Adaptability of the SSL Electric Propulsion-140 Subsystem for use on a NASA Discovery Class Missions: Psyche

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Discovery program missions are cost-capped NASA science missions. As such, there has been an effort in recent years to identify cost savings solutions available in the commercial aerospace market. In previous studies conducted by Jet Propulsion Laboratory the benefits of advanced electric propulsion systems were investigated and their benefits assessed for use in Discovery Programs. Space Systems/Loral identified these studies and began to market its heritage Hall thruster subsystem resulting in the partnership of SSL and JPL on a NASA Discovery mission to the Asteroid Psyche led by the chief scientist at Arizona State University. January 4th 2017 NASA selected the Psyche and Lucy Missions for flight with an anticipated Psyche launch in 2022. The following paper provides a summary of the design and qualification of the Space Systems/Loral solar electric propulsion subsystem and compares the standard geostationary requirements to the requirements imposed on such a system for use on a deep space mission. Additionally, this paper provides a brief summary of modifications made to the Space Systems/Loral system for use on a Discovery Class mission.

I.Introduction

SSL has integrated and operated the EP-100 subsystem (formerly referred to as the SPT-100 subsystem) on geostationary commercial spacecraft for over 13 years, allowing substantial reductions in on-board propellant mass and commensurate increased life compared with an equivalent chemical propulsion system[1,2]. Building on this flight heritage SSL has worked to develop and qualify the EP-140 (utilizing SPT-140 Hall thrusters) subsystem for flight. The EP-140 subsystem is designed to meet a more rigorous set of requirements than the EP-100 subsystem, chiefly more total impulse or throughput to enable more extensive electric orbit raising (EOR) or dry mass capability. The rigorous requirements of the EP-140 subsystem drove a robust design and validation process, such that the majority of all deep space flight requirements were met as part of the qualification for use on commercial geostationary

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communication satellites. With qualification complete SSL saw an opportunity to market a full space exploration Solar Electric Propulsion (SEP) system. This system consists of heritage 100V spacecraft power bus, ancillary low voltage converters and power electronics; 4.5 kilowatt power processing units; propellant feed system; and two deployable SPT-140 modules. Each SPT module includes SPT-140 thrusters, thermal control, holddowns, mechanisms and xenon flow controllers (XFCs). This commercial subsystem is now a key element in the joint ASU/JPL/SSL discovery class mission to the asteroid Psyche. The following paper provides a summary of the qualification of the SEP subsystem and compares it to the requirements imposed on such a system for use on a deep space mission. Section II reviews the top-level requirements imposed by SSL for its internal products and compares them to those of a deep space mission. Section III reviews the system architecture and Section IV provides a brief summary of modifications made to the system for use on a Discovery Class mission.

II. EP-140 System Architecture

The EP-140 subsystem, shown in Figure 1 is the standard commercial architecture which will fly on the SSL 1300[4,5] series bus will be used for the Psyche mission with a few modifications (see Section IV). The EP-140 subsystem architecture has some changes from the EP-100 subsystem currently flying on 29 SSL manufactured spacecraft. Specifically, unlike the SPT-100 thruster, each SPT-140 thruster has a single cathode and XFC. In addition, rather than have a single PPU operate either a North or a South thruster, in the EP-140 subsystem a single PPU can operate any one of the four thrusters at a given time. The EP-140 subsystem contains four SPT-140s, four xenon flow controllers (XFC-140s), two PPUs (PPU-140), four thruster auxiliary support units (TASU-140) two xenon storage tanks (additional tanks for longer EOR missions are shown in Figure 1 as dashed lines), and a propellant management assembly (PMA).

The SPT-140 manufactured by the Engineering Design Bureau Fakel (EDB Fakel) of Kaliningrad, Russia, as implemented on SSL spacecraft, has a discharge power of 4.5 kW and a discharge voltage of 300 V. The XFCs manufactured by Fakel as well, consists of three solenoid valves for propellant isolation when not firing, a thermothrottle for fine regulation of the propellant flow and orifices to split the flow between the anode and cathode at the ratio 20:1. A closed-loop controller in the SSL-manufactured PPU adjusts current to the selected XFC thermothrottle to provide control of the discharge current by regulating xenon flow. The thermothrottle is a capillary tube flow control device which varies the xenon flow rate by changing viscosity with temperature. An increase in heating reduces the flow rate while a reduction in heating increases flow rate.

The PPU provides power to energize, monitor, and control the SPT and its associated XFC. Power input is from the spacecraft 100 V regulated bus. Solar array power is regulated to 100V by the SSL designed and manufactured power control unit (PCU) which also charges and discharges the battery assemblies as required. The PPU can operate any one of four SPTs, one SPT at a time, by configuring high-voltage relays in both the PPU and the TASUs. The PPU is commanded by the spacecraft computer, which also processes all PPU telemetry.

The PPU connection to the thruster and XFC is through the TASU. Included in the TASU are the thruster discharge filter, PPU selection relay which determines which PPU the thruster will receive power from, and a float relay which clamps the thruster discharge circuit to ground when not in use. The TASU also provides ESD protection for all the subsystem external power lines entering the spacecraft. Spacecraft-level commanding is simplified by having all TASU commands provided by the PPU once a PPU/TASU/Thruster set is chosen for a maneuver. Eight ESD boxes used in addition to the TASUs provide ESD protection for all the power and telemetry lines not directly associated with the thruster such as the thermistors and heaters used to monitor and protect the thruster, valves and actuators as well as the actuator potentiometer output.

