MSFC

APL

Robotic Lander Technology Presentation For Discovery 2014

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Robotic Lunar Lander Development Project

Risk Reduction Developing Robotic Lander Technology to the Moon and Beyond

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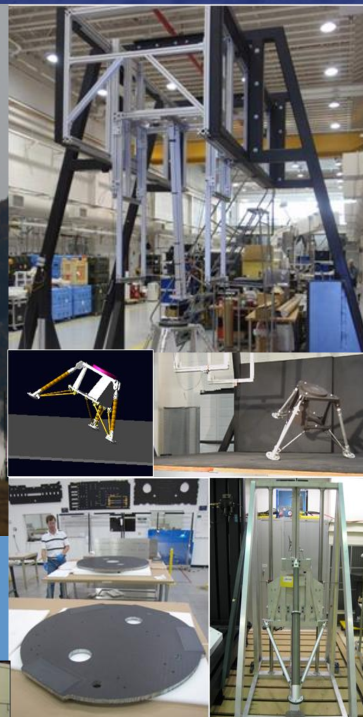
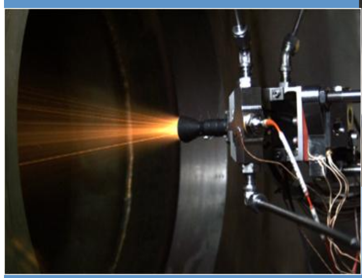
Cold Gas Testbed at MSFC

Robotic Lander Prototype at MSFC

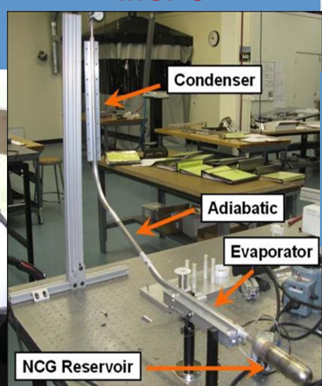


Lightweight Structure and Landing Stability Testing at APL

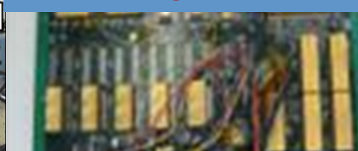


DACS Thruster Testing at WSTF

Battery Performance Testing at MSFC



Variable Link Testing at MSFC

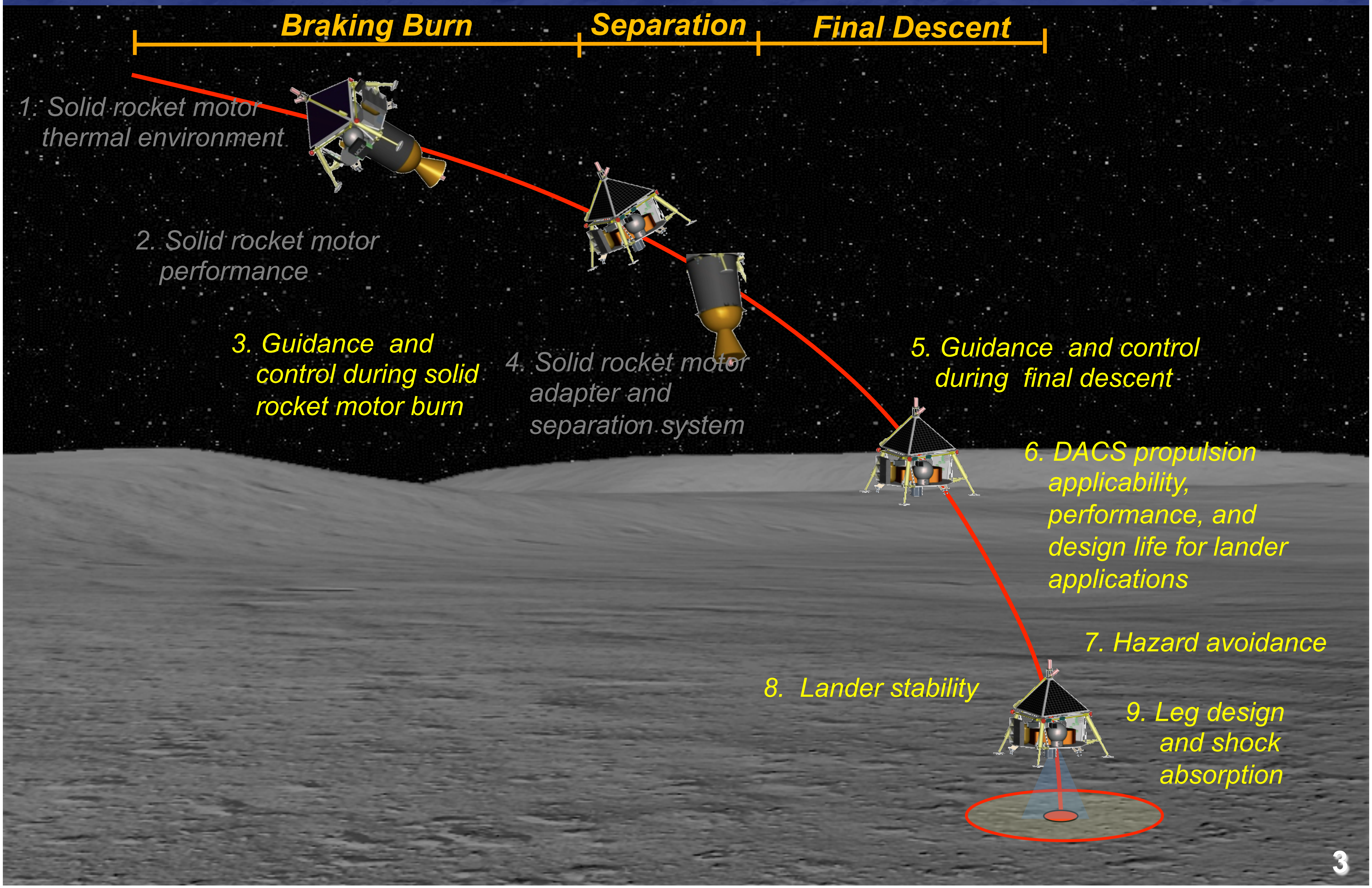


Avionics at APL

	Technical Challenge	Technical Solution(s)	Risk Reduction Activities Status
✓	Soft landing guidance, navigation & control on an airless body	• Star Tracker, IMU, Altimeter, and Landing Cameras	✓ Completed Robotic Lander Prototype @ MSFC ✓ Completed High fidelity end-to-end simulations @ APL ✓ Completed optical nav development & testing. Developed a large image database of descent & terrain profiles collected from helicopter field tests to evaluate landing performance and terrain navigation.
✓	Pulsed, high thrust to weight propulsion (MON-25, 10 kpsi)	• Leverage DoD DACS propulsion technology	✓ Completed DACS thruster test with MON-25 at ILN duty cycle @WSTF ✓ Completed pressure reg. testing at high blow-down ratio ✓ Completed propulsion feed-line characterization testing ✓ Completed propellant tank diaphragm characterization testing.
✓	Providing power through lunar night for 6 year mission	• Solar/Battery: High energy density Li-ion	✓ Completed initial battery performance testing for extreme lunar temps ✓ Completed accelerated battery life testing ✓ Conducting real time battery life testing
✓	Thermally managing day and night operations over large potential latitudes	• Thermally isolate electronics (WEB) • Variable conductance heat pipe	✓ Completed initial testing of multiple Variable Link Options; began inhouse testing; initiated hardware enhancement efforts ✓ Completed component trades on acquisition & rejection hardware ✓ Developed efficient thermal isolation hardware
✓	Managing power in a highly power constrained design	• Develop avionics based on Leon 3 processor	✓ Completed development and TVAC testing of Leon 3 processor card with robotic lander flight algorithms and flight software
✓	Lightweight structures and landing stability	• Composite decks • Inverted tripod lander	✓ Completed design, fabrication and testing of composite decks ✓ Completed design, analysis and stability testing of flt lander legs and developed a computer model simulating landing dynamics and motion. ✓ Completed design, fabrication, and testing of a full size composite Star Motor Adapter test article.

