

Spacecraft Power Source Installation at Launch Complex

Paul Lytal pdlytal@jpl.nasa.gov 818-285-9280
Pamela Hoffman phoffman@jpl.nasa.gov 818-687-7012
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91101

Abstract—For certain space missions, an assembly must be integrated onto the spacecraft as late as possible in the launch vehicle processing flow.¹²This late integration can be driven for a variety of reasons including thermal or hazardous materials constraints.

This paper discusses the process of integrating an assembly onto a spacecraft as late as one week prior to the opening of the launch window. Consideration is given to achieving sufficient access for hardware integration, methods of remotely securing hardware to the spacecraft, maintaining spacecraft cleanliness throughout the integration process, and electrically integrating the component to the spacecraft.

Specific examples are taken from the remote mechanical, electrical, and fluid cooling system integration of the power source onto the Mars Science Laboratory (MSL) Rover at the Atlas V Vertical Integration Facility (VIF) at Cape Canaveral Air Force Station, Florida.

TABLE OF CONTENTS

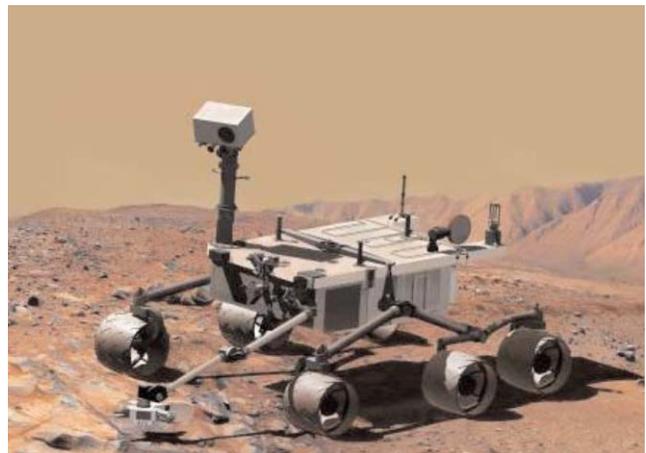
1. INTRODUCTION.....	1
2. LAUNCH SYSTEM AND PAYLOAD ACCESS	1
3. MECHANICAL INTEGRATION APPROACH.....	2
4. ELECTRICAL INTEGRATION APPROACH	3
5. THERMAL INTEGRATION APPROACH.....	4
6. CLEANLINESS CONSIDERATIONS DURING POWER SOURCE INTEGRATION	4
7. POWER SOURCE INTEGRATION GROUND SUPPORT EQUIPMENT	4
8. MECHANICAL INTEGRATION OPERATIONS	5
9. SUMMARY	6
ACKNOWLEDGEMENTS ...	ERROR! BOOKMARK NOT DEFINED.
BIOGRAPHY	6

1. INTRODUCTION

Mars Science Laboratory (MSL) Mission Overview

Following the legacy of the Mars Pathfinder and Mars Exploration Rovers (MER), the Mars Science Laboratory (MSL) Project is a robotic rover mission to Mars led by NASA's Jet Propulsion Laboratory (JPL), scheduled to launch in the Fall of 2011.

The new rover will analyze Martian rocks and soil for evidence of organic compounds and conditions that could have supported microbial life now or in the past. New data from the Mars Science Laboratory mission will provide guidance to scientists and engineers about how and where to search for evidence of life on Mars in future missions.



MSL Power Source Integration at the Launch Complex

This paper describes the involved process of integrating the power source for the Mars Science Laboratory (MSL) rover approximately six days before the opening of the launch window at the Atlas V launch complex in Cape Canaveral, Florida.

The MSL Project chose to integrate the power source so late in the spacecraft integration timeline due to thermal constraints and hazardous material constraints presented by the introduction of the power source.

An overview of the approach selected for the remote mechanical, electrical, and thermal integration of the power source to the rover at the launch complex are described in the sections that follow.

2. LAUNCH SYSTEM AND PAYLOAD ACCESS

The first challenge to overcome when faced with the task of integrating payload hardware at the Launch Complex is access.

The integration path for the MSL Rover power source passed through a door in the launch vehicle fairing, a second

¹US Government work not protected by U.S. copyright.

²IEEEAC paper#1599, Version 1, Updated 2009:10:31

door in the spacecraft Mars entry vehicle fairing, and two heat exchanger panels cantilevered from the aft end of the Rover before reaching the mounting interface on the Rover.