The DSM actuators are rotary actuators used to position both axes of the DSM and are procured from MOOG Chatsworth, CA. The holddown feature redundant release devices (RRDs) which are a split-spool type devices. The holddowns are mechanically and electrically redundant.

The xenon storage tanks shown in Figure 1 manufactured by General Dynamics Lincoln, NE are carbon over wrapped pressure vessels (COPV) with a maximum expected operating pressure (MEOP) of 2700 psia. The total propellant storage is extensible in that more tanks are manifold into the subsystem as required by the mission. The PMA manufactured by Moog East Aurora, NY contains parallel redundant normally closed (NC) pyrotechnic valves to isolate the xenon tanks during ground operations and launch. Downstream of the pyrotechnic valves are parallel redundant strings of solenoid-type latch valves and single-stage bellows-type regulators. The regulators operate at 37 ± 1.45 psia over a xenon flow rate range which supports as few as one SPT-100 thruster operating to up to four SPT-140 thrusters operating simultaneously at full power. The PMA also includes three pressure transducers to allow for system health monitoring and propellant gauging. Both the xenon propellant tanks and the PMA are identical to those used in the EP-100 subsystem.

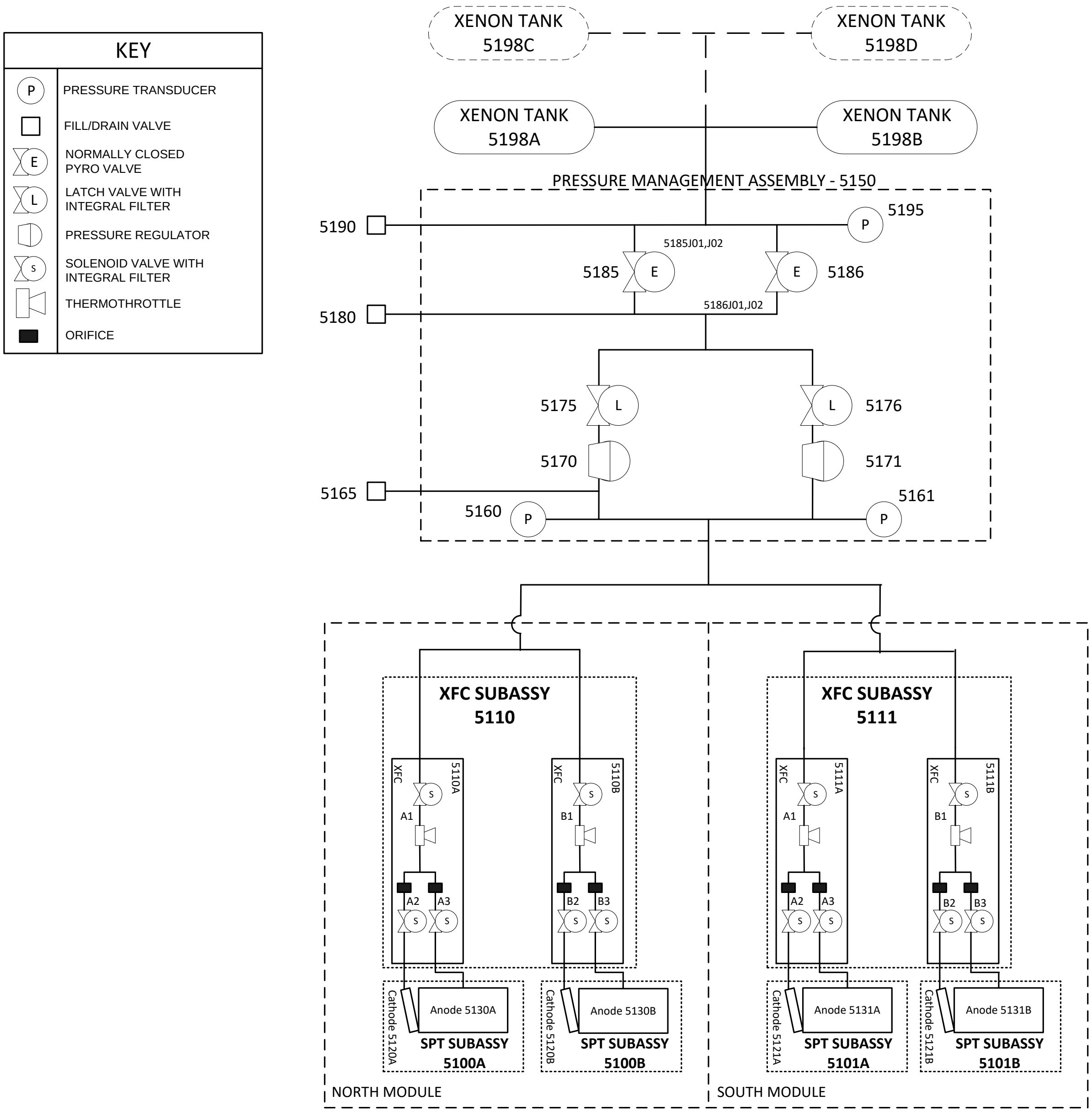

Figure 1. EP-140 subsystem pneumatic block diagram.

