AAS 13-461

FABRICATION ASSEMBLY AND TEST OF THE MARS SCIENCE LABORATORY DESCENT STAGE PROPULSION SYSTEM

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The Descent Stage Propulsion System (DSPS) is the most challenging and complex propulsion system ever built at JPL. Performance requirements, such as the entry Reaction Control System (RCS) requirements, and the terminal descent requirements (3300 N maximum thrust and ~835,000 N-s total impulse in less than a minute), required a large amount of propellant and a large number of components for a spacecraft that had to fit in a 4.5 meter aeroshell. The size and shape of the aeroshell, along with the envelope of the stowed rover, limited the configuration options for the Descent Stage structure. The configuration and mass constraints of the Descent Stage structure, along with performance requirements, drove the configuration of the DSPS. This paper will examine some of the challenges encountered and solutions developed during the fabrication, assembly, and test of the DSPS.

INTRODUCTION

On August 5th, 2012, at approximately 10:25 pm PDT, the Mars Science Laboratory (MSL) Descent Stage Propulsion System (DSPS) used its Reaction Control System (RCS), consisting of eight 250 N thrusters, to guide the MSL Entry Vehicle, with the rover Curiosity inside, through the Martian atmosphere and through parachute deploy. The RCS provided despin of the Entry Vehicle, attitude control prior to atmospheric entry, aero maneuvering during entry via "bank reversal maneuvers," attitude control while flying "lift up," (using the shape and offset center of gravity of the Entry Vehicle to provide lift, which allowed the spacecraft to better control its trajectory and target a smaller landing ellipse), and finally to reorient the Entry Vehicle for parachute deploy to a near zero angle of attack so that the parachute could deploy in line with the Z-axis of the spacecraft. Following separation from the backshell, the DSPS fired the eight throttled 3300 N thrust Mars Lander Engines (MLEs) to divert the Descent Stage carrying

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

Curiosity away from the path of the parachute and backshell, and then slow the descent from over 200 miles per hour (mph) to approximately 1 mph, and land Curiosity safely on the surface of Mars at approximately 10:32 pm PDT. Reference 1 gives an overview of the MSL Entry Descent and Landing System, of which the DSPS is one important element.

The DSPS is the most sophisticated and challenging propulsion system ever built at JPL. The block diagram is shown in Figure 1, but its relative simplicity belies the true nature of the challenges. It is a pressure-regulated monopropellant hydrazine propulsion system that feeds relatively high pressure (in the 700 psi range) hydrazine to the MLEs, and RCS thrusters. The three propellant tanks carried a propellant load of approximately 400 kg. The need for positive isolation of pressurant and propellant prior to the DSPS activation during the eight-month cruise to Mars was accomplished by extensive use of pyrotechnically actuated valves (aka pyro valves). The subsystem design and operation are described in detail in Reference 2, and some very interesting lessons learned from the development of the DSPS are described in Reference 3.

The focus of this paper is on the fabrication, assembly, and system test phases of the MSL DSPS, and some of the challenges encountered and solutions developed during these phases. This work included the initial assembly and test in JPL Building 233 prior to delivering the DSPS to the JPL Spacecraft Assembly Facility (SAF) for spacecraft-level integration, support during system-level testing in SAF and at Kennedy Space Center (KSC), and DSPS final testing and propellant loading at KSC.

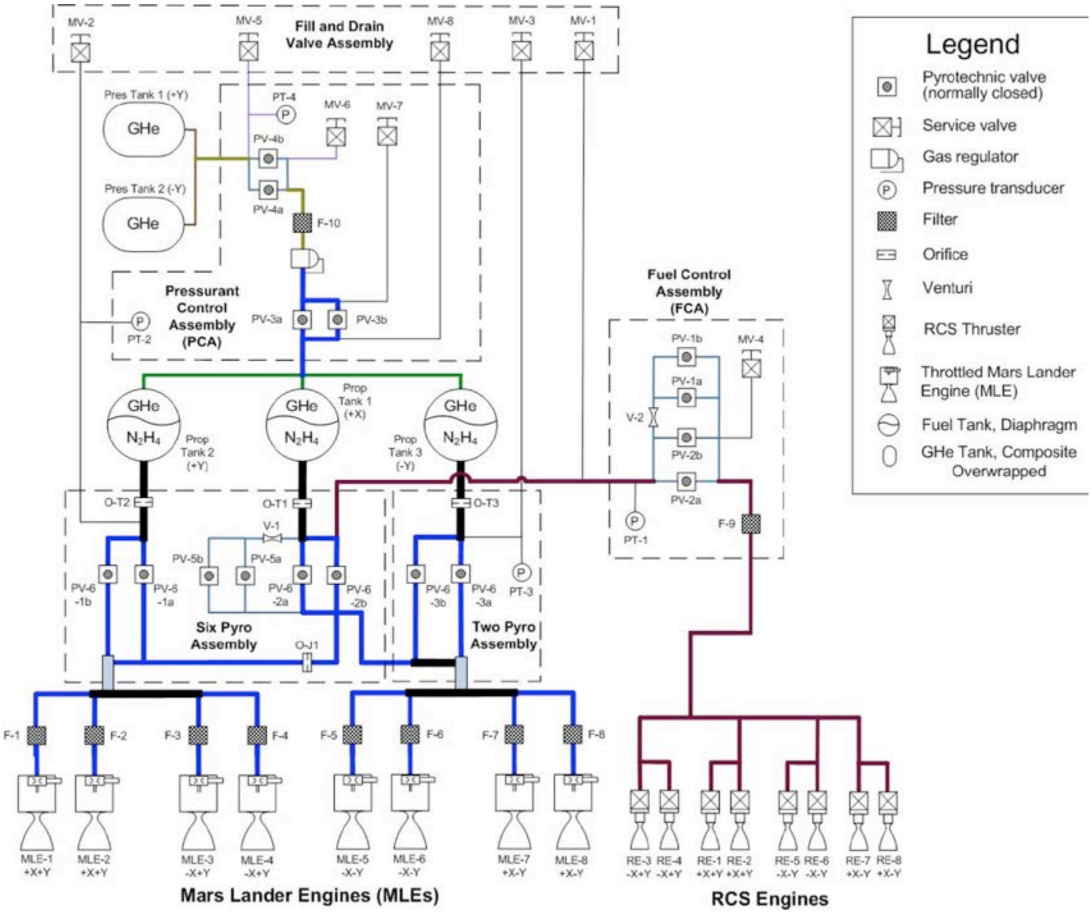

Figure 1. MSL Descent Stage Propulsion Block Diagram.

