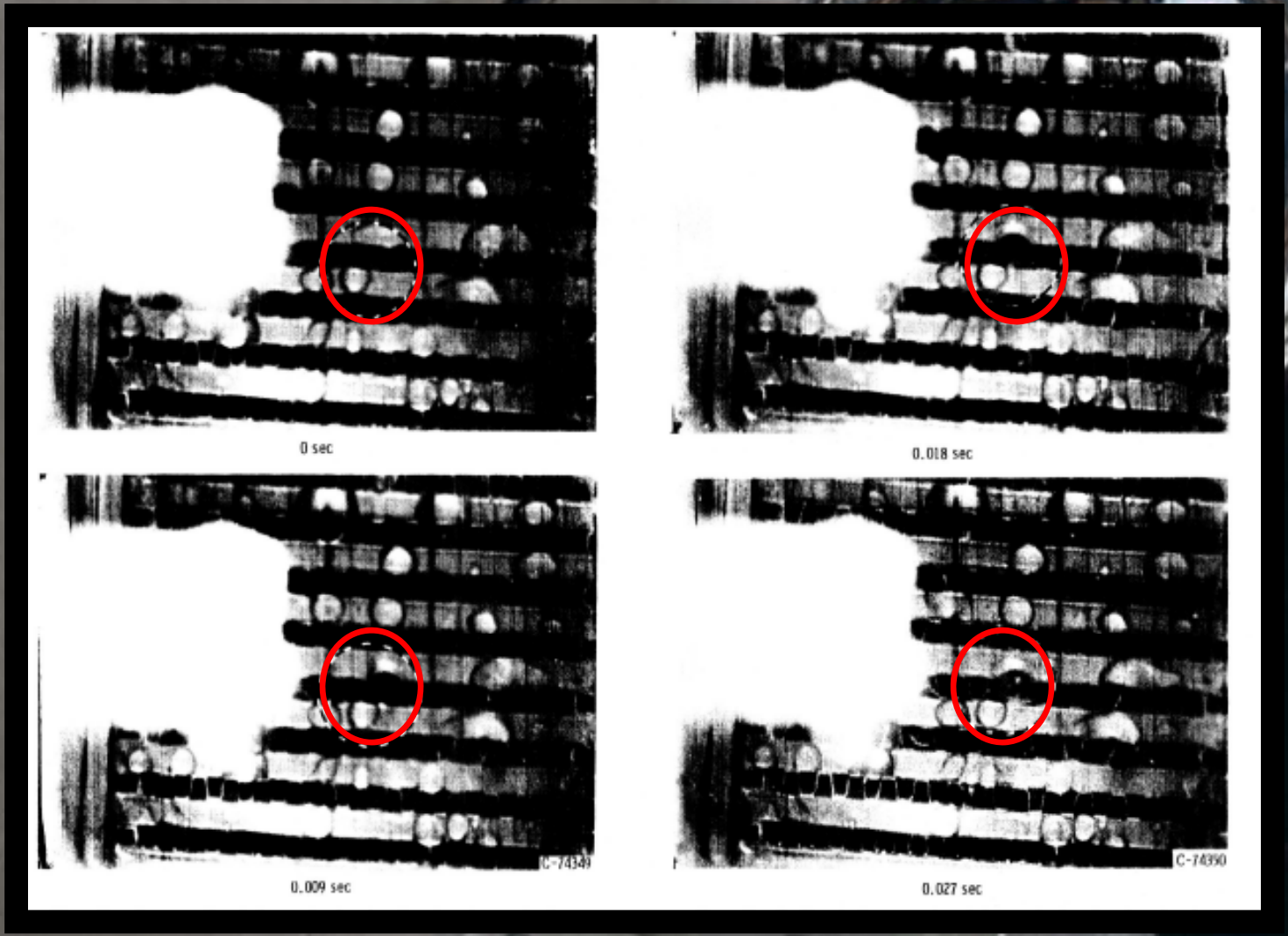


Condenser Exit Temperature 1

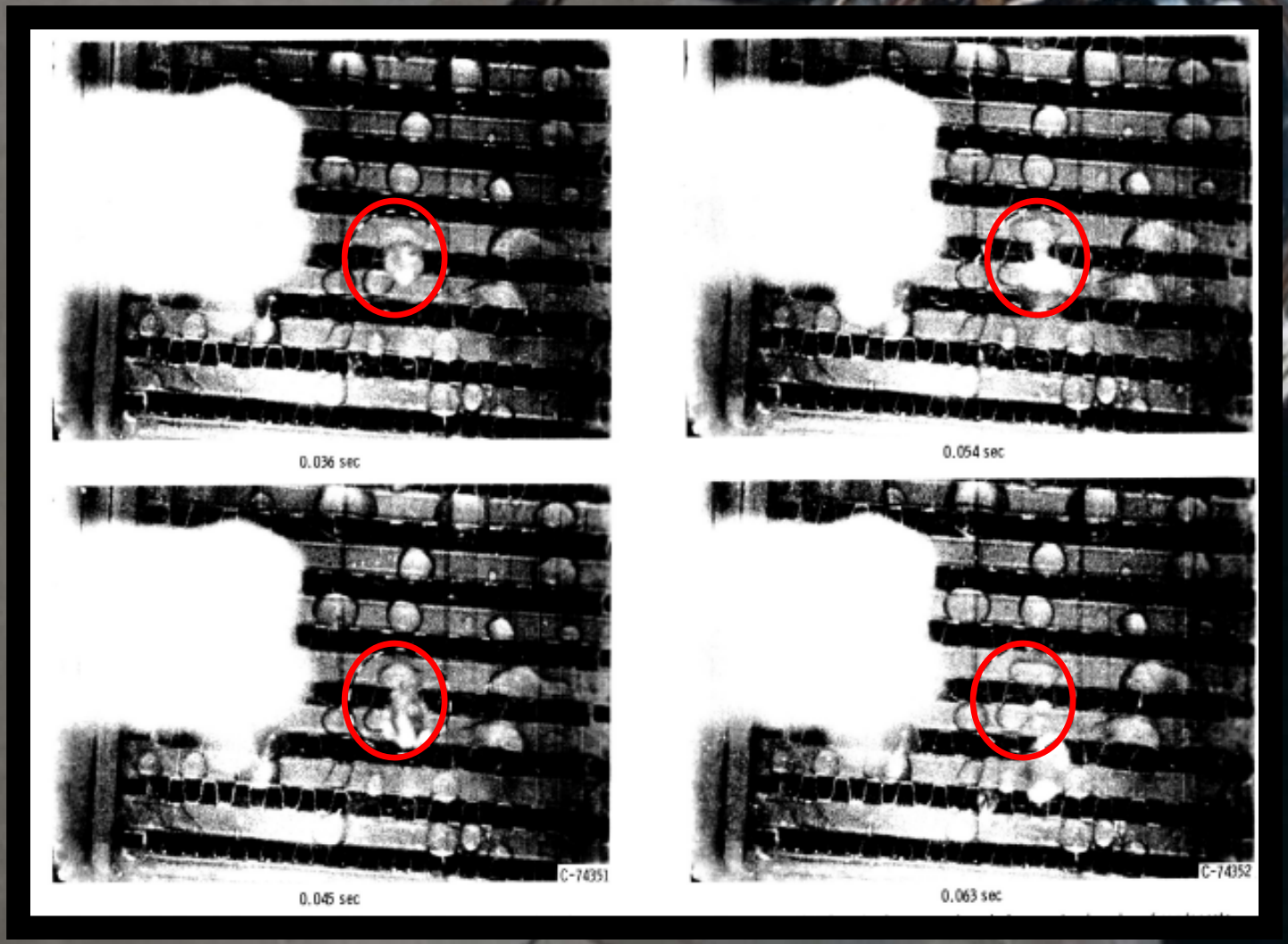