III. Commercial and NASA Requirements Comparison

The EP-140 subsystem must comply with hundreds of requirements. These are derived from the expected launch vehicle capability; reliability; customer-specific requirements; spacecraft geometry and mass; manufacturing; and planned operations. For the sake of brevity only the major commercial requirements, those affecting the design of the subsystem to the greatest extent will be reviewed in this paper. Arguably the key technical requirement and also key to determining the qualification plan is the thruster lifetime or total impulse. To generate this requirement a worst-case reference mission was created. This mission was based on a dedicated Ariane 5 launch. The resulting reference spacecraft has a 5769 kg dry mass, with 615 kg of xenon and 90 days of EOR. Note that this does not represent an actual mission but is meant to bound the worst case to be confident that no future delta qualification of lifetime would be required. The total impulse derived from this target mission, including a 1.5 lifetime margin, is 8.2 MN-s. For comparison the SPT-100 was qualified to 2.5 MN-s. A summary of the SPT-140 life test plan is given in Table 1. As shown in Table 1 there are three main phases of the life test; an EOR phase, a north-south station keeping (NSSK) phase and an EOR margin phase. The majority of testing is performed at the 4.5 kW operating point, though some testing is done at the 3.0 kW operating point which may be used for NSSK on some spacecraft. Also note that during the EOR phase the majority of cycles are 4 hours long, though EOR operations will likely consist of much longer firing times, up to 24 hours. To build up cycle life early in the test program the EOR cycles were broken into 4 hour firings because that is the time for the thruster to reach thermal equilibrium. Table 2 shows the minimum thrust levels that must be met over the course of the life test. Additional requirements during the life test are that there shall be no degradation greater than 6% in thrust, 4% in specific impulse and 3% in specific power over a nominal mission and the direction of the thrust vector relative to a thrusters geometric thrust axis shall be less than 0.75° half-cone angle, measured with an uncertainty no greater than 0.25°.

Performance Requirements

Table 1. SPT-140 life test matrix.

Test	Phase	Power, kW	On time, min	Off time, min	No. cycles	Acc. cycles	Acc. on time, hours	Acc. I_{total}, MNs
1a	EOR	4.5	240	60	234	234	936	0.85
1b		3.0	240	30	27	261	1044	0.92
2		4.5	1440	60	8	269	1236	1.09
3a		4.5	240	60	234	503	2172	1.94
3b		3.0	240	30	27	530	2280	2.01
4		4.5	5760	60	1	531	2376	2.09
5a	NSSK	4.5	120	--	77	608	2530	2.23
5b		4.5	90	20	2900	3508	6880	6.20
5c		4.5	120	60	250	3758	7380	6.65
5d		3.0	30	20	1125	4883	7943	6.98
5e		4.5	120	--	77	4960	8097	7.12
6a	EOR	4.5	240	60	270	5230	9177	8.11
6b	Margin	3.0	240	30	27	5257	9285	8.17

Table 2. Minimum thrust requirements for the SPT-140.

Discharge power, kW	Discharge current, A	Thrust, mN
2875	9.5	153
3000	10	160
4500	15	250

Life testing of the SPT-140 concluded in the spring of 2015, and all the requirements stated in Table 2 were met. The total impulse achieved by the thruster amounted to a throughput of ~470 kg. The endurance and performance demonstrated by the qualification unit met most the requirements of the Psyche mission. Due to available power at distances greater than 3.0 astronomical units (AU) the operational requirements of the SPT-140 differ for the Psyche mission. The thruster is required to operate at lower power levels and higher throughput. The Psyche mission will require the thruster to operate a 1.0 kW and increase the overall throughput by 30 kg. SPT-140 operation at lower power levels is not considered a risk and has been demonstrated[3] and the overall life prediction of the unit far exceeds the additional throughput requirement. Section IV provides details of the life test extension of the SPT-140 thruster at Fakel in 2016.

Dynamic Requirements

In addition to the thruster lifetime requirements a key requirement for all components are dynamic loads. The levels are determined by a combination of launch vehicle types used and also location on the spacecraft as the dynamic loads are a function of distance from the component to the launch vehicle separation ring. As a design requirement SSL hardware must meet flight allowable (FA) and maximum expected flight loads (MEFL) for all viable commercial launch vehicles (Atlas V, Ariane 5, Falcon 9, Proton).

These dynamic loads requirements envelope most commercial launch vehicles and are therefore generally conservative compared to requirements imposed by JPL. Environmental test requirements for the Psyche mission come from the JPL Assembly and Subsystem Level Environmental Verification document (JPL DocID 60133)[6]. These requirements were compared to SSL environmental test requirements. The Pysche mission is currently carrying both the Falcon 9 and Atlas V as launch vehicle options. The loads imposed by these launch vehicles are part of the greater envelope of dynamic loads SSL uses to define its generic launch environment. The mechanical shock and static/quasi-static requirements are an example where the SSL qualification loads do not precisely meet the Psyche mission requirements. For shock, the margin difference is considered very small and benign, SSL also conducts three events per axis as opposed to the JPL requirements of 2 events. SSL and JPL have reviewed the shock margins and agreed that the SSL requirements are acceptable for Psyche. For the static/quasi-static loads, SSL structures are much heavier than those typically used by JPL. Due to this difference in structure mass the requirement is met by design and analysis. Therefore, All SSL dynamic load requirements, including the conservative sinusoidal vibration test requirements, used by SSL meet the JPL standards.

