Testing of the PPU Mk3 with the XR-5 Hall Effect Thruster

IEPC-2017-199
Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

Steven Xu[1], Benjamin Welander[2] and Ron Corey[3]
Aerojet Rocketdyne, 11411 139th Pl NE, Redmond, WA 98052, USA
Martin Leslie[4]
European Space Propulsion, Belfast, United Kingdom
and
Eric Bourguignon[5] and Stéphane Fraselle[6]
Thales Alenia Space Belgium, B-6032 Charleroi, Belgium

Abstract: Thales Alenia Space Belgium (TAS-B) and Aerojet Rocketdyne (AR) have demonstrated the successful firing of the AR-manufactured flight qualified 4.5kW XR-5 Hall Effect Thruster paired with the recently flight qualified TAS-B Power Processing Unit Mk3 (PPU). This paper summarizes the implementation, observations and results from the coupling test, which confirmed that the latest version of the TAS-B PPU can safely command the thruster over the full operating range. The test also characterized start-up and ignition transients for further analysis and PPU development. The XR-5 was safely and successfully initialized, operated and shutdown in response to the PPU commands. Thrust measurements made across the operating range compared well with previous qualification test results.

Nomenclature

AC	=	Alternating Current
AR	=	Aerojet Rocketdyne
A_{rms}	=	Current Root Mean Square
ARTES	=	Advanced Research in Telecommunications Systems
CRP	=	Cathode Reference Potential
EM	=	Engineering Model
ESA	=	European Space Agency
ESP	=	European Space Propulsion
GEO	=	Geostationary Orbit
HET	=	Hall Effect Thruster
HV	=	High Voltage
JPL	=	Jet Propulsion Laboratory
LEEP2	=	2nd Large European Electric Propulsion
mg/s	=	milligrams per second
mN	=	millinewton
PPU	=	Power Processing Unit
sccm	=	square cubic centimeters
TAS-B	=	Thales Alenia Space Belgium
QQ	=	QinetiQ
XFC	=	Xenon Flow Controller

[1] Engineer, Chief and Project Engineer, Electric Propulsion, steven.xu@rocket.com
[2] Specialist Engineer, Chief and Project Engineer, Electric Propulsion, benjamin.welander@rocket.com
[3] Specialist, Business Development, ronald.corey@rocket.com
[4] Former Engineering Manager, drmartinleslie@gmail.com
[5] PPU Product Line Manager, eric.bourguignon@thalesaleniaspace.com
[6] Design Authority for PPU Product Line, stephane.fraselle@thalesaleniaspace.com

I. Introduction

Aerojet Rocketdyne (AR) and its former subsidiary, European Space Propulsion (ESP) based in Belfast, Northern Ireland, conducted a PPU coupling test with joint funding from European Space Agency (ESA) under the Advanced Research in Telecommunications Systems (ARTES 3-4) program and AR. The ARTES 3-4 program goals were to transfer documentation and information required to manufacture and test AR's 5kW class HET at ESP.

AR in collaboration with Thales Alenia Space Belgium (TAS-B) aimed to market AR's XR-5 Hall Effect Thruster (HET) with the TAS-B's PPU Mk3. The multi-company collaboration was an international effort under a strict agreement of all relevant parties.

AR HET experts with ESP and Power Processing Unit (PPU) experts from TAS-B successfully planned, implemented and executed the coupling test at the QinetiQ (QQ) LEEP2 vacuum test facility in December 2015. This test successfully demonstrated the operation of an Engineering Model (EM) XR-5 HET with a TAS-B PPU Mk3 Demonstrator Model including correct installation, thruster conditioning, start-up sequencing and operation across the full operating range.

The main objective of the test was to verify the compatibility of the PPU Mk3 with the XR-5 thruster. The test specifically provided a platform to validate the electrical interfaces between the units, characterize the PPU output, confirm correct thruster performance within ±15%, measure the transient currents on cathode ignitor at thruster start and confirm thruster responds correctly to PPU commands. The test was successfully completed without fault or damage to the units under test. There were no plans for plume measurements or in-depth characterization of the PPU Mk3 with the XR-5 thruster.