Significant coordination was required with the launch service provider to obtain the required access to the payload for power source integration at the launch vehicle stacking facility.

Atlas V Launch Vehicle and Vertical Integration Facility (VIF)

The Mars Science Laboratory Project selected to fly on an Atlas 541 launch vehicle. This is a medium-to-heavy expendable launch system with a 5.4 meter diameter fairing that encapsulates the payload during ascent, only to be jettisoned in the upper atmosphere.

The Atlas V is powered by an RD-180 kerosene-burning first stage engine and a RL10 hydrogen-burning Centaur upper stage. Varying numbers of solid strap-on booster rockets augment the payload capacity of the launch vehicle; for the MSL launch, four solid boosters were used.

Sections of the Atlas V vehicle are stacked vertically in preparation for launch at the Atlas Vertical Integration Facility (VIF) at Cape Canaveral Air Force Base, Florida. Upon completion of vehicle stacking and payload integration, the vehicle is transported to Launch Pad 41 for launch.



MSL Unique Launch Services for Power Source Integration at the VIF

The VIF includes services required for assembling Atlas launch vehicles; the MSL project took advantage of these existing services for the rover power source installation at the VIF. Examples of standard services at the VIF include a 60-ton crane, 2-ton elevator, and fixed facility work levels. But standard services alone were not sufficient to enable the MSL project to install their power source at the VIF.

The Mars Science Laboratory project needed many mission unique services from the launch service provider for power-source integration.

Two temporary work platforms were needed to access either side of the MSL payload at the correct height at the VIF. Two mission-unique access doors were needed in the launch vehicle fairing. These large doors were designed to provide enough clearance for the power-source, integration ground support equipment, and integration personnel to fit through.

To maintain spacecraft cleanliness while launch vehicle fairing doors were open, temporary clean tents with filtered, environmentally-controlled air supplies had to be constructed around each work platform. The MSL power-source was hoisted into one of the clean tents through an access hatch in the roof of the clean enclosure.

A dry-run build-up of all these unique services and a simulated walk-through of the integration was performed well in advance of the launch to check inter-agency interfaces and validate the procedures used in this unique installation process. A description of the integration approach can be found in the sections that follow.

3. MECHANICAL INTEGRATION APPROACH

The mechanical integration of the MSL power source was complicated by the configuration of the spacecraft, the severe handling constraints on the power source itself, and limited access to the power source interfaces on the Rover at the time of integration. These mechanical considerations are described in the sections that follow.

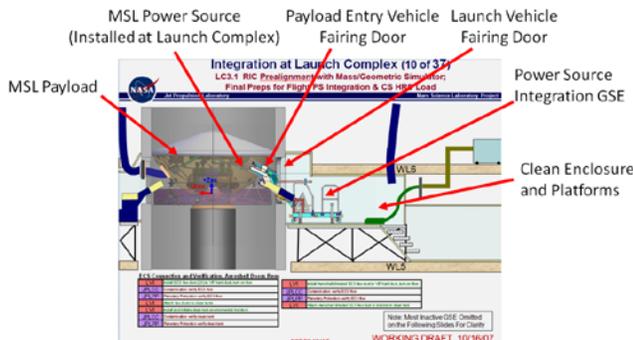
MSL Power Source in the Launch Configuration

The configuration of the MSL spacecraft dictated the complexity of the remote installation of the power source at the Launch Complex.

The power source mounted to the aft end of the Rover at a 29.5degree decline in the launch configuration (rover wheels-up). The bolt interface plane for the power source on the back of the Rover was oriented normal to the integration direction.

The Rover was encapsulated in a composite fairing for protection during entry into the Martian atmosphere—a door was provided in this fairing to provide a path to install the Rover power source.

This entire spacecraft was encapsulated within the payload fairing of the launch vehicle to protect the spacecraft during ascent in Earth’s atmosphere. Large mission-unique doors were provided in the launch vehicle fairing to provide necessary access for hardware and personnel needed for the power source integration onto the Rover.



Power Source Handling Constraints

The power source itself posed several handling challenges. Hazardous material within the power source naturally gives off 2000 Watts of heat; during ground handling operations in room temperature open air, the surface of the power source was approximately 260 degrees Fahrenheit. Thermal protective garments were required for all personnel working in the vicinity of the power source.

