Fabrication Assembly & Test of the Mars Science Laboratory Descent Stage Propulsion System

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The MSL Descent Stage Propulsion System

- In 16 minutes, I won't have much time to really tell you why ...

  ... the MSL Descent Stage Propulsion System (DSPS) is the most challenging and complex propulsion system ever built at JPL.

- So think of this as a very low budget "Super Bowl" ad – trying to entice you to read our paper.

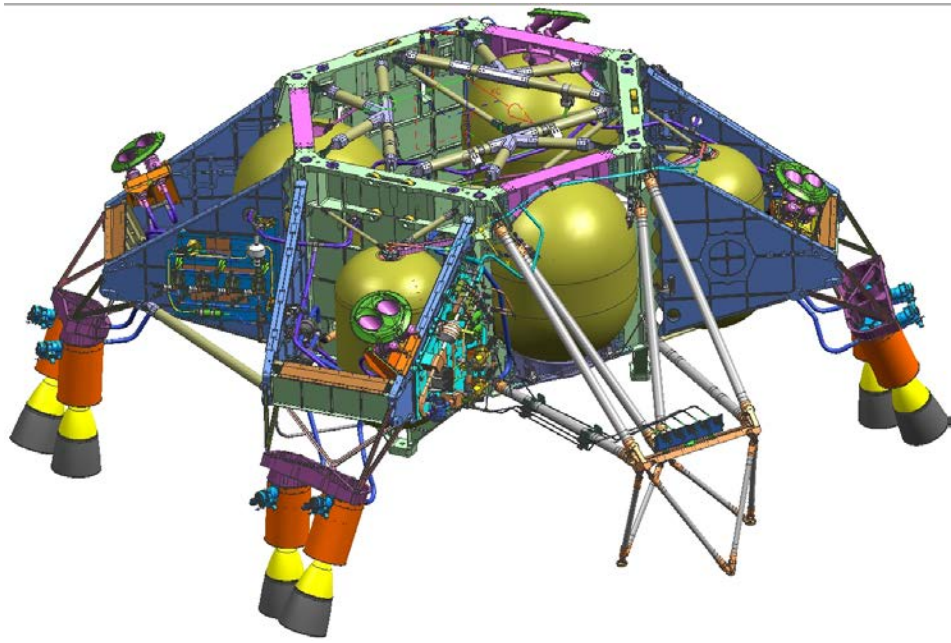
The system configuration constraints,

- e.g. the shape of the aeroshell and the one ton rover we were carrying,

... And the performance requirements

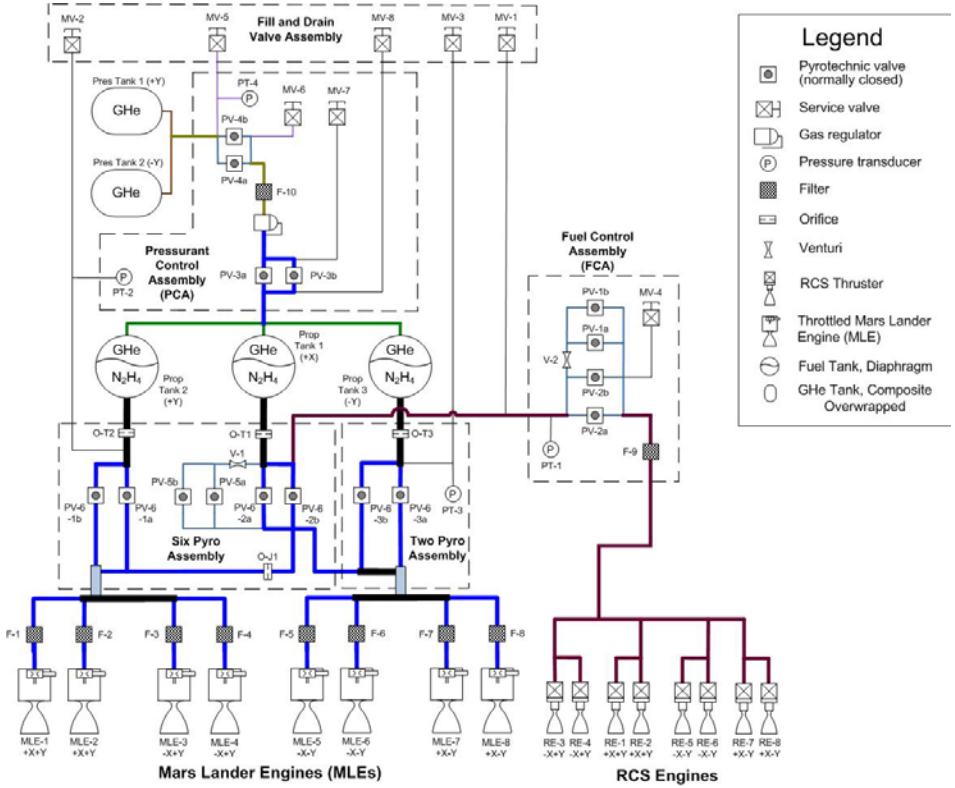
- e.g. a max flow rate of 11 kg. of N_2H_4/sec & a feed pressure > 700 psi,

... drove the design and configuration of the DSPS.



The Deceptively Simple DSPS Block Diagram

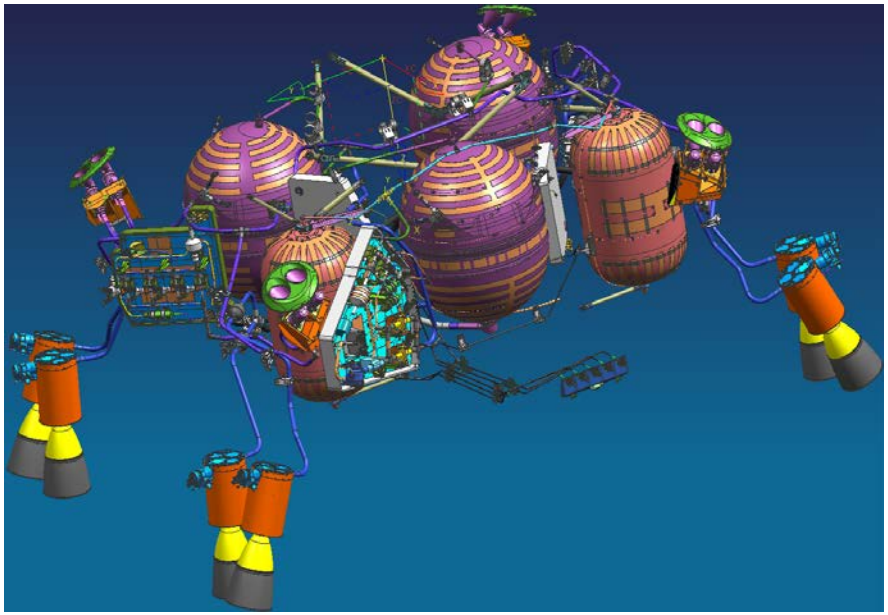
- You've seen the block diagram in two previous presentations ...
  - High pressure feeds 3 propellant tanks, isolated by pyro valves, feeding (8) 250 N RCS thrusters, and (8) 3300 N Mars Lander Engines.



- Here's a quick sampling of some of the fabrication, assembly and test challenges and solutions.

“A bowl of cold spaghetti, put together like a Rubik’s cube”

- That’s how one engineer described the conceptual design early on.
- That observation turned out to be more than just a bit of humorous conjecture.



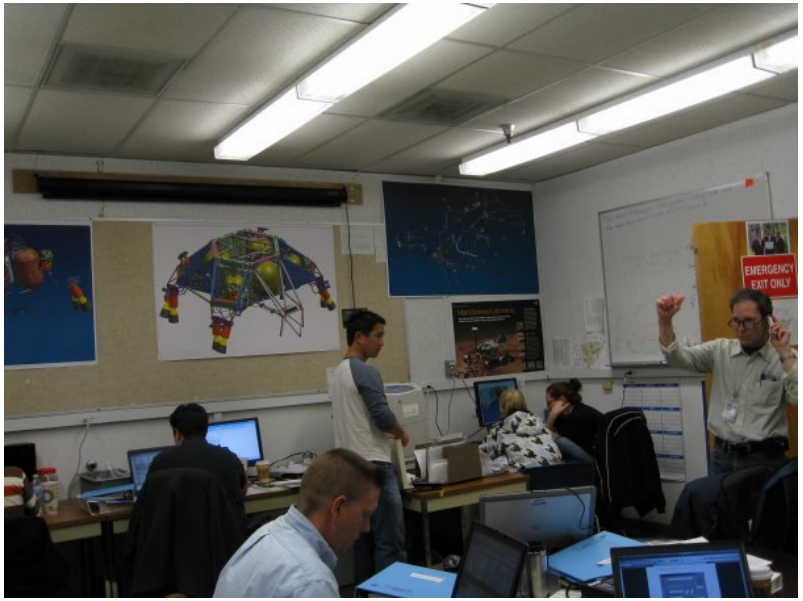
- Most of the major components had to be integrated sequentially.
- Components, subassemblies, even weld heads, tooling, and “Jack” the universal technician were modeled in CAD to verify access.

Schedule – The Critical Path

- The DSPS fabrication, assembly, and test were identified early on, circa 2007, as the critical path for the entire MSL Project.
- DSPS fabrication, assembly, and test is in sequence with spacecraft level integration, assembly and test, primarily due to two inherent operations;
    - welding
    - testing at high pressures.
- Only after the DSPS welding and pressure testing was complete, could the DS be delivered to JPL's Spacecraft Assembly Facility (SAF) for the integration of other subsystems.
- Ultimately the DSPS was delivered to SAF on schedule, September 4, 2008.
- Some extraordinary measures, (at least for JPL), were necessary in order to accomplish this

The Team and the War Room

- A “one team, level field philosophy”... open, unfiltered communication and faith between the MSL Propulsion technicians and engineers.
  - While the various levels of responsibility were respected, all team members—technicians, engineers, and managers—were encouraged to participate on equal footing.
- Daily team tag-ups were held at 6:00 am and again at 3:00 pm during the overlap of 1st and 2nd shift, to discuss status and near-term plans.
  - The War Room was “plastered” with large format CAD images and drawings of subassemblies & the completed system ... Helping to visualize our objectives, & focus discussions during the daily team tag-ups



The Cleanroom is Where It Happens

All outside efforts were focused on getting the tools, hardware, & information needed into the hands of the technicians & engineers in the Cleanroom

1st shift crew consisted of two, or three weld teams of two technicians each, subassembly lead engineers, floor lead, quality engineers and ...

For every person inside the clean room, there was at least one person on the outside providing support to feed the flow of materials and information so that the assembly and test work could proceed expeditiously.