Robotic Lunar Lander Development Project

Re-Cap of Identified Lander Risk Areas: Landing Phase



3. Guidance and Control During Solid Rocket Burn

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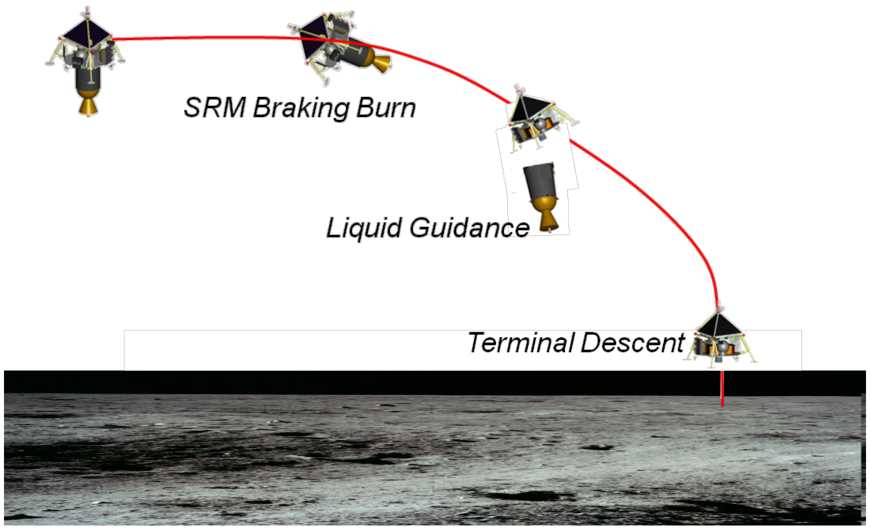
Risk: The last lander demonstrated with SRM braking burn was Surveyor in the 1960s. High precision landing with an SRM has not been performed on a previous mission.

Mitigation Plan: Develop high fidelity landing simulation that includes accurate sensor, actuator, and vehicle dynamics models. Integrate accurate SRM performance model. Develop braking burn algorithms and test in high fidelity simulation.

Status:

- High fidelity simulation development work is complete
- Tool has been developed to calculate optimal guidance/currently exploring methods to approximate this algorithm on a flight processor
- Currently developing combined SRM and liquid guidance algorithm



Have a high fidelity simulation in place to develop guidance and control for SRM burn.

5. Guidance and Control During Final Descent and Landing

Risk 1: Landing capability using DACS / InSpace Engines (pulsed engines) needs to be verified for RLL applications.

Risk 3: GN&C capability difficult to test

Mitigation Plan: Develop high fidelity landing simulation & vehicle (6 dof flying testbed) that includes sensor, actuator, and vehicle dynamics models. Integrate liquid propulsion performance model. Develop landing guidance and control algorithms and verify in simulation and test-bed environments (Cold Gas and WGTA)

Status:

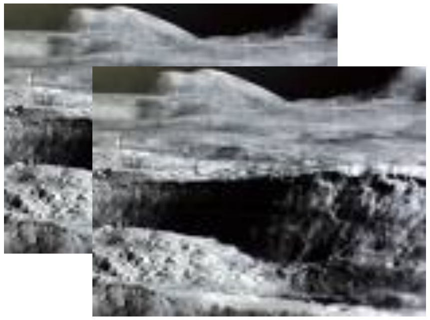
- Algorithms demonstrated on full 6 DOF free
- flying vehicle (WGTA)
- Both low and high precision landing flight algorithms have been identified
- Completed Vehicle Control Testing; Completed Autonomous Guidance System Testing
- Completed Optical Navigation Testing; Completed Optical Hazard Avoidance Testing Over Lunar Terrain Field
- Completed Using Non-NASA Developed Software To Control Flight Functions

The Robotic Lander team has demonstrated a significant capability in the guidance and control of lander systems. 6-DoF Flying Testbed Demonstrated – 42 Successful Flights To Date

5. Guidance and Control During Final Descent and Landing

Risk 2: The optical method of determining relative velocity and position estimate for landing had not been characterized using flight software in a flight processor.

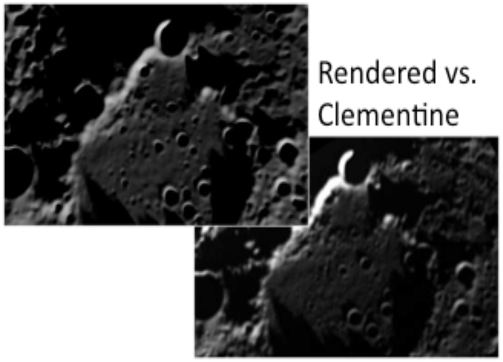
Mitigation Plan: Design, develop and characterize the performance of an algorithm integrated into a flight software framework on a flight-like processor.



Velocity Estimate

Status:

- Updated position and velocity estimation algorithms into a single refactored version of the APLNav algorithm that can perform both phases in order to maximize code reuse
- Optimized the rendering algorithm and onboard map structures to minimize processing time for position estimation algorithm
- Performed a benchmark test of the updated position estimation code to estimate processing load on a flight processor
  - Estimated <15% load, excluding margin, on 133 MHz RAD750 to perform one position estimation every 5 seconds using four 64x64 tile subDEMs per position measurement



Position Estimate

Enhanced capability of an optical approach to position and lateral velocity determination helps to provide a robust, and low cost system.

6. DACS Propulsion Applicability, Performance and Design Life for Lander Applications

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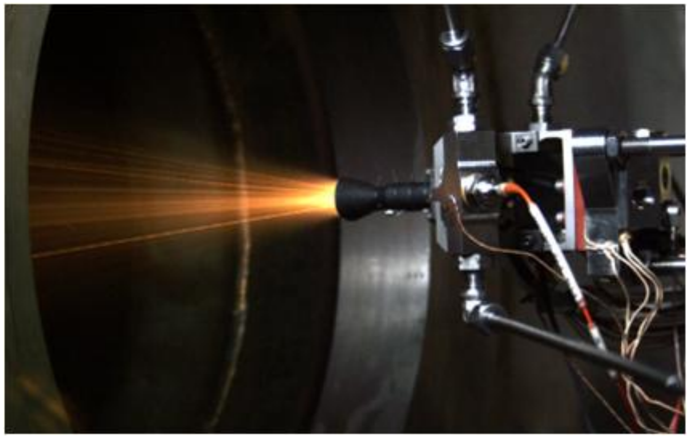
Risk 2: DACS thrusters have not operated for long durations associated with lander missions and limited performance data is available to NASA community

Mitigation Plan: Conduct vacuum tests of MDA DACS thrusters for landing (100 lb) and ACS (6 lb) to evaluate performance and thermal characteristics using a full mission profile.

Status: 100 lb testing completed Sept. 2009, and 6.7 lb test in Sept. 2010

- Conducted 10 tests on the landing engines and 20 on ACS engines
- Thrusters successfully demonstrated RLL flight profile (also continuous 66 sec on landing thrusters, 25 sec on ACS)
- Combustion was stable in all tests
- Temperature measurements show performance below material thermal limit
- Test data from WSTF shows decreased performance than PWR advertised estimates. Potential causes have been identified.
- Additional thermal analysis is recommended to verify thermal performance with flight brackets.
- Thruster valves require redesign for flight



ACS Thruster Tests

DACS test data now exists for lander applications and demonstrates overall feasibility. Remaining modifications and tests have been identified.

