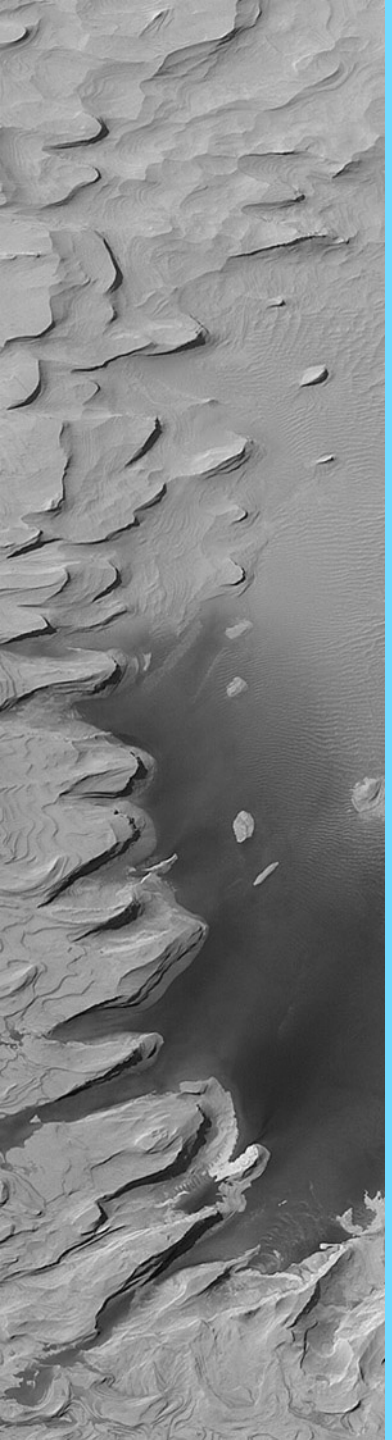
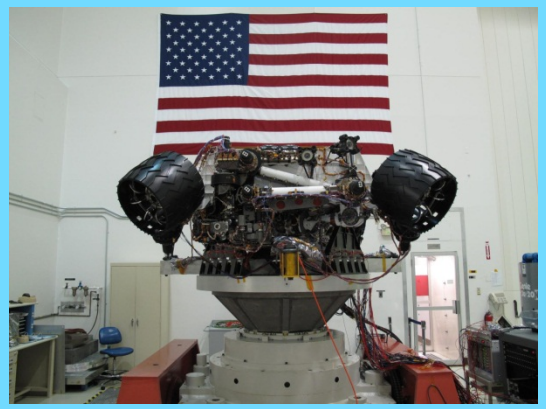


Hardware QA: Preparing and Certifying a Rover To Land on the Surface of Mars

Rick Paynter
MSL HQA Manager
Jet Propulsion Laboratory
California Institute of Technology

Sandia National Laboratories

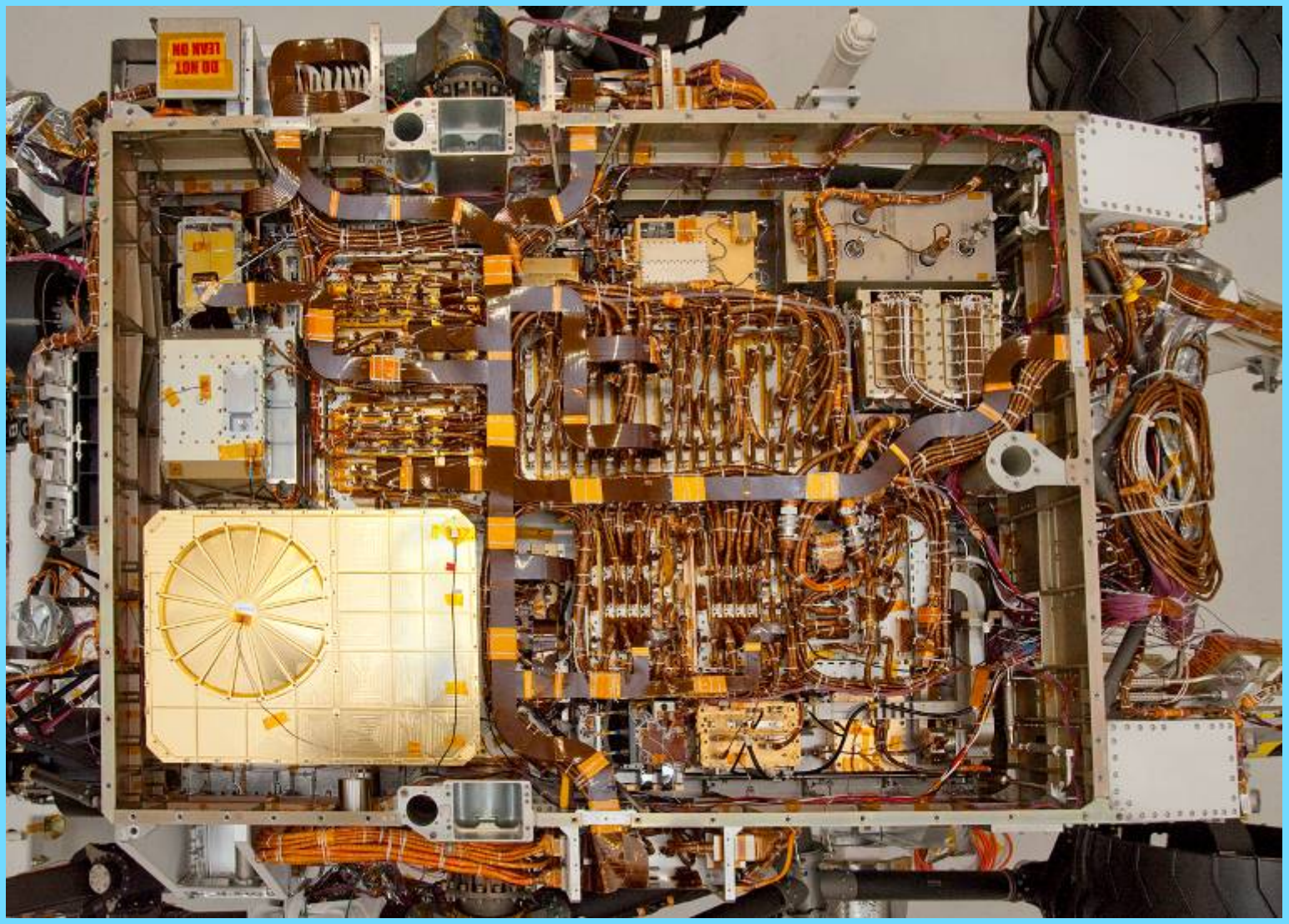
July 25th, 2012



MSL Summary

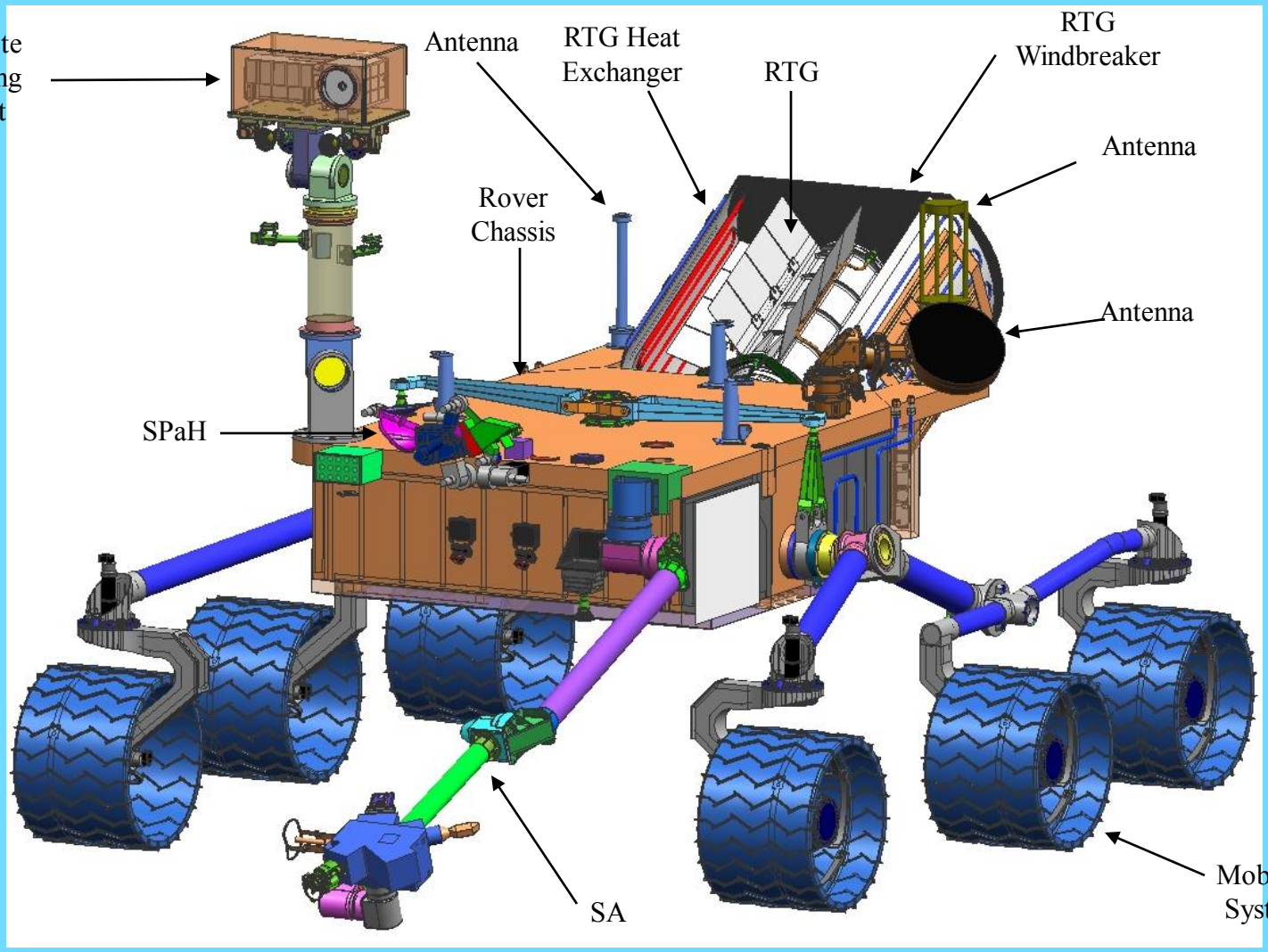
- The Mars Science Laboratory Project presented multiple challenges of complexity for hardware QA personnel
- Technical complexity was a major challenge
- This is a one-of-kind never-before-been-built Spacecraft with a nuclear-powered Rover the size of a small SUV
- It features a never-before-been-used “Skycrane” landing system featuring a Descent Stage which is a complex spacecraft within itself
- Equally complex was figuring out how to support multiple activities at multiple facilities in this country and around the world at the same time