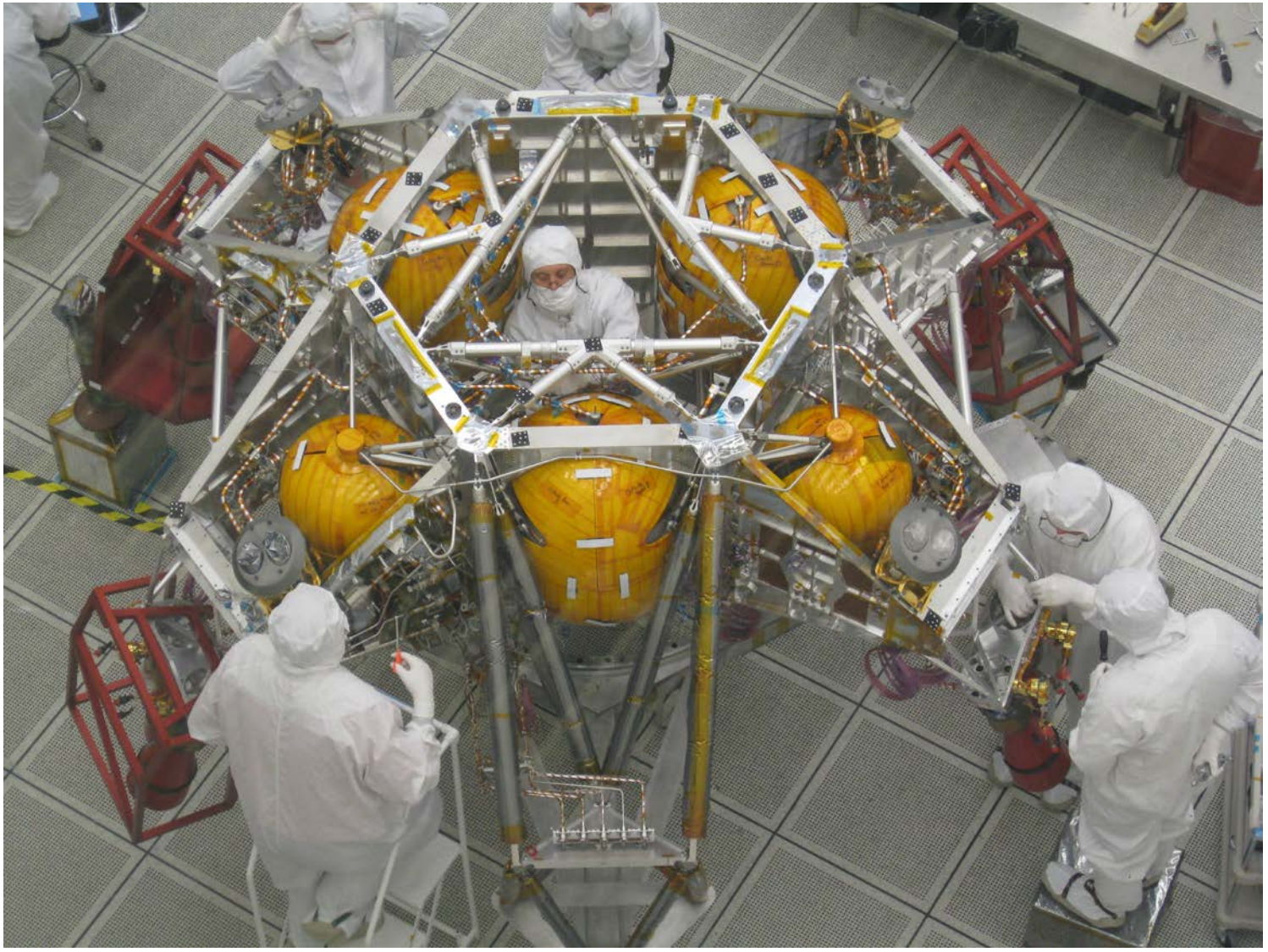
1st, 2nd, & Sometimes 3rd Shift Operations

- The 2nd shift crew consisted of one, sometimes two weld teams, a quality engineer, and the Precision Cleaning Facility operation.
- JPL is not a production house. Operating 2nd & 3rd shift was not very efficient, but was effective & necessary due to schedule critical path.
  - support services were usually not available after normal hours during the DSPS build.
- A 3rd shift was utilized for X-ray of welds when needed, and sometimes installation of thermal hardware.
- We had a surplus of planning, procedures, etc., and almost nothing went according to plan.
  - Yet, an incredibly dedicated team of engineers & technicians was focused, with a sense of urgency, on finding solutions to every hurdle thrown in their path ...
  - Without anyone saying it, this team pretty much adopted the U.S. Marine's motto, "improvise, adapt, and overcome".

Concurrent work on multiple subassemblies

- It was not uncommon to have work progressing on 3 or more subassemblies at once ...
- ... in addition to cabling and thermal installation work.

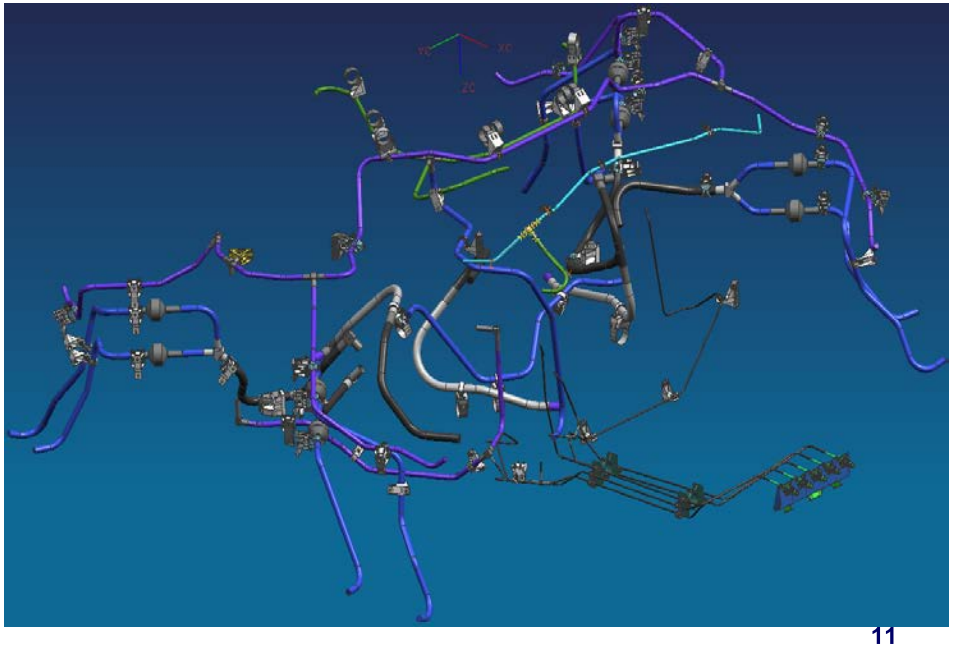
Concurrent work on multiple subassemblies



Interconnect Tubing Challenges

- The DSPS had some relatively large & thick walled tubing – much stiffer than the 0.25” and 0.375” tubing typical on most spacecraft propulsion systems.
- Very late in the schedule, after CDR, the first system level structural dynamics modeling showed evidence of shorting of structural loads through much of the tubing, including some tubing on structural plates.
- A “tiger team” consisting of structural engineers, propulsion engineers, & stress analysts was assembled just a few months before assembly began to address the propellant line load shorting.

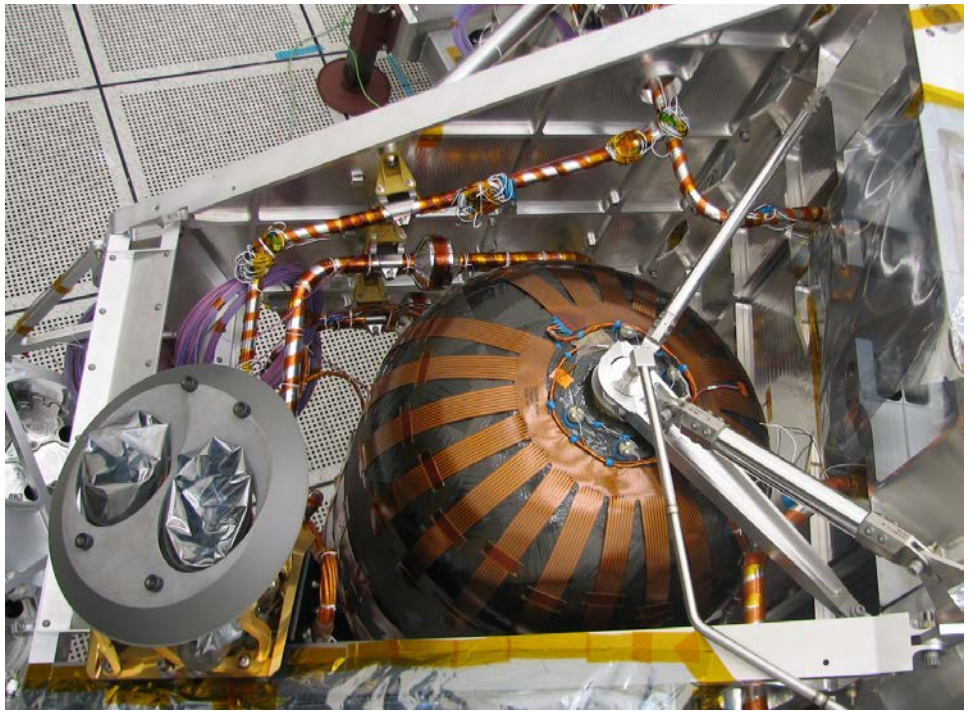
- Recommendations resulted in several design changes to secondary structure, tubing mounts, tubing material, and tubing runs, some as late as 2 months after assembly had begun, literally not quite “just-in-time”.
  - The analytical work of the Prop Line Stress Analysis team is discussed in detail in Reference 4.



Interconnect Tubing Challenges

- The additional work load on stress analysts and structural engineers made for late delivery of secondary structure.
- We substituted stereolithography (SLA) non-flight parts for most of the complex line mounts to allow the work to proceed on schedule, and then swapped out the SLA parts as the flight brackets became available.

- Modifications at JPL's Precision Cleaning Facility weren't ready in time, so at one point, we had contracts at 4 different tube cleaning companies, and were running flight tubing all around the LA area – again, not quite "just-in-time".



Two Very Complex Thruster Assemblies

The RCS nozzles had to be precisely positioned & alignment verified through Computer Machine Measurements to prevent “close clearance” contact with their aeroshell portals during launch and entry vibration.

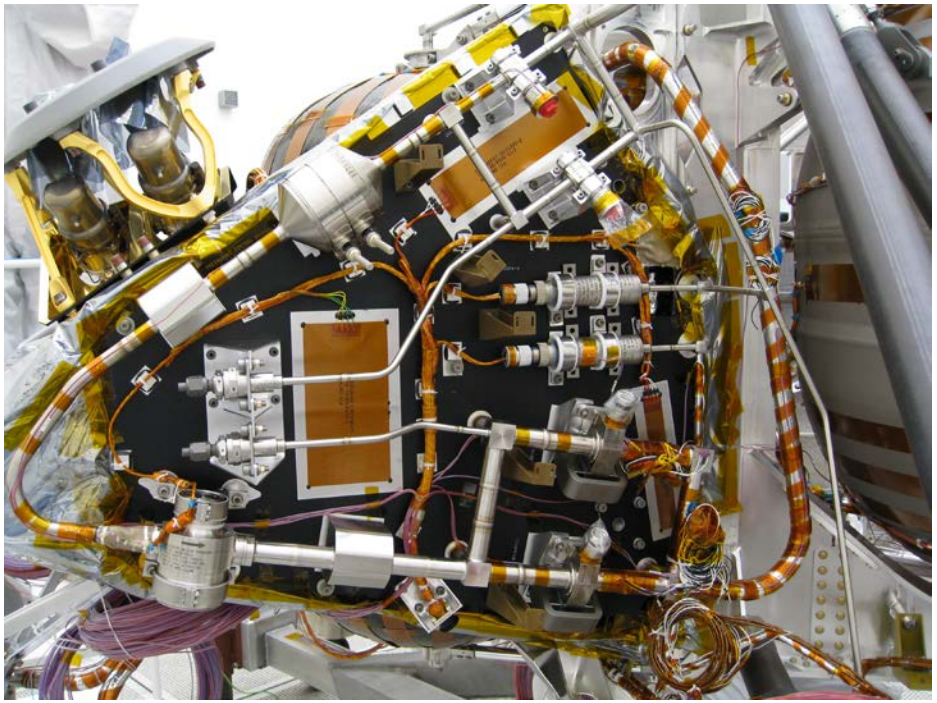
The Mars Lander Engine assemblies included a newly design cavitating venturi throttle valve, with a range of ~ 15% to 100% throttle, an LVDT for position feedback, and nozzles canted 5 degrees apart to mitigate plume sheeting impingement.