CONFIGURATION CHALLENGES

The size and shape of the approximately 4.5 meter diameter aeroshell were limited by the launch vehicle shroud, and by our ability to control an aeroshell of this size entering the Mars atmosphere. The envelope of the stowed rover Curiosity, weighing in at one ton, consumed a significant part of the volume inside the aeroshell, and limited the configuration options for the Descent Stage structure. The configuration and mass constraints of the Descent Stage structure, and other system elements such as the terminal descent radar pallet, and the sky crane deployment mechanisms described in Reference 1, along with performance requirements such as maximum thrust and total fuel required, drove the configuration of the DSPS.

The distributed and yet cramped nature of the configuration necessitated tubing runs connecting the various components be laid out in tortuous paths. This configuration was described early on by one engineer as being “like a bowl of cold spaghetti that has to be put together like a Rubik’s cube.” In fact, that early observation turned out to be more than just a bit of humorous conjecture once the detailed design was near 95% complete. It is one thing to place components into their respective geometric configuration through the magic of computer-aided design (CAD). It became obvious that it would be quite a different process to physically maneuver these components into position, and allow access for human bodies, hands, weld heads, torque wrenches, Ground Support Equipment (GSE) fixturing, and other tools of assembly and inspection.

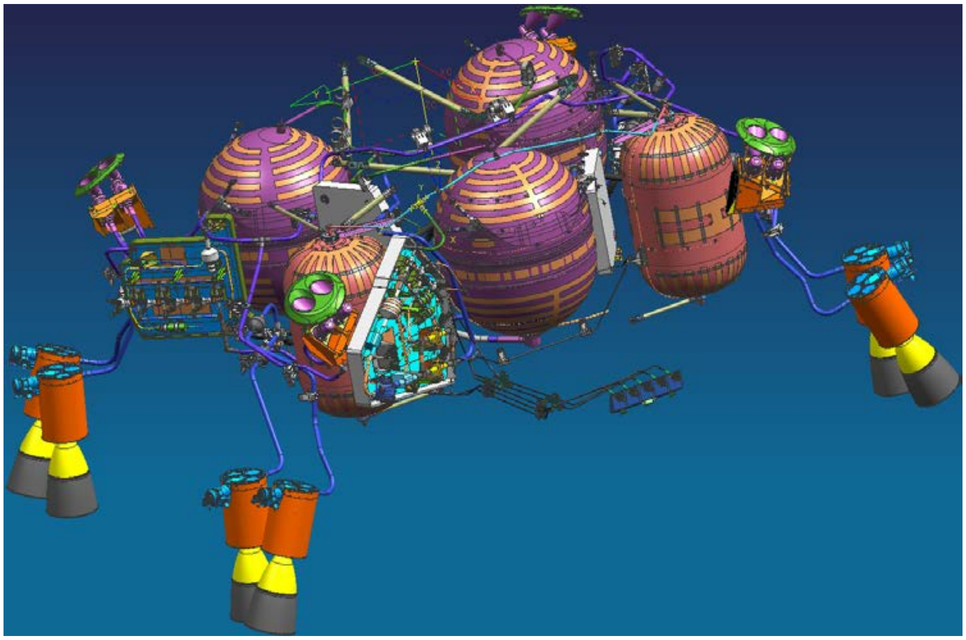

Figure 2. DS Propulsion components—minus other hardware (e.g., structure, thermal, cabling).

Sequential Assembly

Most of the major components had to be integrated sequentially. For example, long before the assembly ever started, all of the components internal to the central hexagon structure, (three propellant tanks, two pyro valve plate assemblies, and various tubing runs), were modeled and maneuvered into position in CAD over and over again until the “choreography” worked. Similar sequencing efforts were used for the pressurant tanks and other components that fit in the outrigger bays. In some instances, physical models were fabricated to verify access for integration in very tight spots. Each of the various weld-heads were modeled and maneuvered into position in CAD to ensure accessibility and removal for each of the 260+ original welds. Quite often, tubing runs, secondary structure, and other components had to be redesigned to account for access. Even then, it was not uncommon to have to design and build unique tooling from one day to the next to complete installation of certain assemblies. In this regard the technicians' ingenuity and machining skill proved invaluable.

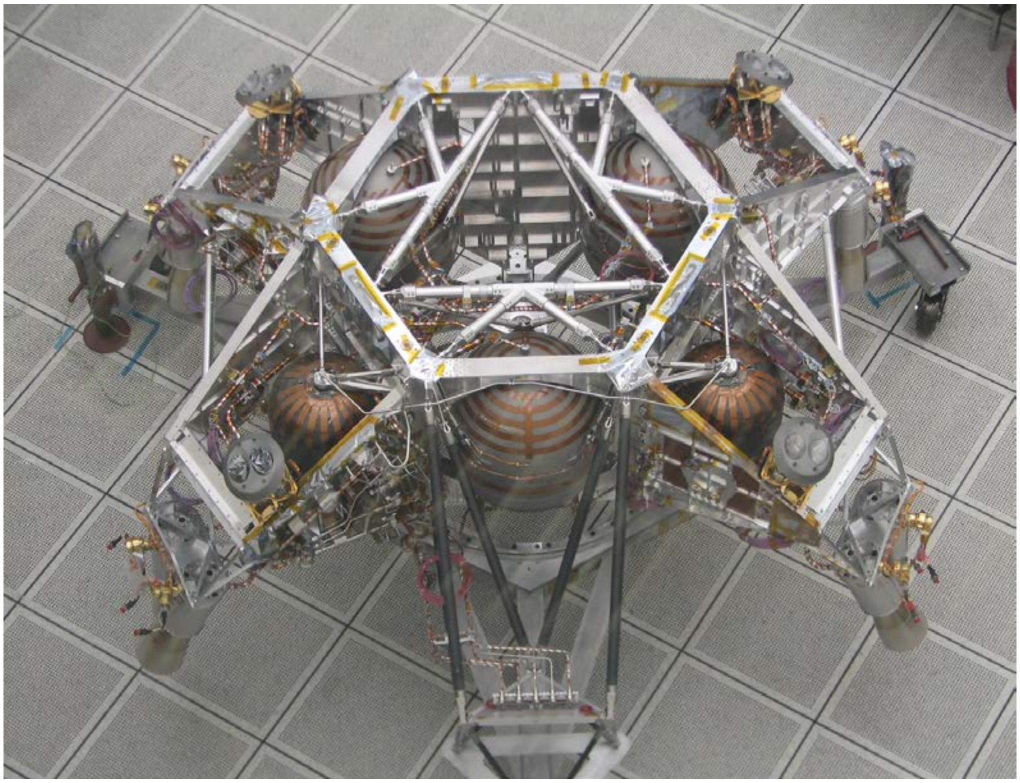

Figure 3. The DSPS completed—minus some thermal and cabling hardware.

