Lessons Learned from the Development of the MSL Descent Stage Propulsion System

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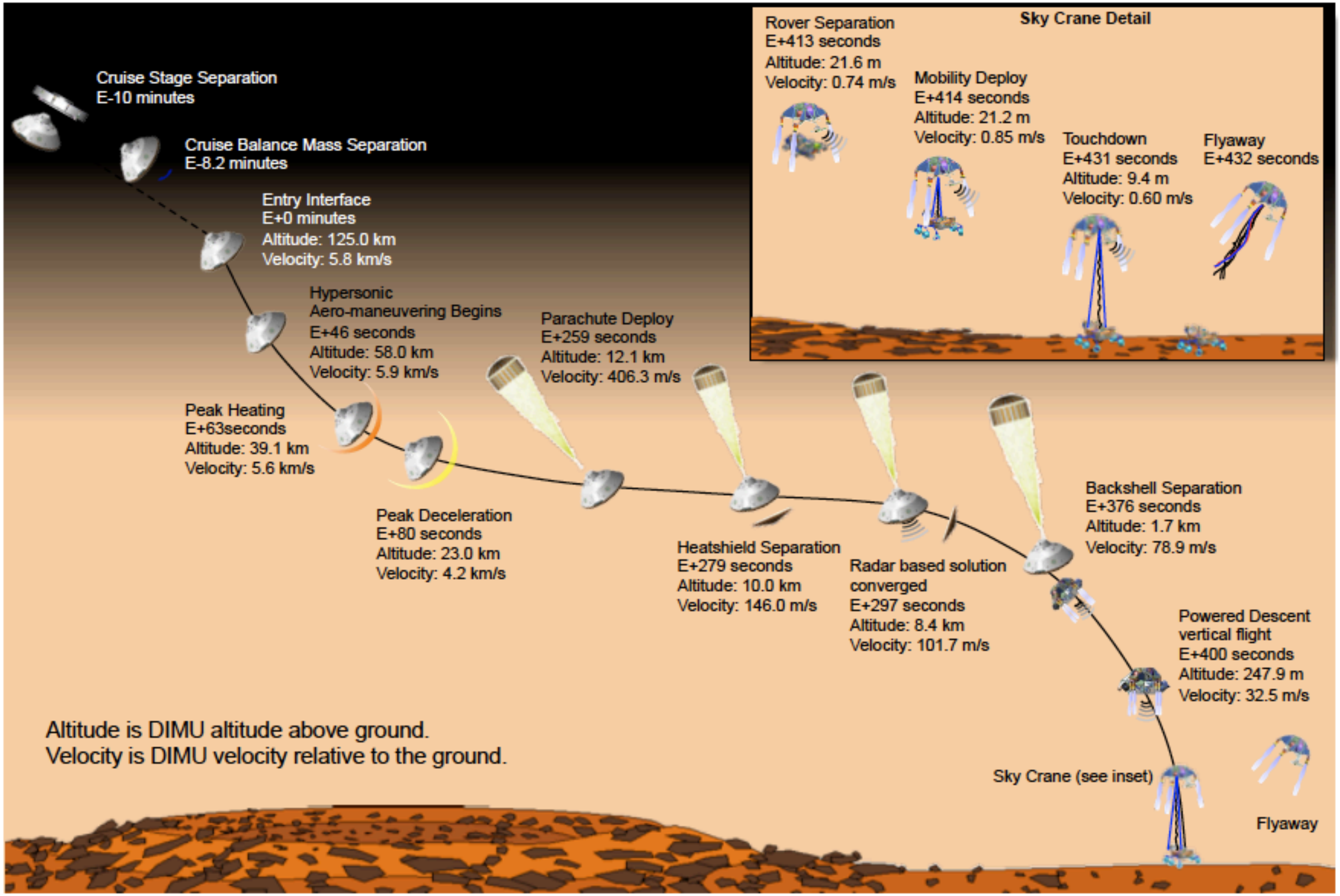