Welding Challenges

- 7 different tubing sizes, 0.25” up to 1.25” O.D, tubing wall thicknesses from 0.028” to 0.083”, various component materials, & varying metallurgical content, all combined to necessitate 53 unique weld schedules and over 260 original welds.
- Many of the welds had very difficult purging setups due to long tubing runs and many dead ends in the system.
- Ultimately the DSPS welding experienced only 2 weld failures out of 260+ (and later still only 2 out of over 300 including the Rework), i.e., a >99% success rate/<1% weld failures.
- However one of those 2 weld failures occurred in a most challenging location. It was a dead-headed purge, on the high-pressure side of the contamination-sensitive pressure regulator; one of the 0.500 inch O.D. × 0.083 inch wall thickness “gun barrel” tubing welds.

EL PLATO DEL DIABLO

- The Propulsion team investigated the problem and devoted roughly 50% of our resources for over two weeks to repair the PCA.
- The problem was arc flow – the weld arc meandered and favored one side of the weld joint. It was intermittent & only exhibited on this thick walled tube & ultimately traced the weld head's grounding method.
- We disconnected the ground within the weld head, and configured a clamping block that bridged the weld joint to be the ground.



A True Team

- Numerous challenges ...
  - late delivery of the primary DS structure,
  - dealing with much larger tubing sizes than JPL had experienced,
  - structural shorting of loads through propellant and pressurant lines,
  - tube cleaning issues,
  - 2nd and 3rd shift operations,
  - personnel shortages in propulsion, structural engineering and stress analysis,
  - and of course the obligatory “impossibly tight schedule”

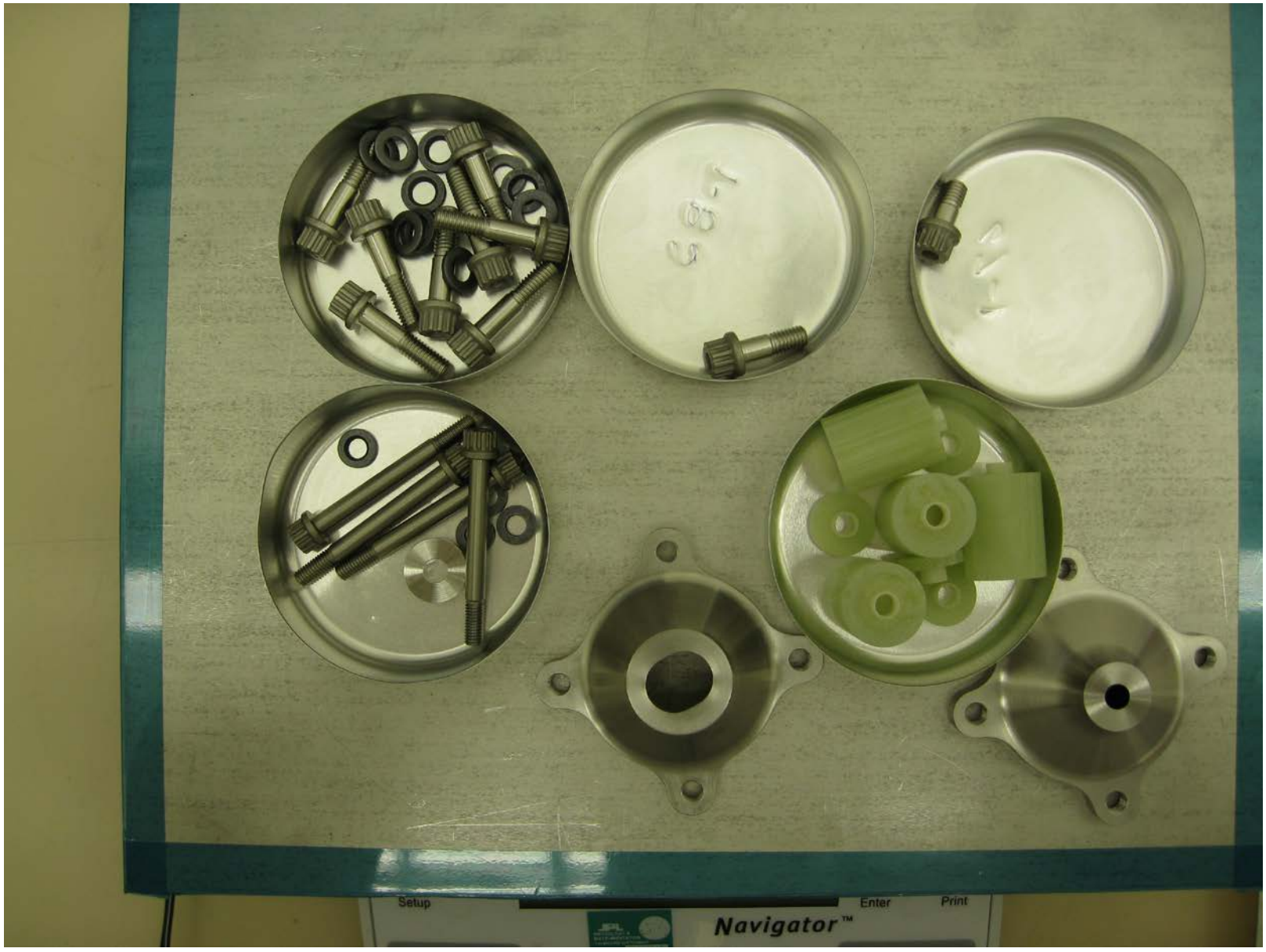
  ... all rounded out a fabrication, assembly, and test experience that will always be remembered fondly by those who participated.

- The NFL season is over, playoff games and the Super Bowl have been played. Fans and team members of any team sport, are reminded over and over that it is a team effort, and without a true team effort, success is elusive.
- We can say with pride and confidence, that we assembled a team of truly dedicated individuals, that came together and worked/played as a team like no other we have ever participated on. The fabrication, assembly, and test, of the MSL DSPS was truly a team effort, which we will remember for the rest of our careers.

Some Photos of the “Build”

- For 7 months, the “War Room” felt to us like a war room.

Some Photos of the “Build”



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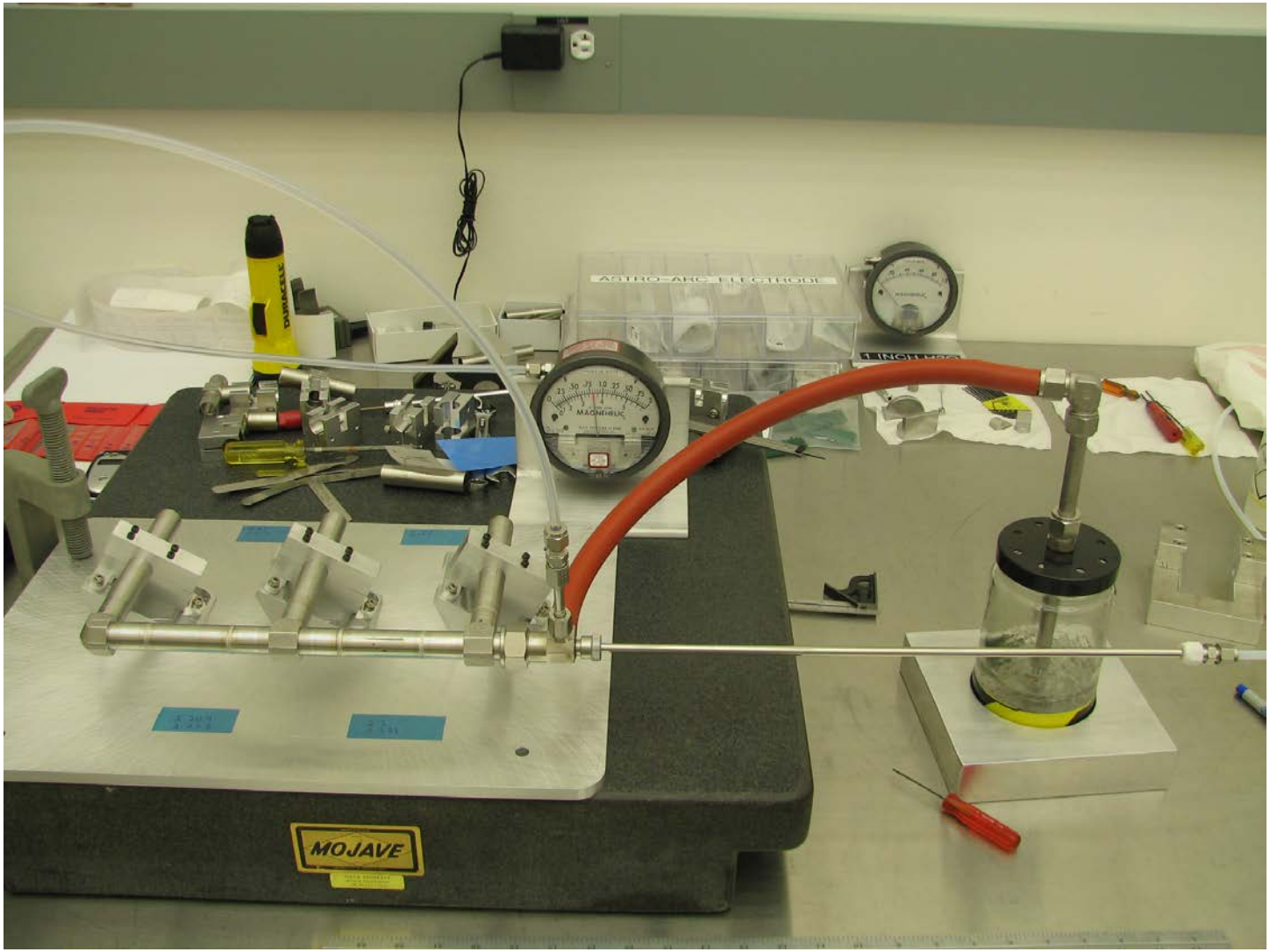

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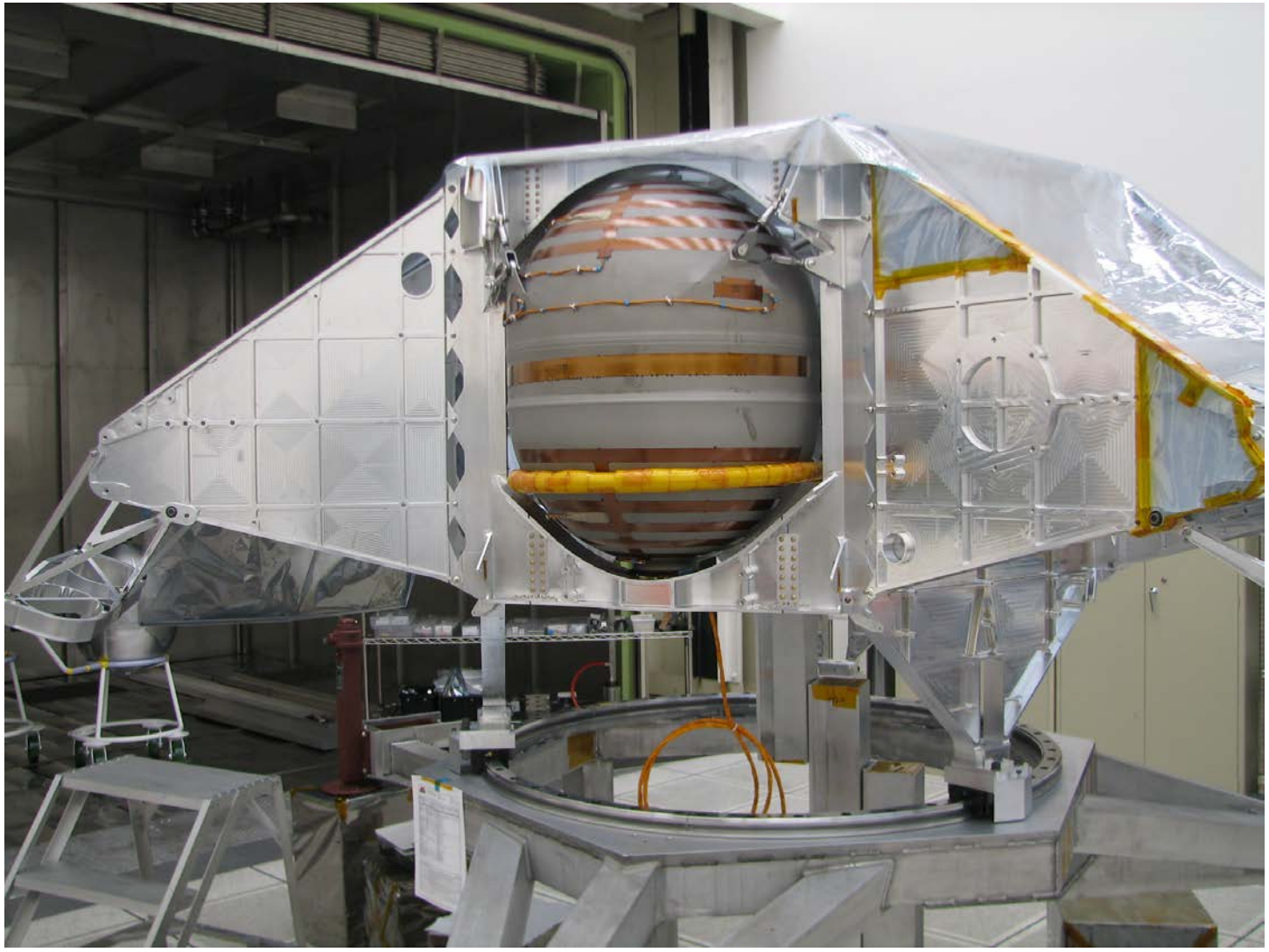