Looking at the photo in Figure 3, one might think that the Descent Stage was quite roomy. However, there were many "keep out" zones where parts of the rover, the sky crane deployment mechanisms, telecom hardware, and other non-propulsion hardware had to fit. Looking at Figure 4, one might understand the reasons for the tortuous tubing runs.

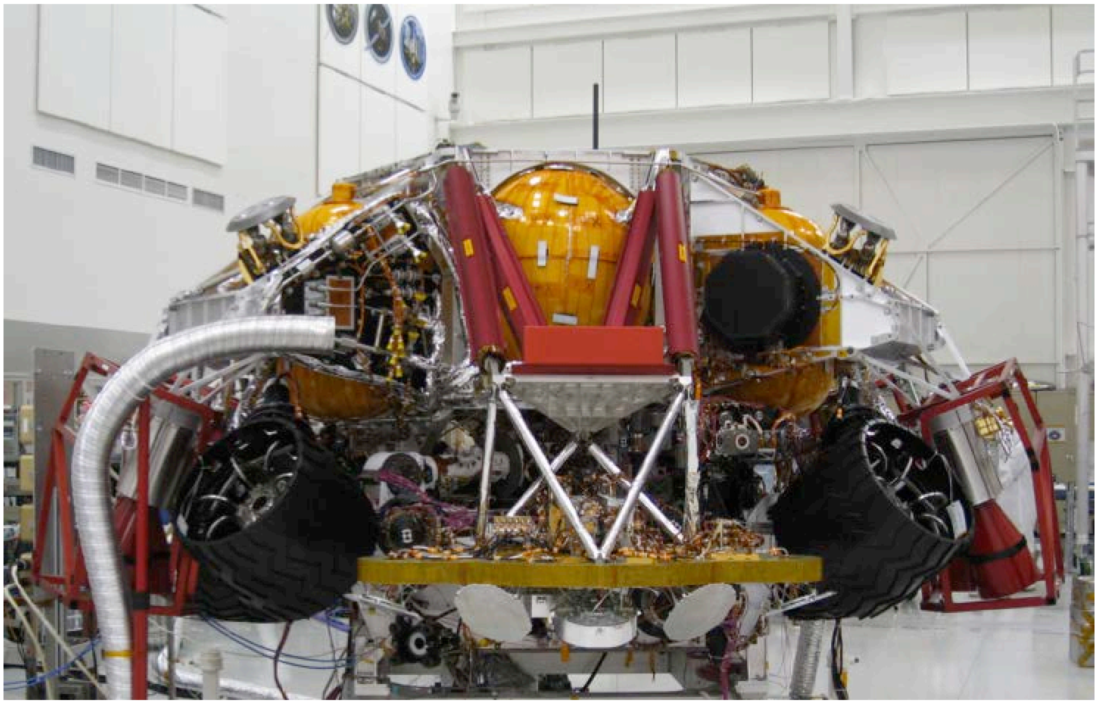

Figure 4. DS Complete with Rover Curiosity tucked underneath its "belly." Minus the few red GSE items, the 4" dia. aluminum flexible pipe on the left, and a few test cables, everything in this photo that is attached to the Descent Stage flies.

SCHEDULE—THE CRITICAL PATH

The Propulsion System for the Descent Stage (DS) was the first subsystem to be incorporated onto the DS primary structure. The DSPS fabrication, assembly, and test was in series with spacecraft-level assembly and test, primarily due to two inherent operations; welding, and testing at high pressures. The welding process produces high levels of electromagnetic compatibility (EMC) and electromagnetic interference (EMI) that are detrimental to electronics and avionics, so all the welding on the spacecraft should be completed prior to delivery to spacecraft-level assembly and test. The proof pressure testing of the subassemblies and completed propulsion system, with some pressure tests >5000 psi, is potentially lethal to personnel, and potentially catastrophic to facilities and flight hardware, and so was performed behind barricades in the JPL Building 233 Cleanroom.

The DSPS fabrication, assembly, and test were identified early on, circa 2007, as the critical path for the entire MSL Project, not just the DS. Only after the DSPS was complete, could the DS be delivered to JPL's SAF for the integration of other subsystems, and the start of Spacecraft level assembly and test (commonly referred to an Assembly Test and Launch Operations, or ATLO[††]). The MSL Project schedule demanded an early September 2008 delivery to SAF in order for ATLO to start in time for a 2009 launch. The originally scheduled nine–month DSPS integration and test (I&T) allocation was reduced to seven months due to late delivery of the primary structure. In addition, the detailed design of subassemblies and tube layouts was done concurrent with the start of the DS I&T, resulting in a "just-in-time" mode of operation.

[††] JPL ATLO occurs at JPL in the SAF and environmental test facilities, and at KSC, where, among other activities, the spacecraft is reassembled, retested, and propellant fueling is performed.

Ultimately, the DSPS was delivered to SAF on schedule, September 4, 2008. However, measures that were extraordinary, at least for JPL, were necessary in order to accomplish this.

THE TEAM ANDTHE WAR ROOM

Key to the successful and timely delivery of the DSPS was propulsion team cohesion. Some of the practices that enabled clear and unfettered communication flow throughout the team include:

- A "one team, level field philosophy." This involved but was not limited to the open and unfiltered communication and faith between the MSL Propulsion technicians engineers. While the various levels of responsibility were respected, all team members—technicians, engineers, and managers—were encouraged to participate on equal footing. In fact, the team building was started months before the flight work with trial welding exercises of some of the more challenging plate assemblies, and laid the groundwork for open communications.
- Daily team tag-ups were held at 6:00 am and again at 3:00 pm during the overlap of first and second shift, to discuss status and near-term plans.
- Co-location of engineers and technicians allowed immediate response to issues and resolution of questions or conflicts. Propulsion engineers moved down to Bldg. 233 immediately adjacent to the technicians' offices and occupied a ~25 foot by 25 foot room dubbed the "War Room."
- Large format CAD images of the bare DS primary structure, each of the propulsion subassemblies, and the completed Propulsion system on the structure were plotted and posted on the walls of the War Room. These images helped the team to visualize our objectives, and served as tools to focus discussions during the daily team tag-ups.
- Lead technicians were included in assembly procedure reviews, both to leverage their skills and knowledge and provide them a preview of engineering intent.
- Project and line management support were available when it came to sharing or efficiently using Laboratory resources, like Quality Assurance (QA) Inspection, the JPL Bldg. 233 Precision Cleaning Facility, and scheduling third shift x-ray inspections.
- The Propulsion engineering group was short-handed and needed help long before the assembly began. That help finally came at the last minute, when JPL managed to recruit two engineers from Northrup Grumman Space Technologies (Redondo Beach, CA) and two engineers from Lockheed Martin Denver. Despite joining our team just as we started the build, and knowing nothing of JPL's internal idiosyncrasies, these four engineers jumped right into the fray, played a huge part in the build, and performed outstanding work.
- Two Co-op engineering students were given real engineering tasks and played a significant part on the team.