Rover Chassis Internal - Complexity

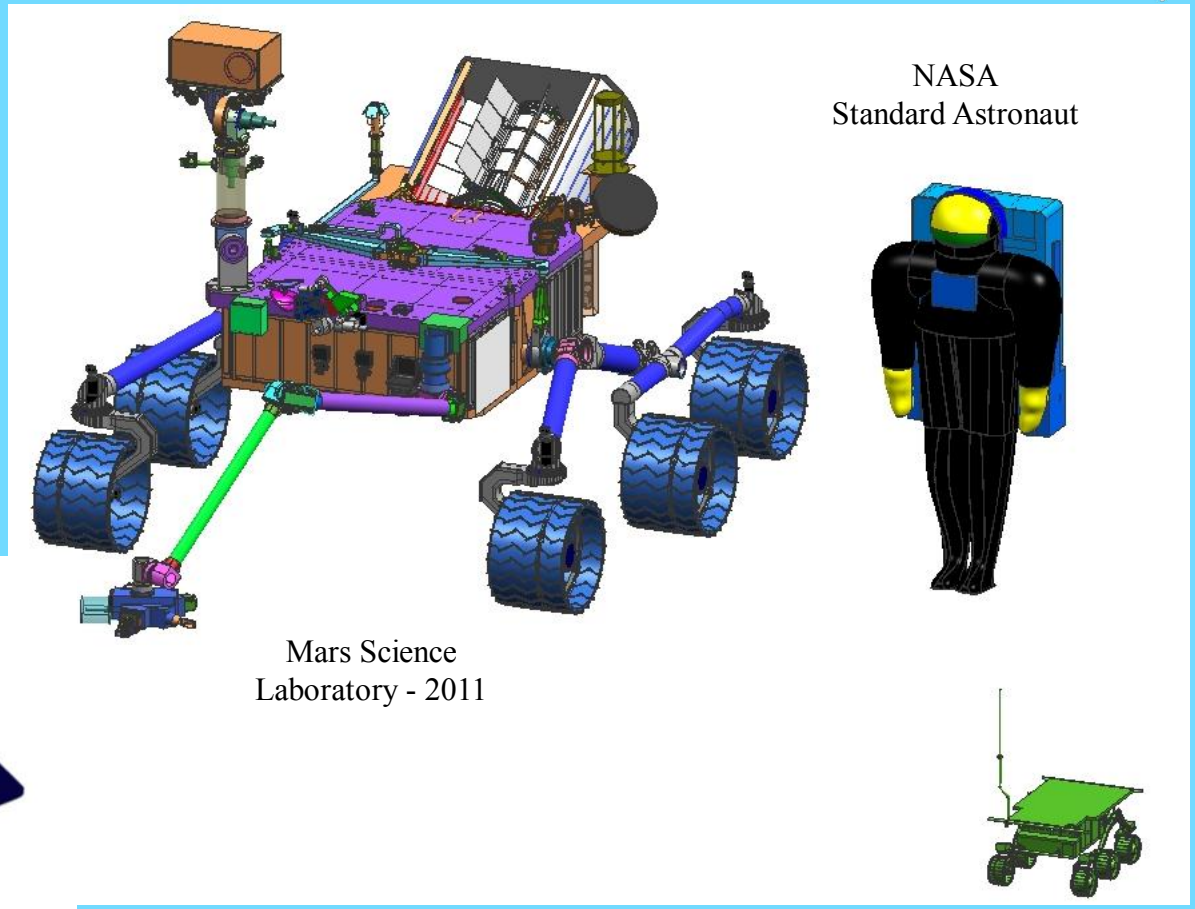


There were over 11,500 connector mates and demates during MSL System I & T

Rover Configuration



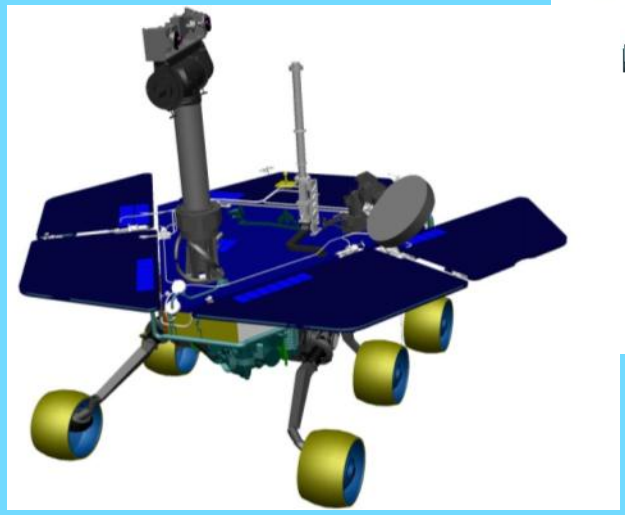
The Bigger Better Rover



NASA
Standard Astronaut

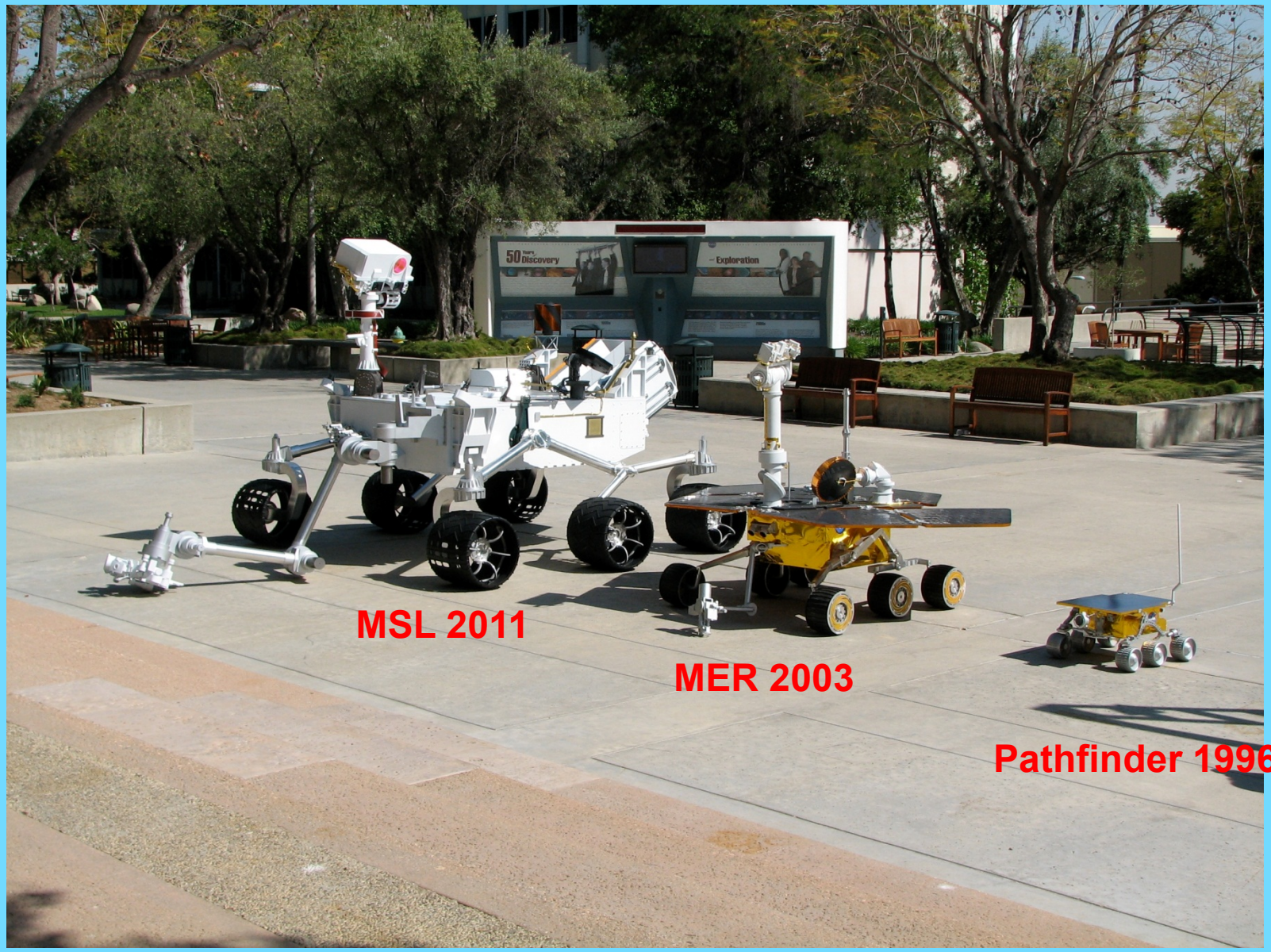
Mars Science
Laboratory - 2011

Mars Exploration
Rover - 2003

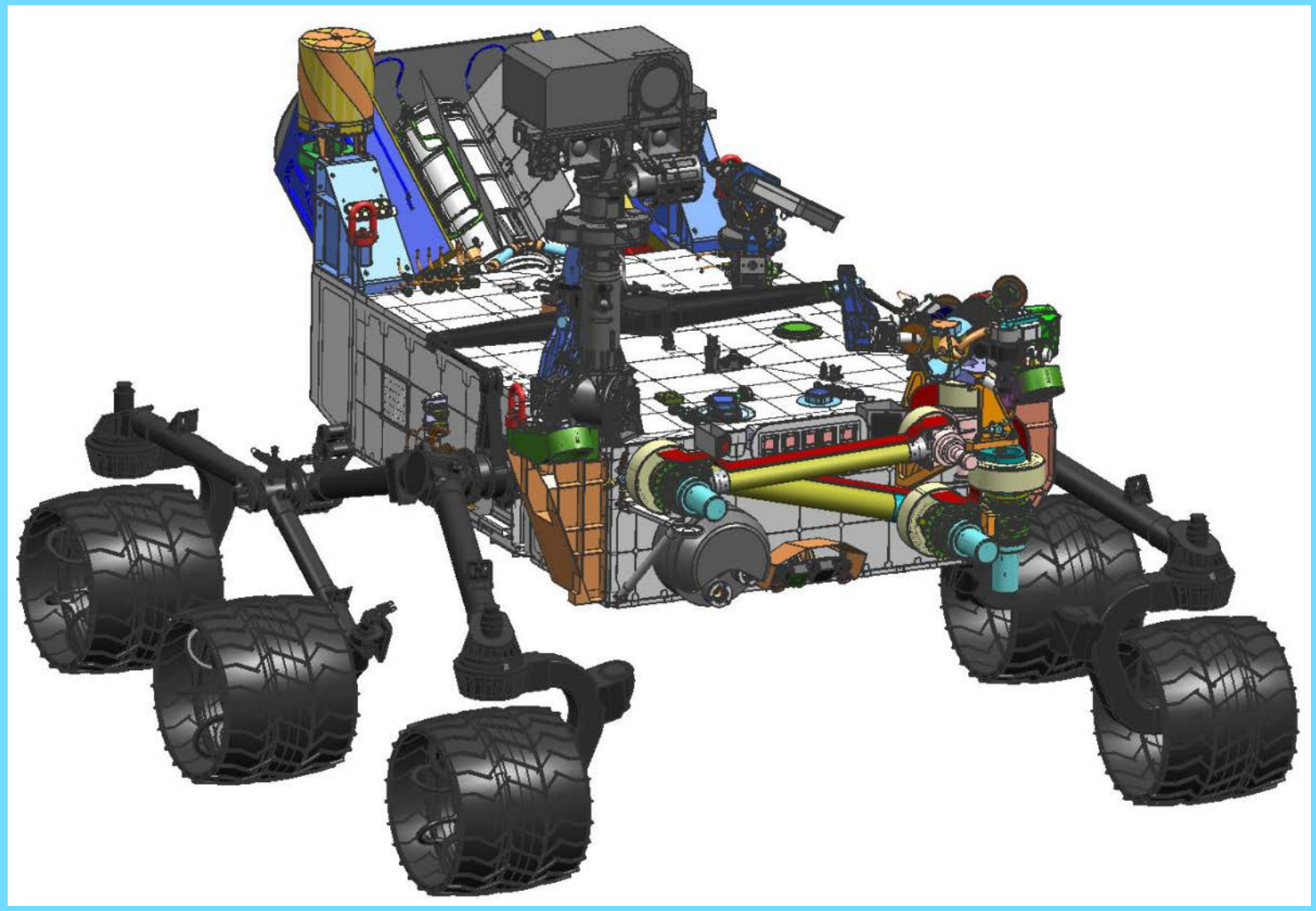


Mars Pathfinder
Sojourner Rover - 1996

Mars Rover Comparison



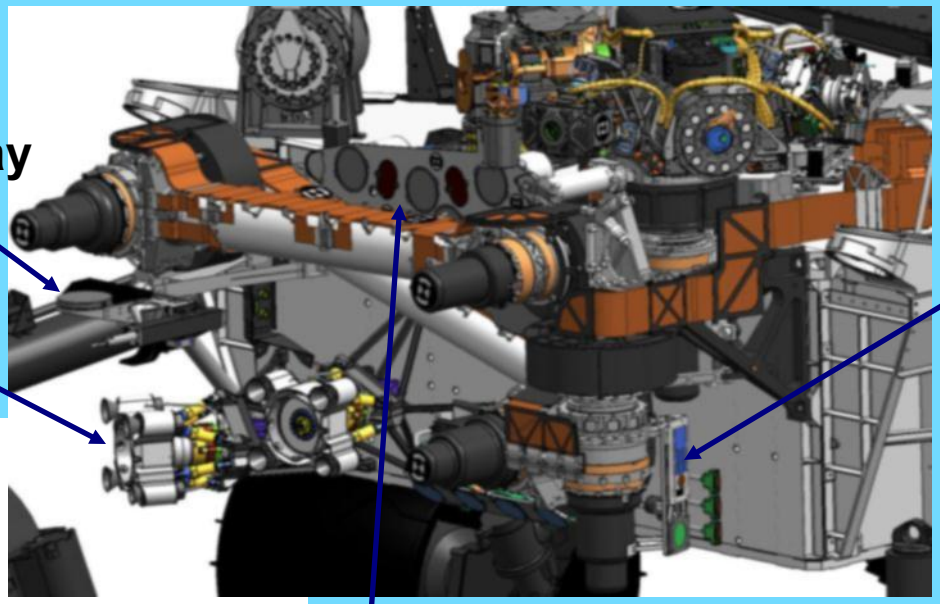