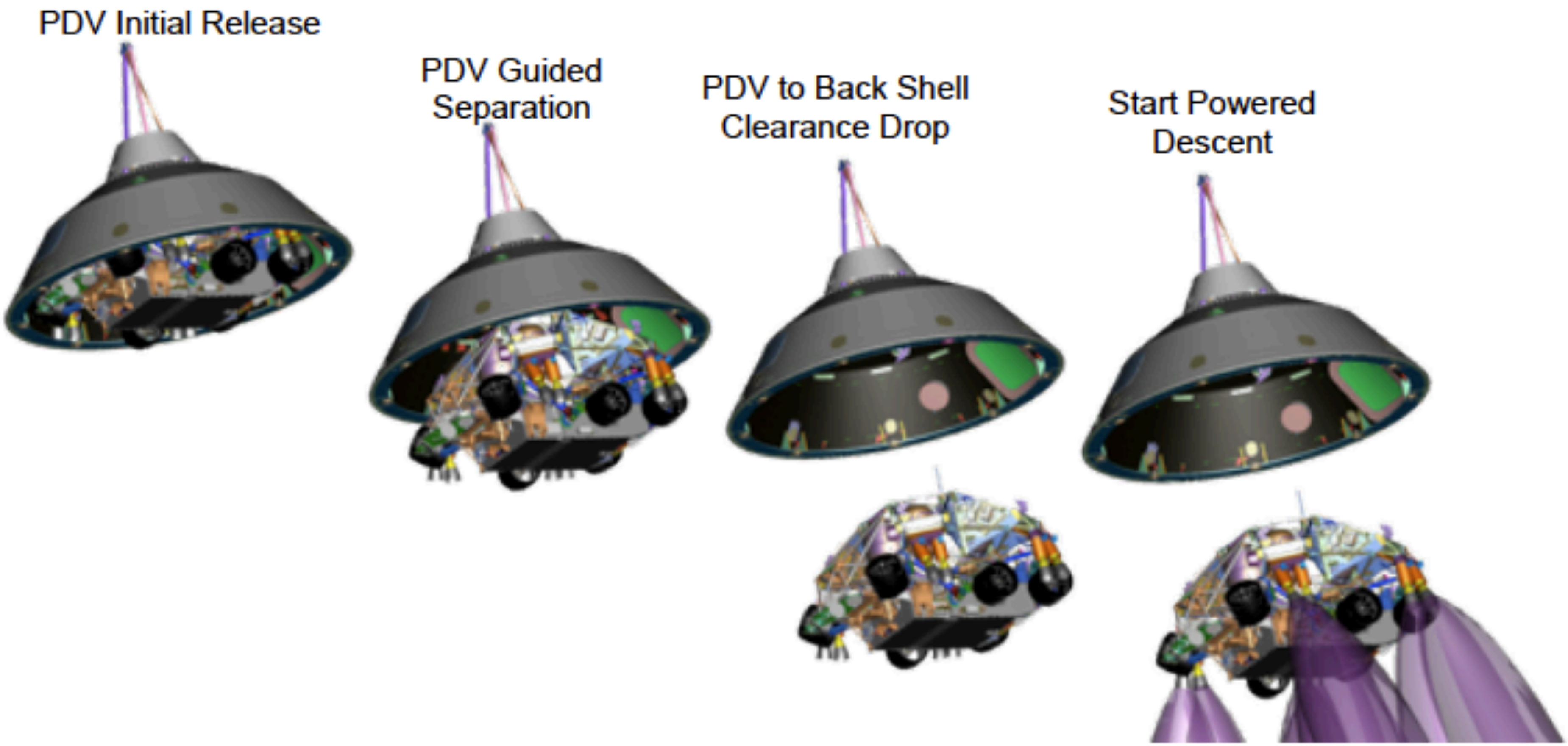
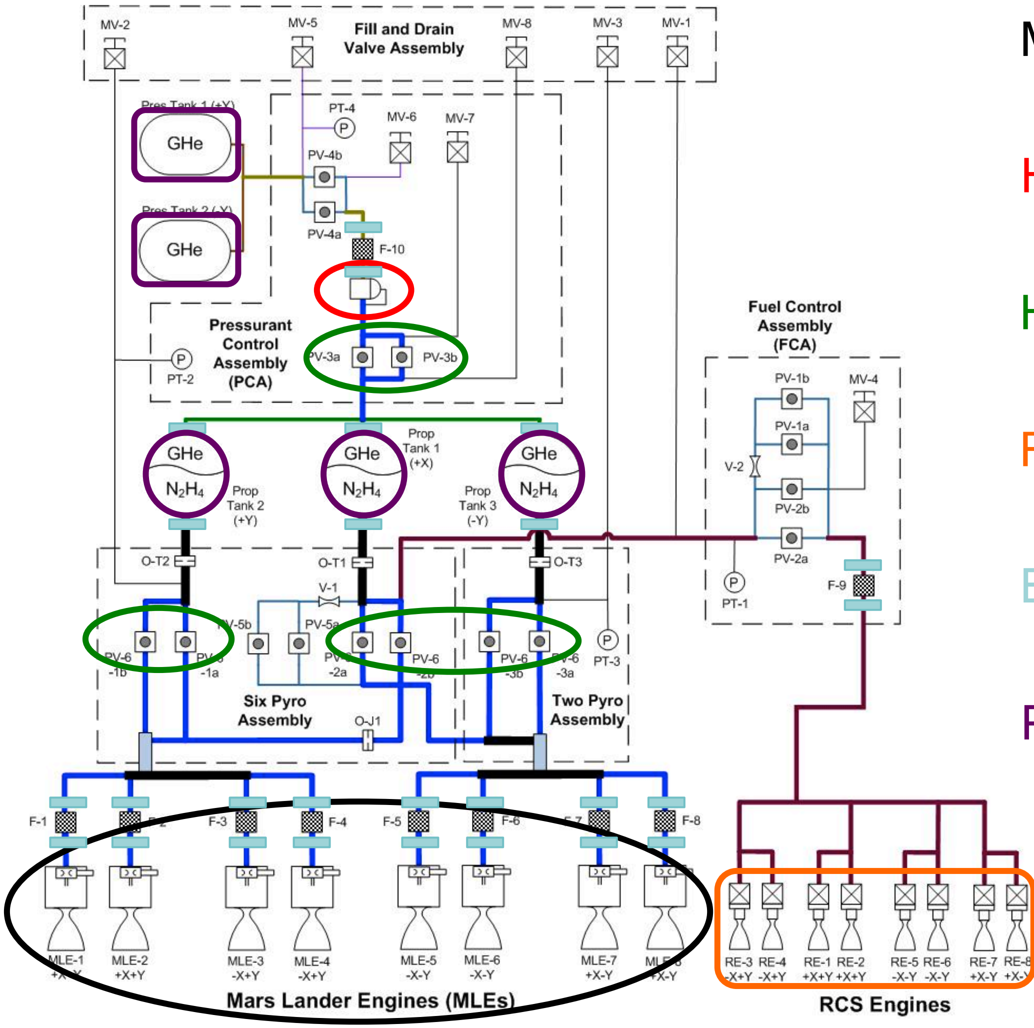
MSL Entry, Descent, and Landing