Condenser Exit Temperature 2

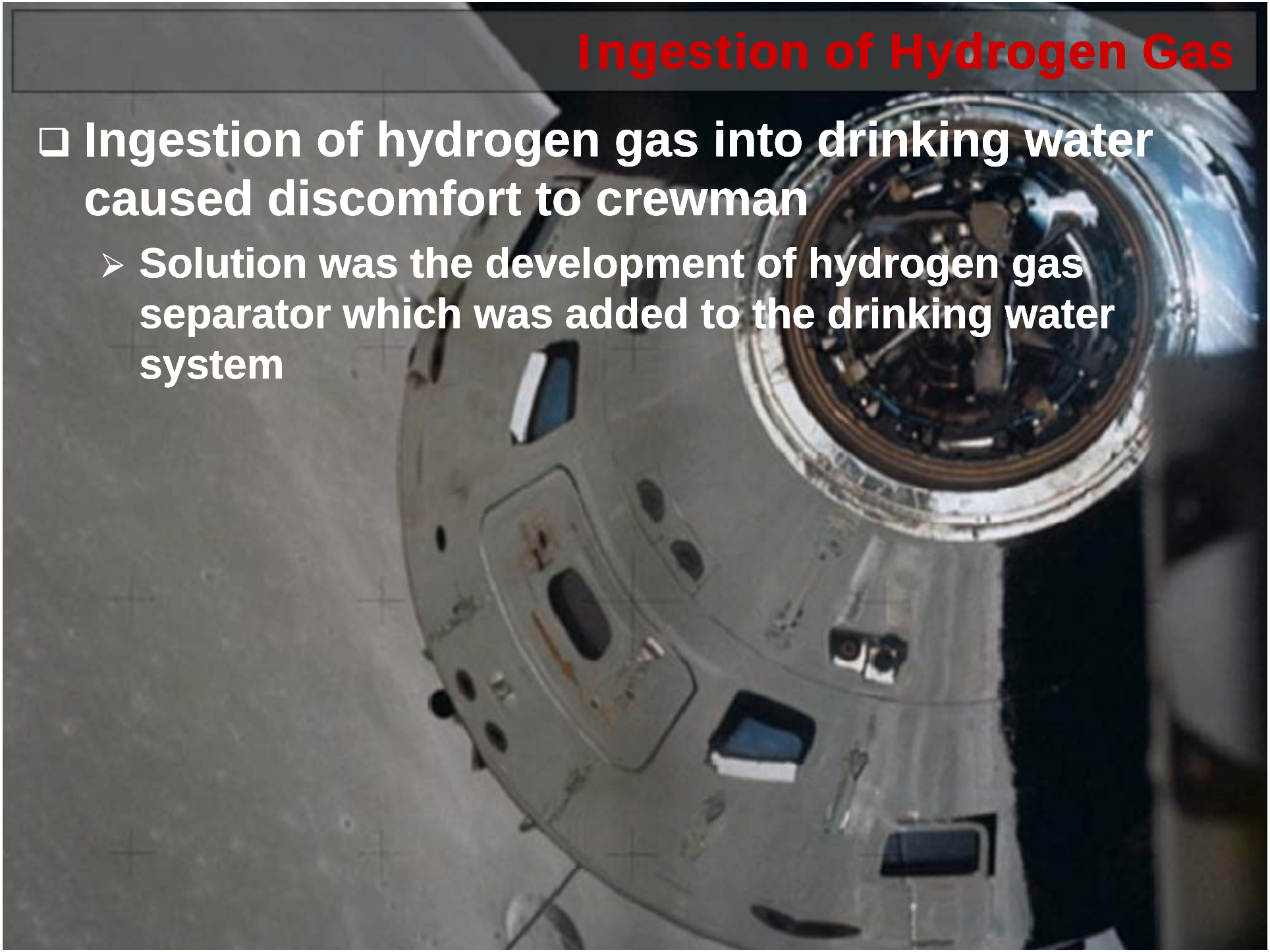
- Water slugging out of condenser



Condenser Exit Temperature 2