Thermal Requirements

Component thermal requirements determine the thermal management strategy for the subsystem. For units located inside the spacecraft bus these requirements are more easily met than for components outside the spacecraft bus such as the thruster and the XFC. The SPT-140 module survival heaters are sized to keep the units within their respective thermal maxima and minima.

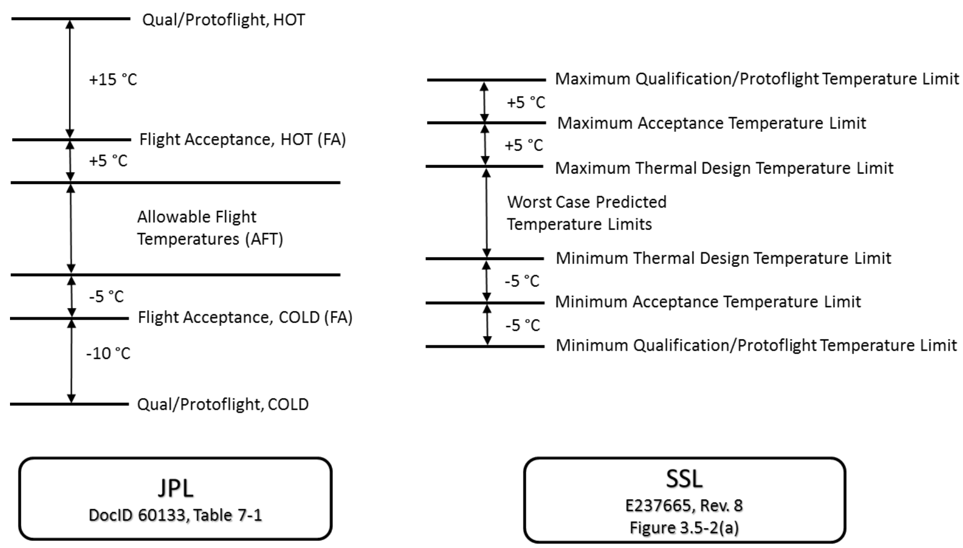

Figure 2. JPL and SSL temperature margin comparisons for internally mounted and external thermally coupled equipment.[6,7]

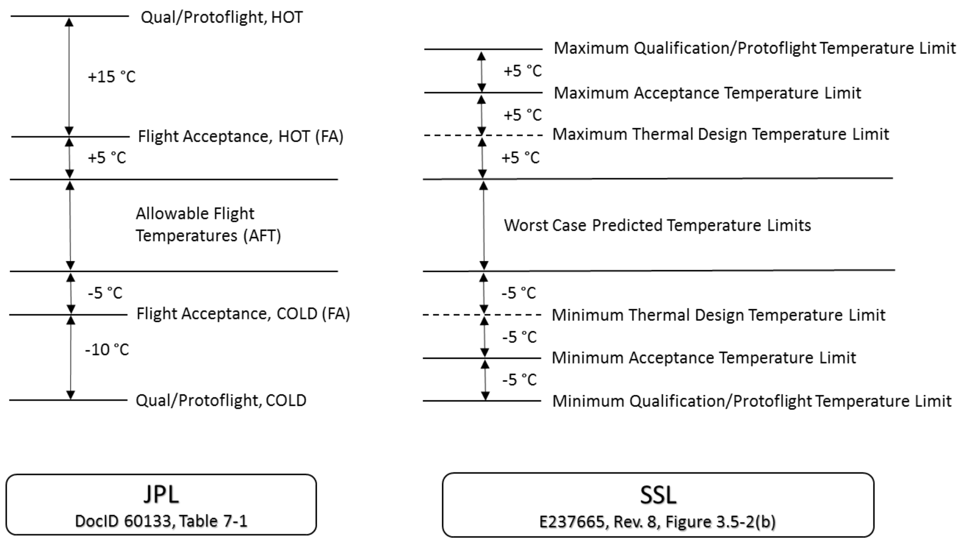

Figure 3. JPL vs SSL temperature margins for externally mounted and thermally isolated equipment.[6,7]

As seen in Figures 2 and 3, the JPL thermal margins are greater than the SSL thermal margins, reflecting the higher uncertainties of deep space missions relative to the well understood geosynchronous environment. To account for the larger uncertainties of deep space the Psyche thermal design applies the larger JPL uncertainties to SSL's heritage qualification limits. This ensures that the SSL hardware will meet the thermal requirements of the deep space mission with the appropriate margins.

Thruster Deployment and Actuator Requirements

The design of the DAPM-actuated SPT Module (DSM) is driven by the projected range of spacecraft center of mass movement and EOR requirements. The SSL 1300 spacecraft has several bus sizes for which the SPT-140 will be utilized. General requirements were defined for the DSM to include the requirement that the DSM (when integrated onto the SSL 1300 bus) fit within the launch vehicles fairings of Proton, Falcon 9, Ariane 5, and Altas V (400/500 series). The DSM was required to be able to direct the SPT aft for EOR, then direct the SPT to fire through the center of mass (CM) for on-orbit NSSK, and then back to the EOR position to allow for de-orbiting. The maximum firing time during NSSK maneuvers was set at 2 hours of continuous firing at any time of day and any season. Similarly, the thermal subsystem design needed to allow for a north and south SPT to be fired continuously 24 hours a day for any season during the EOR phase of the mission. In case of failure (power processing unit, hold down, etc.) the module needed to be capable of performing EOR with a single SPT directed through the center of mass. The module was required to accommodate a spacecraft mechanical pitch bias of ±4° over the spacecraft CM range. The resulting DSM overall range of motion far exceeds the requirements of the Psyche mission which require that only one SPT-140 be fired at a time nominally directed through the spacecraft's center of mass.