Powered Descent Vehicle Separation



New Developments/ Qualifications



MLE and Throttle Valves

High Flow Pressure Regulator

High Flow Pyro Valve

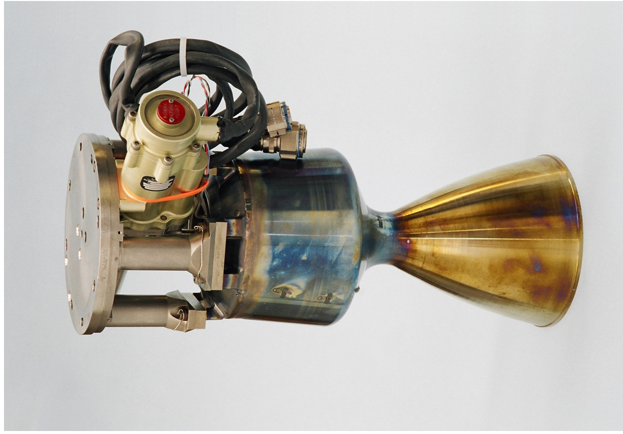
RCS Thruster Valves

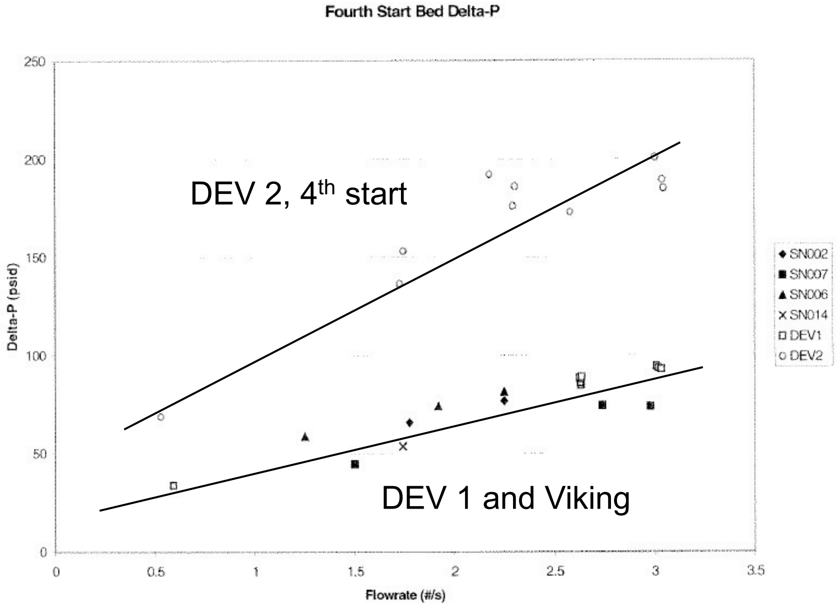
Bimetallic Transition Tubes

Pressurant and Propellant Tanks

Calling the DS Propulsion System Ambitious is an Understatement!

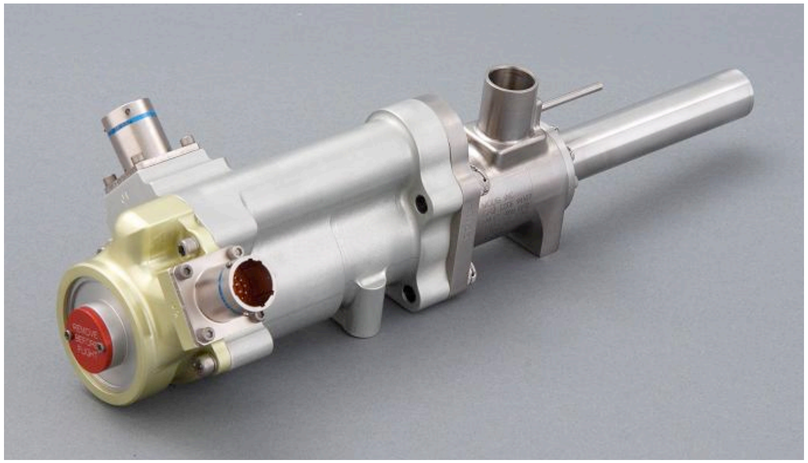
MLE Thrust Chamber (Aerojet)