Stowed SASPaH & Deployed Rover



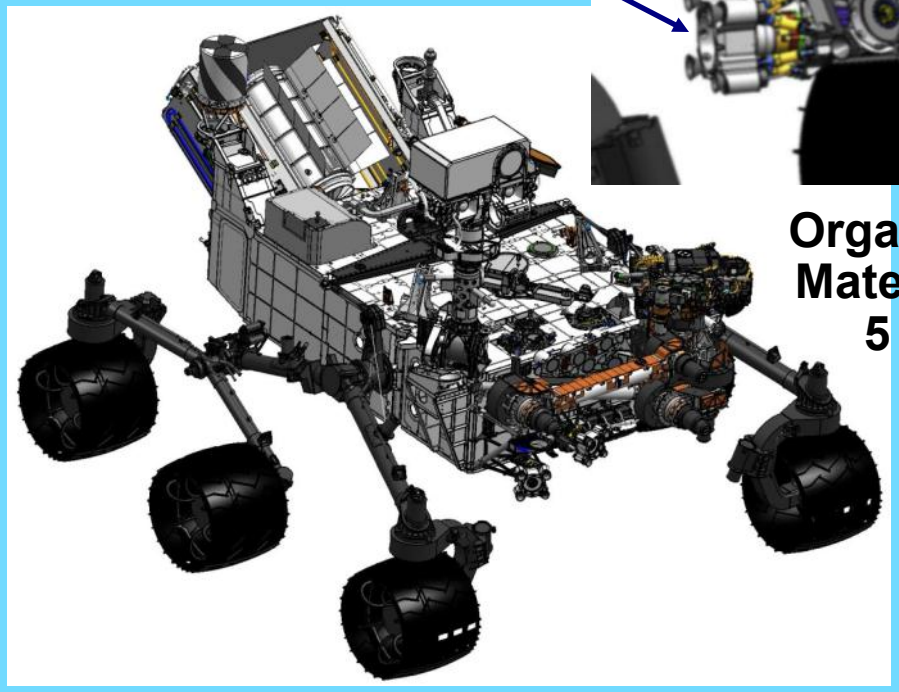
Stowed SA-SPaH & Deployed Rover

Sample Playground & Science Observation Tray

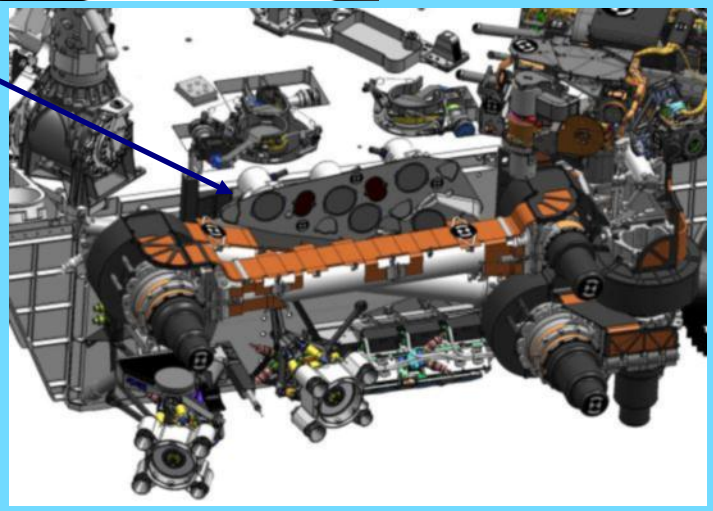
2 Individual Bit Boxes with Bits



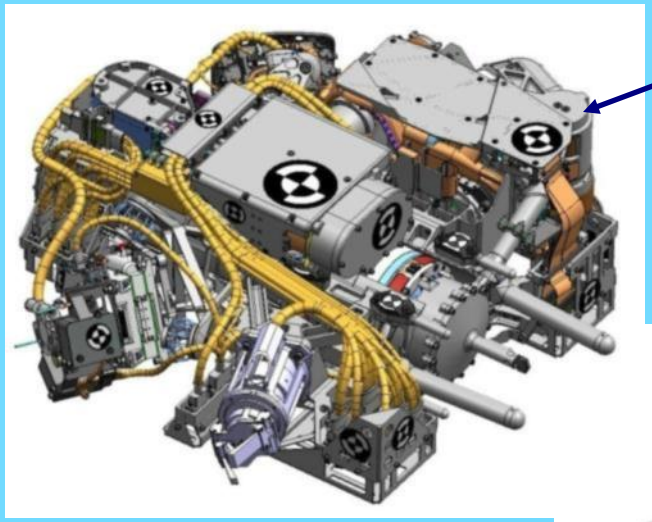
APXS & MAHLI Cal Targets on Robotic Arm Azimuth Actuator



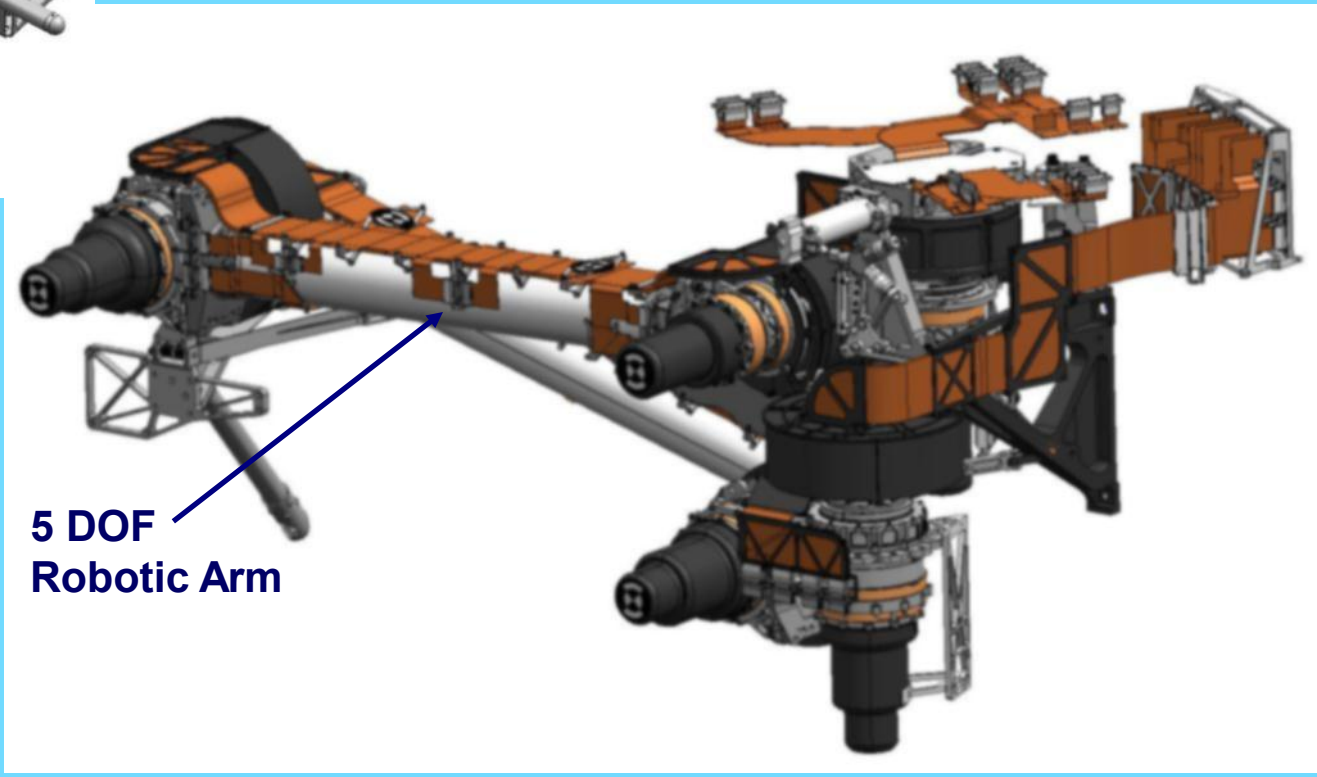
Organic Check Material Box – 5 Bricks



Robotic Arm/Turret



Turret (composed of 5 devices) attaches to the Output Plate of the Arm via the Drill structure