The exterior of the power source was surrounded by delicate heat sink fins and coated in a delicate white paint which flakes and rubs off fairly easily on contact. Serpentine thin-walled fluid lines also surrounded the surface of the power source—these tubes were extremely damage sensitive.

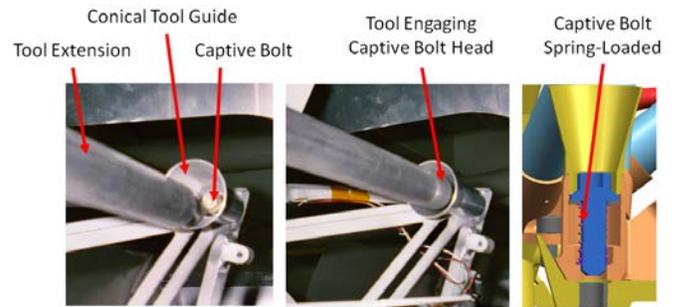
In addition, the power source weighed about 47kg. Clearly, this power source could not be safely installed by hand.

Power Source Remote Mechanical Mate

The power source mechanical installation onto the Rover was accomplished remotely due to difficult/impossible close-up personnel access to the attachment interface for the power source at the time of integration.

The attachment bolt interface plane for the power source on the back of the Rover was oriented normal to the integration direction. Clear straight-line tool access paths were maintained to enable captive bolts in the power source mounting adapter to be engaged with long tool extensions. Conical features served as guides to “funnel” these long tool

extensions into engagement with the captive fastener bolt heads, as shown in the image below.



The captive fasteners also included high temperature locking features (similar to nylon patches) to keep the fasteners from vibrating loose in the course of the mission.

Prior to remotely starting the captive fasteners in the threaded holes of the rover, verification of interface surface contact was required. Color-coded stripes near the Rover interface indicated how far from contact the power source was during integration. Secondary verification was obtained using the physical “feeling” of contact reported by the highly-trained installation technician team.

4. ELECTRICAL INTEGRATION APPROACH

Due to the criticality of the electrical mate of the Rover power source to the Rover near the partially-fueled launch vehicle, connectors between the rover and power source were mated by hand. The special provisions necessary to enable hand-mate access at the Launch Complex are described in the following section.

Power Source Electrical Mate

Following mechanical integration of the power source to the Rover, the power source was electrically integrated to the Rover. Technicians used the same access platforms for electrical integration as mechanical integration. Extender cables from the power out receptacle on the power source and the power in bulkhead on the Rover were pre-routed to locations at the outboard end of the Rover where hand-access would be best during power-source integration.

Just before mating these power source connectors, the voltages of the power source and spacecraft were adjusted and verified to match. This avoided any potential current-flow across pins during connector mates that could (in a low-probability scenario) ignite flammable propellant fumes from the launch vehicle or spacecraft.

5. THERMAL INTEGRATION APPROACH

The power source for the rover required active cooling to keep from overheating itself and the spacecraft before launch. Prior to integration onto the spacecraft, natural convection in open cool air was sufficient to keep the power source from overheating itself. But inside the confined space of the spacecraft entry vehicle, the power source without active cooling could overheat itself and nearby propellant and pressurant tanks in a matter of hours.

Four active cooling systems were used to control power source temperatures during and after integration:

- (1) A ground-only fluid cooling loop flowed a Freon-alternative through a serpentine network of tubes on the exterior of the power source and dumped heat to ground support chiller carts outside the launch vehicle.
- (2) A flight fluid cooling loop pulled heat from a second set of tubes on the power source to radiator panels on the cruise stage of the spacecraft.
- (3) A second flight fluid cooling loop on the rover itself pulled heat radiated off of the power source into more useful locations or shunts on the rover.
- (4) A directed air conditioning duct connected to the entry vehicle to move hot air out of the entry vehicle during and after power source integration.

After power source integration, directed air conditioning and ground cooling were gradually phased out and the two flight fluid cooling loops were required to carry out more heat until the ground service could be completely discontinued.

All fluid cooling loops were designed to be two-fault-tolerant for the safety of personnel and hardware at the launch complex, and to lower the risk posture of the overall mission.