6. DACS Propulsion Applicability, Performance and Design Life for Lander Applications

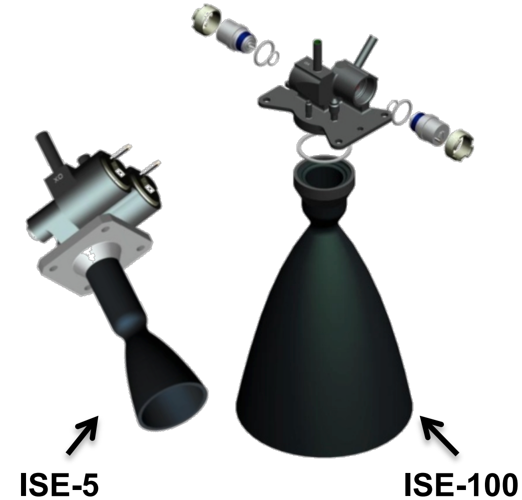
Risk 5: DACS thrusters have not been designed or tested to accommodate latest technology:

- Lightweight and high temperature materials on thrust chamber and nozzle
- Independently actuated mini-cartridge valves to improve performance and reliability.
- MON-25/MMH propellants to operate warm to cold conditions

Mitigation Plan: Incorporate latest technology into design of In-Space Engines (ISE). Develop verification test in vacuum and cold environments.

Status: Preliminary Design Review completed April 2012

- Pratt and Whitney Rocketdyne partnership, with cost sharing on development
- Design of ISE-5 (5-lbf) and ISE-100 (100-lbf) underway
- CDR of ISE-100 Complete
- Fabrication Underway of ISE-5 – Expected Thruster Completion In Summer 2014



Advancing thrusters technology for spacecraft propulsion systems to maximize science payload.

7. Hazard Avoidance

Risk: Hazards exist including rocks and craters that could impair landing stability and could potentially damage the lander.

Mitigation Plan: Determine the level of risk based on available terrain data. Develop terrain models using DEMmaker tool to lander scale that are representative of lunar surface. Develop robustness features into lander design to enhance stability. Explore simple hazard avoidance algorithms using optical approach being used for TRN.

Status:

- Apollo data indicates large landing areas possible with low probability of impacting large hazards (Surveyor approach)
- Approach has been developed to integrate LRO data with DEMmaker to develop terrain models that include lander scale features. This could be used to assess the requirement for hazard avoidance for each mission type.
- A passive hazard avoidance approach has been conceptualized using optical data. Additional funding would be required to pursue this option.

The RLLDP team has tools to evaluate the risk of surface hazards and is interested in exploring mitigation options if necessary.

Apollo 16 Landing Area

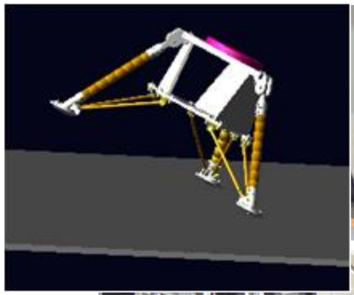
8. Lander Stability

Risk: The ability to develop a lander that touches down in a stable manner, given a variety of landing scenarios, requires an analysis capability that accurately predicts the dynamics.

Mitigation Plan: Develop a simulation capability to accurately predict landing dynamics that can be used to develop future lander designs. Verify the simulation capability via subscale lander stability tests with both rigid and energy absorbing legs.

Status:

- Tested Simple 3-leg and Scale Model with ILN Geometry
- Correlated Data from Simple and Scale Model Test with Analytical Model
- Finalized Analytical Tool for Use in Predicting Lander Stability Limit
- Plan to expand capability to cover different lander concepts and landing scenarios



The RLLDP team has been able to anchor its dynamic models to realistic stability tests providing a significant capability in lander design.

9. Landing Legs and Shock Absorption

Risk: The RLL Team Did Not Have Institutional Experience In Developing Landing Legs

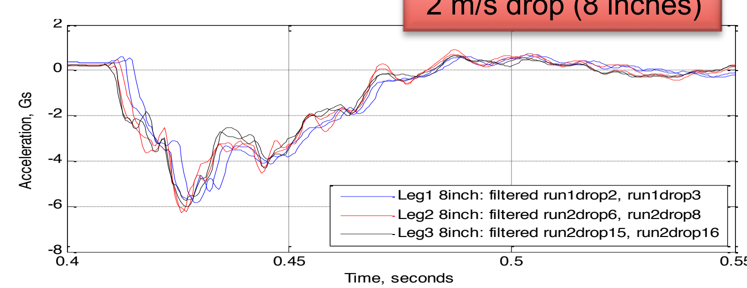
Mitigation Plan: Develop, analyze, and test lander legs using crushable honeycomb aluminum for shock dissipation. Integrate and test flight-like landing legs on WGTA

Status:

- Honeycomb core crush characteristics have been characterized
- Dynamic analysis has been performed using ADAMS to determine appropriate damper settings
- Performed Drop-Tests On A Test Leg Assembly To Validate Analysis & Damper Settings
- Updated lightweight legs (15% mass reduction) Were Fabricated & Installed On WGTA (aka Mighty Eagle); 1st Flown On ARCO7, April 2013; Legs Remain Installed On WGTA

Drop-Test Rig
2 m/s drop (8 inches)

Mighty Eagle begins lateral translation during
Friday, 19 April 2013 Test Flight
Marshall Space Flight Center



The RLLDP team has demonstrated the ability to develop, test & fly full scale prototype lander legs.

Lander Risk Areas: Surface Operations

10. Lunar terrain environment to understand lighting, comm. line-of-sight, and mobility hazards.

11. **Surface Power for continuous operation in extended shadow and long mission durations**

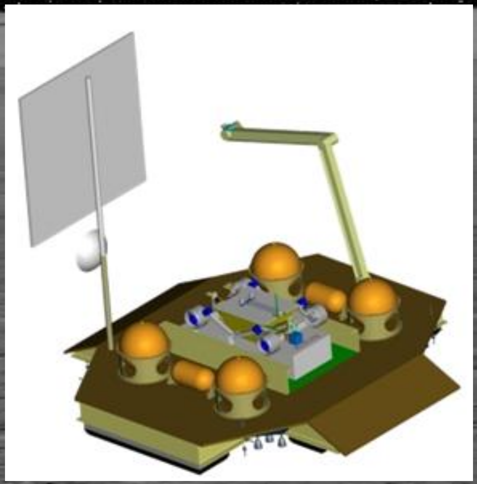
12. **Surface thermal accommodation for global operations continuous for 6 years**

13. Surface to Earth communications

14. Surface to surface communications (e.g. rover)

15. Low power avionics

16. Mini-Mission Operations Center



11. Surface Power for continuous operation in extended shadow and long mission durations

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Risk: Lander batteries will be required to perform outside current experience base with many long discharge cycles operating for up to 6 years duration

Mitigation Plan: Perform thermal and chronological tests of candidate battery chemistries including 6 year operational life, challenging thermal environment (-10-50 deg C), deep depth of discharge, peak loads during thruster firing.

Status:

- Lithium Iron Phosphate (LiFePO4) batteries applicable to ASRG concept completed real-time testing May 2011
- Lithium Aluminum Nickel Cobalt Oxide batteries are undergoing accelerated and real-time testing. Accelerated testing was completed in Dec. 2011 and real-time tests will continue until April 2018
- Lithium Cobalt Oxide batteries are undergoing accelerated and real-time testing. Accelerated testing was completed in Feb. 2012 and real-time testing completed in Apr. 2018
- All battery chemistries have performed well over testing to date.

Three 4-cell packs of SAFT VES-180 Cells (48 Ahr) configured for testing with balance and bypass circuits.