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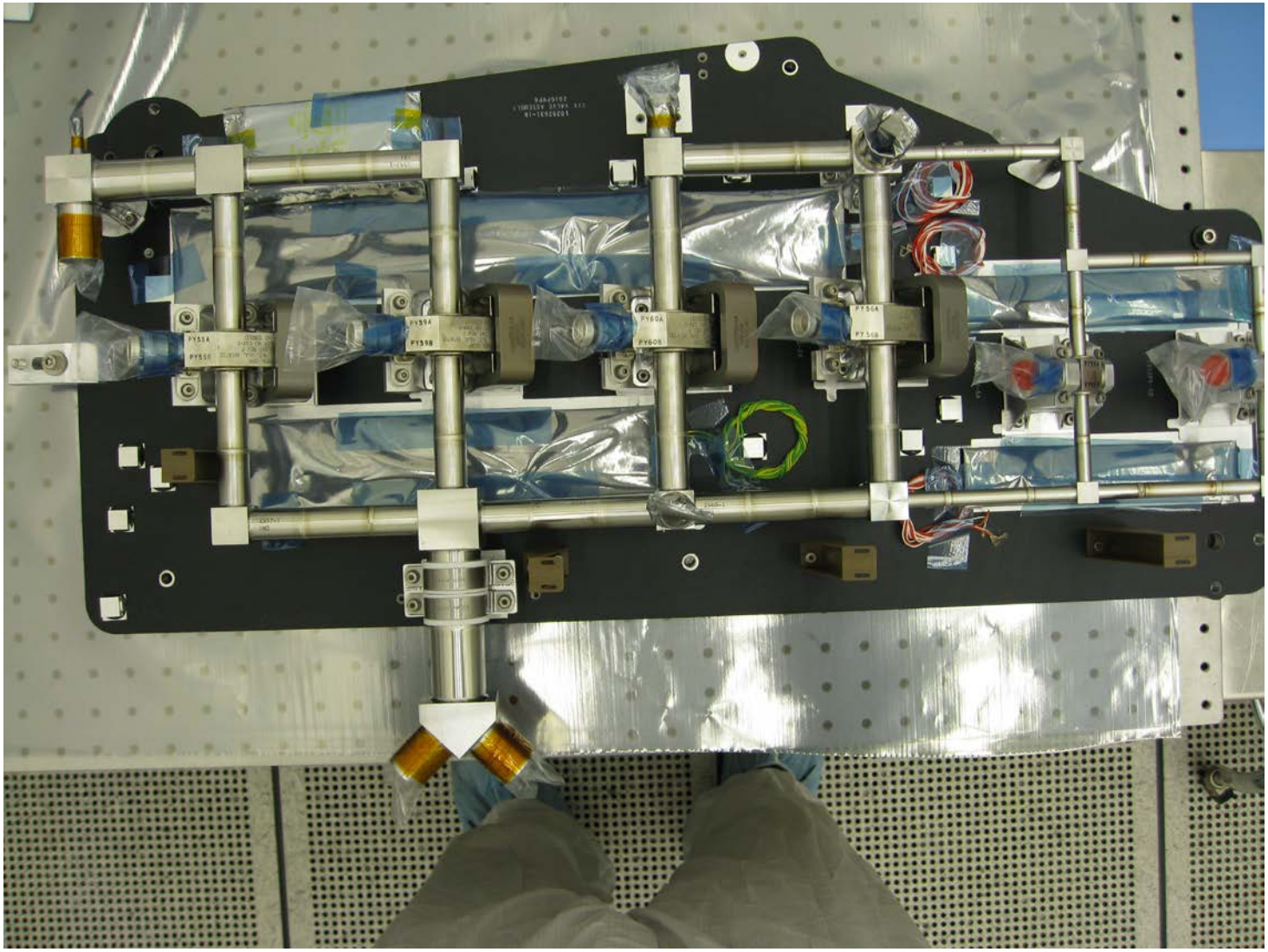

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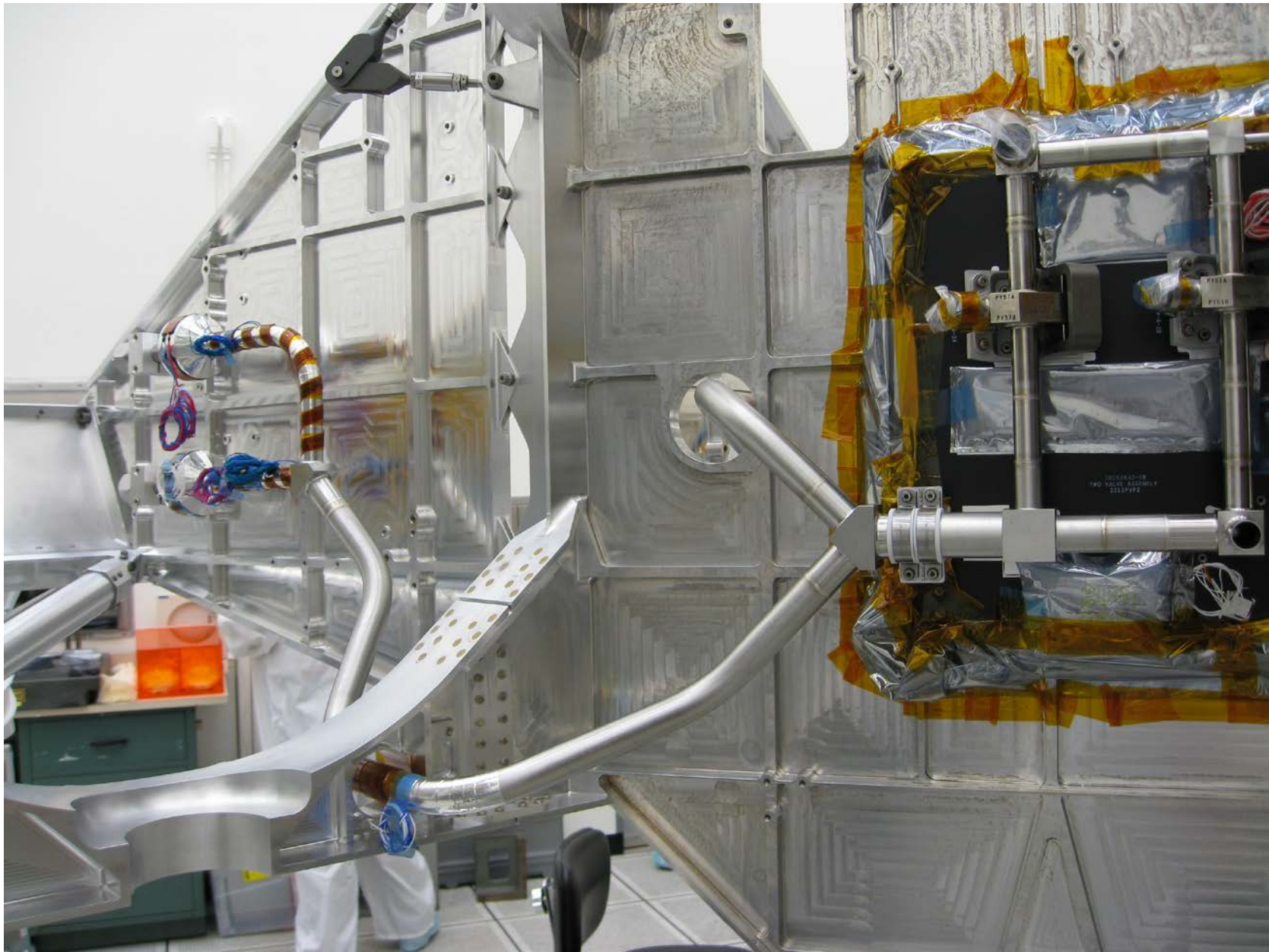

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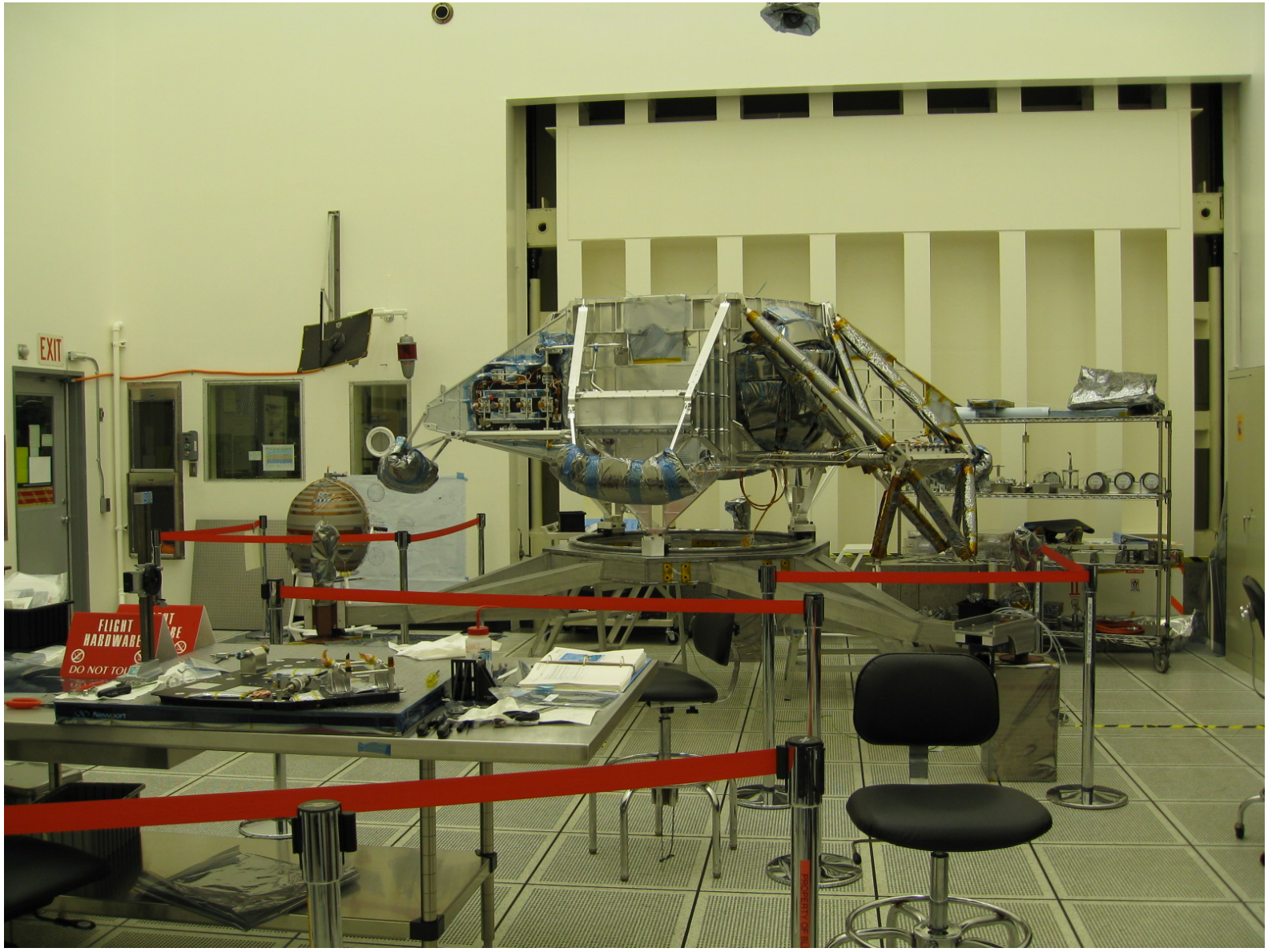