FIRST SHIFT OPERATIONS

First shift typically began at 6:00 am with a review of the previous second shift activities and planning for the day. The crew consisted of at least two weld teams of two technicians each, subassembly lead engineers, a floor lead, one or more quality engineers, and several supporting technicians. It was not uncommon to have work progressing on three or more subassemblies at once, in addition to cabling and thermal installation.

We called them "weld teams" because welding and the associated preparation was the most time consuming of all the DSPS activities. However, these weld teams were also responsible for all aspects of mechanical assembly of the DSPS, e.g. mounting of components to secondary and primary structure. Weld teams typically started the day with pre-weld samples for the welds planned for that shift. These teams were also responsible for the precision fit-up and trimming of each weld joint. Prior to welding and after trimming, parts were re-cleaned either by the Precision Cleaning Facility, by placing in a small ultrasonic bath in the assembly area, or by hand with alcohol. Purge equipment and any tooling that would interface with flight hardware were also cleaned prior to use. Prior to performing a flight weld, the floor lead and quality engineer would typically inspect the fit-up of the joint, the cleanliness of the parts, qualitative assessment of the pre-weld samples, and the purge setup. Each flight weld would then be inspected visually for any obvious signs of imperfection such as discoloration, misalignment of the bead, bead meandering, droop, or distention. All welds were eventually inspected radiographically. Subassemblies were sent to a local contractor for x-ray inspection. System welds were portable X-rayed in-situ on third shift.

The primary limiting factors on first shift were physical space in the clean room and throughput of the Precision Cleaning Facility. This was particularly a problem early in the build when there were several different subassemblies in work and the descent stage structure had been delivered and consumed a significant amount of floor space (Figure 5). Later, when the system was nearing completion, the problem of space inverted as all the work needed to occur on the DS and virtually every square foot of space around the DS was occupied (Figure 6).

Figure 5. Subassemblies in process.

Figure 6. Propulsion beehive.

The average number of welds per shift per team was just under 1 for subassemblies and 0.7 for interconnect tubing. This includes all mechanical fit-up and assembly, but does not include proof and leak testing, thermal, or cabling installation work. Table 1 provides a summary.

Table 1. DSPS Mechanical and Weld Schedule Performance.

Subassembly	Number of Welds	MSL Start	MSL Finish	Duration	Active Shifts	Welds/shift
PCA	32	4/11/2008	5/30/2008	49	46	0.70
6PV	33	3/3/2008	4/4/2008	32	42	0.79
2PV	15	2/22/2008	3/21/2008	28	43	0.35
FCA	26	3/17/2008	4/4/2008	18	25	1.04
MLEM	28	2/21/2008	3/6/2008	14	13	2.15
RCSA	24	5/23/2008	7/30/2008	68	45	0.53
Interconnect						
HEX	22	5/18/2008	7/19/2008	62	37	0.59
MLE	16	6/28/2008	8/1/2008	34	29	0.55
MLEM	10	4/1/2008	4/11/2008	10	17	0.59
PRL	18	5/23/2008	7/16/2008	54	41	0.44
RCS	25	4/11/2008	7/31/2008	111	31	0.81
SVL	16				16	1.00
Total	265	2/21/2008	8/1/2008	162	385	0.69

SECOND AND THIRD SHIFT OPERATIONS

The second shift crew consisted of a floor lead, nominally three mechanical technicians, a quality engineer, and the Precision Cleaning Facility operation. The daily 3:00 pm tag-up meeting with the first shift was essential in establishing overall I&T status and immediate goals and priorities. Second-shift operations were less efficient than first shift. The primary cause for this was the limited availability of supporting personnel. JPL is not a production house. Second-shift operations are rare, and typically only performed once every few years during spacecraft-level integration and test. Before MSL, second-shift operations had never been used during Propulsion system fabrication assembly and test. Basic supplies were not available from JPL "stores" after normal hours, e.g. sheet metal, bar stock or fasteners. On occasion, during assembly, key information must be ascertained or verified (e.g., weld schedule parameters, tooling availability, flight hardware status). When key information or supplies were not available, some operations had to be suspended and the crew focus redirected. The second shift team made the best of it.

Third-shift operations were performed primarily for X-raying of system welds. System weld x-rays had to be performed in-situ, and were performed on third shift when there were minimal personnel in the building. Installation of thermal hardware and cabling were sometimes performed on third-shift. Even though less efficient, second and third-shift operations were absolutely essential. The DSPS could not have been delivered to SAF on schedule without the second and third shifts.

SUPPORT STAFF OUTSIDE THE CLEAN ROOM

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. Real-time support functions included procuring materials and fasteners, machining GSE and tooling fixtures, arranging for support from other groups or facilities at JPL such as shipping and transportation, inspection, QA, etc., and of course a large amount of effort from the Precision Cleaning Facility.

THE COMPONENT PLATES AND OTHER SUBASSEMBLIES

The DSPS had four “plate” assemblies containing the various smaller components (e.g., pyro valves, service valves, pressure transducers). The Fuel Control Assembly (FCA) consisted of a filter, pressure transducer, service valve, and pyro valves; its function was to deliver hydrazine to the RCS system. The “6PV” and the “2PV” plate assemblies consisted primarily of pyro valves; their function was to properly distribute hydrazine from the three propellant tanks to the FCA and the Main Engine assemblies. The Pressurant Control Assembly (PCA) consisted of a large filter, pressure transducers, pyro valves, in-line load shunting blocks, and a pressure regulator; its function was to regulate the ~4500 psi pressure from the two pressurant tanks down to ~700 psi and feed that pressure to the propellant tanks.