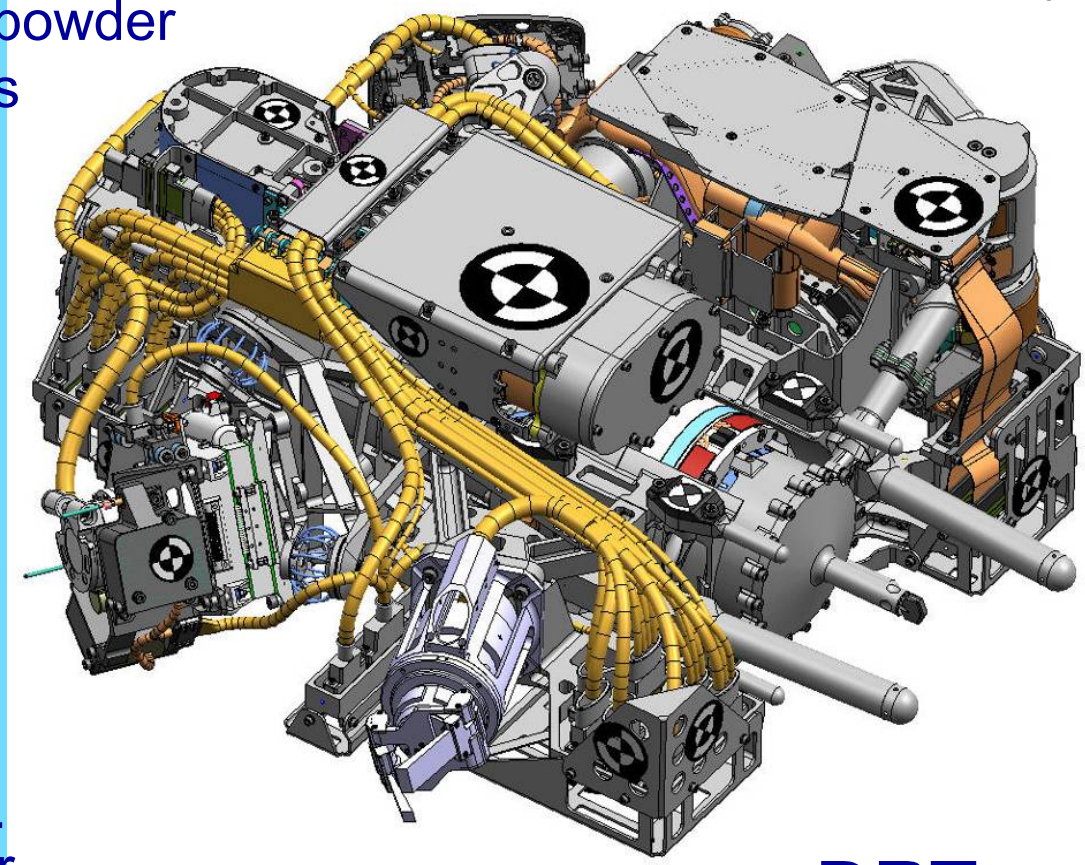


5 DOF
Robotic Arm

5 DOF Robotic Arm/Turret

Drill
Acquires powder from rocks

APXS
Alpha particle X-ray spectrometer

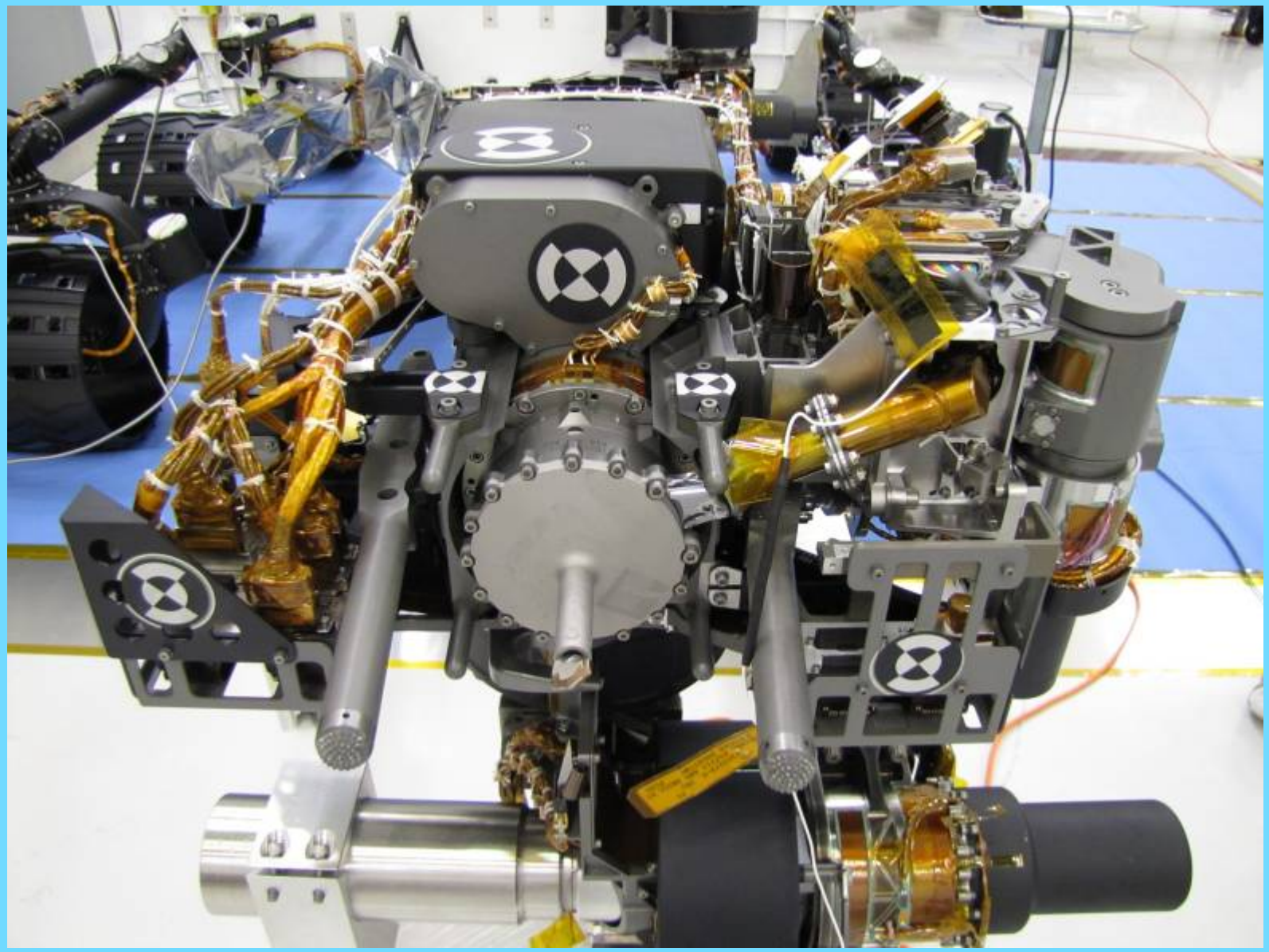


CHIMRA
Scoops regolith, sieves and portions

MAHLI
An imager

DRT
Dust Removal Tool

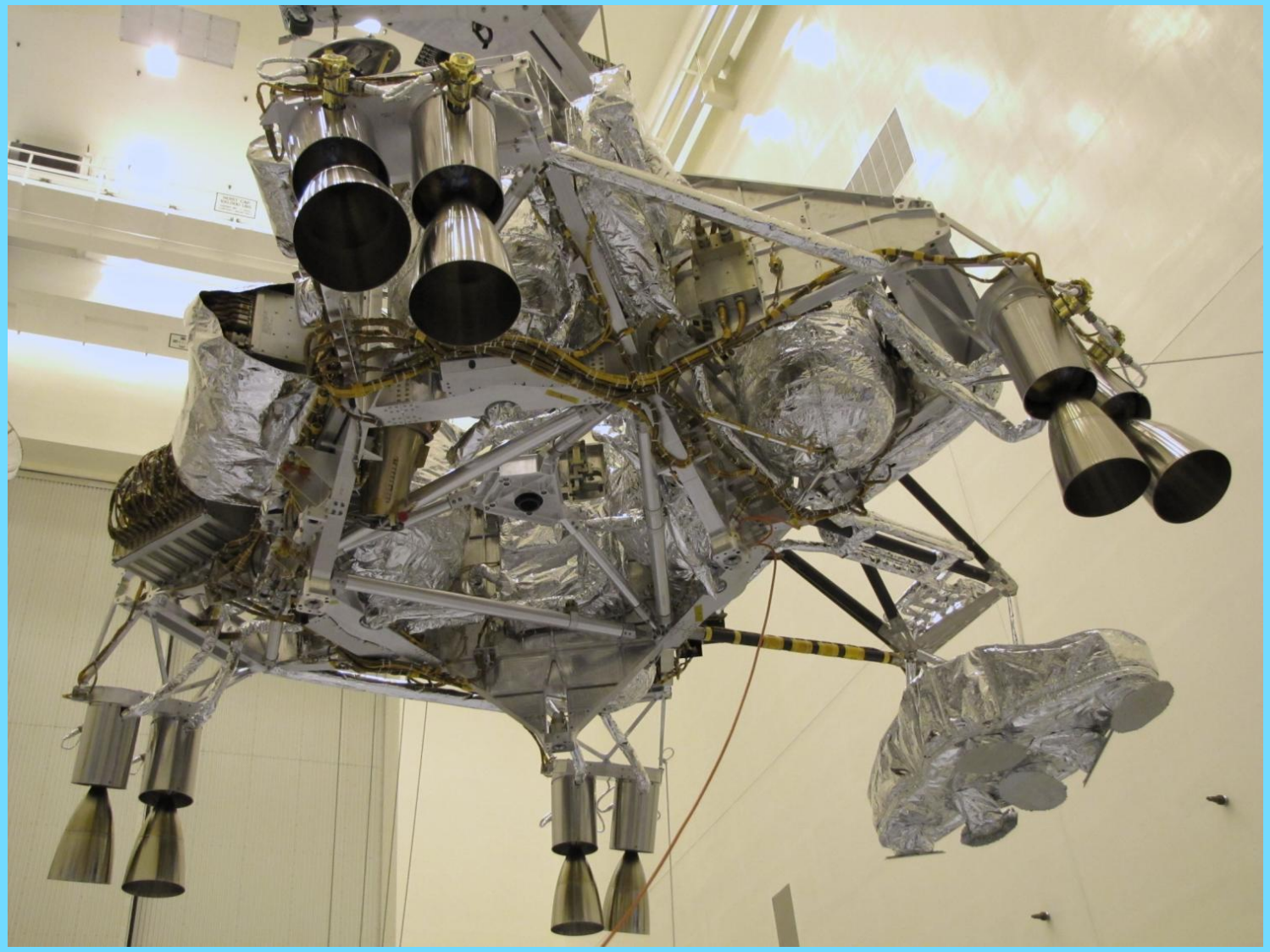
SA/SPaH Turret - Complexity



GSFC-Provided SAM Instrument – Complexity

Testing of the Robotic Arm at JPL

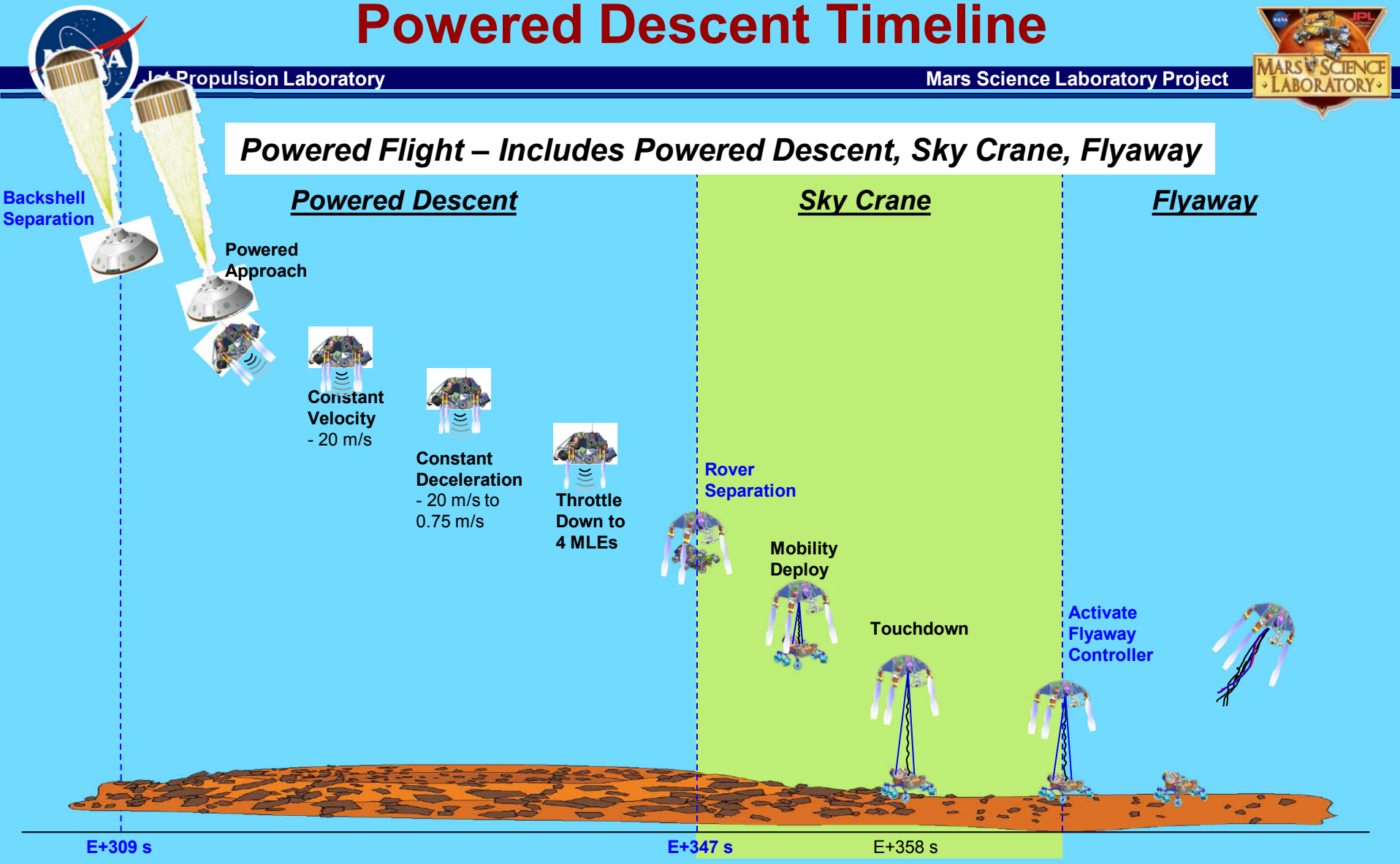
MSL Descent Stage



MSL Landing Facts

- Ten minutes before landing, the Cruise Stage separates from the Descent Stage at ~ 78 miles above the surface
- 98% of the energy needed to slow the entry vehicle down is absorbed by the Heatshield
  - The ~ 15-foot diameter Heatshield is the largest ever flown
- MSL will be the first to utilize a “guided-entry” system, which enables it to land in a far-more precise landing region than in the past (*12-mile ellipse*)
- The largest supersonic parachute ever used will deploy at ~ 900 mph, 7 miles above the surface (*51 foot diameter,165 foot long suspension lines)*
- The Heatshield is jettisoned 5 miles above the surface
  - The Radar is then activated to measure the attitude and velocity of the descent
- After the parachute has slowed the craft to 180mph about 1-mile above the surface, the backshell and parachute separate
- That’s when the Descent Stage’s 8-rocket engines fire to begin to slow the descent ever further

Powered Descent Timeline



X-Band Tones →
UHF 2 kbps →

The Terror of Complexity

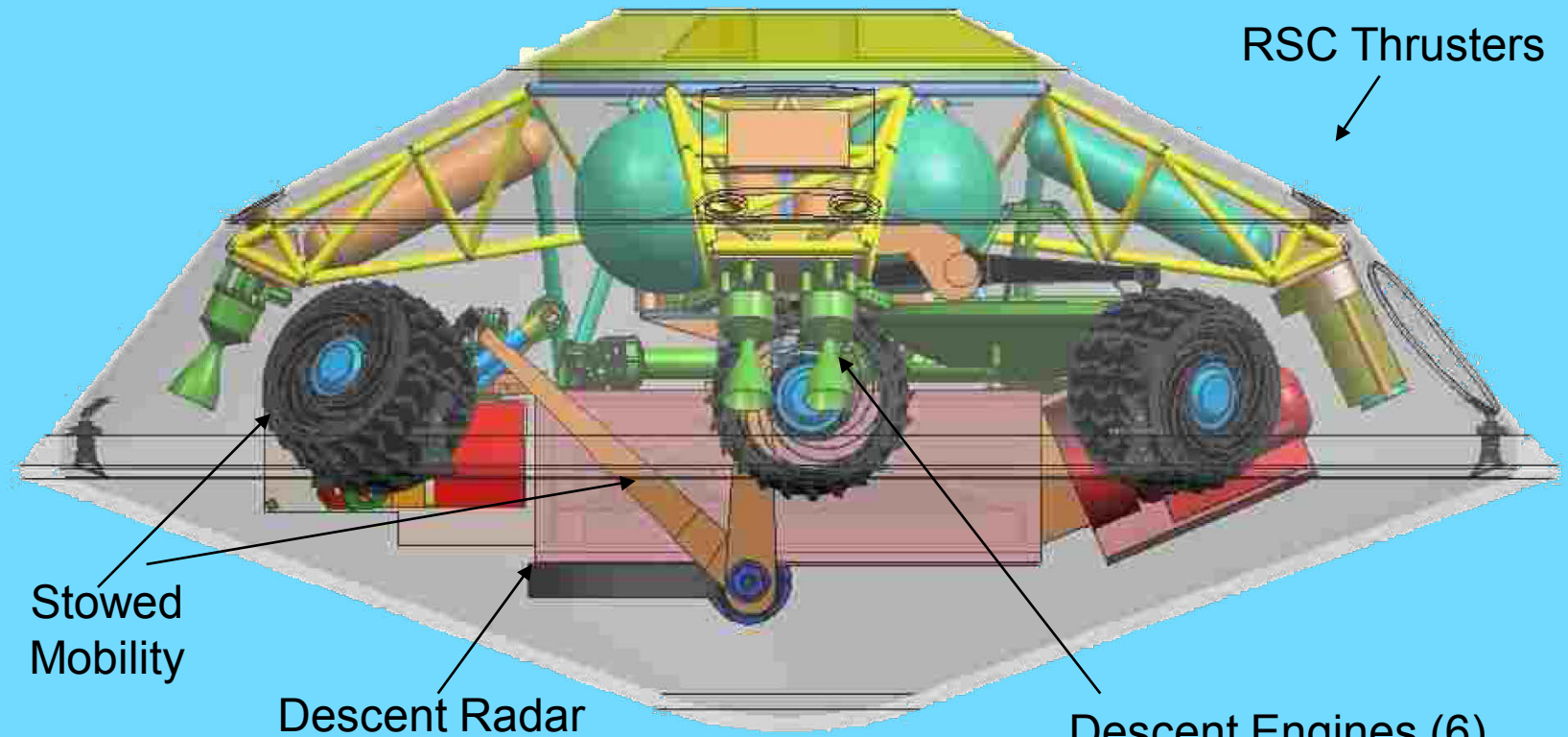
"7 Minutes of Terror"….MSL EDL Aug 5, 2012

- What exactly will it take to land NASA's next Mars rover, Curiosity, on the surface of Mars on Aug. 5?
- It may be described as reasoned - even genius - engineering. But even the engineers who designed it agree it looks crazy.
- Six vehicle configurations,
- 76 pyrotechnic devices,
- 500,000 lines of code,
- Zero margin for error.
- http://marsprogram.jpl.nasa.gov/msl/multimedia/videos/index.cfm?v=49