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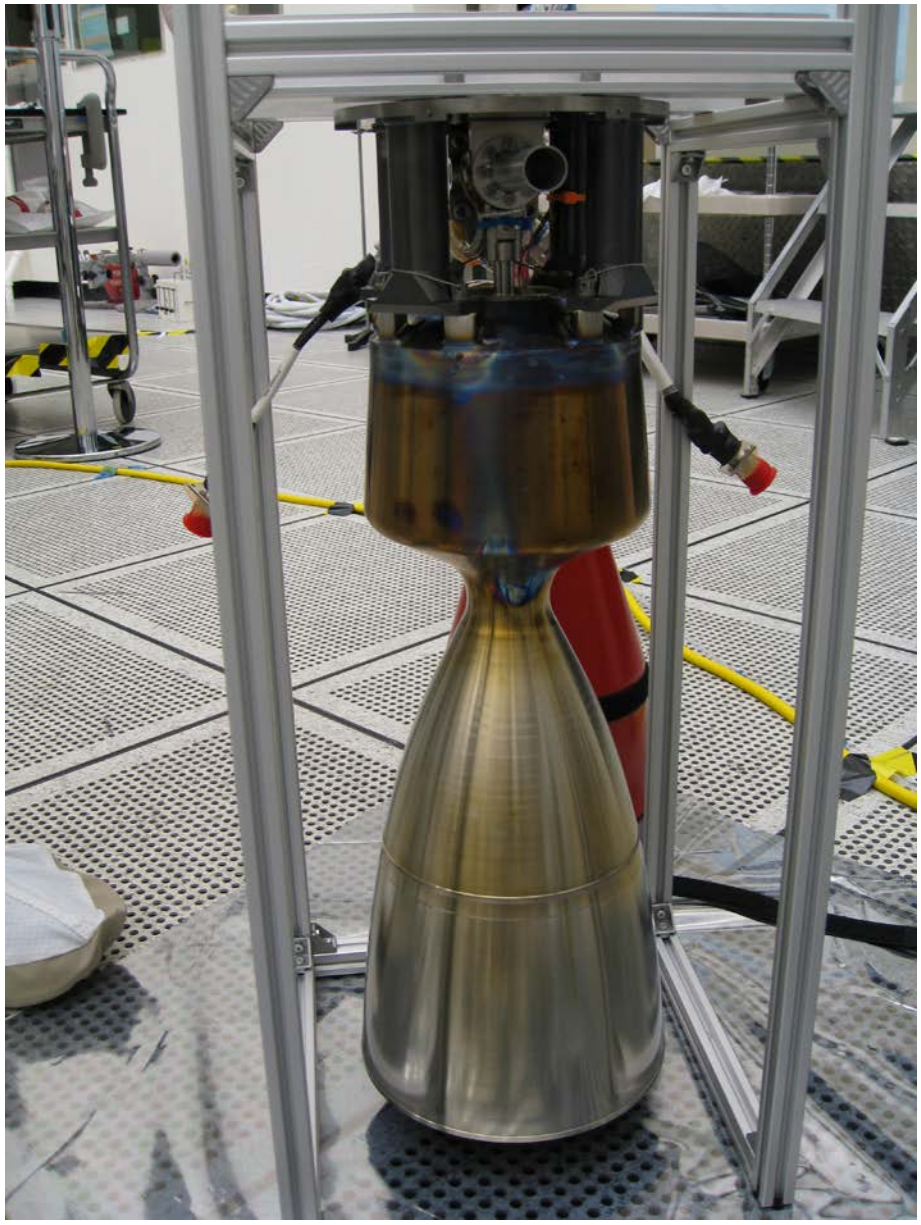

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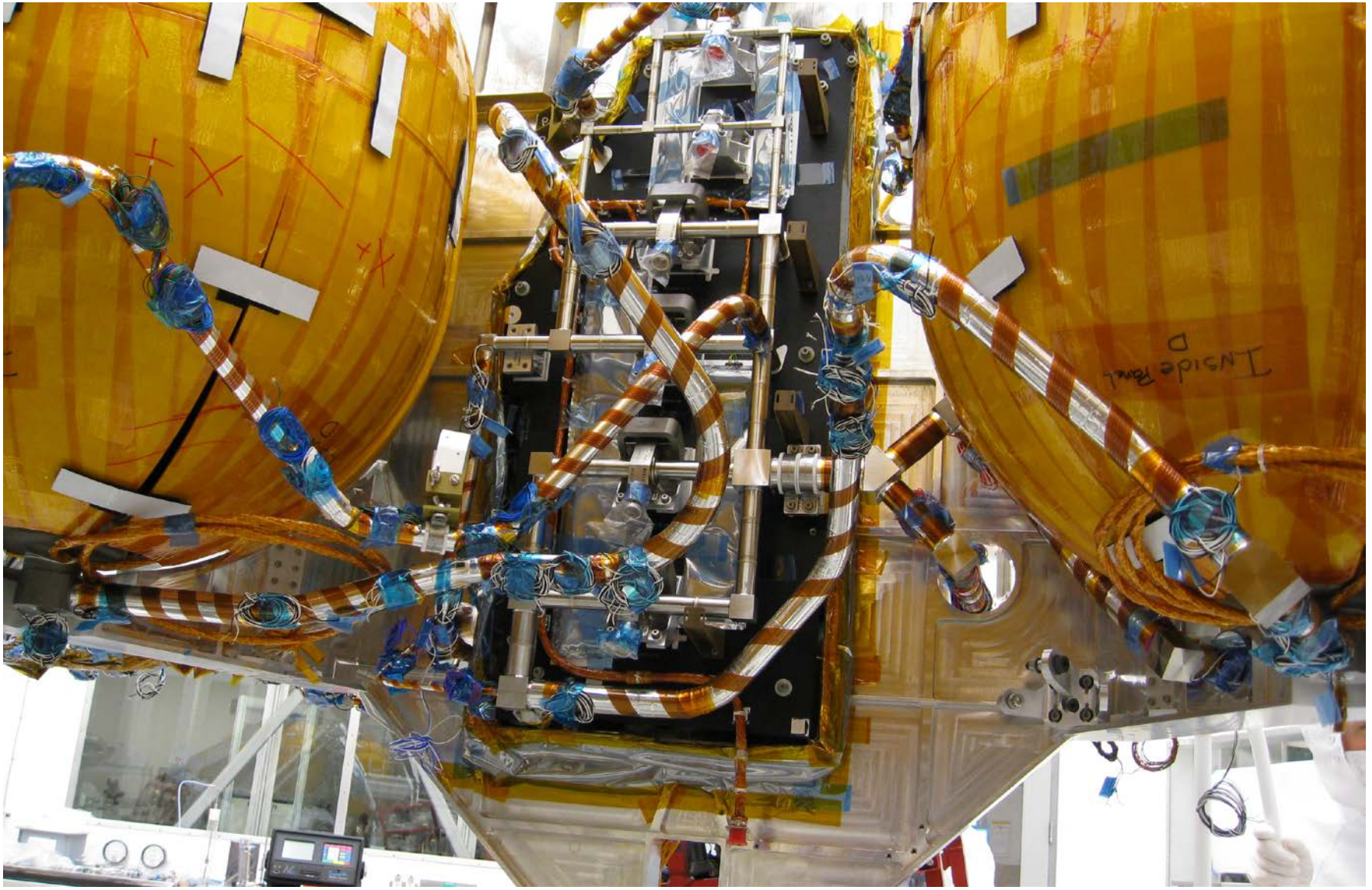

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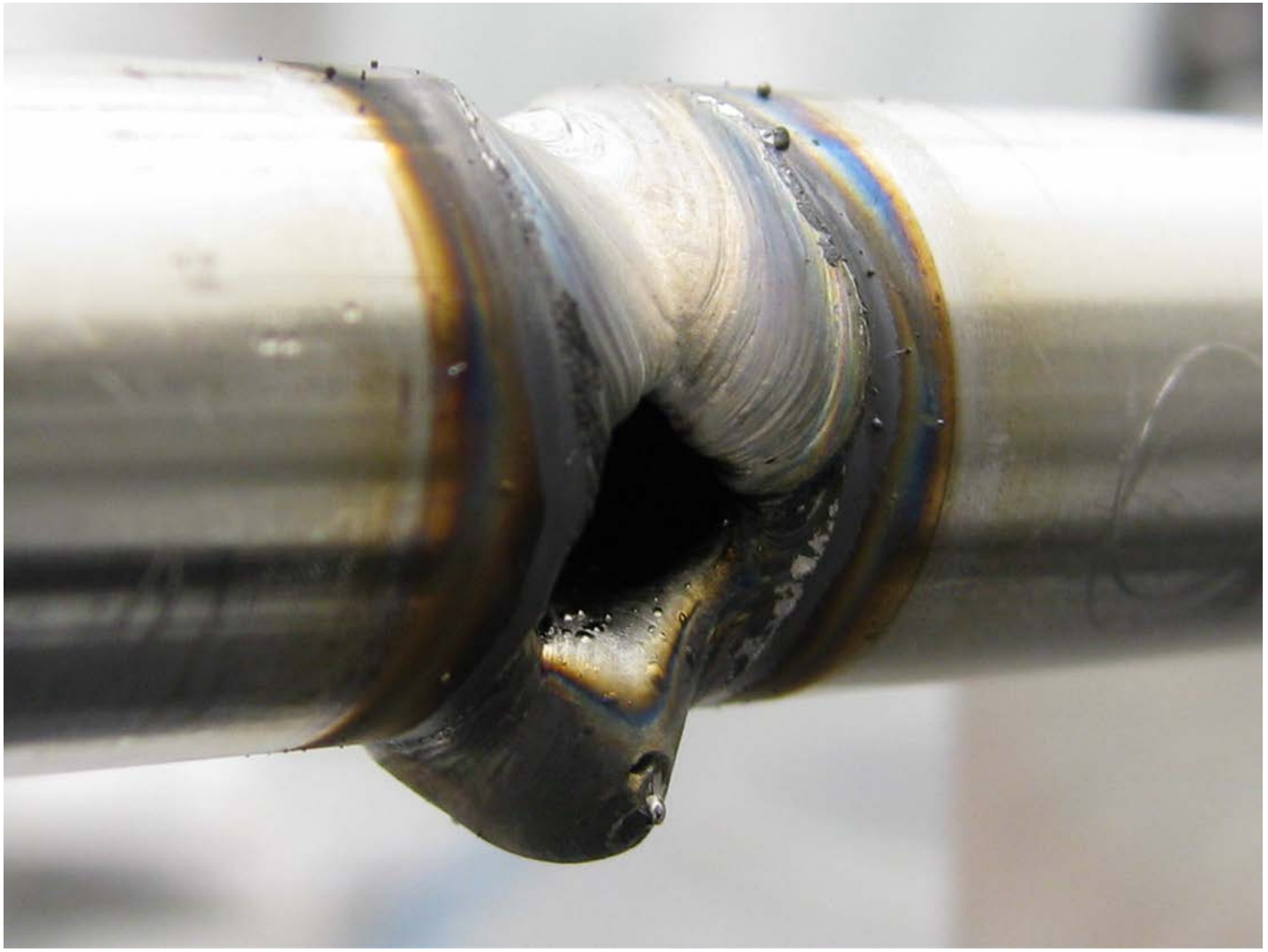