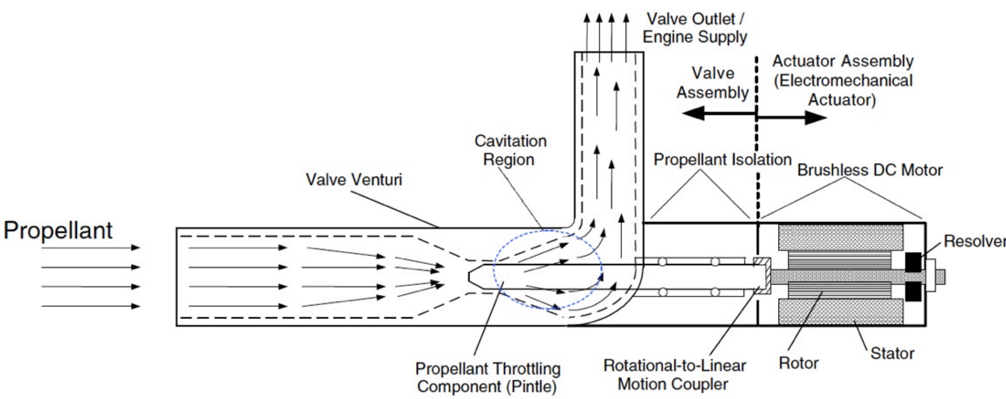




- Experiences
  - After one successful development test, second development engine experienced rapid bed degradation
    - Higher bed pressure drop
    - More breakup of catalyst
    - But – less catalyst loss
  - Concluded anomaly probably caused by cold (4 °C to 10 °C) propellant
    - Higher catalyst packing density than Viking catalyst may have been a contributing factor
- Lessons
  - Propellant temperature can have a pronounced effect on catalyst bed life
  - Subtle changes in catalyst shape and size distribution can have a major affect on potential for clogging by fines

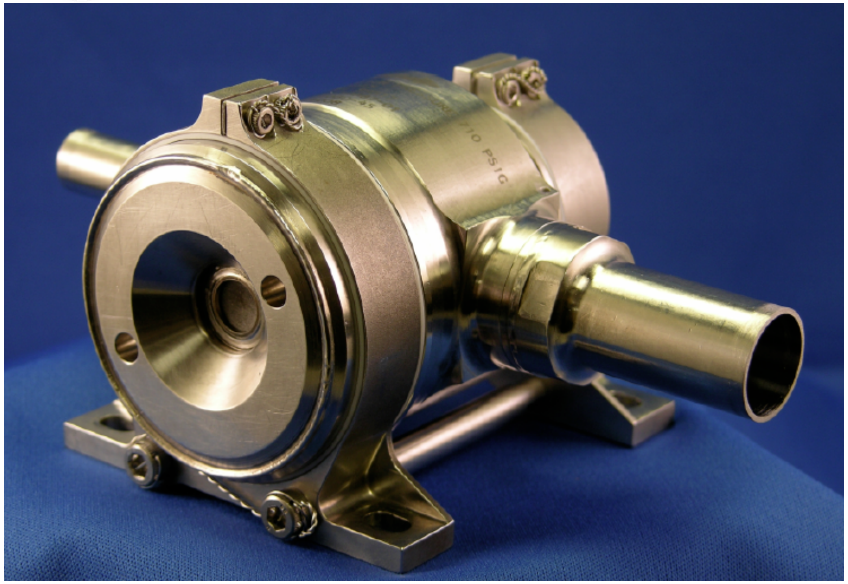
MLE Throttle Valve Assembly (Moog)





- Experiences
  - Leakage past the seals provided for propellant isolation
    - Wear of a Teflon bushing used to guide pintle led to anomalous seal loads and particulate generation when the pintle scraped the valve body
    - Inadequate allowance had been taken of CTE effects on bushing clearance
    - Ball screw design and assembly procedures allowed excessive side forces to develop on the bushing and seals
  - Actuator response significantly degraded when first tested with flight control electronics
- Lessons
  - Design reviews of complex mechanisms must penetrate down to the piece part level, not be performed at the “PowerPoint” level
  - Emphasis should be put one early testing of closed-loop devices with flight-like control electronics

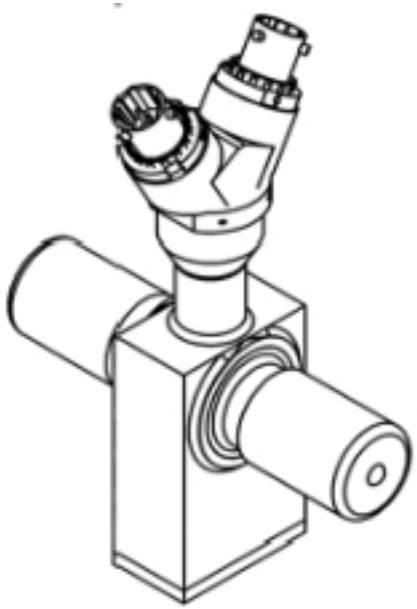
High Flow Pressure Regulator (Vacco)