Power Processing Requirements

The PPU is required to provide 300 +5/-3 V and a discharge current of 9.5 to 15 A to the SPT anode, for the duration of a mission. The PPU is required to provide 28 V opening voltage for 100 ms and 10 ± 2 V holding voltage indefinitely to the XFC valves during thruster operation and is designed to be immune to degradation with respect to specified performance or temporary malfunction caused by the space environment. The electrical output parameters of the PPU as well as the shut-off parameters are commanded from the ground in a range suitably wider than the specified variation of thruster input parameters. To allow for subsystem venting operations, the PPU is able to command three valves in parallel of a single XFC open and close for an indefinite amount of time for whichever XFC the PPU is able to command. Subsystem venting operation can only occur following a PPU OFF command and is prevented from occurring following a PPU ON command. All PPU outputs to the SPT/XFC are protected from externally generated short circuit conditions. No unit in the EP subsystem shall generate a spurious response due to undervoltage or overvoltage that can damage other units or be detrimental to the spacecraft operation during bus voltage variation. The PPU itself shall also be protected from over-current/over-voltage conditions. In-rush current shall be less than 150% of the maximum nominal operating current. Relays used within the PPU and TASU are individually qualified to over 100,000 cycles, and in addition a PPU/TASU pair were subject to 20,000+ cycles as part of their qualification campaign.

The PPU has three 1.5 kW anode discharge converters which are stacked in parallel in order to provide a max 4.5 kW at 300 V to the SPT-140. For use on the SSL 1300 bus a graceful degradation requirement was imposed on the PPU. This allows each anode discharge converter to be isolated from the PPU via ground command. Therefore, the SPT-140 may be operated at 3.0 kW in the event of a converter failure. Isolating discharge converters allows operation at lower power regimes while maintaining efficiencies greater than 92%. In deep space when the SPT-140 is required to operate at incrementally lower and lower discharge powers, anode converters will be sequentially isolated as required. This allows for overall power savings in deep space and translates to mass savings in the form of solar array and thermal hardware design. Figure 4 below provides the overall PPU efficiencies as output power is decreased and discharge converters are shut off.

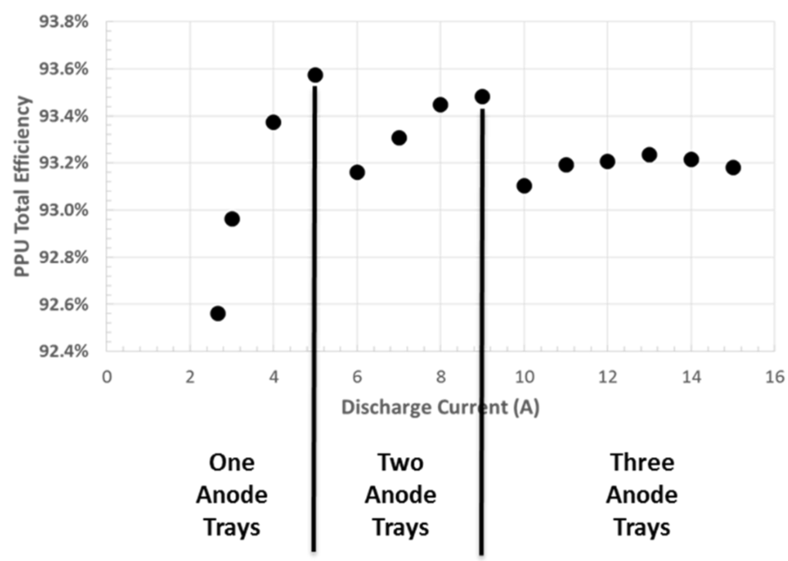

Figure 4. SSL PPU total efficiency as a function of discharge current.

IV. System and Component Adaptations for NASA Mission

Having already met most of the environmental requirements imposed by JPL for deep space exploration missions, very few modifications are required to the robust commercial EP-140 subsystem developed by SSL. Any modifications to the EP-140 subsystem are due to the concept of operations of the Psyche mission. These changes are mainly due to available power at distances from 1.0 AU to greater than 3.0 astronomical units (AU) at the Psyche asteroid. Thus, the operational requirements of the SEP bus differ for the Psyche mission compared to the SSL heritage operational regimes.

SPT-140 Thruster Modifications

The Psyche mission will require thruster operation at lower than qualified power regimes, leading to additional testing performed on the original SPT-140 qualification unit. During this additional testing completed in 2016 at Fakel, the SPT-140 was operated at both at its nominal and low-power regimes as required by the spacecraft when orbiting the Psyche asteroid. Table 3 summarizes the life test extension test matrix. The test was divided in to two additional test phases. Phase 7a and 7b focused on the low power operation with a discharge power of 1.0 and 0.9 kW respectively. The thruster was operated continuously for 250 hours at each operational power point, ensuring the thruster operates nominally at the end of life wear condition. During Phase 8, the thruster was operated at the nominal high power 4.5 kW for approximately 270 hours to efficiently increase the total thruster throughput by 30 kg. The total thruster throughput of 500 kg is essential to lower risk and maintain the required thruster margin for the Psyche mission. At the end of the life test extension, the thruster was operated for 10,371 hours with a total impulse for the thruster was 8.79 MNs.