Due to the DS volume constraints and “keep out” zones, these propulsion plate assemblies had extremely tight layouts with much larger diameter and thicker walled tubing and components than JPL had ever dealt with before. Many tube fittings (elbows, TEEs, tribows etc.), and the in-line load shunting blocks mentioned above, were designed to be bolted to the component plate to “short” loads from inlet and outlet tubing or pyroshock. In retrospect, the design allowed for little if any tolerance stack up from weld shrinkage or weld deflection. The result was a tedious and slow assembly process that invited overthinking of engineering procedures. Detailed procedures, released drawings, and less formal Assembly and Integration Data Sheets (AIDS) were used to define and control subassembly builds. At times flight mockup trial assemblies were used as “pathfinders,” for instance, to ensure adequate access, or to control “weld walk” (an axial deflection of a tube after welding described in detail in the Welding section). In hindsight, the team would probably have been better served by relying more on released drawings and AIDS, rather than detailed procedures, due to the sheer number of details and open questions that are best addressed with the hardware in-hand and in consultation with floor personnel.

A significant improvement in the assembly process involved tack welding (described in detail in the Welding section). Tack welding could be applied to multiple joints in an assembly limiting the amount of fit-up and tweaking required after each weld. Tack welds were performed using the orbital arc weld machine with a special weld schedule to supply three to five partially penetrating tack welds to hold the joint in place for welding. The normal weld schedule would then be run over the tacks. If Tack welds were planned to be used, weld samples were produced before hand using the same tack welds.

Even with the challenges of extremely tight layouts and large tubing and components, the FCA, the 6PV, and the 2PV plate assemblies were assembled, welded, and proof tested in parallel, in ~5 weeks. The assembly and test of the PCA, however, was a different story.

EL PLATO DEL DIABLO

The PCA alone took 7 weeks to complete, and became affectionately know by the team as "el Plato del Diablo" for the challenges encountered during its build. Some of the challenges were simply due to the nature and the function of the PCA. As mentioned above, the PCA's function was to regulate the ~4500 psi pressure from the two pressurant tanks down to ~700 psi and feed that pressure to the propellant tanks (Figure 7). The pressure regulator was the most contamination sensitive component in the entire DSPS, so extra care was taken in the assembly and welding of the PCA. The high propellant flow rate demanded by the MLEs also required high pressurant flow rate to maintain adequate feed pressure. The combination of high pressure, high flow rates, and the propellant/pressurant line structural load shorting (mentioned in the TUBING section above) required some tubing with 0.500 inch O.D. × 0.083 inch wall thickness; basically tubing that looked like a high powered gun barrel.

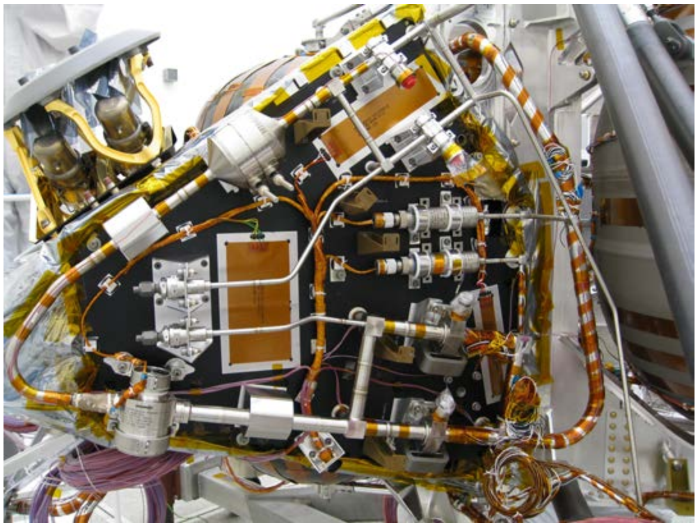

Figure 7. The PCA – aka "el Plato del Diablo"

The DSPS had 53 unique weld schedules, over 260 original welds, some on tubing as large as 1.25 inch O.D., many of which had very difficult purging setups. Ultimately, the DSPS welding experienced only two weld failures out of 260+ (and later still only two out of over 300, including the rework), i.e., a >99% success rate/<1% weld failures. However, one of those two 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 "gun barrel" 0.500 inch O.D. × 0.083 inch wall thickness tubing welds (see Figure 8).

The Propulsion team investigated the problem and devoted roughly 50% of our resources for over two weeks to repair the PCA. Our materials specialist/weld engineer worked with the technician crews trying many new weld schedules over and over to fine tune a weld schedule. This particular tube required high current welds that actually melted two weld heads in the process. The cutout, rework, and replacement tubing welds required special purge, contamination prevention, and alignment fixturing to perform successfully.

Figure 8. One of only two weld failures out of >260 welds.
As ugly as it is, this weld represents a phenomenal overall success rate.

RCS Assemblies

The RCS Thruster Assemblies, of which there were four, each supporting a pair of thrusters, required precise work from both propulsion and structural engineers. The thruster nozzles had to be positioned carefully, and verified through Computer Machine Measurements (CMM), such that their thrust vectors were aligned correctly during both their attachment to their immediate support structure and again to the rest of the Descent Stage main structure and its overall coordinate system. They also had to be positioned such that they would not interfere with their fairing holes during launch vibration and operation. Special positioning tools, mounting structures and special attention to the chronology of installing and torquing each piece of the support structure hardware was vital to achieving the final position of the thrusters (Figure 9).

Figure 9. One of four RCS assemblies.

One specific challenge in building the RCS Assemblies dealt with the "weld walk" mentioned earlier. In the case of the RCS assemblies, weld walk created a problem, but ironically became the solution in the end. An axial deflection of a tube occurs during orbital welding because heat cannot be applied equally and simultaneously around the circumference of the tube; while one area is being heated by the electrode, other areas of the tube are cooling. Depending on the particular weld schedule, the electrode travels somewhat more than 360 degrees, and the last area of the circumference of the tube to be heated, is the last to cool. This can create a slight axial angle on the welded tube. This deflection can usually be corrected by bending the tube back into place to meet the next part. However, in the case of the RCS Thruster Assemblies, stress analysis determined that the tubes connecting to the thrusters should not be adjusted or loaded with additional residual stress. The problem was helped by the fact that the tubes being welded to the thruster were shaped like a "U" and since their ends were parallel to each other, the weld walk on one end could be used to compensate for that on the other end. A mock-up structure was built to test this theory, precise clocking angles were chosen to achieve the desired movement of the tube ends and welding was carried out with minimal final displacement.

MLE Assemblies

The MLE assemblies were also quite complex, consisting of cavitating venturi throttle valve, with a range of ~ 15% to 100% throttle, an LVDT for position feedback, thrust chamber with a radial catalyst bed and nozzles (Figure 10). The throttle valve motors were driven by a Descent Stage Motor Control Actuator. The MLEs were mounted in pairs, and each pair was canted 5 degrees apart to mitigate plume sheeting impingement. Precise alignment of the MLEs was also required. However, the part of the DS primary structure that the MLEs were mounted to had already been precisely aligned and verified by CMM prior to delivery for DSPS integration.