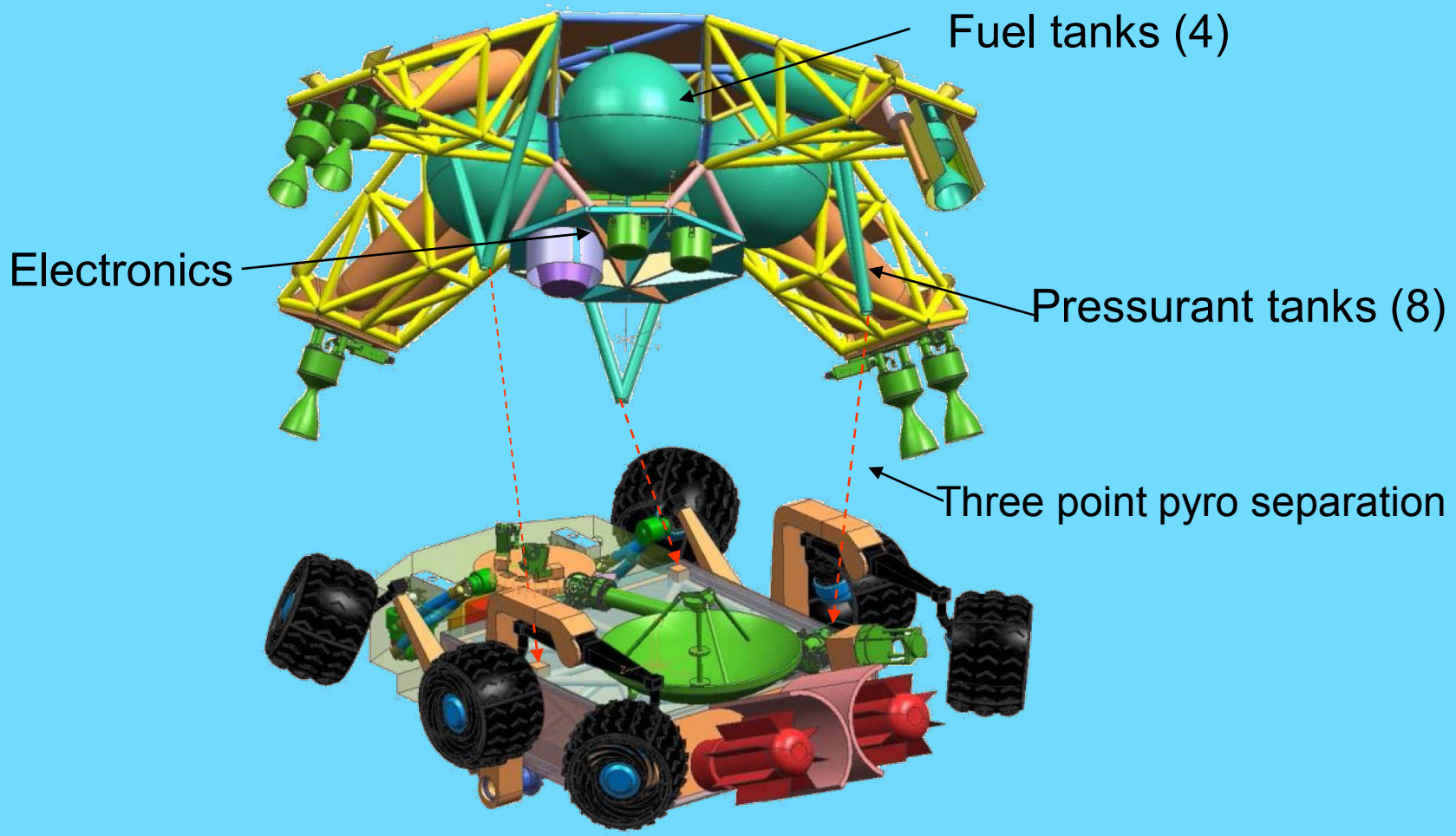
EDL Terminal Descent Trade Study
October 2003

- Options considered
  - Legs
  - Airbags
  - Pallet
  - Hybrids of legs, airbags
  - Skycrane
- Selected: Skycrane
- Justification
  - Best slope and rock tolerance
  - Lowest landing energy and design complexity (highly modelable)
  - No rover egress issues
  - Feed forward to future large payload missions (modular design and clean interfaces)
  - No major unknowns in control design (based on initial simulations)
  - Understood and manageable development and operational risks

Entry Configuration (w/SkyCrane)



Descent Stage (w/Skycrane)/Rover Assembly



Hazardous Op's – Rover Over Descent Stage

Engineering and QA Challenges

- → Most complicated spacecraft and largest, most sophisticated rover ever launched to land on another planet
- → 13,200mph to Zero in seven minutes
- → How to assure the highest quality and reliable systems and subsystems possible?
- → How to implement the highest-level of checks and balances?
- → Skycrane Subsystem presented some unique and interesting challenges

Why Did We Need the Skycrane?

- Why not use the airbag method of landing like on previous missions?
  - MSL Curiosity was too heavy
  - Exceeded the mass that any airbag landing system could tolerate
- Mass of Curiosity = ~2000 lbs.
- Mass of Spirit/Opportunity = ~400 lbs.
- Another challenge: Could not execute an end-to-end, test as you fly, system test simulating the MSL Skycrane landing
- This was because of a number of factors, including budget and building a test-stand able to simulate an end-to-end system test
- Could not reproduce the speed of entry and the environmental conditions that MSL will experience during the descent into the Martian atmosphere

Engineering and QA Challenges

- The Skycrane "maneuver" comprises the final 12 seconds before landing
- That's 12-seconds for all of this!!!!
- The Skycrane subsystem consists of the following hardware:
  - Bridle Umbilical Device (*or affectionately referred to as the BUD!*)
    - *This BUD's for Sandia!!* ☺
  - Umbilical Device Assembly (*Signal transmit and receive cable harness*)
  - Bridle Device Assembly (*Three Nylon Bridles*)
  - Bridle Spool Assembly
  - Umbilical Retraction Mechanism
  - Descent Brake/Descent Rate Limiter
  - Confluence Pulley
  - Bridle Exit Guide Assemblies (3)

Engineering and QA Challenges

- In the absence of an exact end-to-end system test
  - Tested the Skycrane subsystem in sections
- Utilized engineering qualification hardware (*very flight-like*)
  - Executed what was called the Skycrane Full-Motion Drop Test
  - Performed while the Skycrane and Rover hardware were suspended from a crane in the propulsion assembly building
- Tested the BUD Subsystem inside a thermal chamber
  - Tested the deployment of the umbilical cable and bridles while at the expected cold temperatures which will occur during the MSL landing
- Both tests were very successful!
- QA was fully-involved with this testing, including
  - Verification of the test set-up
  - Witnessing both of these tests
  - Post-test Inspections
- Along with additional flight acceptance tests of the actual flight hardware, this gives us a high-level of confidence that the Skycrane will function as intended

Engineering and QA Challenges

- → Hardware Quality Assurance implemented QA-coverage on Engineering Model and Test Model activities
- → Two primary reasons for doing this:
  1) Introduce the rigor associated with developing the assembly and test processes and procedures with QA on-board to help with that process
  2) Allow the QA Engineer's to get familiar-with the hardware and processes/procedures such that they were a lot smarter when it came time to build and test the flight units
     - → *Therefore, providing more value to the Project*
- → It was necessary to develop a strong presence at our key suppliers and we were not bashful about insisting upon a number of JPL QA Mandatory Inspection Points (JMIPS)
- → Tried to maintain a consistency of QA-resources, meaning that in many cases, the QAE responsible for the suppliers' JMIPS followed the hardware after delivery and supported the hardware activities that occurred at JPL

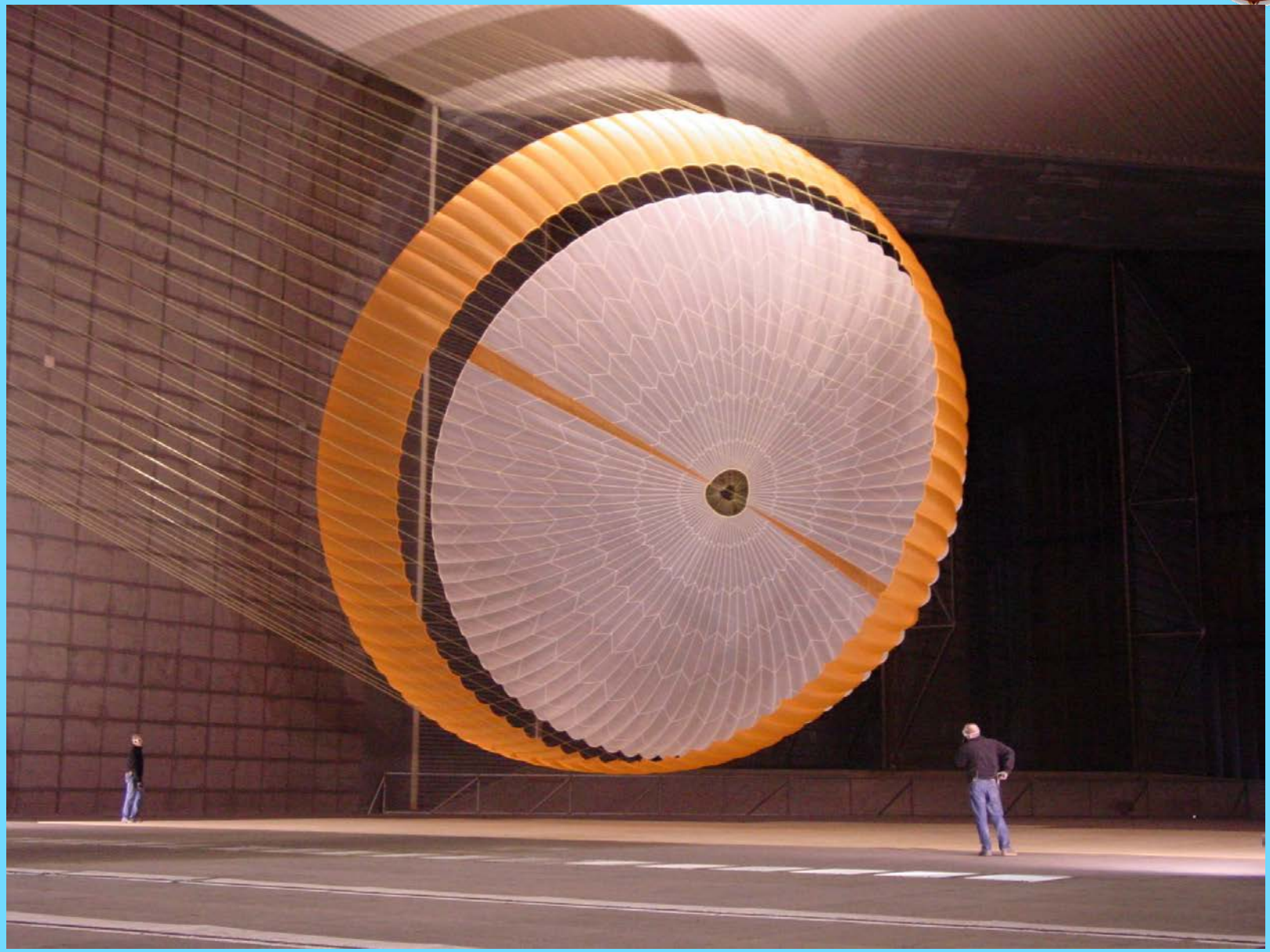
Engineering and QA Challenges

- Some changes in the design resulted from early testing of the components of the Skycrane subsystem
- For example, the original tethers, or Bridles, from which the Rover is suspended from the Descent Stage during the Skycrane maneuver, were made out of a hybrid of nylon and vectran materials
  - Thermal testing indicated that the material got too stiff when subjected to colder temperatures
  - This resulted in a design-change to just using nylon as the material for the three (3) Bridles
- In addition to the testing of the various sections of the Skycrane that occurred, there was also a lot of modeling and analyses that were performed to verify that we had a high-degree of confidence that the design would be successful
- For example, there was a concern about the umbilical re-contacting the Rover and damaging hardware, specifically the UHF Antenna, after it is severed at the beginning of the Descent Stage flyaway sequence
  - *The probability of this occurring was calculated to be only 1.2% after an extensive analysis, including Monte Carlo results, and umbilical separation testing was performed*