II. Experimental Apparatus

A. Power Processing Unit Mk3

The TAS-B 100V PPU Mk3 [1] (Fig 1) features all the power supplies required to operate a typical HET where a single cathode and magnet coils independent from the discharge supplies are used. It also features an output select function which enables the user to switch between HET's on the spacecraft. It communicates with the satellite platform through a 1553 bus and receives its power from a 100V bus.

The PPU was installed in an environmentally controlled clean room at the QQ facility and it provided up to 4.5 kW of anode power by parallel connection of two 2.25 kW discharge supplies. The system consists of a primary input bus, separate power supplies for anode, magnet circuit, cathode heater and cathode ignitor, xenon flow control (XFC) supplies, and a sequencer, which ensures automatic control and monitoring of the thruster operation via the satellite communication interface bus.

Figure 1. TAS-B 100V PPU Mk3

The discharge current was measured using current probes on the harnesses and the discharge voltage measurements were performed with differential voltage probes connected on a dedicated breakout box, which enabled measurement of the voltages at the PPU connectors (sense lines connected at harness connector level independent from the power lines).

B. Vacuum Facility

QinetiQ's LEEP2 [2] vacuum chamber located in Farnborough UK (Fig 2) is designed for operation of electric thrusters. The facility was able to operate the XR-5 at xenon flow rates of up to 17 mg/s while maintaining an observed vacuum pressure between 3.0 x 10^{-5} and 8.5 x 10^{-5} Torr. The largest section of the chamber is 3.8 m diameter x 4 m long, the conical section is 0.9 m long and the small section is 2.6 m diameter x 5 m.

The thruster exit plane location was selected to minimize thruster chamber interactions and leave the 2.6 m diameter section free for pump arrays. The thruster as shown in Fig 2 was situated at the chamber mid-point firing downstream at the ion beam target, which consists of graphite tiles fixed to a series of pipes through which cooling water is provided from a closed loop water chiller. The walls of the chamber were protected using a stainless steel sacrificial liner and the internal panel configuration minimizes chamber wall material sputtering and although metallic, the walls were noted to have a significant deposition of graphite from previous thruster firings so the risk of sputter deposition onto the thruster was considered to be minimal. Grafoil liner was not applied to the walls downstream of the thruster due to the short duration test, but they were installed above and around the thruster exit plane to shield the thrust balance from potential plume impingement.

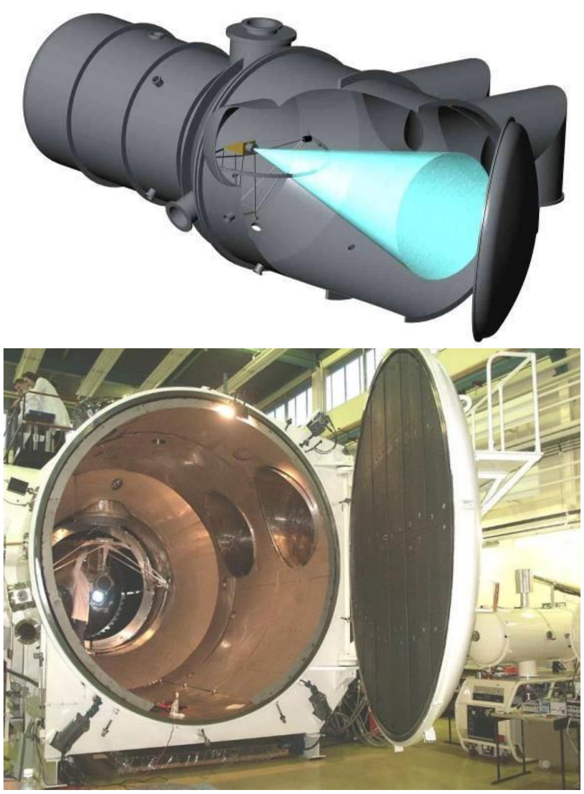

Figure 2 QinetiQ's LEEP2 vacuum chamber

C. XR-5 Hall Effect Thruster

The heritage XR-5 HET [3] shown in Fig 3 was developed by AR during the early 2000s. The XR-5 is fully qualified and has extensive on-orbit heritage for GEO satellite applications at power levels from 3.0 to 4.5 kW and at both 300 V and 400 V. The thruster design underwent an extended test campaign, demonstrating a total of 10,400 hours of firing time, more than 7300 starts and 8.7 x 10^6 N-s of total impulse. It has been extensively tested and characterized over the last decade, along with further extended life tests on its subsequent variant, XR-5A.