Several battery chemistries look promising to support a wide range of stressing mission requirements including long cycles and deep discharge cycles, wide range of operating temperatures, and up to 6 year operational life.

12. Thermal Accommodation for Global Lunar Operation with Continuous 6 Year Operations

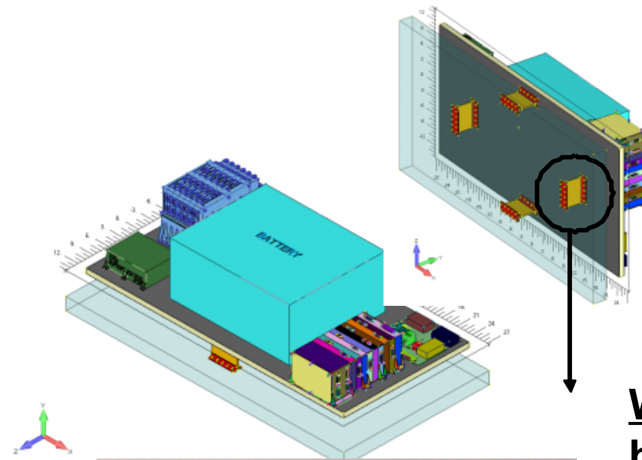
Risk 1: Maintain operating temperatures during the long, cold lunar night

Mitigation Plan: Configure critical electronics into a Warm Electronics Box (WEB). Develop and test WEB base plate isolator concept.

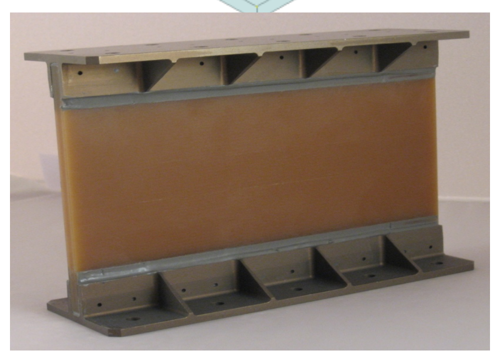
Status:

- Isolator concepts have been designed and tested at APL; report complete
- Concept thermal and structural analysis has been performed
- MLI has been designed; more concept work with integrated analysis
- Heat loss and mitigation analysis underway for harness design

Isolation concepts have been shown to minimize heat loss making it feasible to limit power requirements necessary to survive extended cold conditions.



WEB base plate



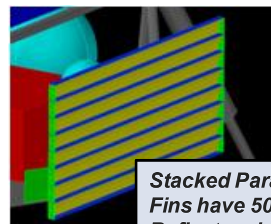
12. Thermal Accommodation for Global Lunar Operation with Continuous 6 Year Operations

Risk 2: Sufficient heat rejection during the hot lunar day at or near equator operations with changing Sun angle and possible dust deposits reducing radiator performance.

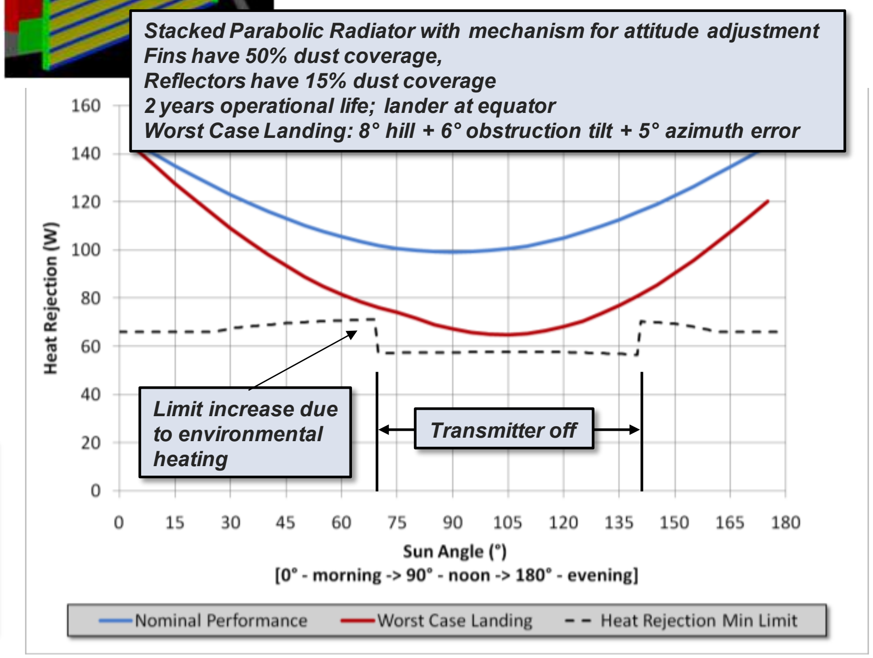
Mitigation Plan: Develop radiator design options and conduct thermal analysis. Fabricate and test radiator options as appropriate to validate models.

Status:

- Identified potential radiator concepts and configurations including concepts taken from Apollo ALSEP experiments and James Webb.
- Radiator performance has been assessed for several configurations and examination of radiator design aspects was initiated
- Integrated End-To-End Thermal Management System Performance Demonstrated Analytically



Stacked Parabolic Radiator



Isolated Thermal Electronics Box, Variable Link and Parabolic Radiator Was Shown To Be Viable.

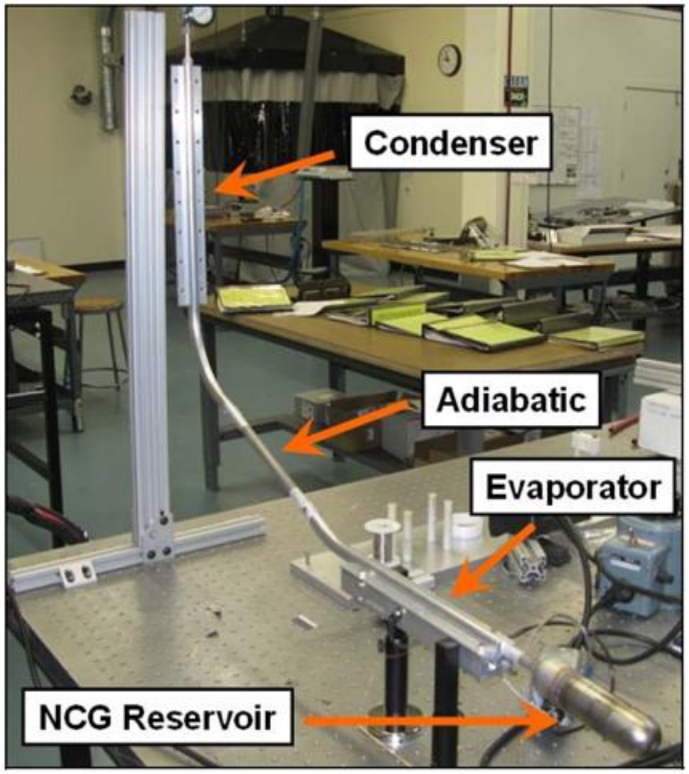
12. Thermal Accommodation for Global Lunar Operation with Continuous 6 Year Operations

Risk 3: Due to the potential thermal extremes and requirements for continuous autonomous operation, a passive thermal system may be inadequate.

Mitigation Plan: Conduct studies to identify candidate approaches. Develop and test several candidate concepts.

Status:

- Completed concept studies identifying loop heat pipes and variable conductance heat pipes as leading candidates
- Initial hardware demonstration of a hybrid wick variable conductance heat pipe (VHCP), loop heat pipe(LHP), and VHCP/LHP hybrid has been completed with overall good results, although some issues remain
- Thermal vacuum testing for VCHP and LHP with Hybrid Concept Completed
- High-k plates for heat acquisition and spreading design, fabricated and ready for testing.