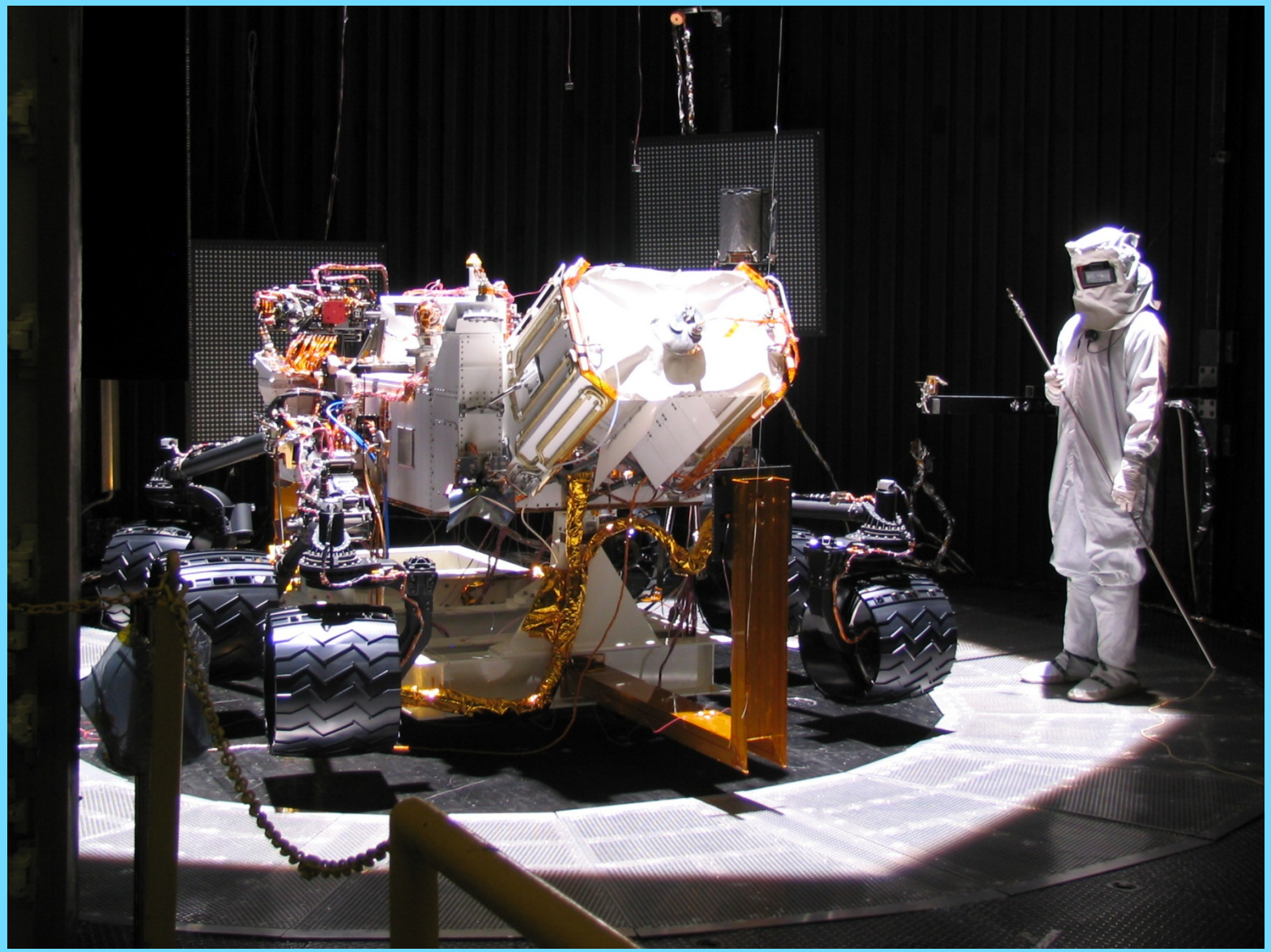
Engineering and QA Challenges

- We decided it would be prudent to implement a QA-principle that we use on spacecraft parachutes on the Umbilical Deployment Device (UDD)
- On parachutes, the flight parachute is never deployed, tested or unpacked after packing for flight
  - This is because of the risks associated with damaging the textile/soft goods when deploying a parachute packed for flight
- We get QA involved early-on to experience and witness the parachute packing process on test parachutes
- Frequently, the packing procedure is modified once you actually start actually packing the parachute
  - *Remember….all Mars parachutes are of a custom-design and the MSL parachute is the largest ever assembled and sent to another planet*
  - It is absolutely essential that the parachute deployment is flawless
- Having the same QAE involved with the development of the packing procedure and witnessing the packing of the test parachutes, they can provide much more value as a verification source by verifying that the flight parachutes are packed precisely and properly
- So the same principle applies for the UDD
- We implemented the same QA-Plan because it is absolutely essential that the Umbilical deployment is flawless

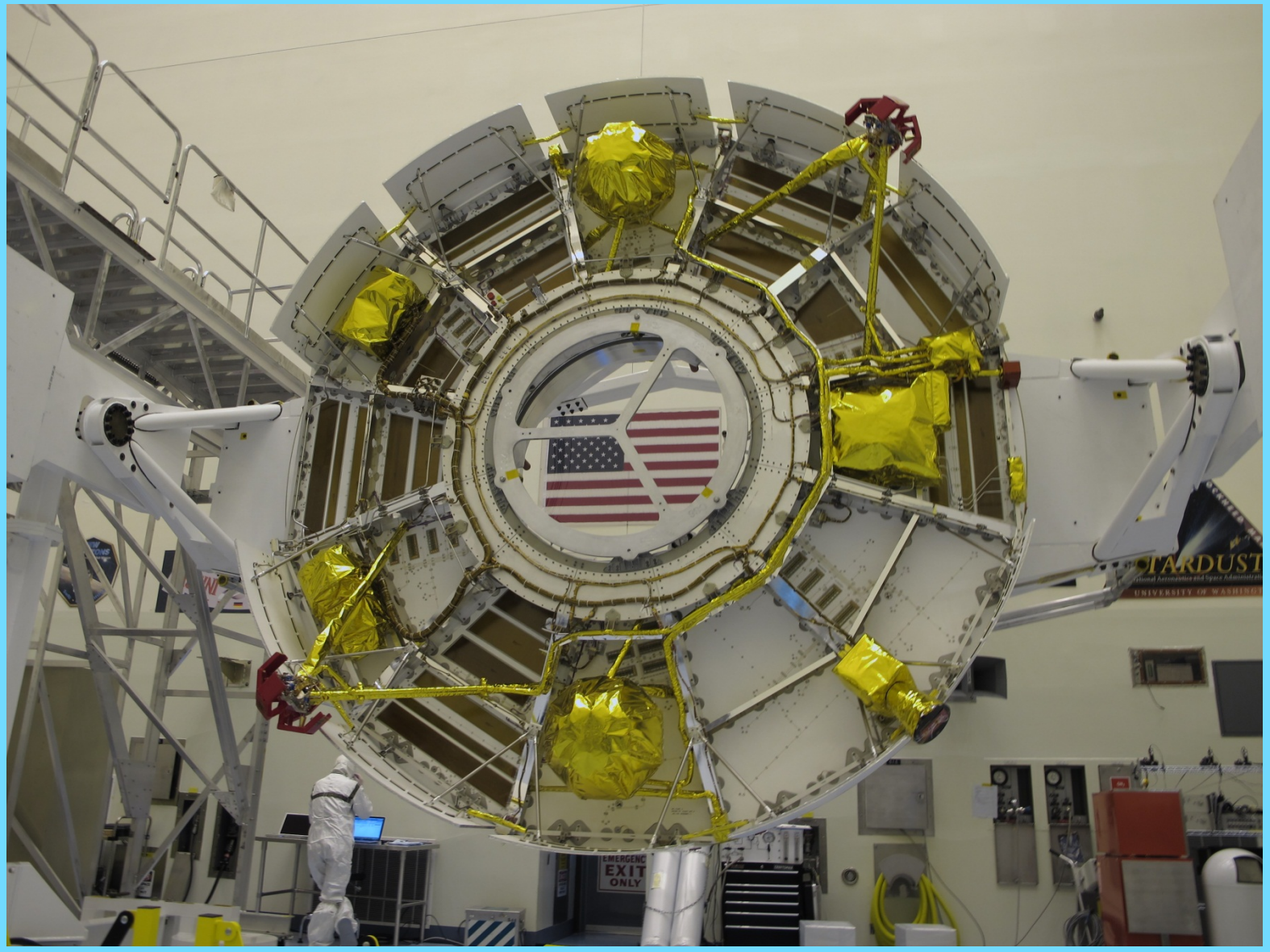
Parachute in Wind Tunnel



Rover in Solar Thermal Chamber



Cruise Stage



Radioisotope Thermoelectric Generator(RTG) - QU

Flight Certification

- Certification of flight hardware that is going to land on Mars is a process that takes years at JPL
- Starting with piece-part hardware, everything, including brackets, fasteners, washers, polymerics, etc. must be certified for flight by QA
  - This is done by QA generating an Inspection Report
- When suppliers deliver components and, in some cases, complex assemblies (*Actuators, Inertial Measurement Units, Science Instruments, etc.*), an Inspection Report (IR) is required that:
  - Accepts the hardware for flight and/or
  - Flags open items that must be completed before flight
- As assembly and test operations proceed, a rigorous process of inspections and documentation reviews are constantly performed by Engineering and QA, culminating in QA generating a Final IR
- Once electronic and mechanical components and assemblies are ready to be delivered to System-level (*Spacecraft-level*) Integration and Test, a Hardware Review Certification Record (HRCR) Form must be completed and an HRCR Review is convened

Flight Certification

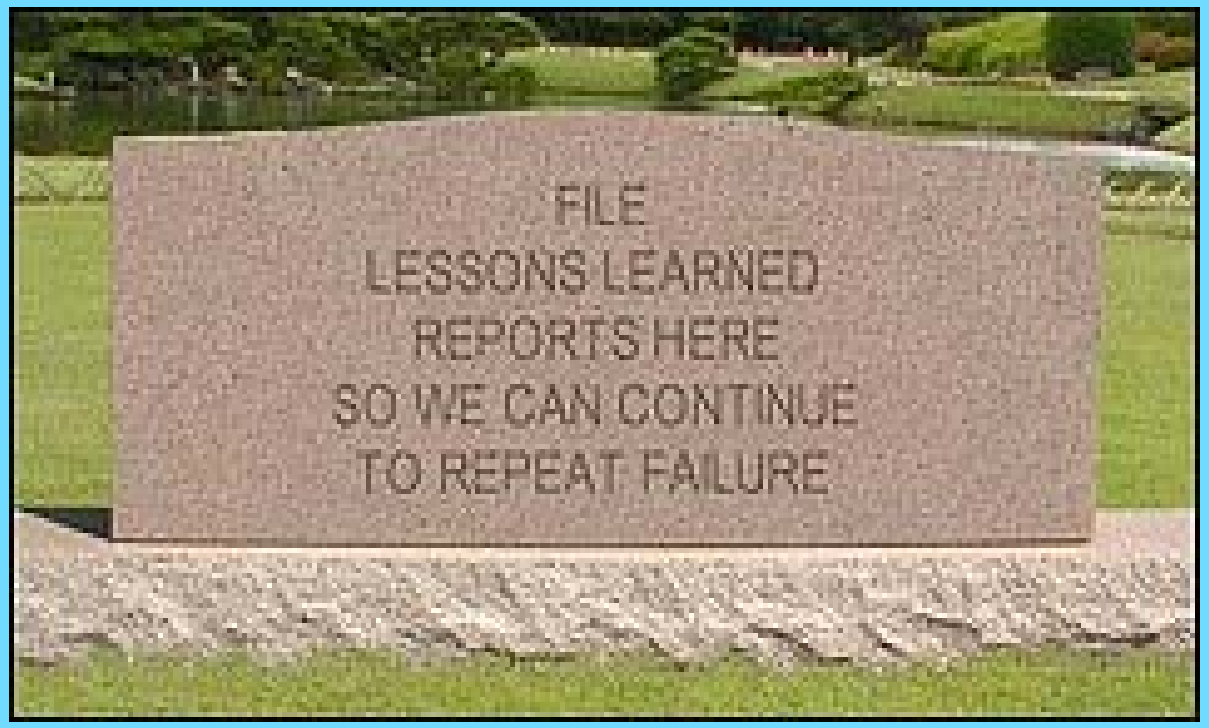
- The HRCR Process is a series of 23 questions and 13 Data Attachments which comprise the End Item Data Package delivered to the Project, along with the hardware
- It includes questions to be answered and objective evidence of compliance indicating that the hardware is flight-worthy
  - These include items such as reliability analyses, requirements matrices, as-built lists, materials and electronic parts approvals, environmental test records, waivers, etc.
  - It is also required that instructions describing handling and operating constraints be delivered at this time
- The delivering organization, including QA, must certify the hardware and the receiving organization must approve the receipt of the hardware
- Prominent Project Engineers and Managers, including Project QA, must sign the Form indicating approval of the transfer of the hardware
- Many times Action Items are generated at the Review
- The hardware is not considered acceptable for flight until all of the HRCR Action Items are formally approved for closure by designated Project personnel, including QA

MSL QA Lessons Learned Topics

- Early Project Involvement
- Planning QA Coverage/Managing Resources
- Critical Hardware Handing and Transportation
- Generating Lessons Learned

Past Lessons Learned Reports

Don’t Let this Happen!



MSL QA Lesson Learned #1

- "Early Project Involvement"
  - **QA Needs to Get Involved With the Project Early-On With the "End-Game Deliveries" in mind right away**
- "Implementing Quality Early-On for the MSL Project"
  - Presented at QLF on 9/27/2006 by Paynter
- Get to know your QA counterparts at:
  - Your sub-tier suppliers
  - Your industry partners
  - Your international partners
  - All flight hardware providers
- ***Hit the road!*** ***Visit*** your Suppliers if you can early-on
- It makes a positive difference when you can meet face-to-face

MSL QA Lesson Learned #1

- Give a presentation to your hardware suppliers/providers about the Project's objectives
- People appreciate the "big-picture"
- They take more ownership in a product when they understand how and where they "fit" into the "big-picture"
- Make them understand how they can significantly contribute to mission success
  - This goes for your sub-tier suppliers as well as your employees *in-house*
- There is something about "QA-Speak" between QA-counterparts that helps a lot during the course of hardware developments with external suppliers
- This really pays-off at the time of the end-game delivery!!