Figure 10. A pair of MLEs

INTERCONNECT TUBING

The propellant load requirement for the DSPS was ~400 kg. of hydrazine, the majority of which was to be fed to the eight MLEs in less than a minute. The flowrate, along with several other factors, resulted in seven different tubing sizes ranging from 0.25” up to 1.25” O.D., and wall thicknesses ranging from 0.028” to 0.083” inches. The various tubing sizes, wall thicknesses, tubing and component materials, some with varying metallurgical content, all combined to necessitate 53 unique weld schedules and over 260 original welds (before the rework).

Due to the large flowrates and pressure levels of the DSPS, much of the tubing was of relatively large diameter, or thick walled, and much stiffer than the 0.25” and 0.375” tubing typical on most spacecraft propulsion systems. After the Propulsion Subsystem CDR and the spacecraft-level CDR, the first system level structural dynamics modeling showed evidence of shorting of structural loads through the larger and thicker walled tubing. At about the same time, detailed CFD analyses of the RCS thruster plume interaction with the vehicle determined that relocation of all the RCS thrusters—and redesign of the propellant line run—was necessary. A “tiger team” consisting of structural engineers, propulsion engineers, and stress analysts was assembled just a few months before assembly began to address these problems (e.g., propellant tank outlet line load shorting, MLE feed line load shorting and RCS line frequency decoupling), which resulted in several design changes to secondary structure, tubing mounts, tubing material, and tubing runs, some as late as two months after assembly had begun. Redesigned tubing layouts and fabrication were literally being performed “just-in-time” for some of the tubing runs. The analytical work of the Prop Line Stress Analysis team is discussed in detail in Reference 4.

As mentioned earlier in the CONFIGURATION CHALLENGES section, most of the tubing runs connecting various components were laid out in tortuous paths, over, under, around, and through holes in the panels of the central hexagon, and the eight outrigger panels extending radially outward from four of the six hexagon panels (see Figures 11 and 12). On some spacecraft, JPL’s Propulsion and Fluids Group bends tubing in-house. However, the MSL tube bending was subcontracted out-of-house due to the sheer volume of tubing to be bent, the complexity of the tubing runs, and the schedule constraints.

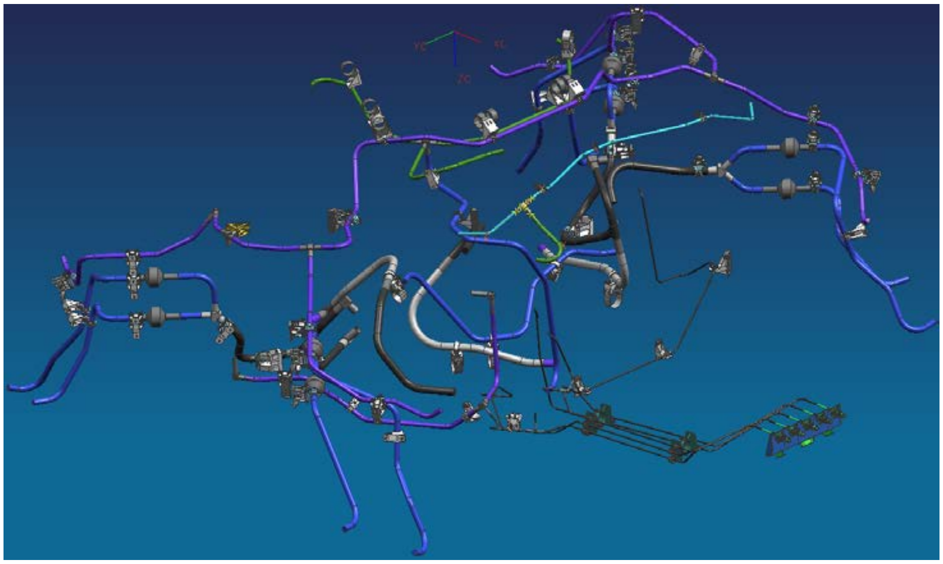

Figure 11. DSPS tubing “in space.”

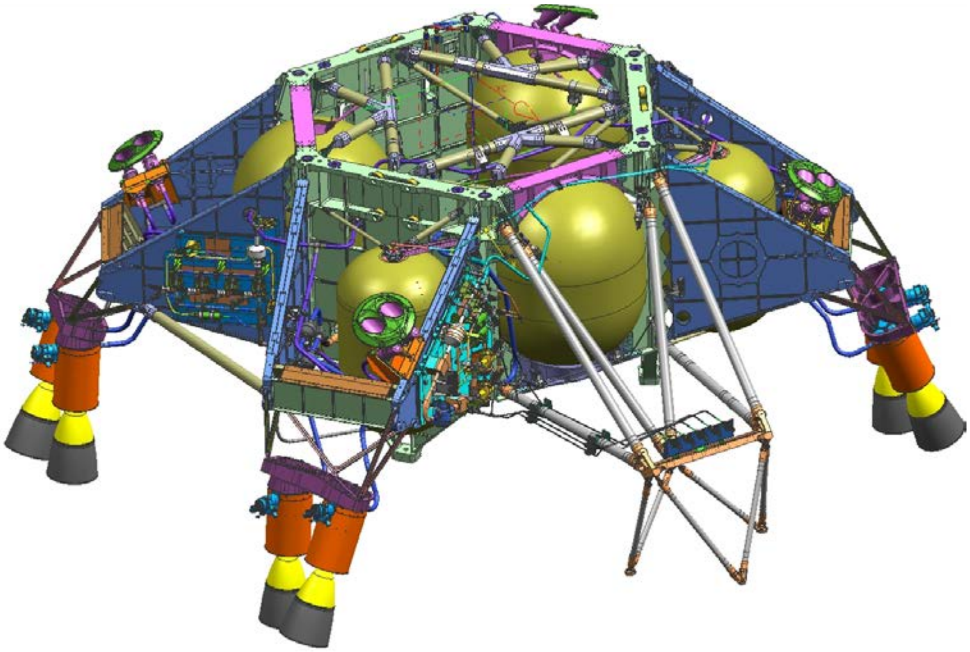

Figure 12. DSPS tubing with structure and other propulsion components.

JPL's Bldg. 233 Precision Cleaning Facility was undergoing major remodeling and upgrades in preparation for the MSL DSPS work. Unfortunately, a few issues were discovered in the process, and not all of the upgraded capabilities were ready in time for the DSPS build. While most of the DSPS fluid fittings and shorter tubing sections were cleaned in the Precision Cleaning Facility, most of the longer sections of tubing were cleaned out of house. At one point, this nearly brought work to a standstill. Upper management helped the Propulsion team get priority in the procurement process to contract outside precision cleaning services. For a while we had tube cleaning contracts going on at four cleaning facilities outside JPL, and were shuttling flight tubing all over the Los Angeles area in order to minimize the disruptions to the schedule.