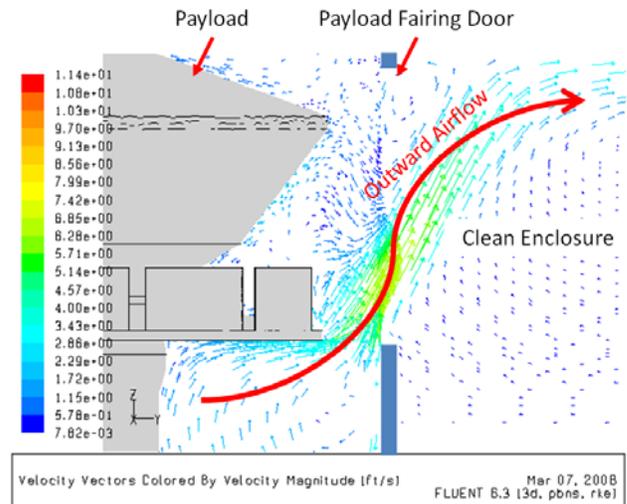
6. CLEANLINESS CONSIDERATIONS DURING POWER SOURCE INTEGRATION

The power source integration also had to adhere to the strict cleanliness requirements of the MSL Project.

One of the science goals of MSL was to seek out organic compounds on the Martian surface—in order to avoid finding “stow-away” organic compounds from Earth while on Mars, the rover needed to be kept exceptionally clean.

To meet these stringent requirements, power source integration personnel inside the clean enclosure were required to wear nomex full-cover clean suits. A positive pressure difference was maintained between the highly-filtered air inside the clean enclosures and the normal air outside to prevent uncontrolled outside air from entering the clean enclosure.

Similarly, a separate source of clean air connected to the Payload Fairing provided positive pressure inside the payload fairing, so that air flowed out of the payload fairing into the clean enclosure instead of the converse.



Dry nitrogen purges were also provided to sensitive components on the MSL spacecraft. These purges were directed at components particularly sensitive to contamination as well as overheating. The purges were maintained after power source integration on MSL and continued up to the time of launch.

7. POWER SOURCE INTEGRATION GROUND SUPPORT EQUIPMENT

Custom ground support equipment was required to meet the specific constraints imposed by a launch complex integration of the power source onto the rover. Assemblies include a cart for installing/removing the power source from the Rover, a fixture for lifting and rotating the power source, and several access platforms for installing the power source, access doors, and related items.

Power Source Integration Cart

The Power Source Integration Cart was used to advance the MSL power source up to the attachment interface on the Rover.

Through a combination of counterbalance weights and constant-force springs, the ground support integration cart provided a six degree-of-freedom “floating” mechanical mate for the power source. A “floating” mechanical mate was required due to the uncontrolled relative motion (i.e. swaying) between the work platform and the tip of the launch vehicle.

A more rigid system of advancing the power source up to the payload could have resulted in large, undesirable loads transfer between the payload and the ground support integration cart through the power source.



The integration distance to the power-source mounting interface on the spacecraft was approximately seven feet past the outer surface of the payload fairing. Deployable “diving-board work platforms” on the power-source integration cart cantilevered through a door in the payload fairing to allow technicians access to the payload, as shown in the figure below.

To reduce the number of ground support interfaces that needed to be coordinated with the launch service provider, MSL chose to provide their own deployable diving board platforms built into the power-source integration cart. This also facilitated integration training exercises onto payload mockups with realistic access.



Power Source Lift/Turn-Over Fixture (LTOF)

Due to the weight, high temperature, and fragile surface of the power source, a fixture was needed to safely hoist and rotate the power source for the Rover.

The fixture included a carriage and quick-release-pin interface for simply transferring the power source on and off of the Power Source Integration Cart.



The Rotation Fixture was designed to rotate the power source from the vertical (storage) orientation to the inclined (installation) orientation.

A non-backdrivable gear train ensured that rotation could be stopped at any time in an emergency without the power source ever being left in an unsafe configuration.

8. MECHANICAL INTEGRATION OPERATIONS

Summary of the Power Source Integration Sequence

Due to the weight, high temperature, and fragile surface of The power source arrived at the launch complex early in the morning for hoist to the top of the VIF. A breathable (mesh) cage surrounded the power source to protect it without causing the power source to overheat.

Once inside the VIF at the appropriate level, the mesh cage was removed and the Rotation Fixture was connected to the power source. The power source was hoisted and rotated to the installation angle, and then transferred onto the Power Source Integration Cart inside the clean enclosure.