MSL QA Lesson Learned #2

- "Planning QA Coverage"
  - **It is essential for QA to stay "one-step ahead" of the hardware activities so that proper QA-coverage can be planned and provided**
- It is ***vital*** to deploy your QA-resources in a timely manner
- In some cases, the work will go on if QA is not available to support it
- Since QA is a "Service Organization," we need to be proactive to stay informed so that we can be at the right place at the right time!
- Communicate and share information regularly
- A little bit of extra effort can go a long way!

MSL QA Lesson Learned #2

- "Managing Resources"
  - **QA Managers and Leads Need to Strategically Match Their Engineers and Inspectors with the Job and the Customer**

- First and foremost, it is important to deploy your QA-resources in accordance with the skill-set needed to perform the work
- But in some cases, it is also important to deploy your resources so that you do not get "*personality conflicts*" which may adversely affect the work (*and your mental well-being!*)
- One strategic match that paid-off was matching experienced QAE's with inexperienced Engineers

MSL QA Lesson Learned #3

- "Critical Hardware Handing and Transportation"
  - **Work with your Safety Engineer to develop a strong hardware handling and transportation plan early in the program**
- MSL offered several challenges with regards to transporting hardware from place to place
  - This included cross-country transports as well as transports from Europe to JPL and vice versa
- My first recommendation is always for QA to hand-carry
  - It is the only way that you can guarantee the safety and the quality of the hardware is not compromised
- You can run into real challenges when the hardware requires an X-Ray exemption in this day and age!

MSL QA Lesson Learned #3

- Since 9/11 it has become increasingly more difficult for QA to hand-carry flight hardware on a commercial airliner
  - *With or without an X-Ray Exemption!*
- So we formed alliances with United, Jet Blue and TSA
- Although the paperwork at first was onerous, after we understood the system, it became rather routine
- Communication was key to the successful implementation of this process
- In instances when it was not feasible to hand-carry the hardware, we made arrangements with Jet Blue
- They allowed us to go on the tarmac at JFK and Burbank Airports to ensure that our actuators/motors were packed and secured properly in their cargo bay

On the Tarmac to Retrieve Spaceflight Hardware Out of the Aircraft's Cargo Bay

MSL QA Lesson Learned #4

- "Generating Lessons Learned"
  - **QA needs to generate Lessons Learned during the Project and should not wait until the end to do so**
- Writing down lessons learned should become a normal routine of your work
- As with a lot of things in this business, the "*devil is in the details*"
- Sometimes, the *details* within a lesson learned is what can make a difference in implementing that lesson learned in a future application
- Generate the entire lesson learned while it is "fresh" in your mind
- Don't wait to do it!

Lessons Learned Conclusions

1) Get the word out early! QA should get involved early in all facets of the flight hardware development

2) Nothing beats good, solid communications and sharing information, especially between QA-counterparts

3) Develop a strong critical hardware handling and transportation plan early and spread the word about it!

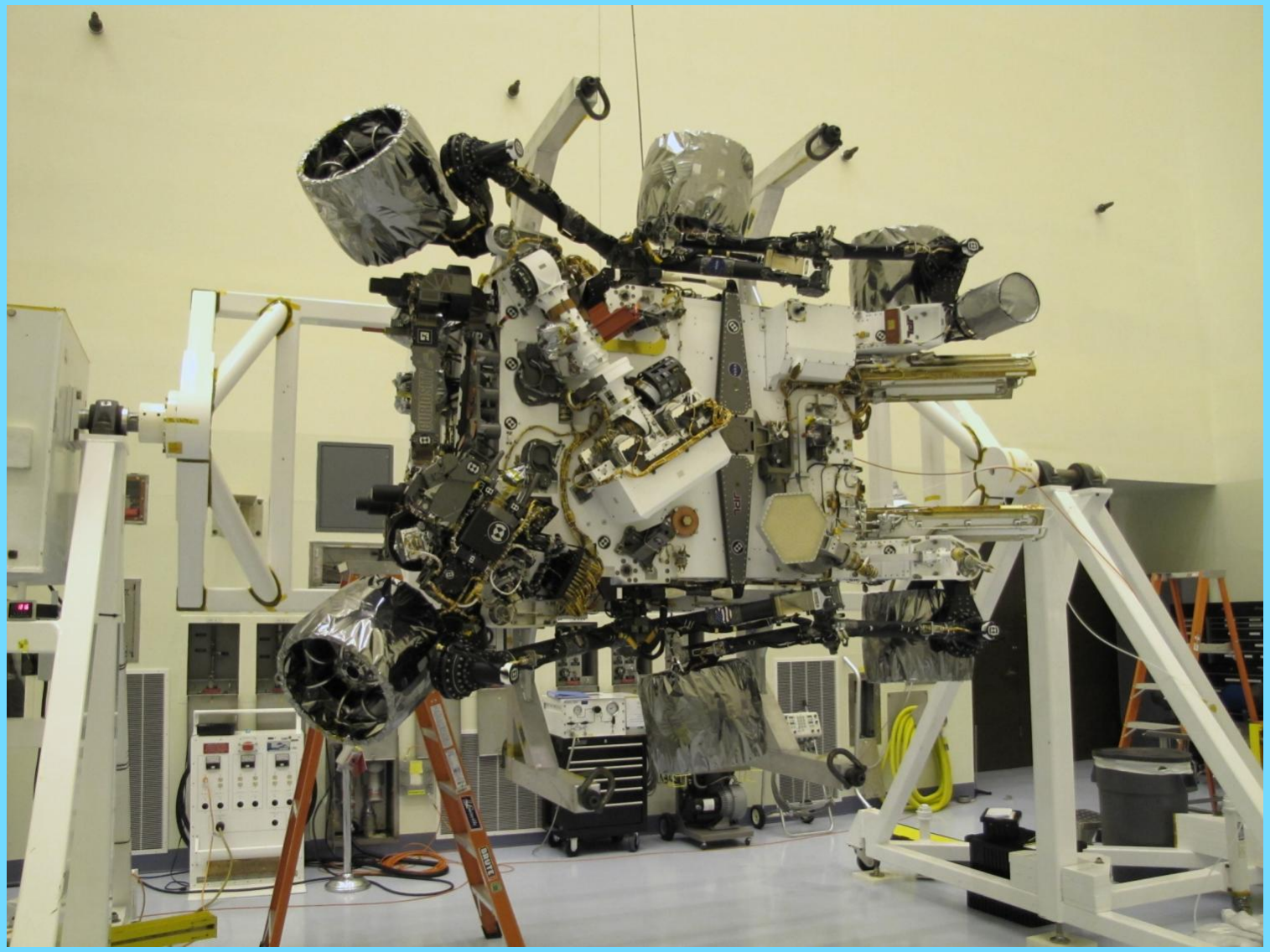
4) “QA-Speak” speaks volumes at delivery time

5) Generate Lessons Learned during the Project, not after

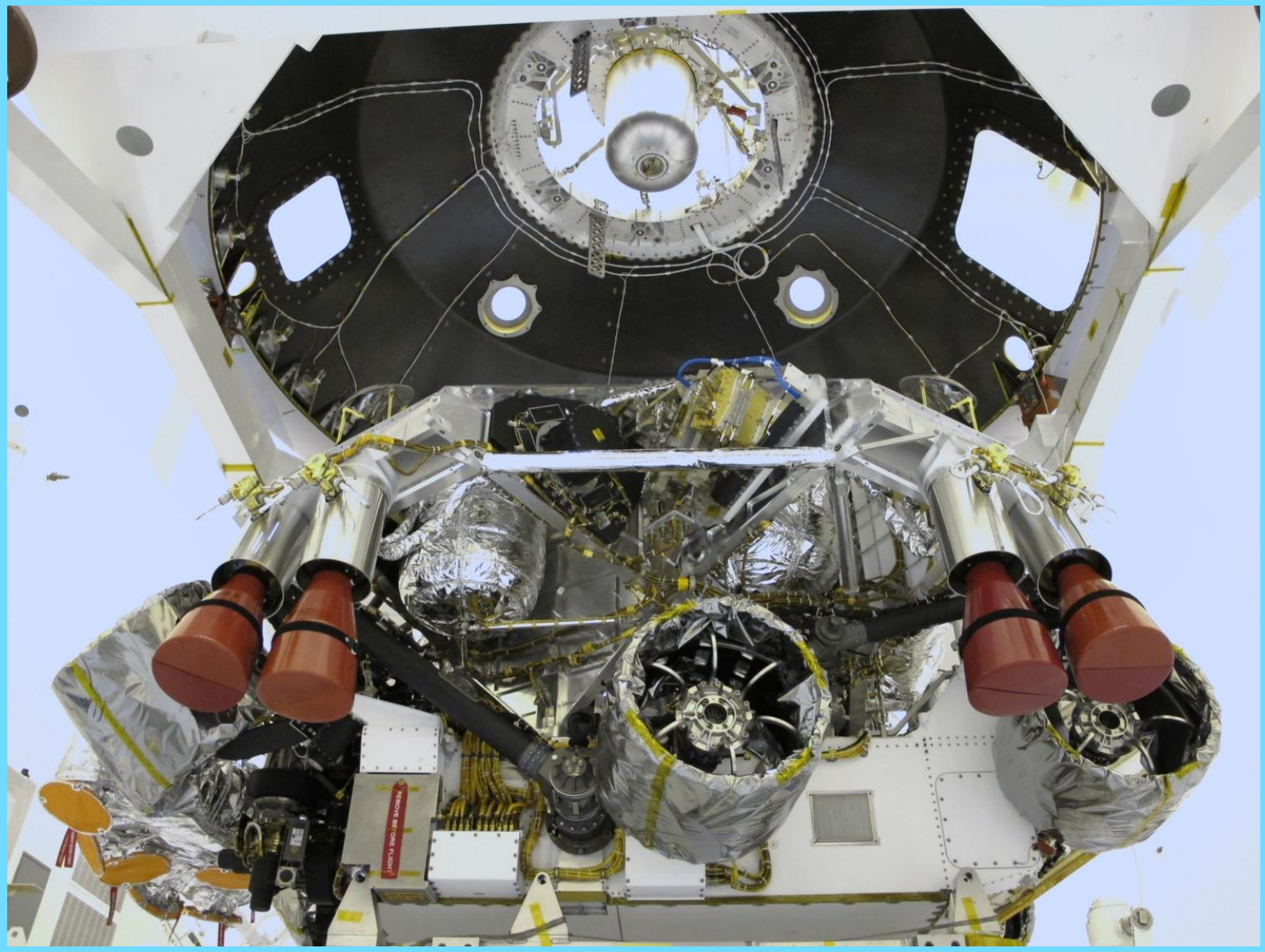
6) This is a tough business! Don’t lose your sense of humor….Enjoy the experience!

Thermal Vac/Solar Simulator

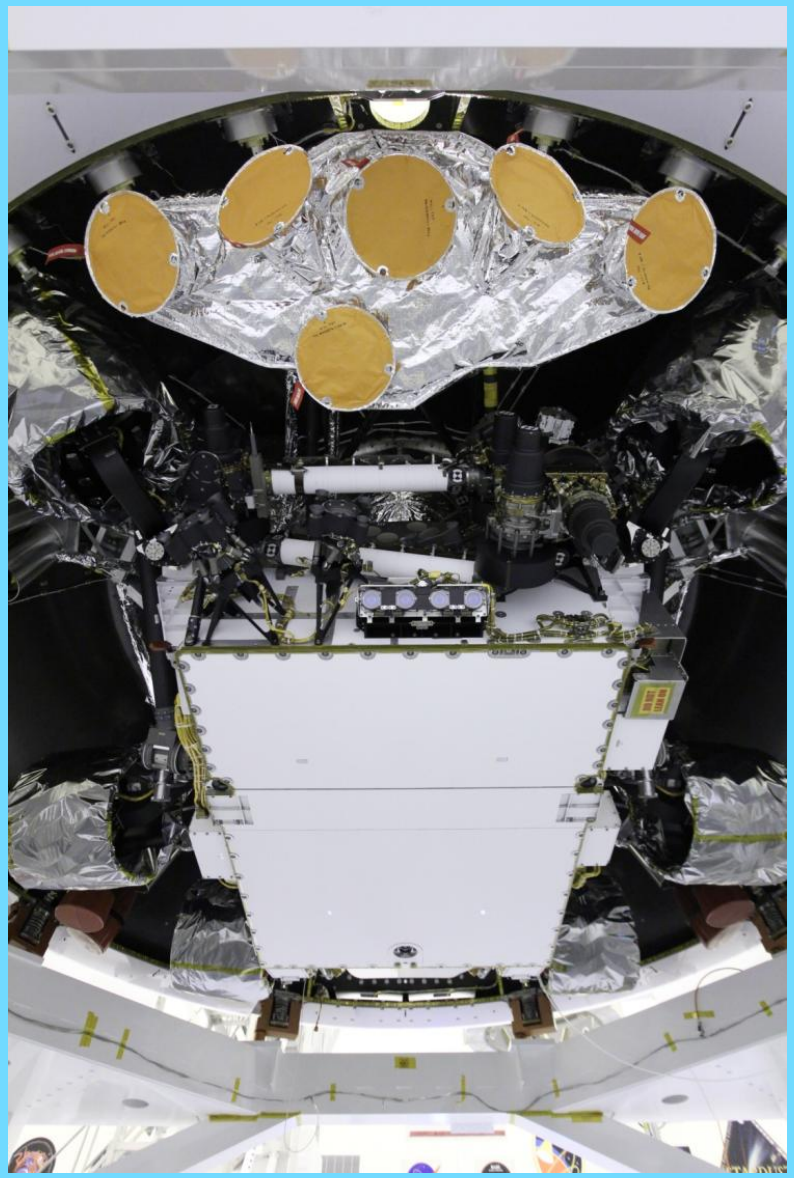
Rover on Rotation Fixture For Mass Property Measurements