For this test, an engineering model of the XR-5 was created using the same manufacturing processes as production level thrusters. The unit under test was uniquely instrumented with four k-type thermocouples (Fig 4) to monitor back plate, outer magnet coil, cathode body back shell and anode housing temperatures.

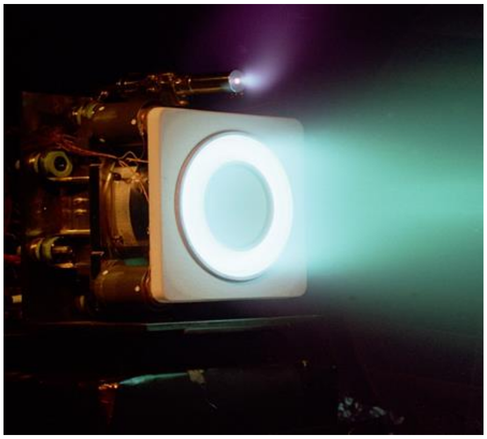

Figure 3. AR's XR-5 Hall Effect Thruster

The thruster was installed onto the facility thrust balance via a mounting adapter plate and torqued to required installation torque, taking care to verify correct alignment with the thrust balance axes. Electrical connections were made between the thruster and the thrust balance terminal block. All electrical connections from the terminal block, together with additional thermocouple wiring from the propellant lines were routed through the chamber passthrough to a clean room located directly adjacent to the vacuum chamber by a two-piece custom, shielded harness. The thruster body was electrically grounded to facility ground and not floated for the duration of the test.

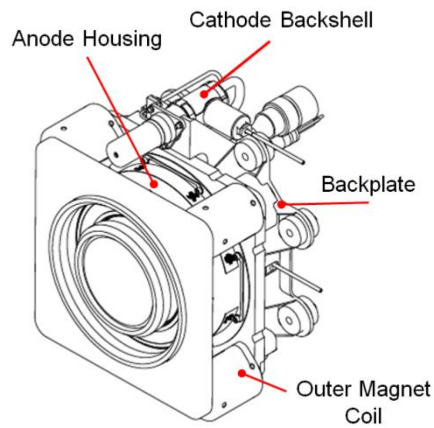

Figure 4. Thermocouple Locations

D. Xenon Flow System and Propellant Lines

The xenon propellant was supplied via the facility flow controller system, controlled by a PC co-located beside the PPU inside QQ's clean room. The flow control unit is a standard QinetiQ support equipment flow unit that delivers xenon within a defined flow range with a nominal flow accuracy of ±1% for both anode (19.5 mg/s) and cathode (3.9 mg/s). The anode flow controller was calibrated for 0-20 mg/s range and the cathode was calibrated for 0-5 mg/s range. The propellant lines were connected to the thrust balance supply lines using VCR fittings and electrical connections were made between the thruster and the balance terminal block. The propellant used was aerospace grade xenon with 99.99995% purity. A particle filter was installed upstream of the flow control unit, with two similar filters installed downstream of the both the cathode and anode components between the pressure transducer and thruster inlets.

An additional line heating system was installed for these tests to allow bake-out of the xenon propellant lines as part of the thruster pre-conditioning before operation. This bakeout consisted of a number of ceramic type line heaters installed on the propellant lines where accessible both inside and outside the chamber. The calibrated flow controllers were installed in a thermally controlled unit so lines heating could not be applied directly in this area. xenon lines mounted near the thrust balance also did not get baked out to avoid adverse effects on the calibration. The heaters on the vacuum and atmosphere sides were controlled by separate variable power supplies to maintain the propellant tube temperatures of 70 to 100^{o}C for at least 12 hours ensuring complete outgassing of any remaining volatiles.