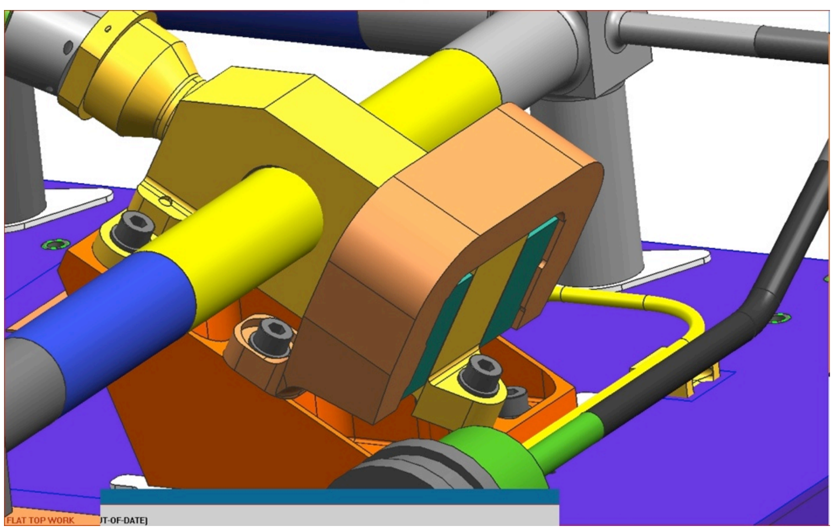


- HFPR Based on Shuttle 750 psi design
- MSL units modified, tuned, and tested to MSL requirements by IPDT
  - Vacco
  - United Space Alliance
  - Indyne
  - JPL

- Experiences
  - Tuning of the regulator to achieve stable operation and meet requirements was time consuming
  - Encountered leakage through metal of regulator cap caused by stringers in parent material
    - Material in-spec but at extremes of allowable ranges
  - Failed (leaky) welds on cap seal weld
    - Poorly designed weld prep
- Lessons
  - Pilot-operated regulators are highly complex devices which can require considerable resources to adapt to a new application
  - Early involvement of Materials & Processes (M&P) specialists can avoid problems with in-spec but abnormal material conditions and/or poorly conceived processes

High Flow Pyro Valve (Conax)





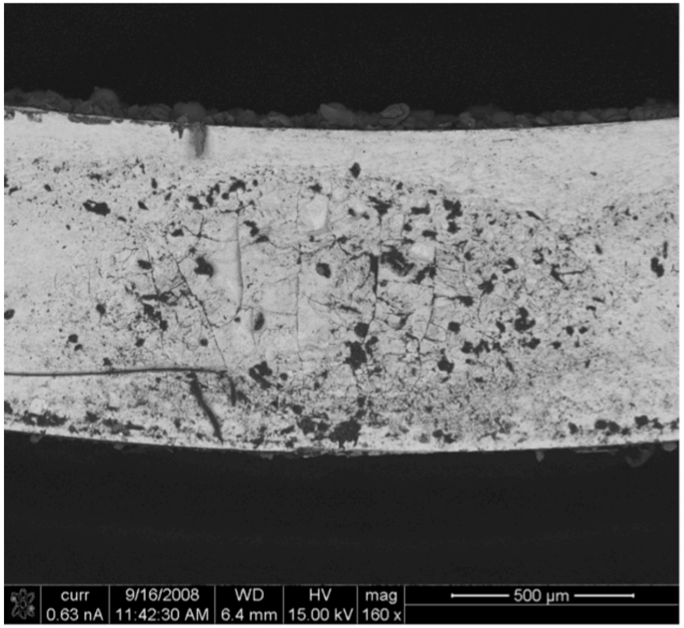
- Experiences
  - Management turnover at Conax contributed to slips and oversights
  - Booster ignition failures and PCA burn through required PCA redesign
  - Ram retention failures required "magnetic latch" fix at the last minute
    - "Heritage" ram retention scheme wasn't really heritage
- Lessons
  - Lack of management continuity in a development task should be corrected early (and loudly, if need be!)
  - Heritage is an easily abused concept
    - Small changes can have large impact
  - Development and qualification tests should not be simply evaluated with pass/fail criteria, but examined for signs of incipient failure
    - Early signs of marginal booster ignition were neglected for years
    - Early indications of ram retention issues were overlooked