SECONDARY STRUCTURE FABRICATION

The Propulsion team was not the only group at JPL experiencing personnel shortages. The stress analysis process became a serious "bottle neck" to the work flow when an unexpected and huge amount of additional work was created by the shorting of structural loads through the propellant and pressurant tubing (Reference 4). In turn, this bottle neck in stress analysis helped cause late delivery of most of the secondary structure needed to mount the tubing. One of the Bldg. 233 Propulsion technicians was very creative in quickly designing and machining our own GSE secondary structure as a "stand-in," but this process also became a bottle neck and consumed the full-time one of our key technicians in that he couldn't be in the Clean Room and the machine shop at the same time. Stereolithography (SLA) or "3-D printing" of complex parts was becoming common for prototypes and other non-structural uses, and the selection of materials that could be used in SLA was rapidly expanding to include some polymers with significant strength. A quick assessment was made of the loads that the secondary structure for mounting tubing would see in earth gravity and it was apparent that secondary structural parts made via the SLA process could be quite suitable as "stand-in" parts until the flight parts arrived. We requested that the engineer responsible for our secondary structure place additional orders for SLA parts for most of the tube mounting brackets and other small secondary structure. These

SLA parts, which were geometrically identical to the flight components, were installed to allow the work to proceed on schedule, and then removed as the flight brackets became available. In process documentation and QA inspection assured removal of all non-flight components.

WELDING

As mentioned above, the many different tubing diameters, wall thicknesses, materials, and varying metallurgical content, all combined to necessitate 53 unique weld schedules and over 260 original welds before the rework, and over 300 welds including the rework.

JPL's Propulsion and Fluid Systems Service Group developed and certified 53 different weld schedule combinations. Several different welding machines were used for tubing ranging from 1/4 inch to 1 1/4 inch in diameter. The tube wall thicknesses varied from 0.028 to 0.083 inches thick.

Orbital welding equipment and techniques were used on all MSL Descent and Cruise Stage fuel systems. This process provides precise computer-aided control of weld current, electrode travel speed, and O.D. shield gas flow to produce consistent and repeatable weld results. The weld head stays stationary within a clamp head and the tungsten electrode rotates (orbital) around the tube weld joint, normally a little more than 360 degrees while varying the current to control heat buildup. Pushing the button is easy. The engineering and technician expertise in qualifying the weld schedules, and the preparation of each weld is the hard part.

One of the major challenges in fabrication occurred in dealing with the previously mentioned "weld walk" – an axial deflection of a tube after welding, produced by the heat built-up and released during the orbital welding process. This deflection greatly affected our ability to maintain concentricity and minimize induced loads. This was critical because of the compact nature of the components and tubing runs within the system. A number of experiments were performed, which required out-of-the-box thinking to control weld deflections. The solution was a combination of "orbital tack welding", custom fabricated "bridge clamps", and control of the start and end positions of the weld arc. Several of our welding system manufacturers told us that tack welding could not be performed with our equipment, but that didn't stop this team. Some of these welding heads had a limited clocking position for a high-frequency start point (0 degrees). A high-frequency start is needed to jump the gap to start the weld process. Tack welding programs were developed that worked on our orbital welding systems. The tack weld program starts at the "0 degrees" start position, producing the first tack weld. The program then rotates the electrode at a lower current level while maintaining the arc and makes a second tack at the "144 degree" position, then repeats this 144 degree rotation and tack process three more times, finishing with the fifth tack at "576 degrees from the 0 degree start position. This gave us five equally spaced tacks. The required weld schedule was performed over the tack welds to complete the weld process. Bridge clamps served as an alignment tool during and in conjunction with the orbital weld process.

We also found that the direction of the weld deflection was a function of weld arc starting and stopping positions and that we could control the deflection to some extent by clocking the start of the weld appropriately, We took this a step further and created a recovery weld, which basically was a short deration low amp weld that only affected about 1/4 of the tubes outer diameter. Its purpose was to create a controlled deflection at the weld joint to regain concentricity and minimize induced loads. The recovery weld process was used in instances where tack welding was not desirable for some reason or another, for instance in the RCS assemblies described earlier.

The DSPS design required a lot of dead head welds, which did not allow for normal internal purging prior to the weld. We developed a coaxial tubing purge process, which involved inserting a smaller diameter tube within the tube to be welded, which stopped near the weld joint – simple enough, however, performing this purge process while maintaining cleanliness was the real trick. This allowed for good pre-purge turbulence within the dead head configurations.

Our thickest walled tubing was the 0.083 inch “gun barrel” mentioned earlier. The weld head qualified for this weld exhibited an idiosyncrasy, in which the weld bead meandered along the weld joint and favored one side of the tube joint. It was found that this meandering was the result of arc flow. Arc flow is related to grounding and will cause the arc to favor the grounded position(s) within the weld head. To overcome this we disconnected the ground within the weld head and configured it so the clamping block was grounded and equalizing the overall ground.

TESTING

Pre Delivery to SAF/ATLO Testing

Most of the testing of our Propulsion components, such as the RCS thrusters and MLEs is performed at the valve and thruster manufacturers prior to delivery to JPL. JPL engineers are usually in attendance for most of the important component testing. The Propulsion fabrication, assembly, and some of the Propulsion system testing takes place prior to the start of the official spacecraft ATLO, yet is very similar to ATLO. The unique elements of Propulsion ATLO are the welding, and the proof pressure and functional testing of subassemblies, and proof pressure and functional testing of the DSPS as a system. For instance, the PCA underwent functional testing of the pressure regulator, and pressure transducers, as well as subassembly proof pressure and leak testing.

ATLO Testing

During the spacecraft level of integration assembly and test in SAF, the Propulsion team mainly supported other system-level tests such as RCS thruster phasing tests supporting the Guidance, Navigation and Control (GN&C) team, MLE Throttle Valve tests supporting the EDL team, and various other system tests that sometimes required pressurization and functional checks of parts of the DSPS.

KSC Launch Operations and Propellant Loading

At KSC, the Propulsion team supported all the same types of system-level tests that were performed at JPL in SAF. The most important activities for the Propulsion team at KSC were loading propellant into the Cruise Stage and the Descent Stage propulsion systems. Due to the critical and hazardous nature of this work, propellant loading plans and procedures were developed and practiced over and over in dry runs long before the team arrived at KSC. The skills, dedication, and professionalism of the engineers and technicians involved in the propellant loading operations was evident when the loading operations were completed without incident, and quicker than expected, allowing precious schedule time to be used for other spacecraft activities. One of the senior KSC Safety personnel remarked that this was the smoothest propellant loading operation he had ever seen.