Hybrid wick VCHP Test Article

Several heat pipe options have been successfully demonstrated as options to transport heat for extreme surface environments.

SUPPORT MATERIAL

1. Solid Rocket Motor Thermal Environment

Risk: For RLL, the SRM will need to be thermally controlled during cruise and, during descent, be protected from lander engines during thrust correction maneuvers, cruise and SRM braking.

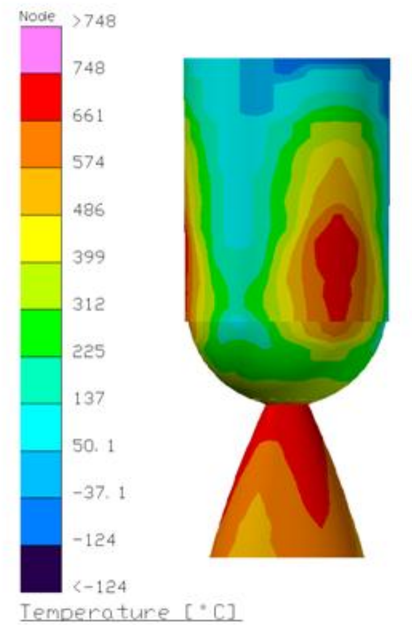
Mitigation Plan: Quantify potential thermal environments, assess the need for thermal mitigation measures such as high temperature insulations, coatings, heat shields, etc. through analysis and testing.

Status:

- Thermal analysis has been completed including plume interactions indicating the need for high temperature insulation or plume shielding.
- Results indicate that normal MLI will not work for this application and a new high temperature MLI is in development to mitigate plume interaction
- High temperature MLI testing was performed at Oakridge National Labs July 2010
  - Initial tests look favorable but instrumentation issues limited the conclusiveness of the data
- A follow-on test is being planned

A thermal protection approach for the SRM has been identified and analyzed. Initial tests have been performed.

External Blanket Temperature after 50 sec of Plume Impingement w/ 6 Descent Thrusters



2. Solid Rocket Motor Performance

Risk: There is uncertainty in SRM thrust vs. time profile due to motor-to-motor propellant burn rate variation and temperature effects on burn rate that could result in reduced landing accuracy or larger burden on liquid propulsion system

Mitigation Plan: Obtain SRM data to statistically characterize performance to model and bound performance for GN&C design and analysis.

Status:

- Star 30 BP and 30E motor modeling completed April 2010 for small lander class
  - Motor data gathered from two vendors
  - Modeling matched flight data to 1% accuracy
  - Performance adequate within modeled temperature ranges
- Star 48V kickoff meeting Jan 2011 for medium class landers
  - Initial performance for temperature variations provided
  - Data being gathered for motor to motor variations

SRM performance characterized for lander applications.

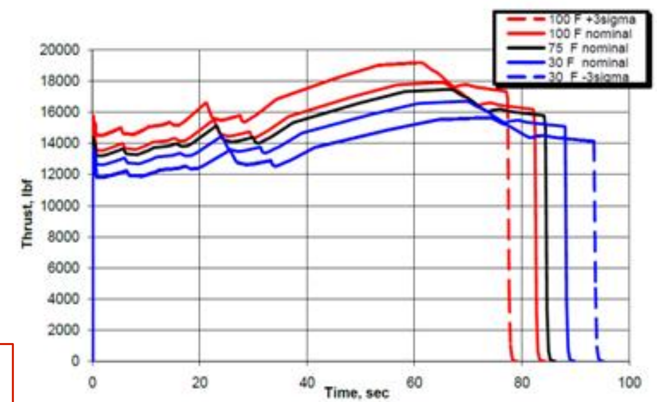


Figure 5. Vacuum Thrust vs Time

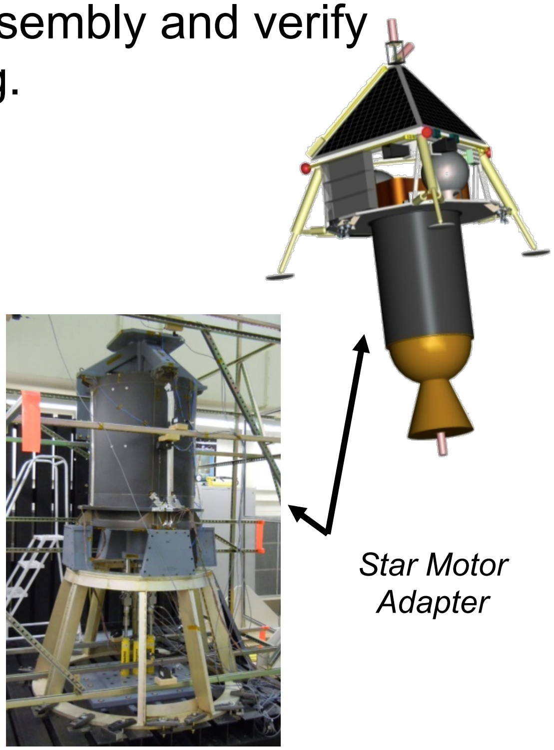
4. Solid Rocket Motor Adapter

Risk: A lightweight composite SRM adapter and separation system is required to achieve the ability to land large payloads. Such a system has not yet been flown in a similar application.

Mitigation Plan: Design and procure a solid motor adapter assembly and verify performance by static, vibration, and separation system testing.

Status:

- SMA Fabricated and Assembly Completed (Sept 2011)
- SMA Test Program Completed (Oct 2011)
- Test Data Analyzed and Report Completed (Jan 2012)
- SMA Currently in Storage at APL



RLLDP has made significant progress demonstrating specialized lightweight composite structures.

6. DACS Propulsion Applicability, Performance and Design Life for Lander Applications

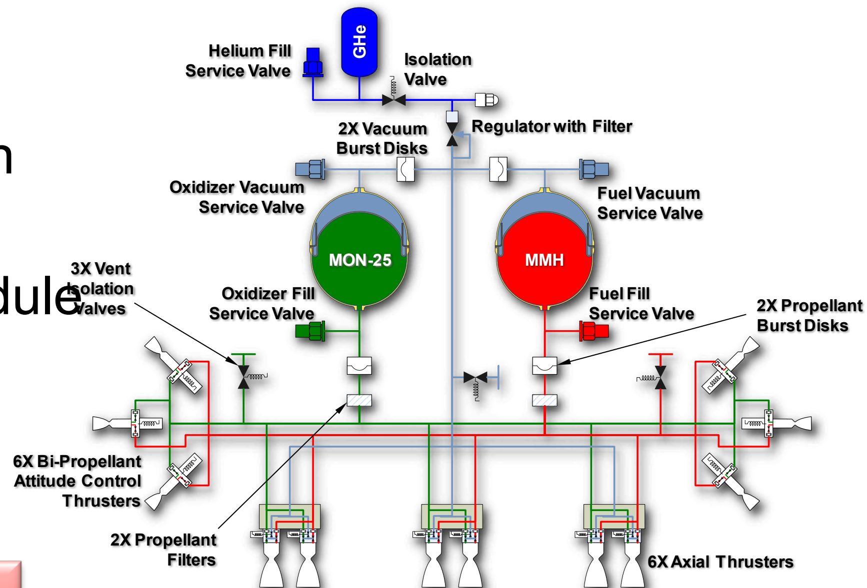
Risk 1: High pressure propulsion system applicability to lander applications including packaging, performance, and cost.

Mitigation Plan: Conduct propulsion study with multiple perspective vendors trading architectures, propellant, and components to arrive at both high pressure DACS and COTS based design solutions.

Status: Completed June 2008

- Accumulated and extensive propulsion database
- Validated cost and procurement schedule models

High pressure systems look favorable for small and medium class landers.