Descent Thruster Valve (ValveTech)

Aerojet MR-107U Thrusters for MSL
With VTI Valves

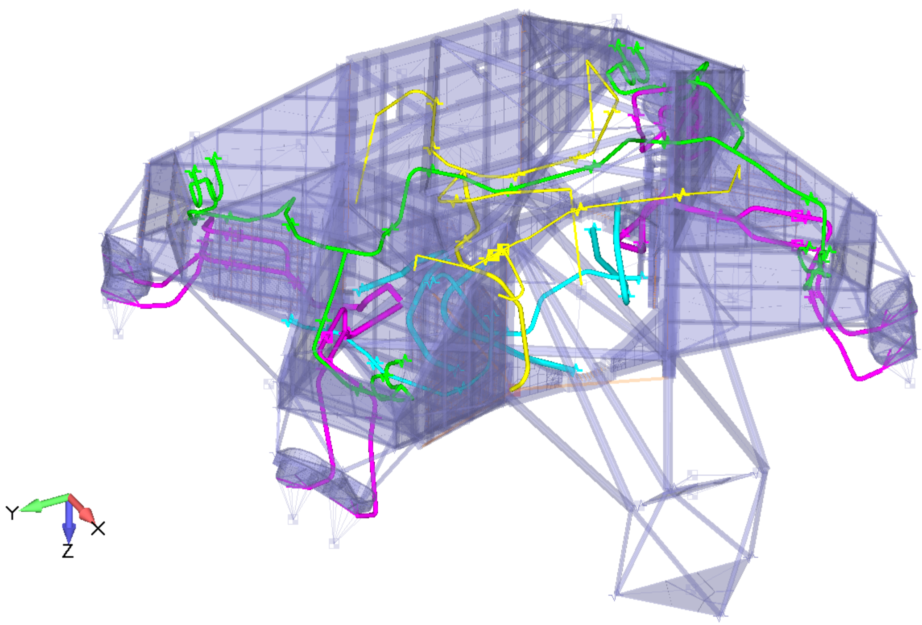
- Experiences
  - Failures due to metal fragments generated during valve assembly
  - Slow closing response failure due to Johansen block effect
  - Leakage due to improperly vented seal
  - Leakage attributed to deformation of seal by excessive “squeeze”
  - External leakage through stringers in valve bodies
  - “Failed closed” valves in thruster hot fire due to high inlet pressure, high temperature, and inadequate seal retention
- Lessons
  - Beware of design changes for ease of manufacturability
  - Early involvement of M&P is important
  - Unique operating conditions should be tested early in development
  - Face-to-face meetings can be invaluable
  - Design reviews need to penetrate to the piece part level, not “viewgraph engineering”

Bimetallic Transition Tubes



- Experiences
  - One qual transition tube failed tensile test, but with “acceptable” strength
  - Several Ti – to – CRES transition tubes failed fatigue testing on first cycle
  - Investigation showed melt zones and formation of brittle intermetallics at joint
  - Vendor for inertial weldments routinely accepted lots where some LAT units failed ultimate tensile test requirements
    - Same signature as failed transition tubes
  - Learned that the vendor had much better experiences using a different Ti alloy, but did not pass this along
- Lessons
  - Bimetallic transition tubes can be a major risk item and require close scrutiny
  - Any failures of weldments or transition tubes at the solid state joint should cause rejection of the lot and review of process
  - Early M&P specialist involvement is critical (does this sound familiar?)