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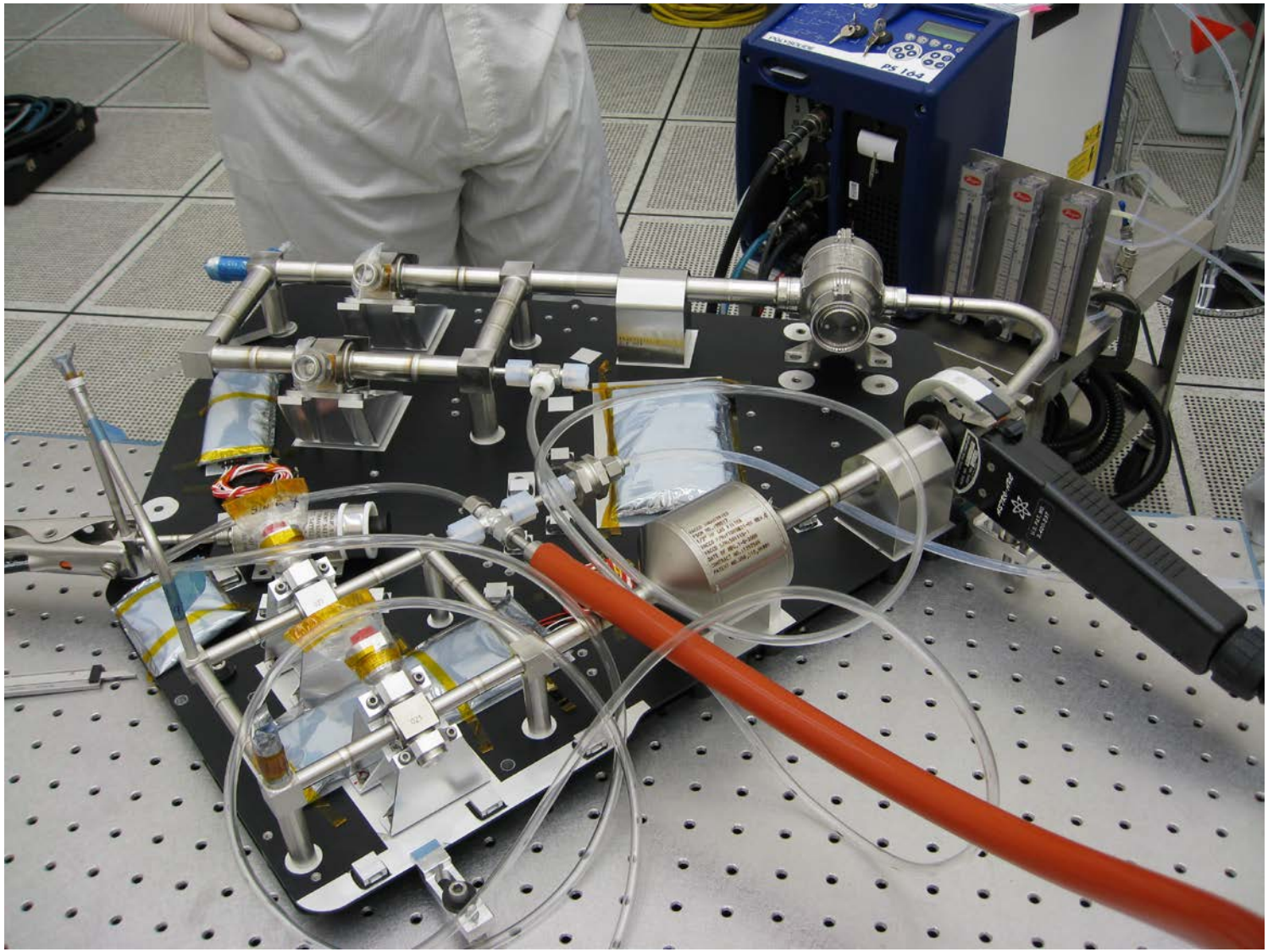

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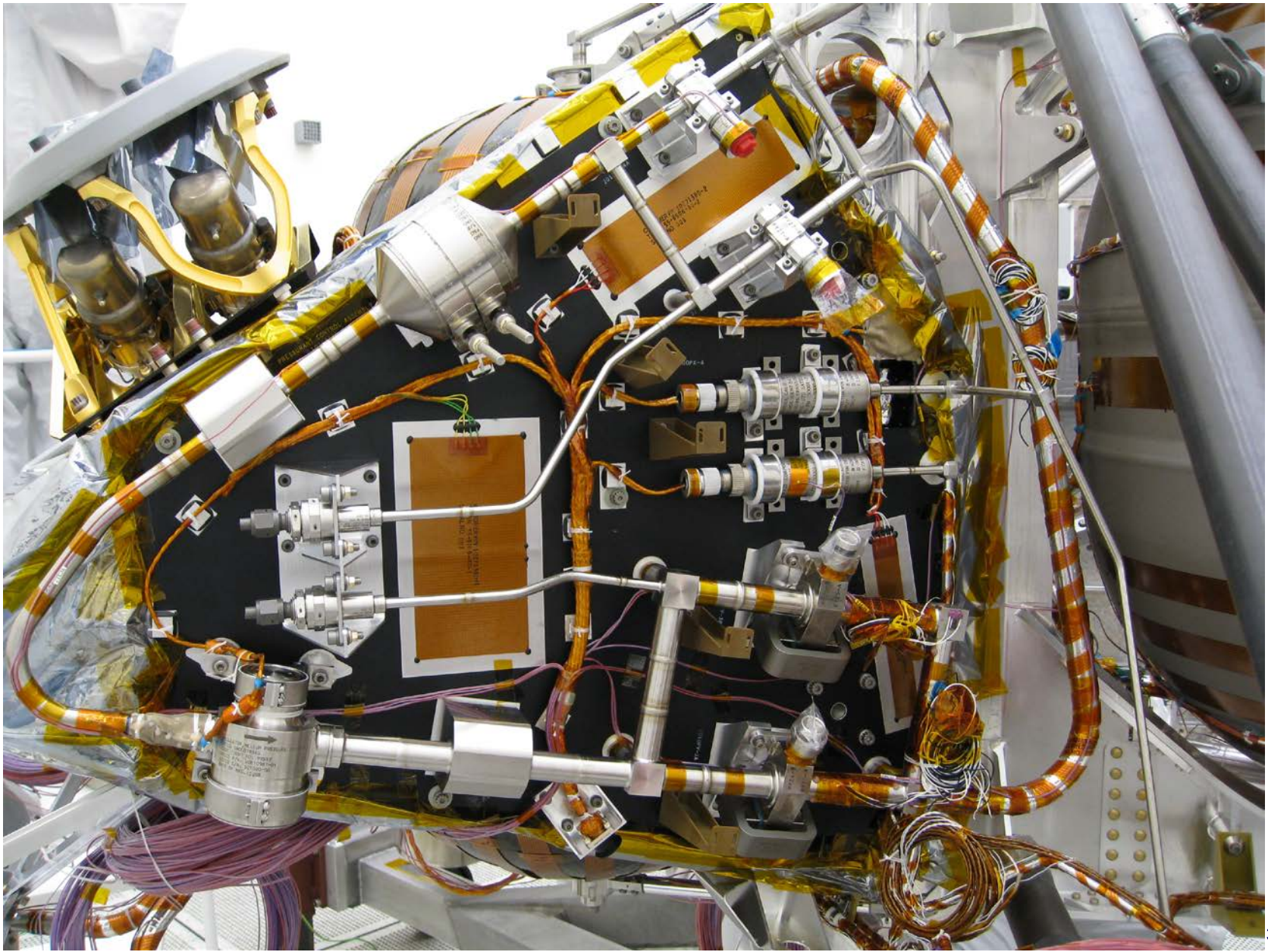

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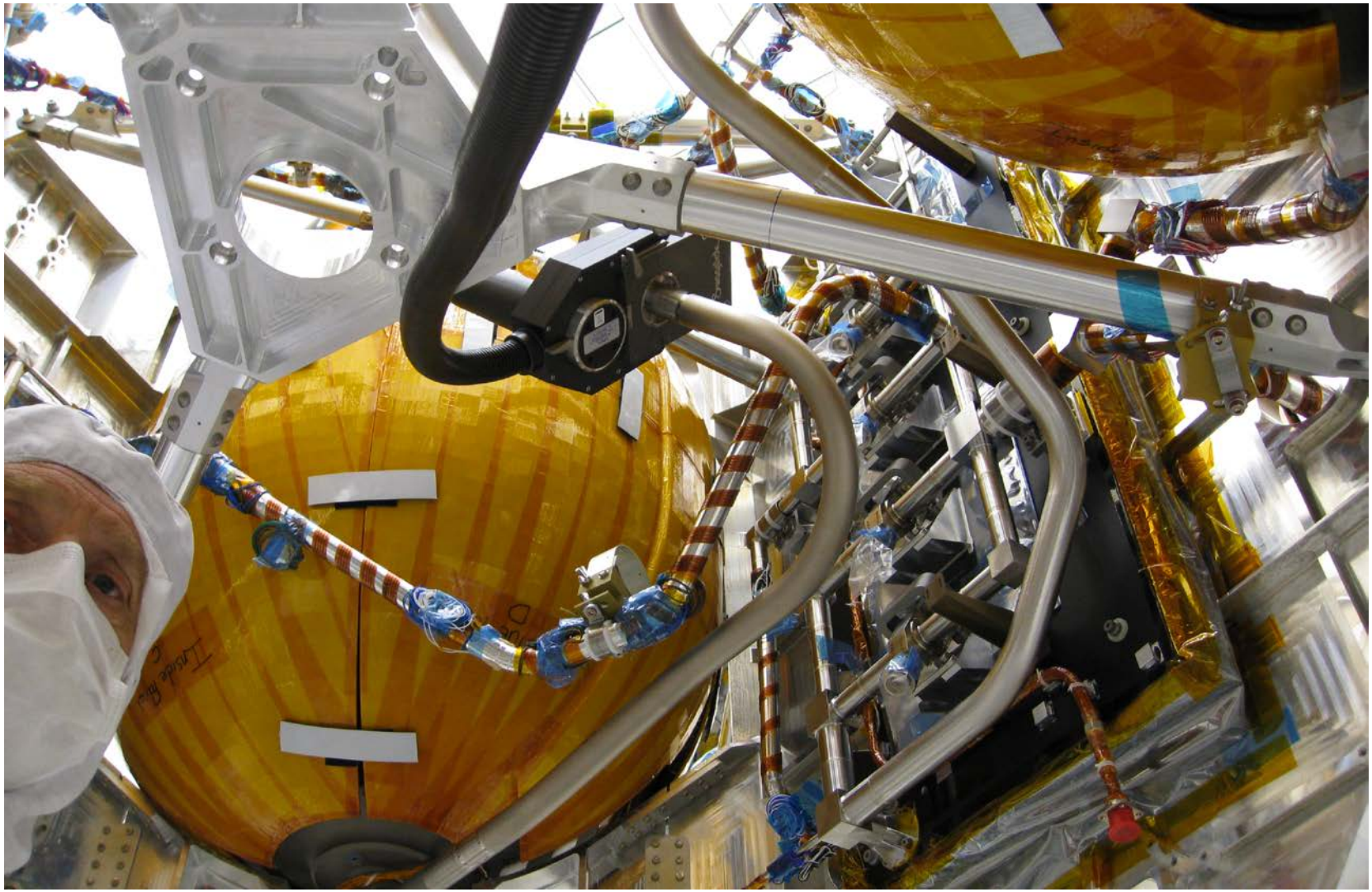