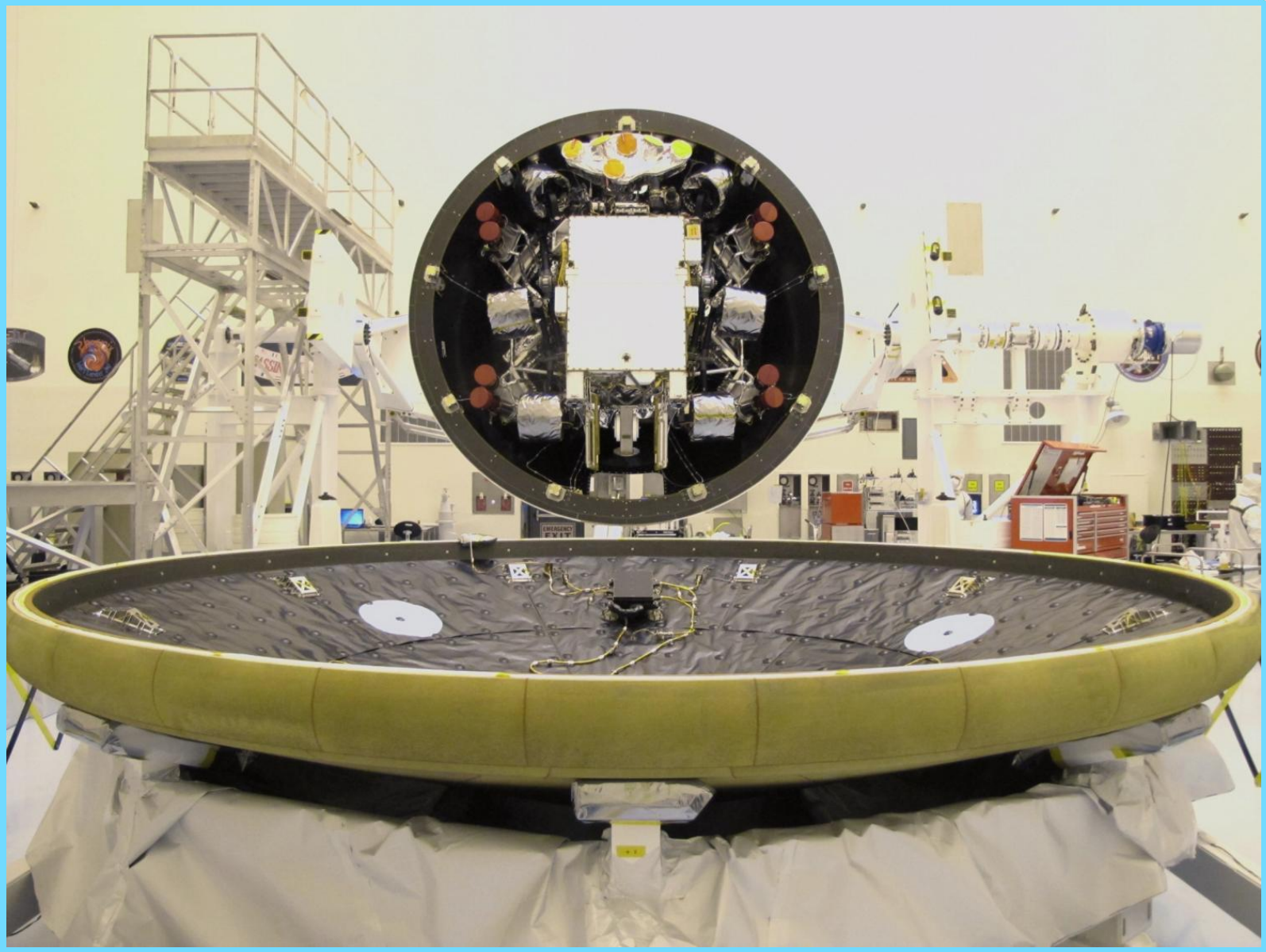
Backshell above D/Stage and Rover



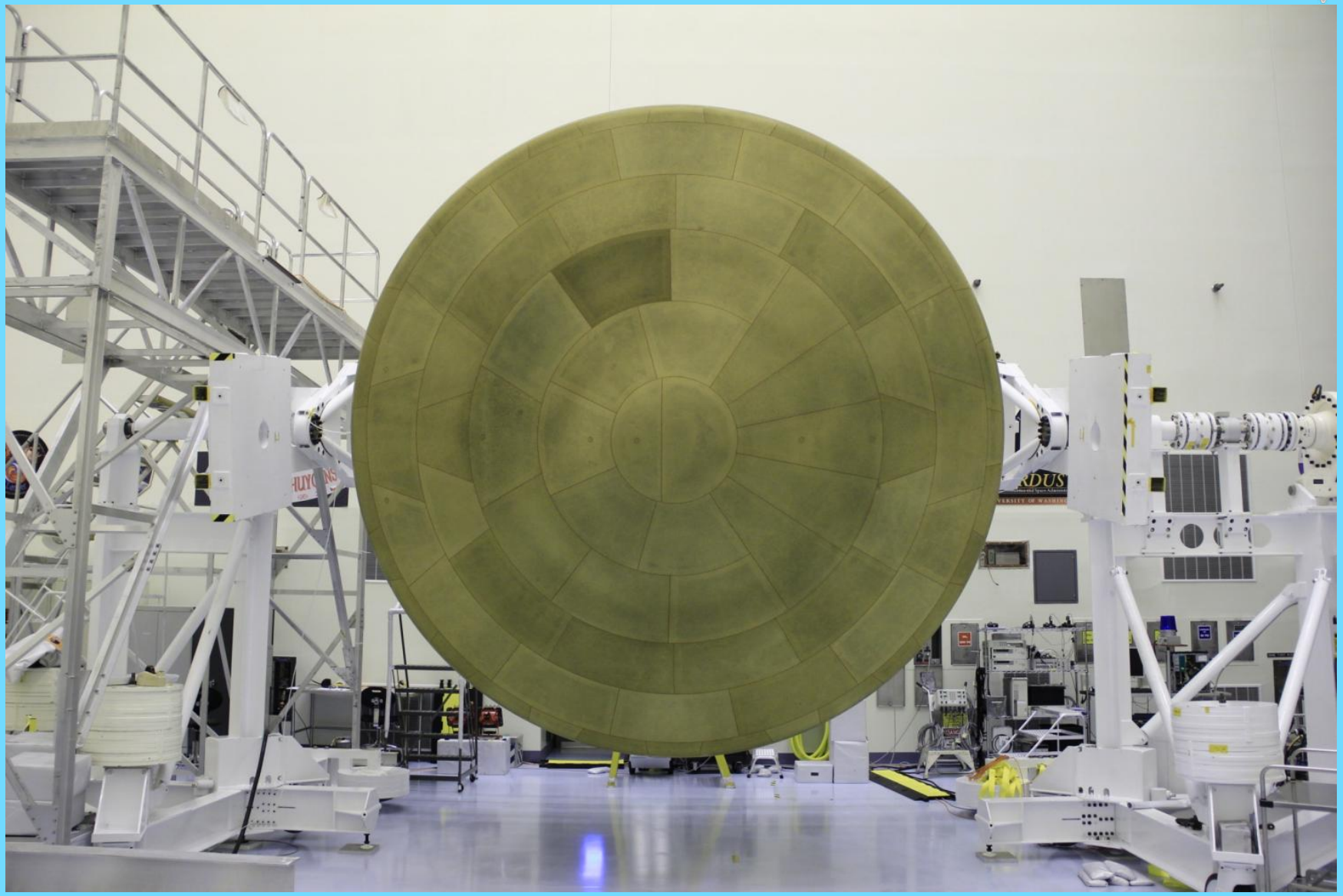
PDV Mated To / Inside Backshell



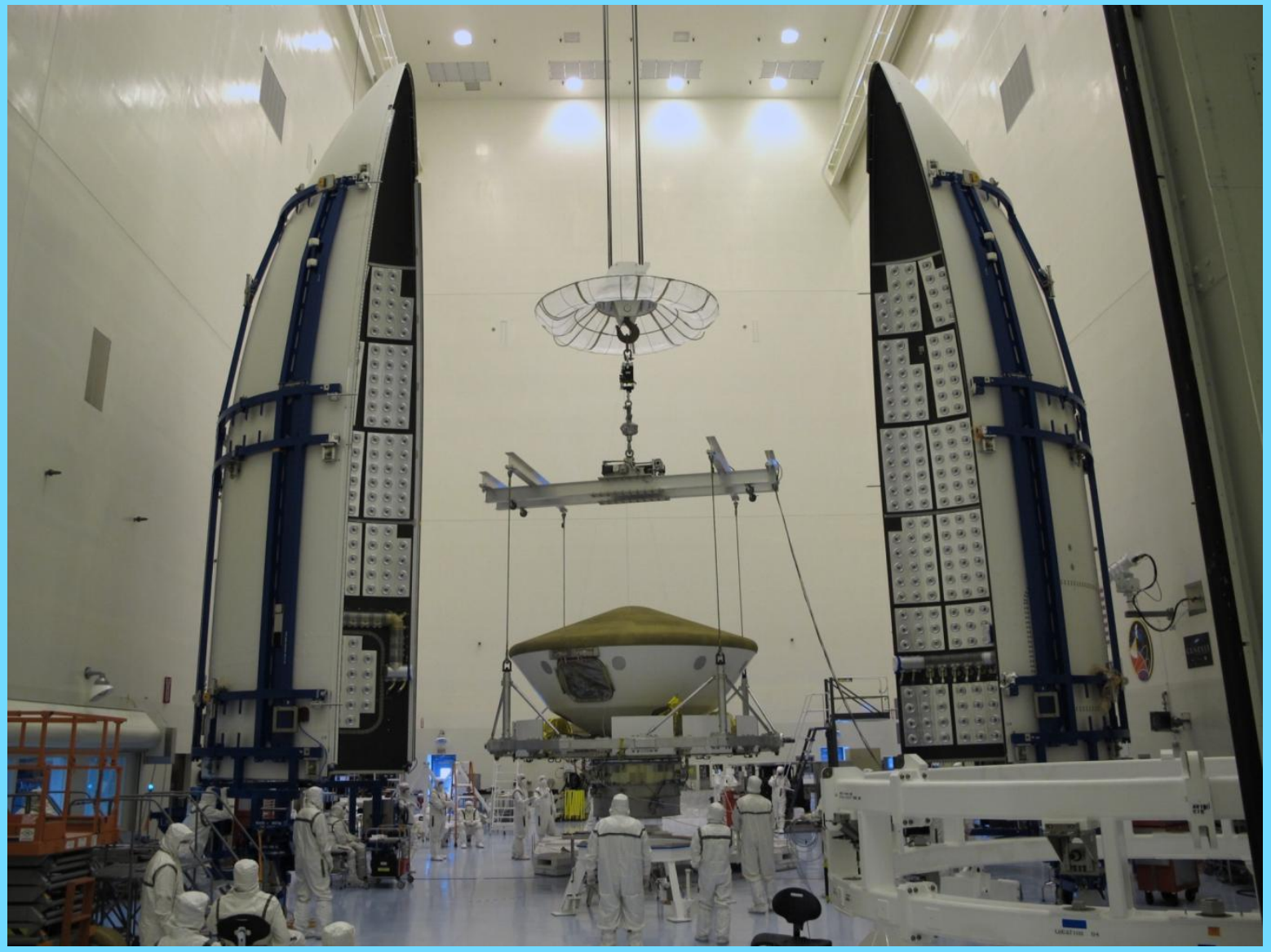
Backshell/PDV Rotation with Heatshield



MSL Stacked Spacecraft – Final Rotation



MSL Mate to Atlas Payload Fairing



Transporting to Launch Complex (LC-41)

Hoist atop Atlas at LC-41

Final Atlas Preps at LC-41

MSL Launch - KSC – Atlas 5 – 11/26/2011

Conclusions

- A NASA News Conference on July 16th, 2012, called it the most significant event in the history of planetary science!!
- It was essential that Quality Assurance be “built-into” the hardware, every step of the way, before launch
- QA was faced with multiple challenges in supporting large and complex engineering systems never before built nor landed on Mars
- The complexity of MSL hardware mandated that QA personnel were highly knowledgeable about the details of their hardware
- Early deployment of QA personnel was vital in order to be able to provide greater value later as a flight hardware verification resource
- Principles of space parachute quality assurance were successfully applied to skycrane hardware development
- QA certification of flight hardware that is going to Mars is a process that takes years
- Knowledgeable and proactive QA can make significant contributions to mission success

Conclusions

- → However, I realized that we will be "violating a JPL Flight Project Practice (FPP)" this time
  - → ***Quality Assurance personnel perform receiving and shipping inspections on all critical hardware whenever the hardware enters or leaves any facility***
  - → We will not be performing a receiving inspection on Mars ☺
  - → We have not yet set-up a receiving inspection station to do so
    - →*I bet one day we will!*
- → For now, we will have to inspect using photo-documentation from the high-definition photos taken by MSL's Cameras
- → The world and the history books will generate the Final IR for MSL!

MSL Landing

MSL's 354 million-mile journey will be completed

August 5th, 2012

10:31 pm PDT

Don't miss it!!