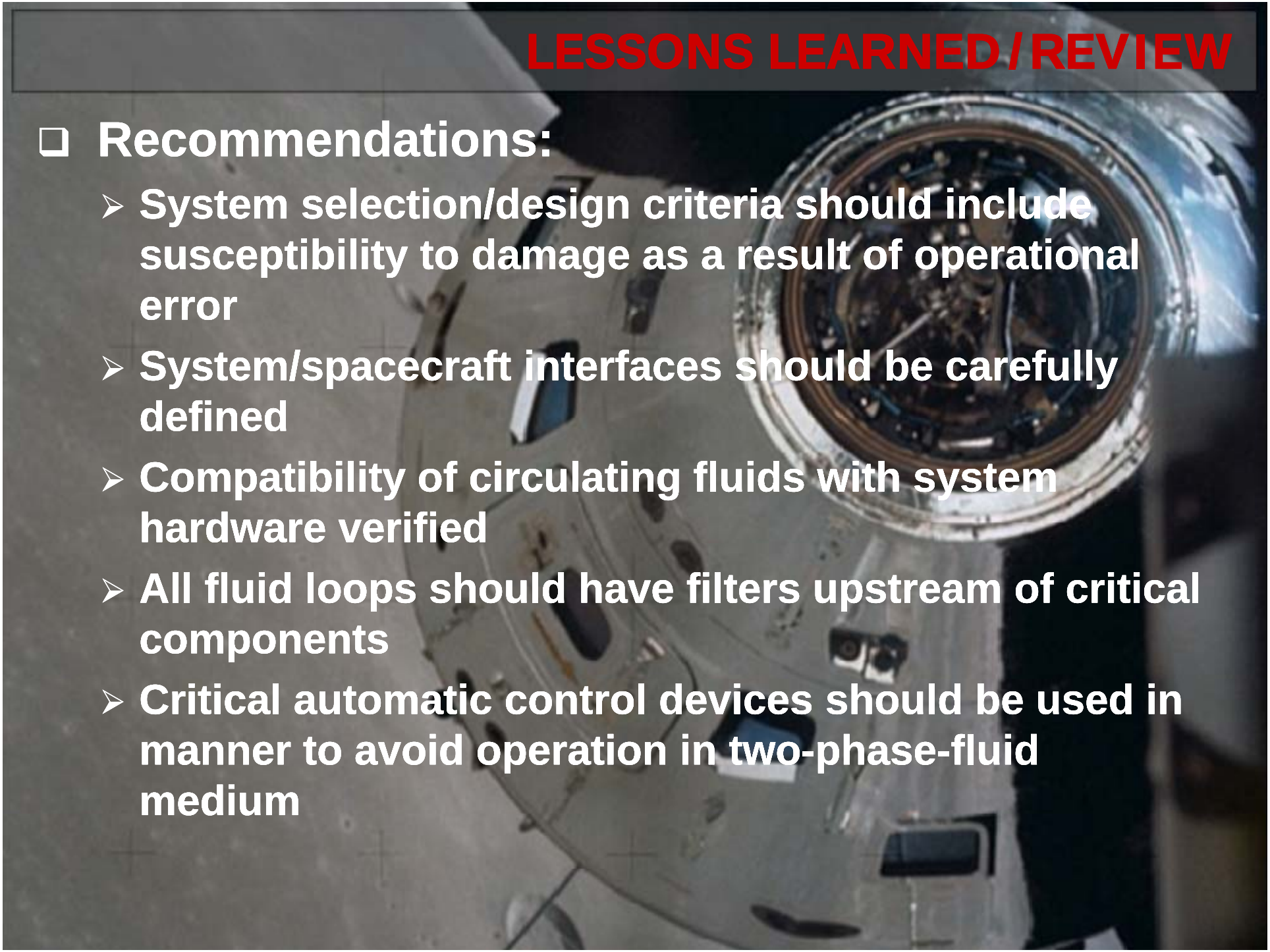
Ingestion of Hydrogen Gas



- Ingestion of hydrogen gas into drinking water caused discomfort to crewman
  - Solution was the development of hydrogen gas separator which was added to the drinking water system