Propulsion Schematic of Solar/Battery Lander

6. DACS Propulsion Applicability, Performance and Design Life for Lander Applications

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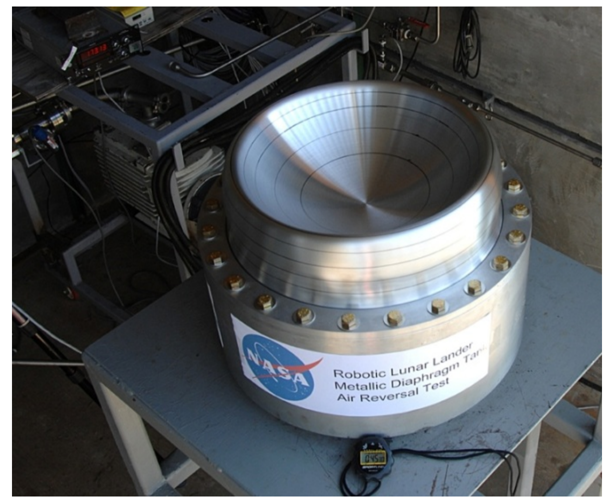
Risk 6: Metal diaphragm tanks have not been used with high pressure (800 psia) systems

Mitigation Plan: Conduct metal diaphragm tank test to characterize the metal diaphragm operations:

- Verify capability of operating at 800 psia instead of 325 psia.
- Determine expulsion efficiency
- Demonstrate diaphragm cycle life
- Familiarize propellant loading/unloading

Status: High pressure testing is complete

- AMPAC provided a tank test article (loan basic) for test setup
- Conduct test at actual flight regulated pressure with representative mission duty cycles
- Highly instrumented test setup with visualization, sensors, and metal diaphragm cycle life assessment
- Test matrix composed of multiple tests w/ & w/o diaphragms, air-reversal, pad pressure variations



A baseline has been established for future metal diaphragm tank testing at cold temperatures.

6. DACS Propulsion Applicability, Performance and Design Life for Lander Applications

Risk 3: Pulse modulated throttling has no data on system interaction and response

Mitigation Plan: Simulate the operation of a complex propellant feed system:

- Assess feed system response to pulse modulated throttling with bipropellant hypergolic thrusters.
- Priming of evacuated propellant feed lines
- High duty cycle testing, 160,000 cycles at operational pressure, 10 ms on, 20 ms off

Status: Design, fabrication and testing is complete

- Designed a propellant feed system layout based on the APL Solar Power Robotic Lunar Lander.
- Fabricated the feed system using RS-34 (PKIV) attitude control thruster valves as surrogates for COTS R-4D thrusters.
- Using water as a propellant simulant, ran diagnostic cycle tests, as well as specific mission duty cycles.
- Analyzed results for fluid dynamic interaction, waterhammer, and pressure slump
- Analysis of test data underway to determine effects on the system

Propellant Feed System test setup

Cold Flow Test Setup Characterized Expect Propulsion System Interactions

6. DACS Propulsion Applicability, Performance and Design Life for Lander Applications

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Risk 4: NASA has never flown a high pressure propulsion system for long duration spaceflight.

Mitigation Plan: Evaluate a high pressure regulator for RLL application including leakage, stable regulation, and its ability to operate under extreme conditions. Conduct waterhammer testing and analysis to better understand this phenomena on high pressure propulsion systems.

Regulator Testing Status: Testing and test data analysis complete

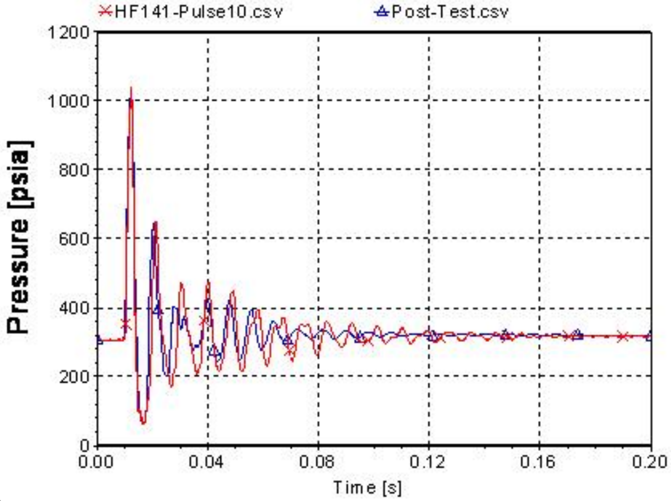
- Conducted >12 successful tests with stable outlet pressures, leakages, excellent slam start performance
- Simulated test of mission profile for all phases of ILN mission

Waterhammer Status: Completed in Dec. 2010

- Conducted 22 tests with 300 separate valve actuations
- Successfully anchored model for future design efforts
- Mitigation schemes have been proposed

NASA now has experience with high pressure regulators and has developed a waterhammer database and modeling capability of high pressure propulsion systems.

Actual Test Regulator



Comparison between Waterhammer simulation results and test data.

Surface Ops - 13. Lander to Earth Communications

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Risk: Developing a communication system that meets spectrum requirements, harsh environments, low power, and multipath issues with the surface.

Mitigation Plan: Pre-coordinate RF spectrum allocations for different mission options, conduct a market survey of candidate RF components, develop and test candidate antennas, and perform multipath analysis.

Status:

- A draft NTIA Stage 1 was submitted for various RLL variants in an effort to pre-coordinate communication system characteristics
- A ILN directional antenna was designed analyzed and tested at Redstone RF anechoic chamber. Tests matched very well with simulation software prediction.
- A market survey has been performed on potential RLL RF components including NASA centers and industry.
- Multipath analysis indicates potential concerns for low elevation communications associated with ILN and other missions. Mitigation approaches are being evaluated.

Conceptual Model in position inside RF Anechoic Chamber

The RLLDP team has successfully developed antennas, evaluated components, and conducted surface multipath analysis to significantly reduce lander development risk.

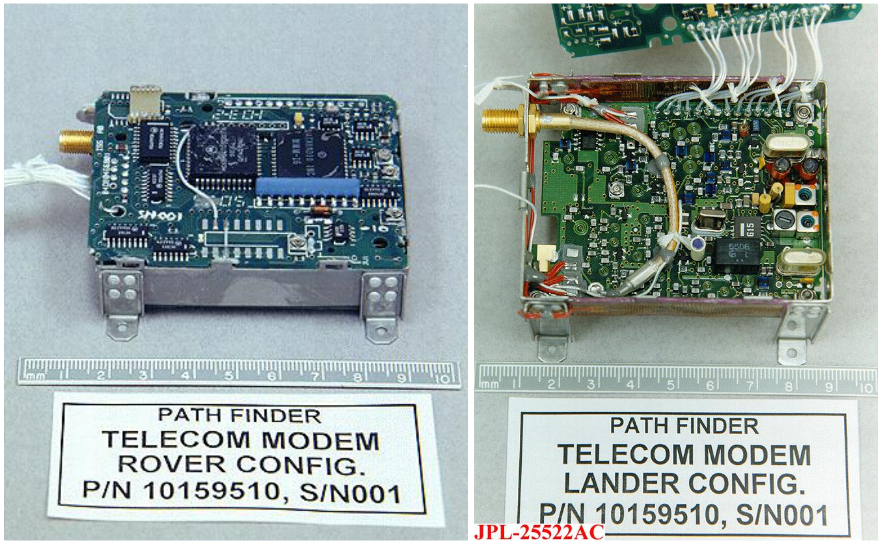
Surface Ops - 14. Lander to Rover Communications

Risk: A surface-to-surface communication system that meets low-power, low-mass and high data-rate requirements while being insensitive to multipath and able to survive the harsh lunar environment may be challenging to find or design.