Before installing the power source onto the spacecraft, ground fluid cooling was serviced on the power source, access platforms were deployed through the launch vehicle fairing door, and directed air conditioning in the rover entry vehicle was verified running.

The power source was then remotely bolted to the rover via the Power Source Integration Cart. Electrical and fluid line connections were made to the spacecraft, and flight cooling loops were serviced and stabilized. Once stable, ground fluid and air cooling systems were then deserviced. The power-source installation was complete after entry vehicle door installation and final spacecraft closeouts.

Following power source installation, launch vehicle fairing doors were installed and the launch vehicle was prepared for transport to the launch pad.

Integration Trailblazer

Significant inter-agency coordination is required between the power source provider, the launch service provider, and the spacecraft integration team. To validate procedural handoffs and hardware interfaces, an early dry run of the installation was performed, referred to as Trailblazer.

This Trailblazer operation was intended to uncover potential problems with the integration approach with ample time to recover without any impact to the spacecraft launch window.

A power source simulator was used in Trailblazer to validate the mechanical handling and clearances of the power source. Lessons learned from the Trailblazer operation were re-validated in follow-up training sessions at JPL.

Integration Training at the Jet Propulsion Laboratory (JPL)

Extensive power source integration training was performed at JPL to minimize the time required to install the hazardous power source at the launch complex.

A mockup of the rover interface with representations of spacecraft, launch vehicle, and facility close clearances was built at JPL to facilitate training. Times and distances from the power source were tracked for all personnel in each round of training; times were found to reduce exponentially with each of the early rounds of training.

Backups and alternates were cross-trained for each role so that absences during the targeted integration time would not impact the launch schedule.

Training was performed with a power source simulator with very similar geometric and thermal properties to the actual power source. The simulator even generated the same amount of electrical power as the flight power source, providing opportunity for electrical integration training.

The overall integration (mechanical, electrical, and fluids) was practiced extensively as a single integration team; cross-training across primary disciplines increased the number of available alternates tremendously.

Integration Training at Kennedy Space Center (KSC)

Electrical checkout testing of the flight power source on the flight spacecraft at KSC months prior to launch provided an opportunity for a high-fidelity practice run of the mechanical, electrical, and fluids integrations prior to the final power source installation at the launch complex.

Though simpler configurations could have been selected for the electrical checkout testing with the flight power source, the project chose to perform the integration in a configuration similar to what needed to be performed at the launch complex for training purposes.

This also allowed for detailed validation of the process and flight hardware interface fit checks at a less-schedule critical point in time. The offload sequence was also done in a manner similar to what would be done in an emergency scenario at the Launch Complex.

9. SUMMARY

Due to thermal and hazardous material constraints, the power source for the Mars Science Laboratory rover had to be integrated at the Launch Complex. Integrating the power source at the Launch Complex required complex provisions for hardware access, personnel access, electrical integration, and thermal control. Extensive training, hardware development, and advanced planning were required to coordinate interagency integrated operations and ensure a successful integration.

REFERENCES

- [1] MSL Launch Systems Engineer, James E. Colvin, Jet Propulsion Laboratory.
- [2] MSL Rover Chassis Cognizent Engineer, Peter M. Illsley, Jet Propulsion Laboratory.
- [3] Launch Site Integration Engineer, Joan M. Wenaas, United Launch Alliance.
- [4] Aerospace Conference Web site www.aeroconf.org/

ACKNOWLEDGEMENT

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

BIOGRAPHY

Paul Lytal received his B.S. and M.S. degrees from Stanford University. He has been a mechanical engineer in the Spacecraft Mechanical Engineering section of the Jet Propulsion Laboratory for 6 year, designing and building flight structural components and ground support equipment for the MSL and AMD Projects. Paul is currently the Power Source Integration Engineer for the MSL Project.

Pamela Hoffman received her B.S. degree in Mechanical Engineering from the University of California, Berkeley in 1987 and her M.S. degree in Mechanical Engineering from the California Institute of Technology in 1989. She has been working at NASA's Jet Propulsion Laboratory for the last 22 years developing a variety of deep space missions including Galileo, NSCAT, Cassini, Europa Orbiter, Pluto Kuiper Express, Mars Exploration Rover, and Mars Science Laboratory. Currently, she is the Project Element Manager for the Mechanical Thermal Subsystem on the Soil Moisture Active & Passive Mission.