E. Thrust Stand and Oscilloscopes

The performance specification [2] of the QinetiQ inverted pendulum thrust balance is given in Table 1. To verify the thrust accuracy, a thruster is fired until thermal equilibrium and its results are then recorded. Once the thruster is off, three calibration cycles are performed. Each cycle consisting of sequentially applied a series of increasing, then decreasing, known force levels. This calibration data is subsequently processed with the thrust measurement obtained to minimize systematic errors. The thruster was thermally isolated from the balance in order to minimize the potential for thermal drift the entire device.

Parameter	Specification
Operating Mode	Steady State Thrust
Thrust Range	1-500 mN
Thrust Uncertainty	±1mN (2σ)
Bandwidth	0.1-0.0001 Hz
Thruster Mass	<15kg

Table 1. QinetiQ Thrust Balance

Two LeCroy oscilloscopes were used to monitor important thruster parameters throughout the test. The first scope was used to capture short events on anode voltage, ignitor voltage and current. A second scope captured the anode and cathode reference potential (CRP) voltage as well as the discharge current and was eventually used for AC for oscillation measurement. In addition, all the anode, magnet, ignitor current and voltages as well as the CRP voltage and PPU input current consumption were monitored with a Yokogawa scope recorder. The discharge current oscillation was also measured with a spectrum analyzer to assess frequency domain data.

III. Performance Results

A. Performance

The thruster performance was measured between 2.0kW and 4.5kW. The cathode flow rate was approximately 7% of the target anode flow rate throughout the test. The test was performed with thruster starts that ramped up the discharge power gradually.

Table 2. Measured Thruster Performance Of The XR-5 With PPU Mk3 Was As Expected

Set Point	Discharge Voltage (V)	Discharge Power (W)	Cathode Flow Rate (mg/sec)	Anode Flow Rate (mg/sec)	Chamber Pressure (Torr)	Corrected Thrust (mN)	ISP (s)	Efficiency (%)
1*	300	4500	1.5	14.7	8.25×10^{-5}	273	1719	50.4
2*	375	4500	1.2	12.3	6.75×10^{-5}	250	1889	50.7
3*	400	4500	1.2	11.8	6.53×10^{-5}	251	1970	53.0
4*	300	4000	1.3	13.5	7.43×10^{-5}	252	1736	52.8
5*	300	3000	1.1	10.8	6.08×10^{-5}	196	1679	52.9
6*	350	3000	1.0	9.5	5.25×10^{-5}	184	1798	53.3
7	375	3000	0.9	8.9	4.95×10^{-5}	180	1859	53.8
8	300	2000	0.7	7.8	4.35×10^{-5}	137	1639	54.0
9	400	3000	0.8	8.2	4.43×10^{-5}	172	1957	54.0
10	400	2000	0.6	6.0	3.23×10^{-5}	118	1831	52.1
11	300	2250	0.7	8.6	4.58×10^{-5}	147	1618	51.2
12	350	2625	0.7	8.6	4.20×10^{-5}	158	1735	50.5
13	375	2813	0.9	8.5	4.65×10^{-5}	169	1850	53.8
14	400	2668	0.7	7.4	4.20×10^{-5}	152	1907	52.3
15*	350	3500	1.1	10.8	6.08×10^{-5}	203	1742	48.8
16*	400	4100	1.1	10.8	6.08×10^{-5}	229	1966	53.0

*These points were performed at background pressures above 5.0×10^{-5}.

A total of 16 thruster operating conditions were evaluated for this test shown in Table 2. These conditions were selected based on the following criteria:

1. AR heritage reference operating points that can be compared to published thruster performance.
2. ESA proposal requirements in support of ARTES 3-4.
3. Limited facility pumping speed to operate the thruster at higher flow rates, which necessitated the use of lower flow rate operating points.

Due to logistical considerations, a facility was chosen that was at a higher pressure level than what the XR-5 was qualified to test at. This initially constrained the number of original set points that were planned for the test as the pumping speed of the QQ chamber resulted in exceeding the qualified heritage upper pressure limit of 5.0×10^{-5} Torr near the thruster when total flow rate went above 9.76 mg/s. Since the XR-5 has been stably operated at an upper pressure limit of 1.0×10^{-4} Torr during a facility effects measurement [4]; the team agreed that limited time (<20 minutes) at higher pressures would be sufficiently low risk and allow for completion all the necessary test points.