Mitigation Plan: Conduct a Communication System market survey to determine whether existing or developing systems can be used to meet requirements. Where possible, leverage existing systems used on the Mars Exploration Program.

Status:

- Completed a communication system market survey and identified 10 existing crosslink radios as potential candidates, although more technical details will be required.
- Developed a quadrifilar helix antenna which provides excellent omnidirectional surface coverage while offering significant multipath rejection capability for both rovers and landers.



A communication systems market survey has identified several candidate lander-to-rover 2-way communication systems, some of which were used for Mars missions.

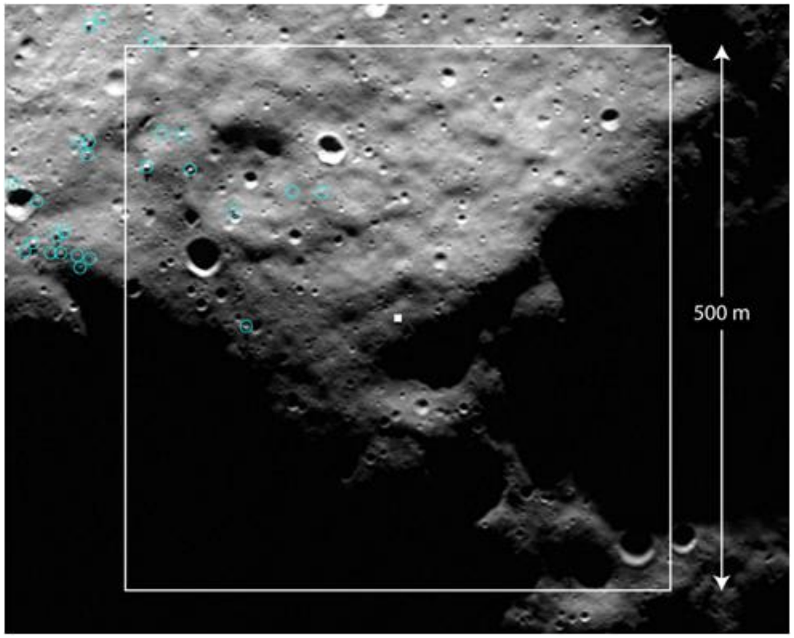
Surface Ops - 10. Lunar Terrain Environment

Risk: Specific mission terrain is not known and terrain features can be critical in understanding lighting, communications, landing hazards, and mobility hazards.

Mitigation Plan: Update DEMmaker tool developed under ALHAT to provide detailed terrain information based on LRO data and populate smaller scale features with statistical lunar models. Document process and develop example terrain for a hypothetical Shackleton Crater rim mission.

Status:
- DEMmaker has the capability to incorporate the latest LRO data into a useable digital elevation map
- High resolution LROC imagery has been used for actual rock placement
- General process has been developed and will be documented in FY2011 along with data products for a sample landing location

DEMmaker allows the capability to quickly incorporate terrain data to provide the design team with the necessary environmental data to develop lander missions.



One Meter Scale Boulders Identified from LROC Imagery

Surface Ops - 15. Low Power Avionics

Risk: Many RLL applications including ILN mission require high performance processing in a low power, low cost package.

Mitigation Plan: Conduct market survey and trade study on potential flight processor options. Develop and test a concept based on the LEON3FT processor.

Status:

- LEON3FT based flight computer has been under development that includes low power, ASIC for high speed communications, and a large storage capacity. This architecture will also accommodate spacewire and CAN bus which may be applicable to several potential RLL payloads.
- Prototype flight computer qualification has been completed, raising it to TRL-6
- Architectures based on this flight processor have been conceptualized to incorporate a co-processor to accommodate TRN that is not currently funded.

Successful development and environmental testing of a LEON3FT provides the RLLDP team with a high performance flight computer.

Surface Ops - 16. Mini-Mission Operation Center

MSFC NASA APL

Risk: No lunar lander mission operations experience.

Mitigation Plan: Fly lander test articles using flight-like software and operations teams.

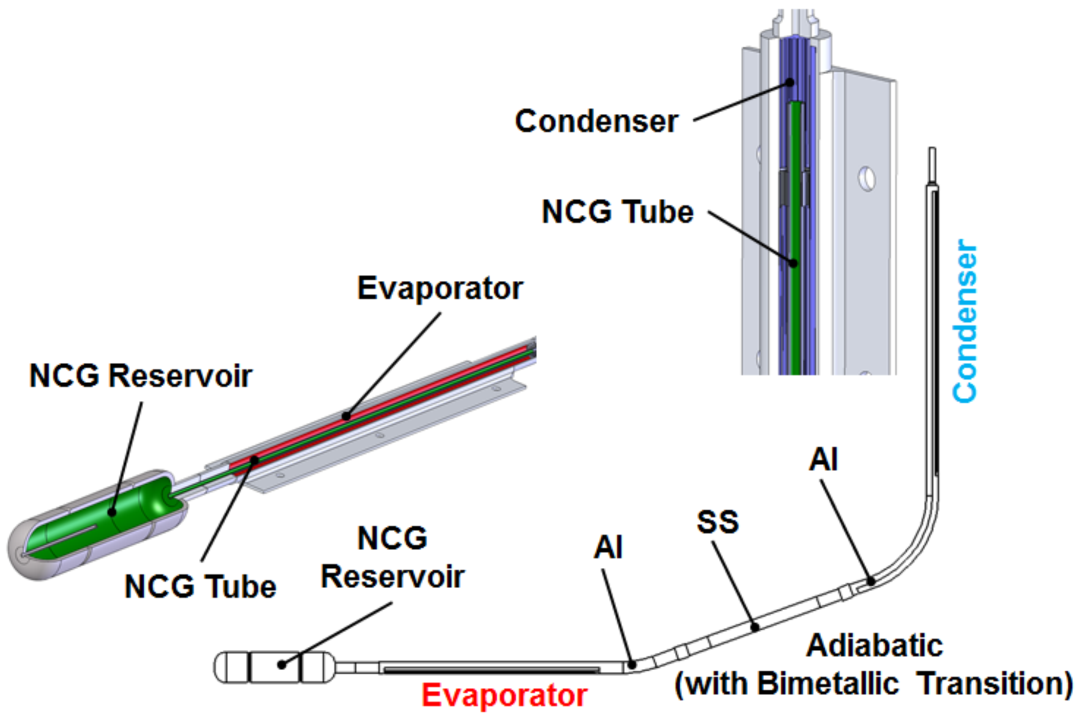
Status:

- The Warm Gas Test Article test program is set up to mimic a flight program
  - Utilizes the same ground data system software for command and control as would be used a robotic lunar lander mission
  - Operations personnel to gained experience with the L3 "InControl" ground data system software
  - Flight-like design and development of the ground/flight software interfaces,
  - Flight-like the integration and testing of the ground/flight software, and development of the flight test operations procedures
- The entire life cycle for ground system and mission operations was exercised:
  - software installation/configuration,
  - command and telemetry database build,
  - command and telemetry display development,
  - command script development,
  - operations product validation,
  - real-time command & telemetry processing,
  - telemetry playback, telemetry data archiving, and post-flight data retrievals, including telemetry plots and history reports.
- Two console positions, Command (CMD) and Data (DAT).
  - CMD uplinked the guidance, navigation, and control (GNC) sequences to the flight computer and issued commands
  - DAT monitored and reported vehicle telemetry

Successful implementation of minimal operations team.