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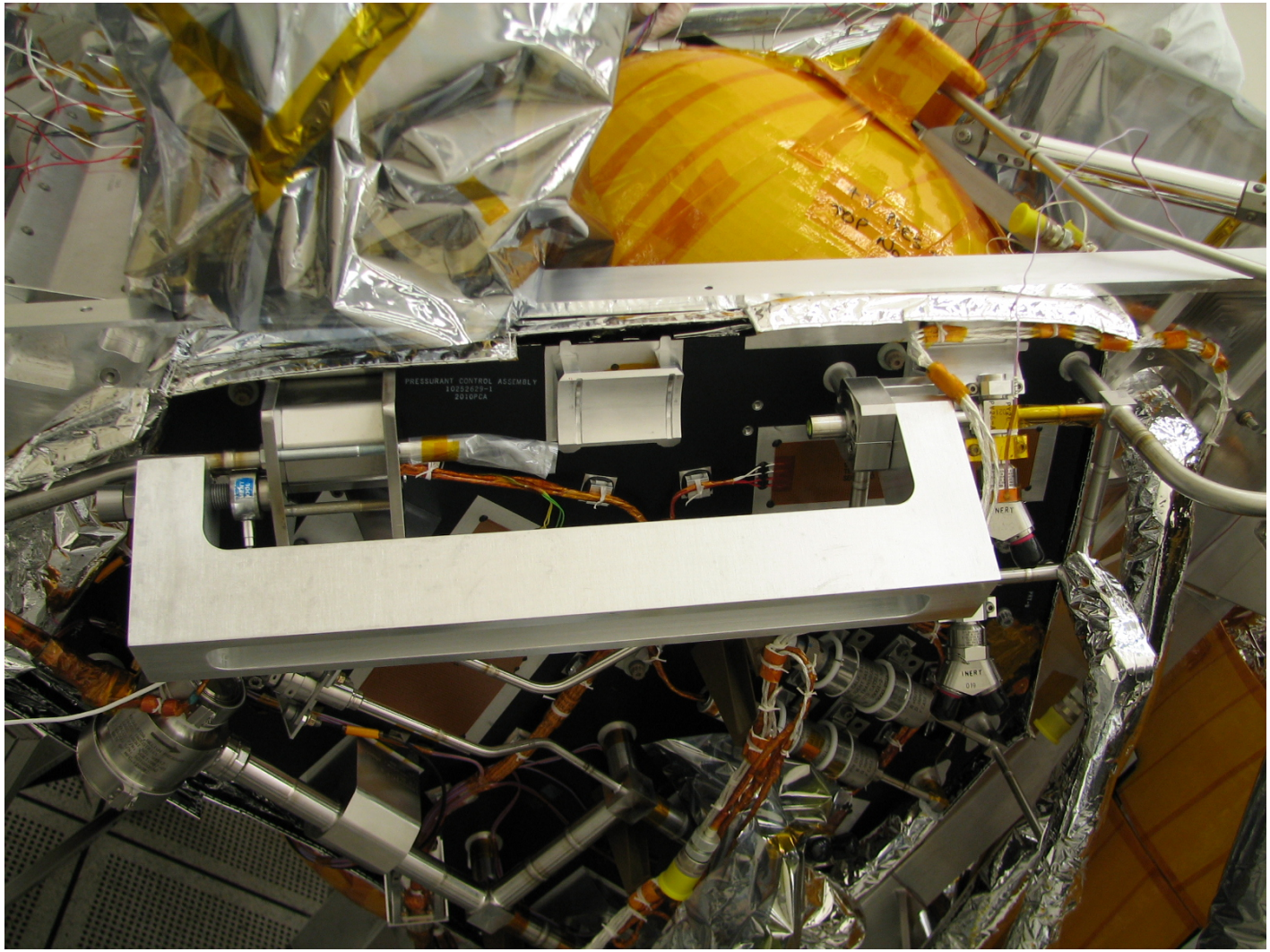

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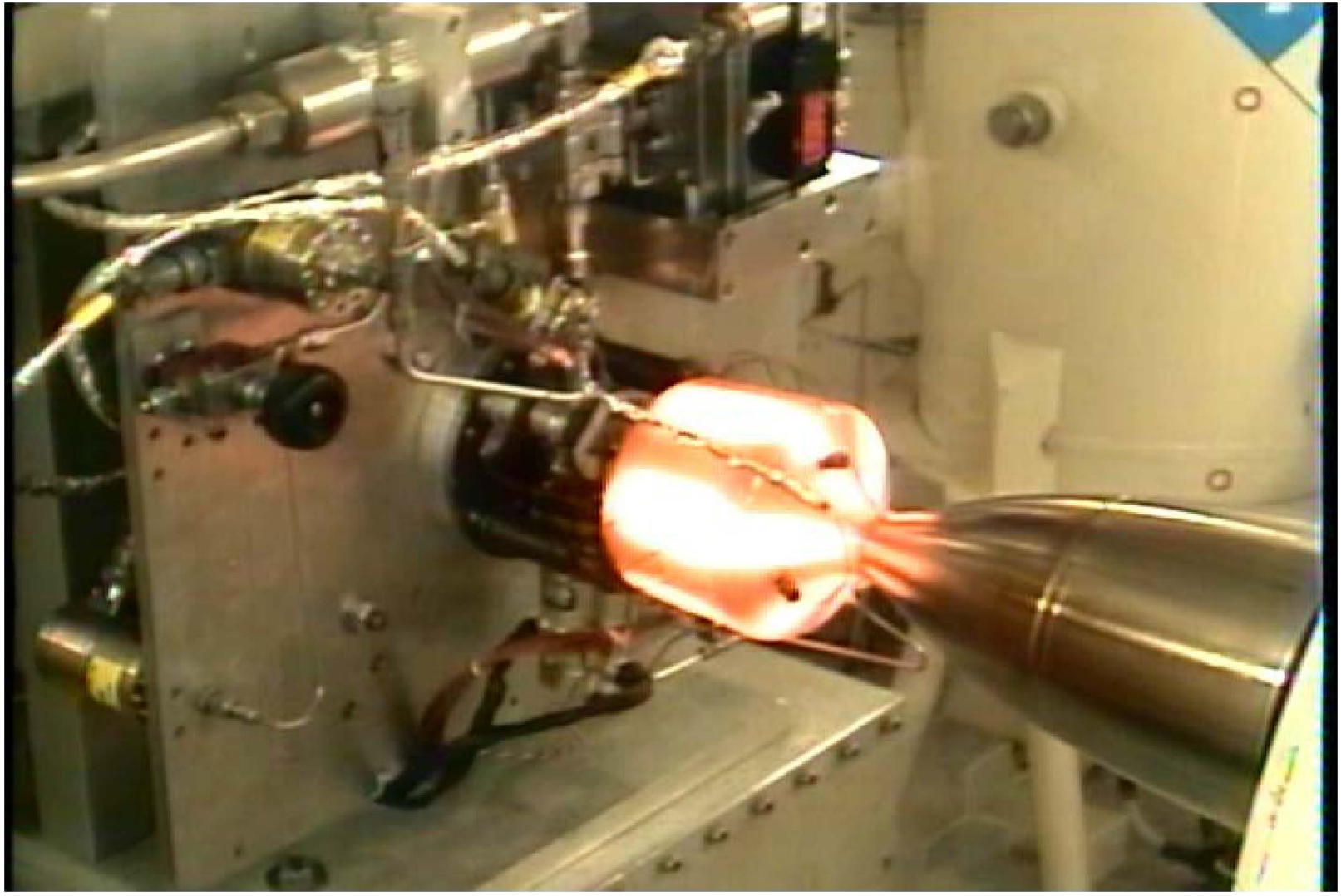

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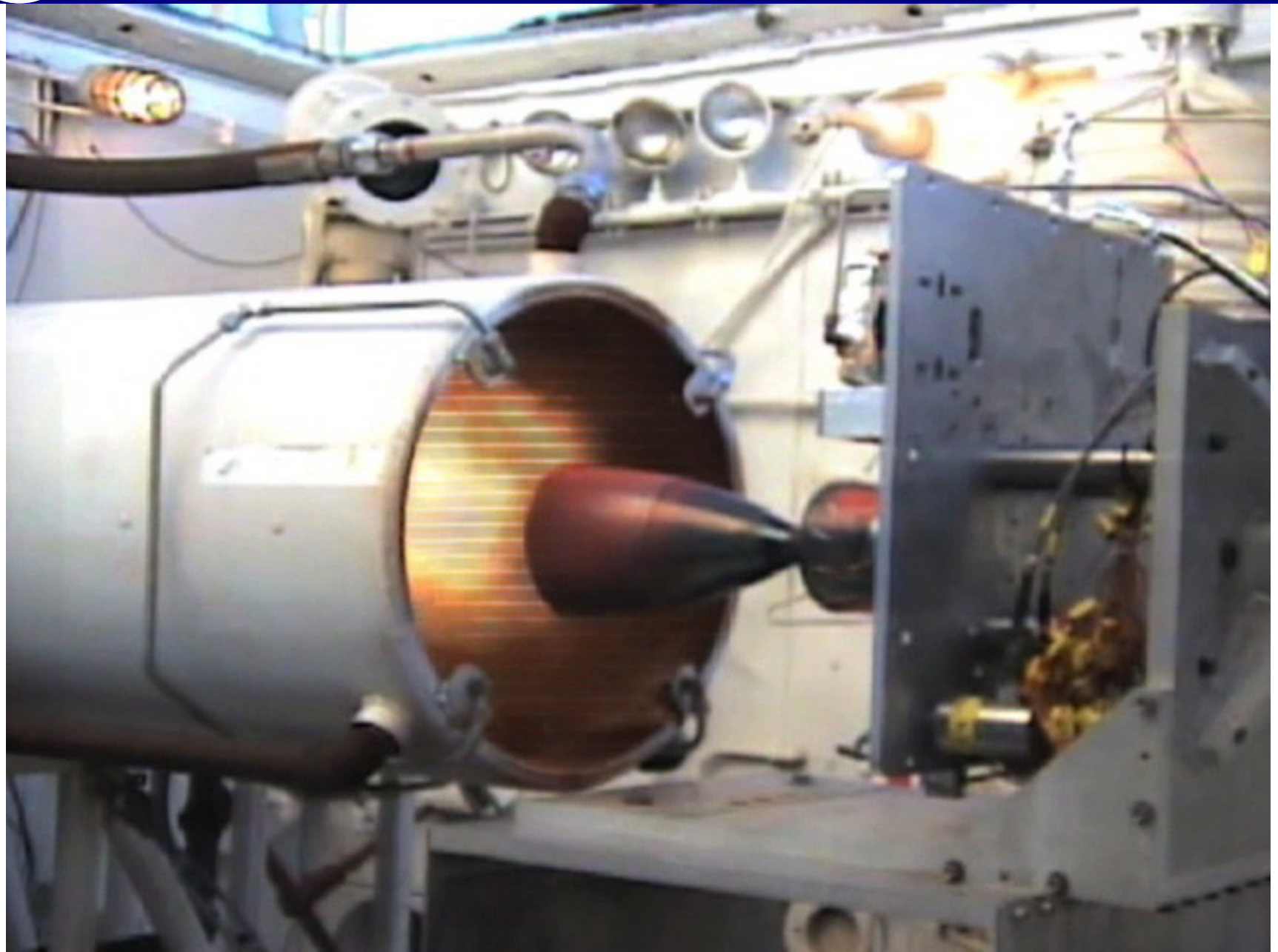