Reference performance testing of the SPT-140 thruster was performed at the start of life test extension, after Phase 7 and after Phase 8. Figure 5 shows the thruster performance during the life test extension. Specifically, the uncorrected thrust and specific impulse are shown as a function of time during the test for the nominal operating conditions of 3.0 and 4.5 kW. The measured thrust meets the minimum requirement as stated in Table 2. Additionally, the end of life performance meets the Psyche thruster performance requirements at the nominal operating power points.

Table 3. SPT-140 life extension test matrix.

Test	Phase	Power, kW	On time, min	Off time, min	No. cycles	Acc. cycles	Acc. on time, hours	Acc. I_{total}, MNs
7a	Low Power	1.0	15000	--	1	5405	9627	8.33
7b		0.9	15000	--	1	5406	9877	8.36
8	EOR	4.5	420	60	5	5422	10362	8.79

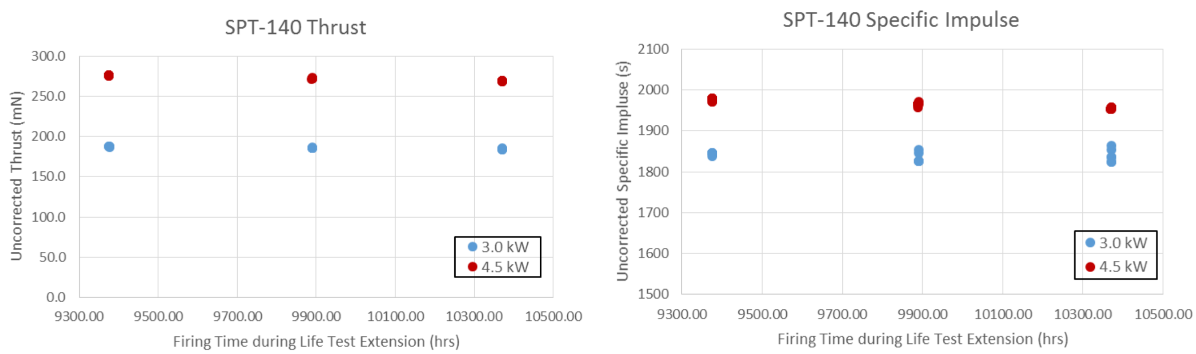

Figure 5. SPT-140 Reference performance data during the life test extension operating at 3.0 kW and 4.5 kW.

Propellant Management Modifications

Extended operation at discharge currents lower than 10 A require the subsystem to alter the XFC used on the commercial bus. Due to thermal limitation, a thermothrottle type XFC cannot be used to throttle the SPT-140 below 2.1 kW. A proportional flow control valve (PFCV) type XFC will likely be used instead, which requires a simple change in the PPU architecture to remove the thermothrottle circuitry and replace it with the control logic for a PFCV. This has already been demonstrated by testing at JPL with an engineering model thruster, PFCV and PPU altered to operate a PFCV[3]. With this simple alteration the SPT-140 was throttled from max power, 4.5 kW to 800W. Figure 6 below shows the flight-like power electronics in test at JPL along with images of the development model PFCV and active thruster at peak and minimum power.

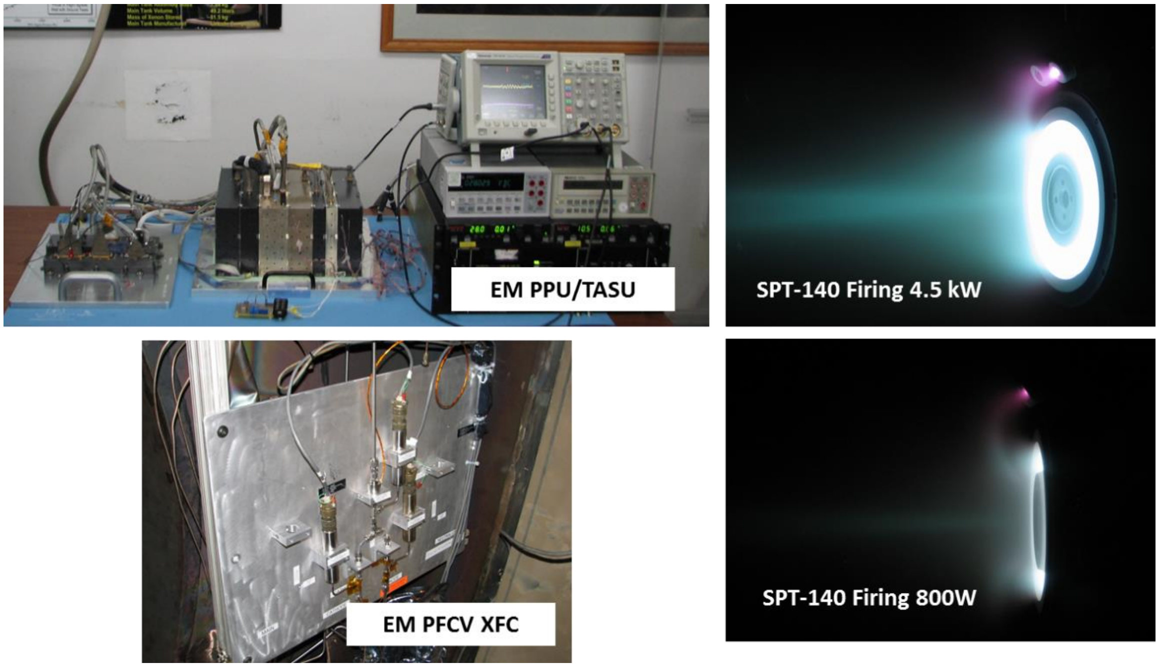

Figure 6. SPT-140 operating at 800 W and 4.5 kW with engineering model (EM) PFCV XFC controlled by engineering model (EM) TASU & PPU.