ADDITIONAL VARIABLE LINK DATA

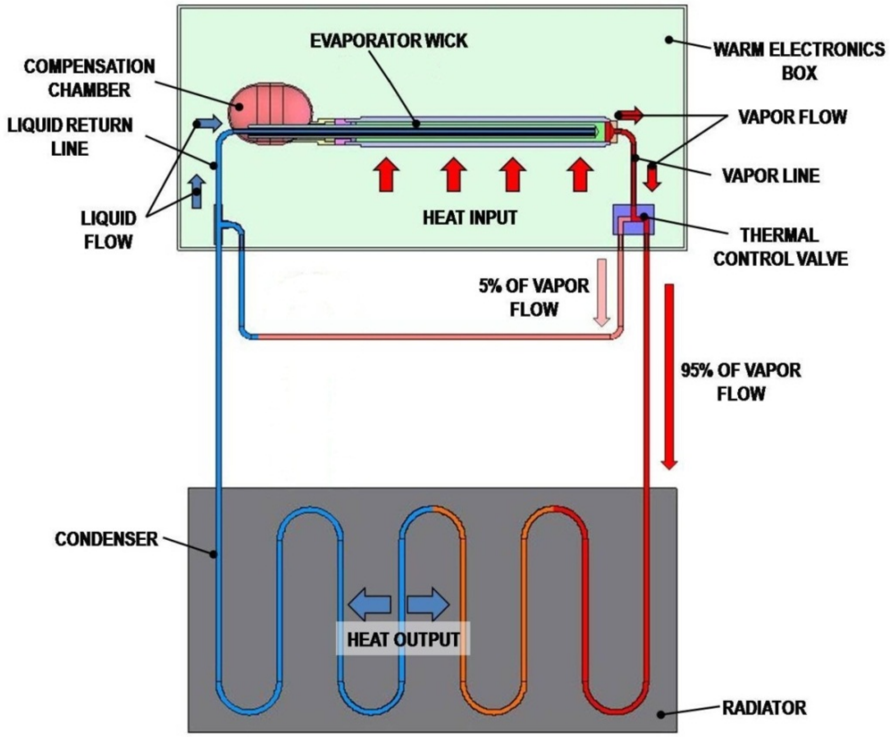
Hybrid Wick Variable Conductance Heat Pipe (Advanced Cooling Technologies, Lancaster PA)



- *During warm lunar day operation higher amounts of heat acquired at the evaporator will force the non-condensible gas (NCG) toward the evaporator maximizing the amount of useable area in the condenser and heat transferred by the pipe.*
- *During the lunar night cold conditions, the lower temperatures and reduced heat entering the evaporator will lead to more NCG in the condenser eventually shutting off the condenser and isolating the evaporator, preserving heat for those items attached to the evaporator.*
- *The reservoir is placed near the evaporator to decrease its size and to promote passive operation of the heat pipe.*

Ref: Peters, Hartenstine, Tarau, Anderson. "Variable Conductance Heat Pipe for a Lunar Variable Thermal Link", AIAA 2011-5120, International Conference on Environmental Systems, Portland, OR, 2011.

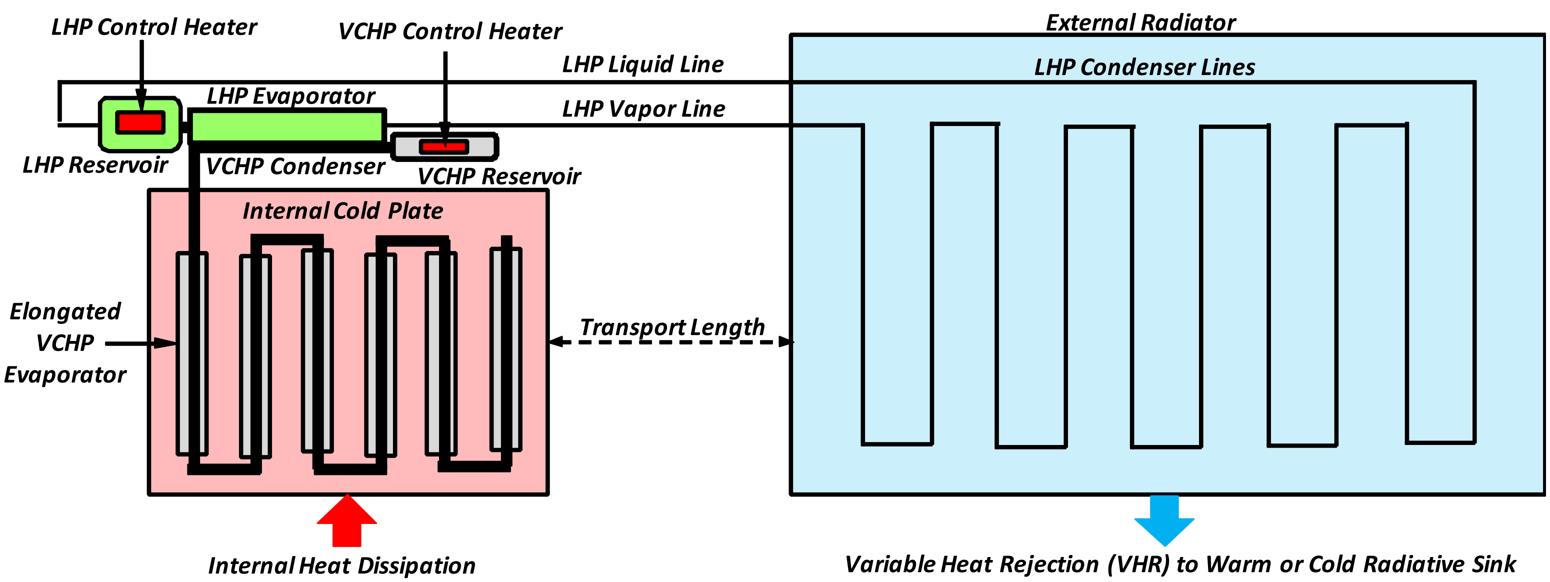
Loop Heat Pipe with Thermal Control Valve (Advanced Cooling Technologies, Lancaster PA)



- *During Lunar day operation, (left), the LHP removes the waste heat from the WEB and transports it to the radiator where the heat is rejected to space.*
- *During the Lunar night operation (not shown), the majority of flow in the LHP will bypass the radiator minimizing heat loss.*
- *Changes in thermal control valve inlet temperature (evaporator exit) will passively adjust the valve spool resulting in a change in the ratio of two outlet vapor streams from the thermal control valve. Sufficient drop in temperature will eventually shut off the flow to the radiator; conversely, sufficient increase will allow full flow to the radiator.*

Ref: Walker, Hartenstine, Tarau, Anderson. "Loop Heat Pipe with Thermal Control Valve for Variable Thermal Conductance", AIAA 2011-5231, International Conference on Environmental Systems, Portland, OR, 2011.

Hybrid Variable Conductance Heat Pipe/Loop Heat Pipe (ATK Space – Beltsville MD)



The specially designed loop heat pipe and variable conductance heat pipe can independently, or together, passively alter their heat transport behavior, depending on thermal conditions, to provide variable heat transport ranging from near complete isolation (shut down) to high conductance, efficient heat transfer and rejection (full flow).

Ref: Bugby, Farmer, Stouffer. "Development and Testing of a Variable Conductance Thermal Acquisition, Transport, and Switching System", AIAA 2013-3435, International Conference on Environmental Systems, Vail, CO, 2013.

Key Abbreviations Used Within This Presentation

- CGTA = Cold Gas Test Article
- Divert and Attitude Control System = DACS
- ILN = International Lunar Network
- LHP = Loop Heat Pipe
- LRO = Lunar Reconnaissance Orbiter
- LROC = Lunar Reconnaissance Orbiter Camera
- RLL = Robotic Lunar Lander
- RLLDP = Robotic Lunar Lander Development Project
- SRM = Solid Rocket Motor
- TRN = Terrain Relative Navigation
- VHCP = Variable Conductance Heat Pipe
- WGTA = Warm Gas Test Article