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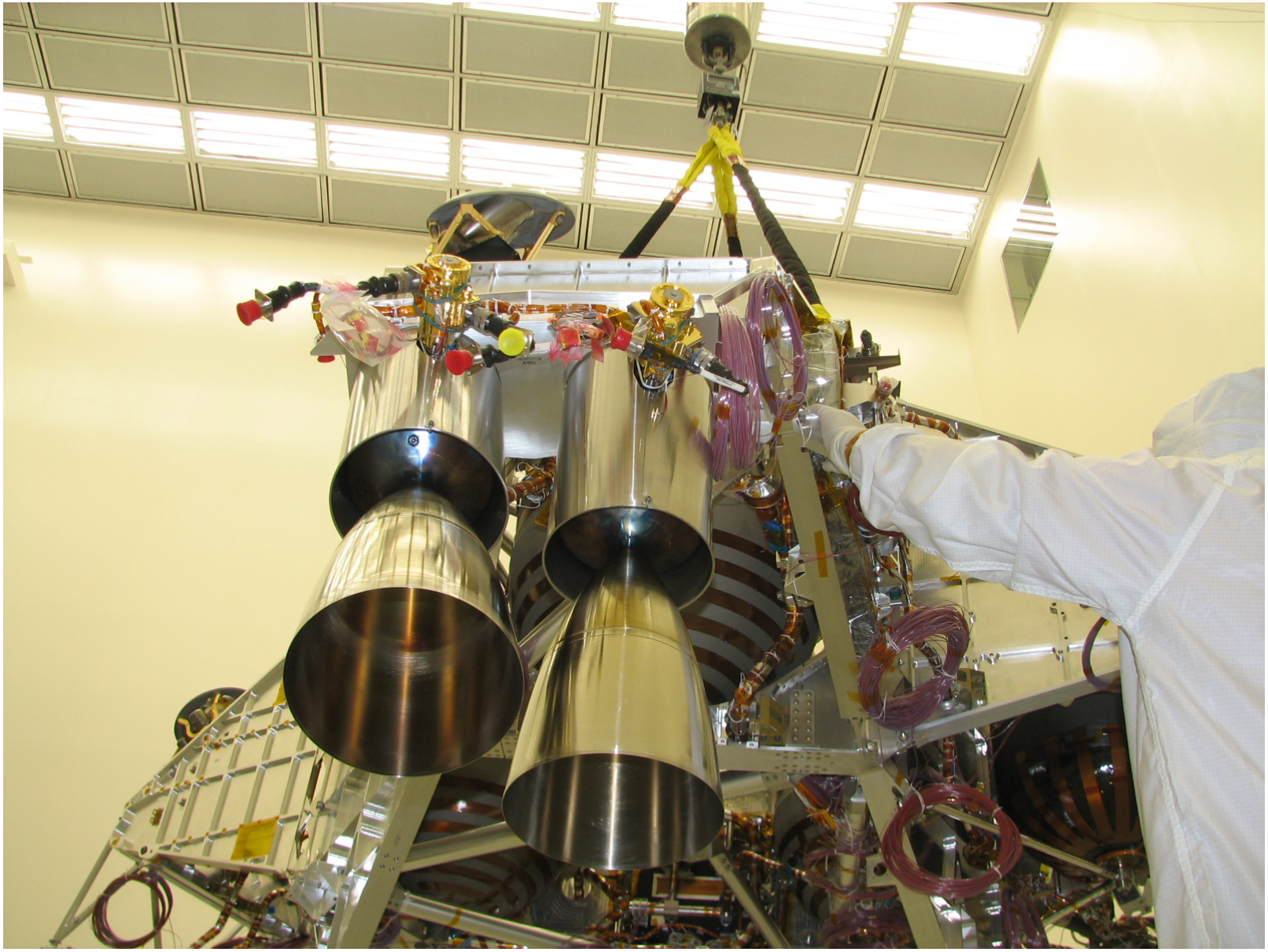
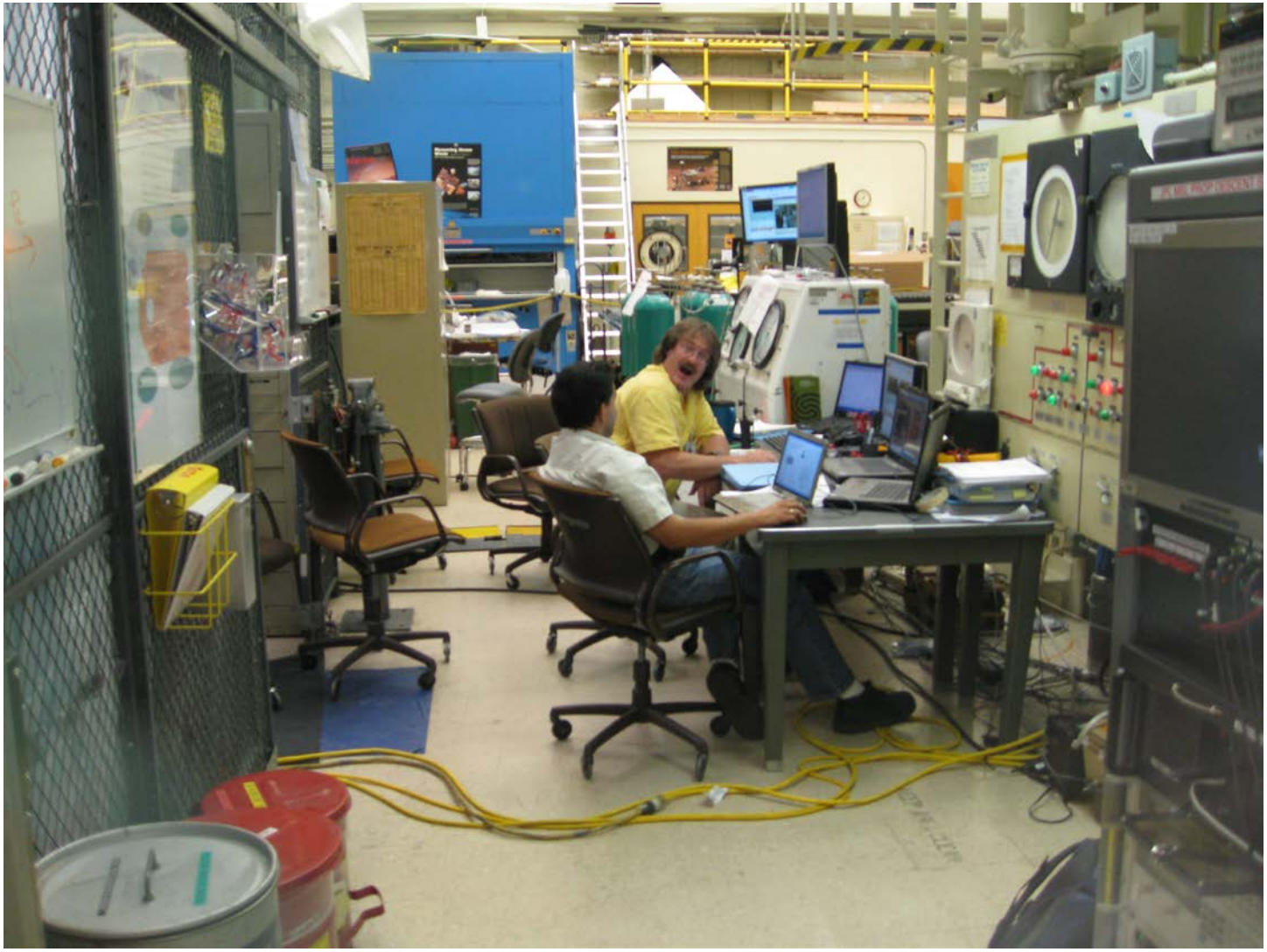


Some Photos of the “Build”

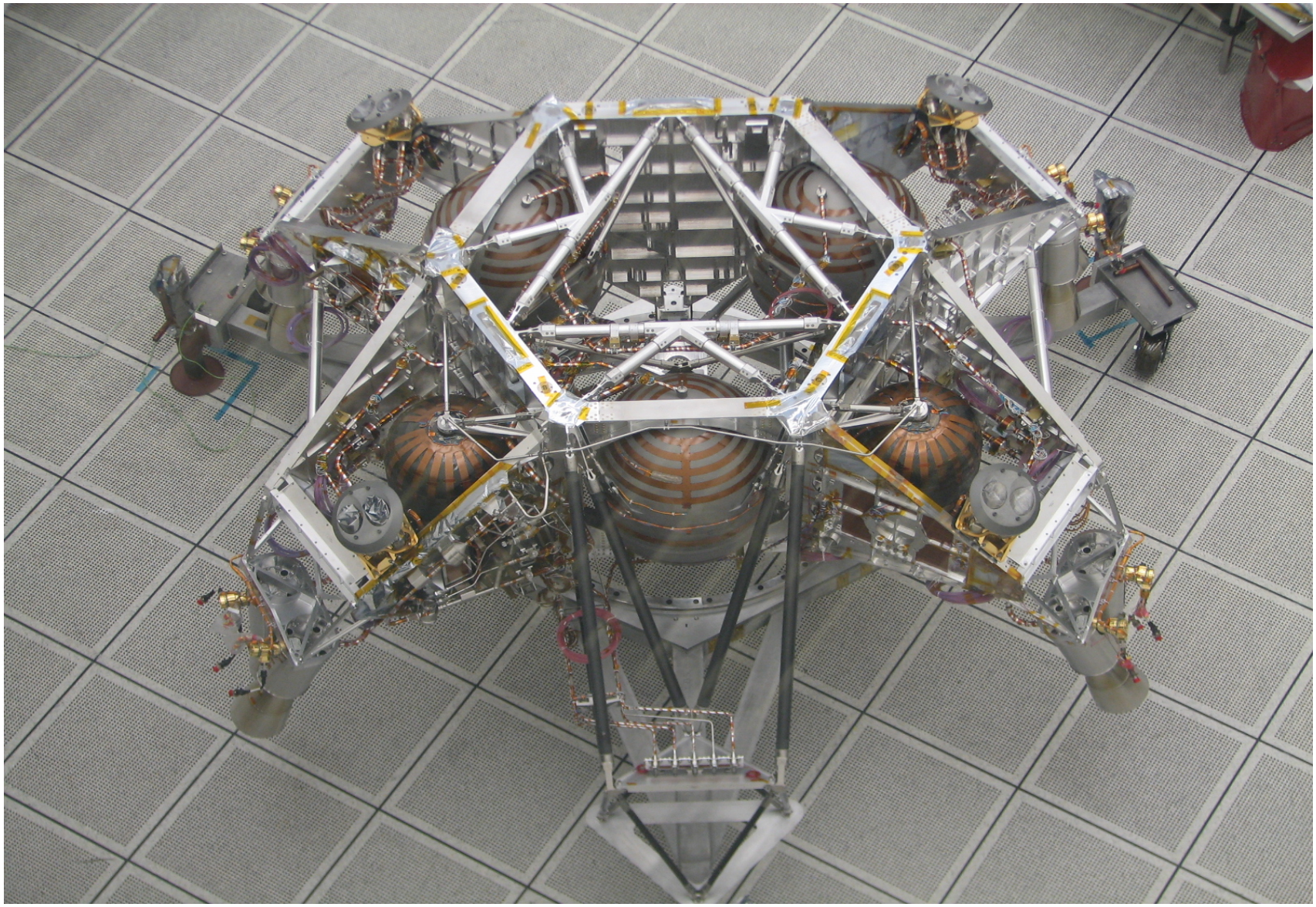
The Last Weld

Test Conductor



(Most of) The Team

DSPS Complete – Before Spacecraft Integration



System Testing

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System Testing

Fueling Operations – Men in Scape Suits

Fueling Operations

Final Integration with Curiosity

Final Integration with Curiosity

Final Integration with Curiosity