Power System Modifications

As stated in the previous section the PPU receives a regulated 100V input from the SSL power conditioning unit. The delivery of a regulated power input is complicated by deep space missions due to the ever increasing distance from the Sun. Therefore, essential to the psyche mission is a SEP power train capable of operating a Hall Thruster as the mission flyies beyond 1.0 AU. SSL has arrived at a solution which both utilizes heritage SSL hardware while maintaining high efficiencies within the power subsystem even at the furthest distance from the sun equating to a minimum power level.

A unique solution is being proposed which allows SSL to use heritage hardware to provide a continuous regulated 100V to the electric propulsion subsystem. Because solar array (S/A) voltage increases with increased distance from the sun, SSL has designed the S/A for the Psyche mission to be lower than 100 V at beginning of life (BOL). With a reduced input voltage the SSL PCU will boost array voltage to the desired 100 V for the SEP PPU. The voltage boosting shall be performed by the existing converters within the PCU typically used to boost battery voltage on the SSL 1300 bus. On heritage SSL commercial mission battery voltages range between 48 to 95 V and converted up to 100 V on the bus. These same converters will be used to boost S/A voltage when required in the early phases of the mission. Power conversion losses are easily tolerated during these early mission phases as excess power is available to the spacecraft.

Over the course of the mission's trajectory away from the sun, the optimal solar array voltage for generating the maximum (or peak) power rises as the arrays cool. The initial voltage is selected such that the array's peak power producing voltage reaches the required PPU input voltage of 100V, including solar array degradation and low intensity illumination affects, at the end of the mission. When the S/A power production is at 100V, the power conversion "boost" stage is no longer needed, and is replaced with a diode pass-through circuit from the solar array to the PPU. This eliminates the boost stage conversion losses, thus conserving power when array power is at its minimum and all available power is required for PPU operation.

The novelty in this hybrid solution lies in optimizing the selection of the initial solar array voltage such that existing off the shelf hardware from commercial geosynchronous applications designed to operate on 100V input power can be directly applied to mission trajectories of varying solar intensity resulting in a SEP powertrain tuned to impose the lowest losses at the point at which the power available is at its minimum. For an example, for a mission that starts at

1 AU and reaches 3.3 AU in to the outer solar system the initial voltage selected would be approximately 60 volts. This application trades higher losses when excess power is abundantly available in return for flight proven hardware that is far more economical than sophisticated deep-space-specific peak power tracking approaches that strive to minimize power train losses over the entire mission.

This unique solution uses a different configuration of the PCU converters as compared to typical SSL geosynchronous missions. To retire the risk of unforeseen problems using SSL boost converters in this manner, an engineering qualification model (EQM) PCU was modified into the Psyche configuration, as shown in Figure 7. Extensive tests were performed using the setup show in Figure 8 to evaluate operation of the system in this mode. The tests focused on supplying the boost converters with voltage from solar array simulators and varying the array voltage and load current while monitoring bus voltage and load current to verify stable operation. The test was performed over the full range of operating conditions encountered over the course of the Psyche mission demonstrating the stability of the system under worst case steady state and transients. The authors would like to emphasize that this is only a configuration change to the SSL PCU and does not require changes to the converter designs.