THE REWORK

PCA Rework:

Several months after the delivery of the DS to ATLO, problems were revealed in relation to the titanium-to-stainless steel transition joints that were supplied as inlet and outlet tubes on several components, including the MLE filters, the propellant tanks, and the FCA and PCA filters. Reference 3 describes in more detail why it was decided that these transition tubes needed to be replaced. In summary, failures had occurred on fatigue life samples after a very small number of cycles and after only one cycle in at least one case. An investigation concluded that there had been a process control failure in the formation of the joints and that there was no non-destructive evaluation that could exonerate them. The team proposed and project agreed to replace all of the transition joints in the system.

Several options were considered and tested for implementing a fix, including new transition joints, cryofits, mechanical fittings, brazed joints, and, for the filters, new filters with CRES housings. Early work focused on cryofits and mechanical joints in order to minimize or eliminate orbital weld operations on the DS with flight avionics installed and to minimize the schedule impact of the rework. In December of 2008, the project announced a slip in the launch date from 2009 to November 2011 due to a number of technical challenges in other subsystems. Consequently, a new plan was developed to remove all avionics from the DS prior to the rework to allow more conventional welded solutions, and the DS was moved back to JPL Bldg 233. The design settled on a new CRES body filter to replace the MLE filters and a new braze joint to replace the transition joints everywhere else. The new joints were a socket design using a silver-palladium braze alloy and successfully completed a full qualification program including tensile, fatigue, burst, and propellant compatibility testing. A total of 26 transition joints were replaced, which required cutting out and replacing several components, including a filter on both the PCA and FCA.

What would sound like an easy swap-out of components, was in reality a significant endeavor that required some creative solutions. The task was particularly challenging on the Pressure Control Assembly (PCA) which required replacement of the high pressure filter at the inlet of the contamination sensitive pressure regulator. This required cutting and re-welding of the same 0.500 inch O.D. × 0.083 inch wall thickness “gun barrel” tubing that had caused so much grief on “el Plato del Diablo” the first time. This time however, the team was ready.

First of all, precise planning was required to ensure that both the cuts and welds required for the removal and replacement of the filters could be done with the allotted length of pipe available. Appropriate clearance had to be given for both the cutting tools and weld heads required and re-welds had to be accounted for in case of a weld failure. These complications were also relevant in the initial build of the DSPS, however, weren’t as problematic when a long piece of pipe could be slowly cut down to fit in place and welds could be done on a work bench. In this case, everything was already in place and there was very little, if any, margin for error, requiring every cut and weld to be performed with precision down to the thousandth of an inch.

Second, the process of cutting one component out of the system posed the problem of creating particles that could potentially contaminate other sensitive components nearby. This was the case with the removal of the PCA filter, which, in its installed configuration, was positioned directly upstream of the ultrasensitive pressure regulator, such that any particles created by cutting the filter downstream of its outlet could easily fall into the tubing leading up to the regulator inlet, and could not be easily recovered. Also, the plate itself could not be easily uninstalled and repositioned more favorably at this point. The solution to this problem was bold, yet simple—turn the Descent Stage upside-down. Fortunately, the SAF was able grant our request for this maneuver, and a careful vacuum-aided cut could ensue.

Lastly, a challenge arose involving the potential preloading of the reinstalled filter on the PCA. In the initial build, components could be welded together before being secured to the plate so that the assembly would not be loaded following weld shrinkage, as the components were pulled together. However, when cutting out a component after the final assembly, the tubing adjacent to it, which was bolted to the plate, had to be pulled apart before the replacement filter was welded in, so that after the weld shrinkage, the tubing would then be in an unloaded position. This scenario introduced several questions as to how far the adjacent components could be pulled back and what the implications of welding in compression and tension would be on the size and integrity of the weld. Therefore, a mock-up plate using spare components was used to test procedures and make precise weld shrinkage measurements, and a special tool was designed to simultaneously spread the adjacent components and measure the force being applied, while also providing clearance for the weld head (see Figure 13). Several trial experiments later, an optimal procedure was devised, which allowed for the adjacent components to be stretched and released slightly with each weld such that in the end, there were minimal loads in the line and the filter was replaced cleanly and successfully.

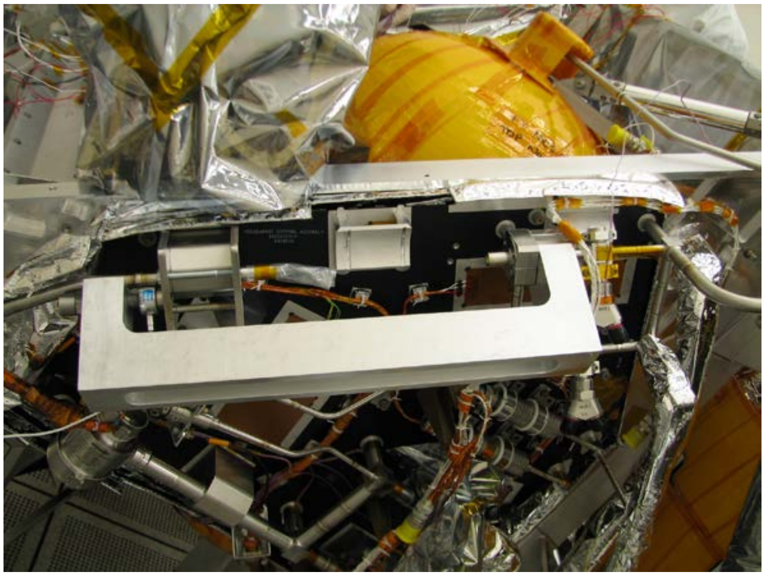

Figure 13. This special tool (large aluminum piece) simultaneously spread the adjacent components and measured the force being applied.

CONCLUSION

The numerous challenges associated with the fabrication of the MSL DSPS, (e.g., late delivery of the primary DS structure, dealing with much larger and more varied tubing sizes than any personnel at JPL had previously experienced, structural shorting of loads through propellant and pressurant lines, tube cleaning issues, second and third shift operations, personnel shortages in propulsion, structural engineering and stress analysis, and of course the obligatory “impossibly tight schedule”) rounded out a fabrication, assembly, and test experience that will always be remembered fondly by those who participated.

As this paper is being finalized, the NFL season is over. The playoff games and the Super Bowl have been played. Fans 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, focused on solutions, 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.

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