System Configuration and Tubing Size

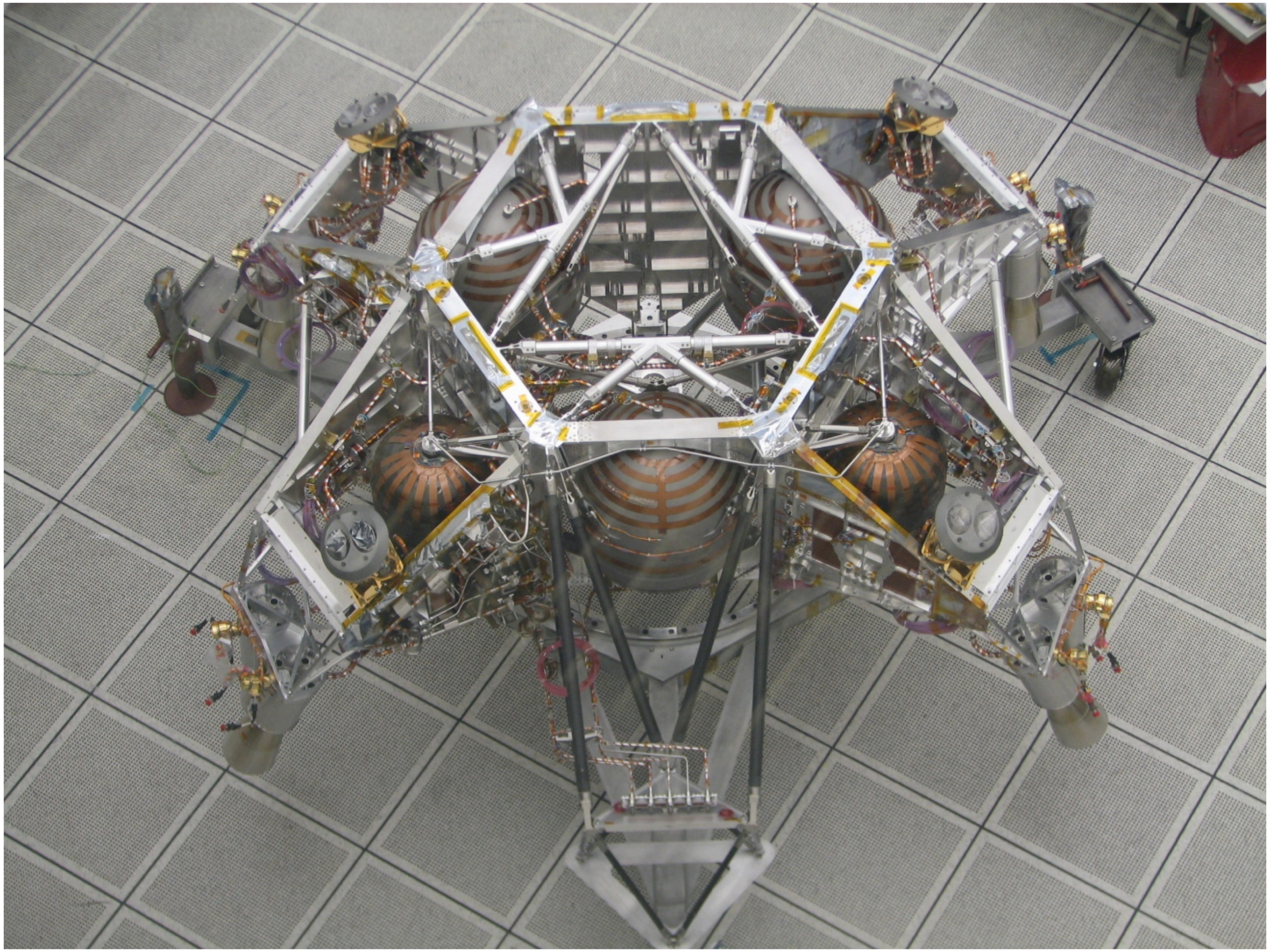


Legend

Purple Lines: MLEs
Green Lines: RCS Thrusters
Blue Lines: Tanks to Pyro Assemblies
Yellow Lines: Pressurant Lines

- Experiences
  - Large line sizes required for DS propulsion had stiffness comparable to that of structure, leading to development of substantial stressed under flight loads
  - This required very detailed stress analyses and fatigue analysis of the feed system
  - Late recognition of the magnitude of this effort resulted in very late design changes (during fabrication)
- Lessons
  - When propulsion lines are large enough to have stiffness comparable to that of the structure is is possible to induce very large stresses that are difficult to model
  - If possible, either the structure should be stiffened or complaint elements should be introduced to the feed system to minimize stress levels

Conclusion



In spite of the challenges, we delivered! And Landed!

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