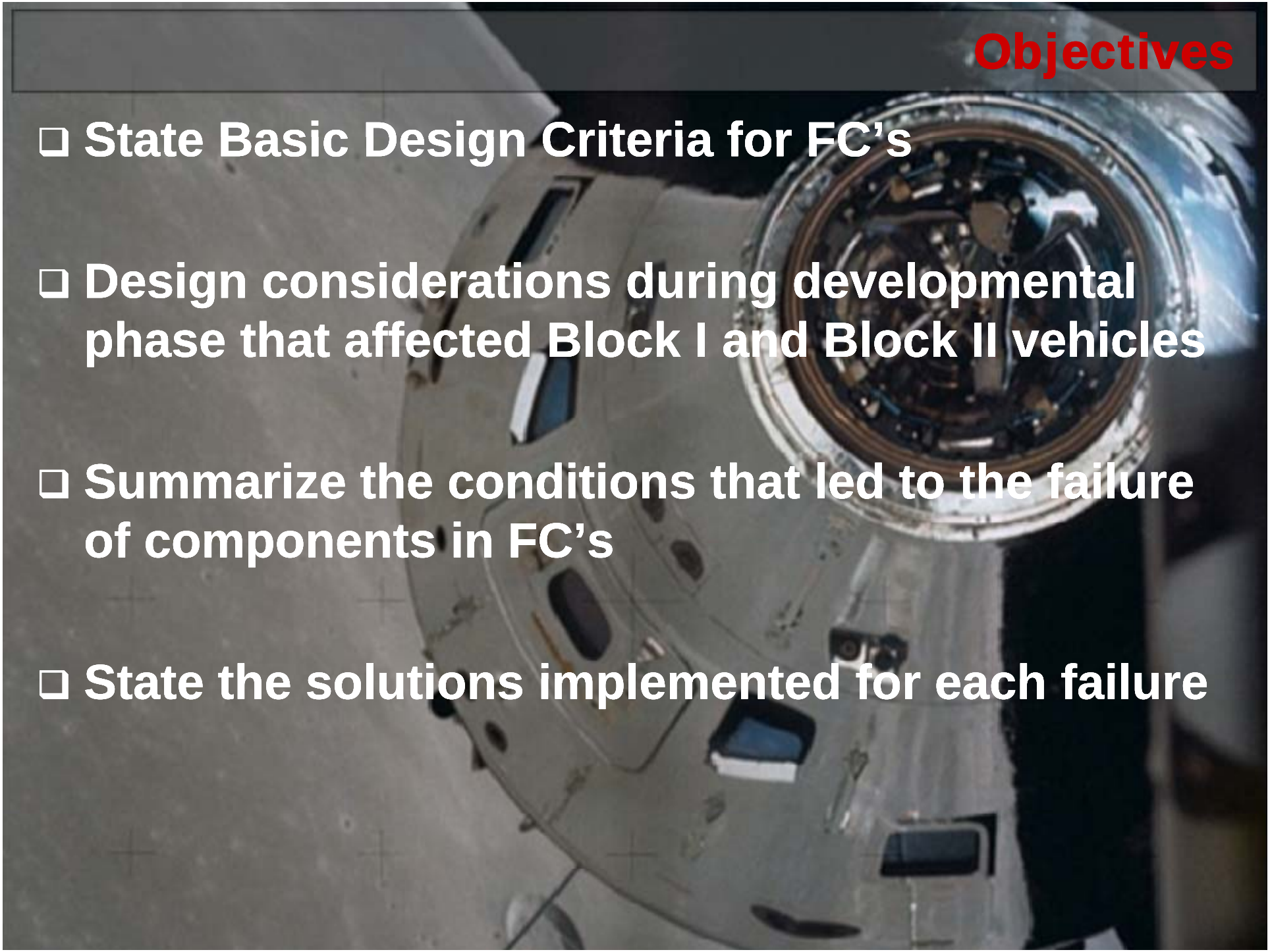
Lessons Learned / Review

- Some problems were unique to the FC and others were caused by integration with other spacecraft systems
- Operational errors caused the costly failure of several FC's during early servicing and checkout operations
- Contamination was a serious problem for spacecraft subsystem
- Redundancy philosophy that was instituted by FC system designers resulted in system and mission flexibility



LESSONS LEARNED / REVIEW

- **Recommendations:**
  - System selection/design criteria should include susceptibility to damage as a result of operational error
  - System/spacecraft interfaces should be carefully defined
  - Compatibility of circulating fluids with system hardware verified
  - All fluid loops should have filters upstream of critical components
  - Critical automatic control devices should be used in manner to avoid operation in two-phase-fluid medium



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