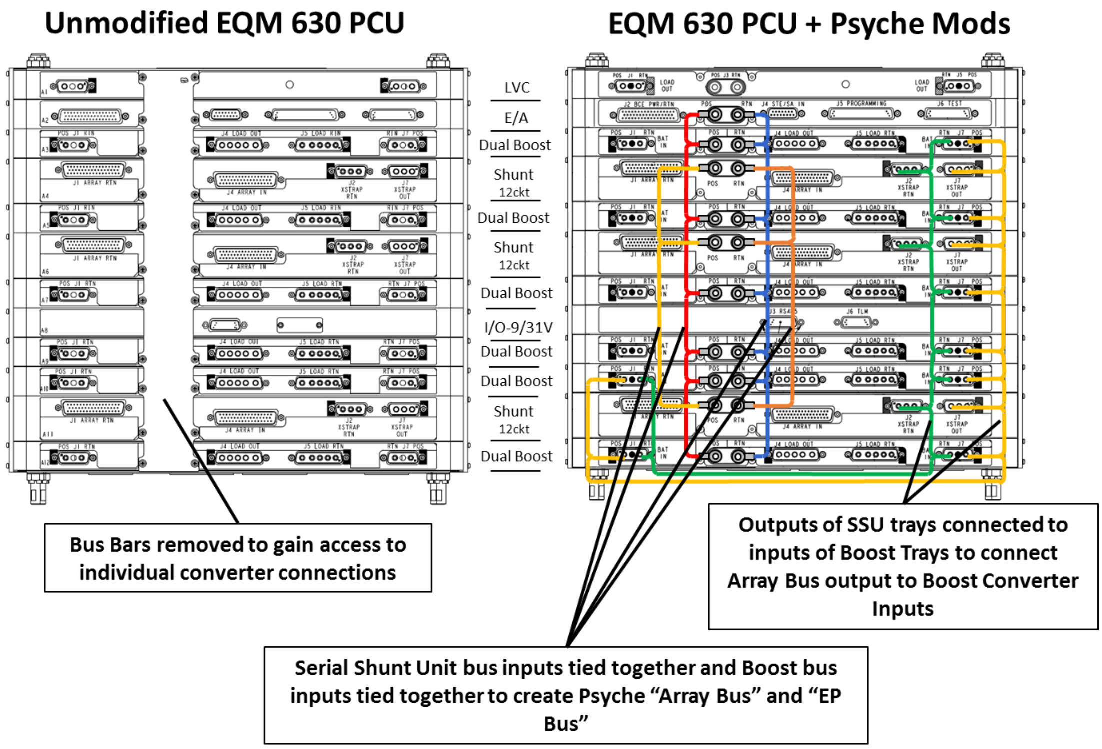

Figure 7. SSL comparison of heritage PCU and modified PCU outlining configuration changes for Psyche.

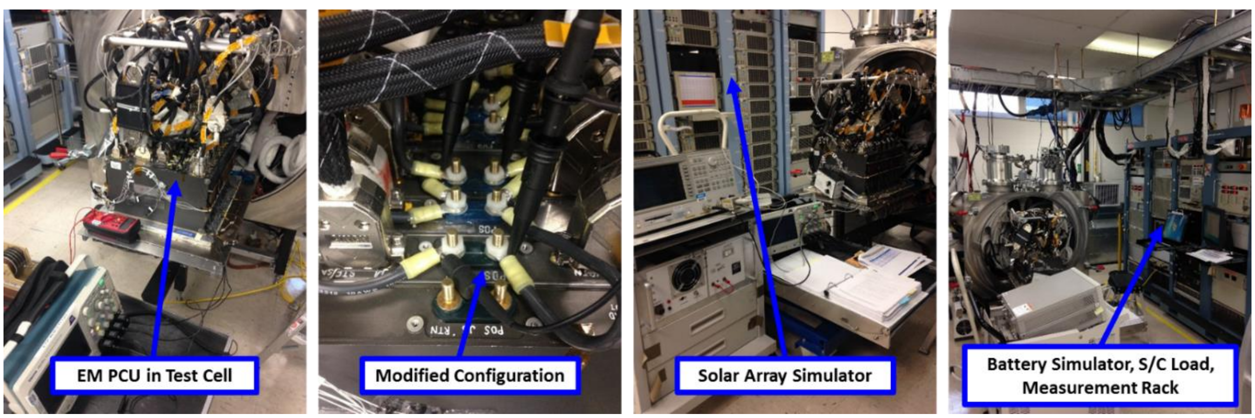

Figure 8. Psyche modified PCU test setup.

V.Conclusion

As part of the Discovery Class Mission, JPL and SSL are working together to demonstrate that commercial hardware meets the stringent requirements of deep space missions. The SSL qualification philosophy provides hardware which survives in the geostationary environment for 15 years. The SSL SEP system will only require slight modifications to the power and EP-140 subsystems to enable operations of the Psyche spacecraft from 1.0 to greater that 3.0 AU around the Psyche asteroid. Thus the products provided by SSL to its commercial customers are robust and reliable and are easily adapted, to meet deep-space mission requirements. The SSL SEP system is purposefully extensible for the commercial market, which translates into an agile subsystem for deep space missions.

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References

1 Corey, R. L., Gascon, N. P., Delgado, J. J., Gaeta, G., Munir M. S., and J. Lin, "Performance and Evolution of Stationary Plasma Thruster Electric Propulsion for Large Communications Satellites," AIAA 2010-8688, 28th AIAA International Communications Satellite Systems Conference, CA, 2010.

2 Delgado, J., J., Baldwin, J., A., and Corey, R. L, "Space Systems Loral Electric Propulsion Subsystem: 10 Years of On-Orbit Operation," IEPC-2015-04/ISTS-2015-b-04, 34th International Electric Propulsion Conference, Kobe-Hyogo, Japan, 2015.

3 Garner, C. E., Jorns, B. A., van Derventer, S., Hofer, R. R., Rickard, R., Liang, R., Jorge Delgado J., "Low-Power Operation and Plasma Characterization of a Qualification Model SPT-140 Hall Thruster for NASA Science Missions," AIAA-2015-3720, 51st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Orlando, FL, 2015.

4 Corey, R. and Pidgeon, D., "Electric Propulsion at Space Systems/Loral," IEPC-2009-270, 31st International Electric Propulsion Conference, Ann Arbor, Michigan, 2009.

5 Delgado, J., Corey, R., Murashko, V., Koryakin, A., and Pridanikov, S., "Qualification of the SPT-140 for use on Western Spacecraft," AIAA-2014-3606, 50th AIAA Joint Propulsion Conference, Cleveland, Ohio, 2014.

6 Jet Propulsion Laboratory, (2013, April 13), Assembly and Subsystem Level Environmental Verification Requirements, unpublished internal document.

7 Space Systems/Loral, (2015, Aug 14), Generic Environmental Requirements Specification, unpublished internal document.