As the intent of the test was to verify system capabilities at full power, it was accepted by the team that at higher background pressures, performance measurements are more subject to errors. The Hall thruster community [5] generally regards any performance measurements collected below a background pressure of 5.0x10^{-5} to be sufficiently reliable.

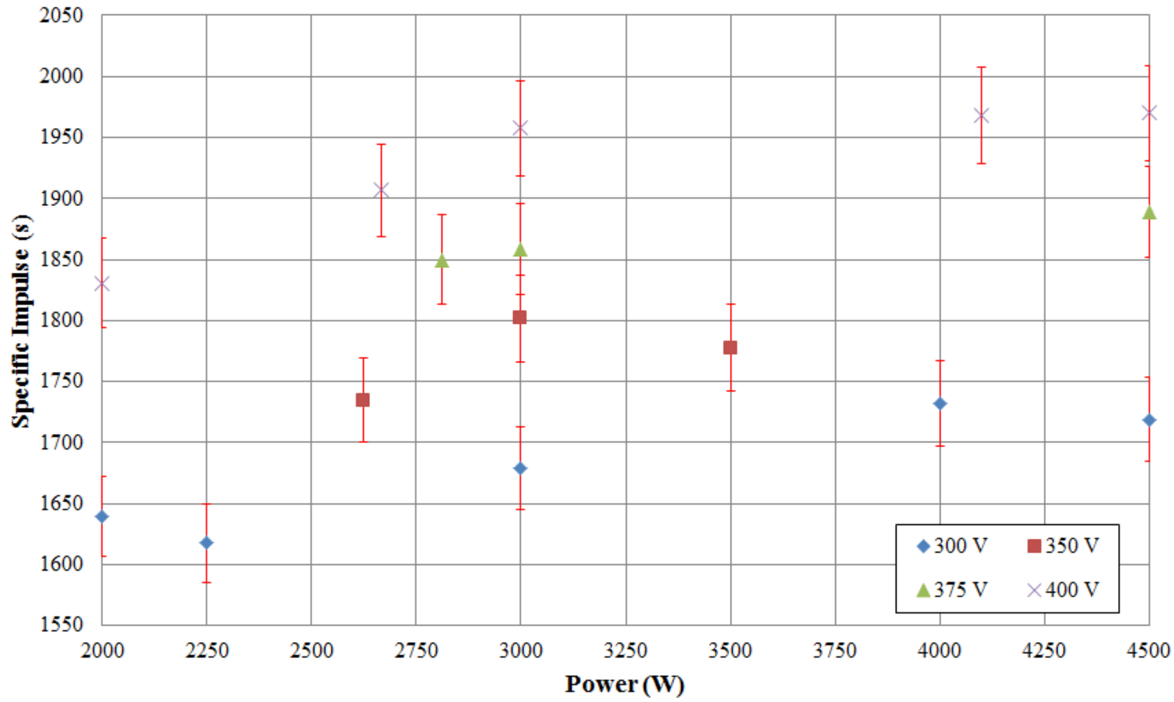

Figure 5. Specific Impulse Performance Results of the XR-5 with PPU Mk3
(*Fairly Stable Isp results for discharge power above 2750W*)

A plot of specific impulse for different power levels are shown in Fig 5 to detail the resulting performance of the XR-5 with the PPU Mk3. The specific impulse was shown to be fairly stable within measurement uncertainty for all discharge voltages above 2750W. The thrust stand and flow controller contributed an estimated uncertainty of ±2% to the specific impulse. Due to the path-finding nature of the test the team did not determine a facility specific pressure correction through pressure mapping at various operating points. The raw thrust values were zero-corrected and power corrected.

A comparison was done between the qualification life test time-averaged thrust of the XR-5 and the results from this test shown in Table 3. It shows that overall the performance tracks well with the nominal operating conditions of the XR-5. At the 4.5kW points, limited time was spent characterizing the thruster with the PPU Mk3 due to the limited pumping capability of the facility.

Table 3. Good Correlation between Qual XR-5 Thrust and Mk3/XR-5

Operating Conditions	Heritage Qual Thrust (mN)	Mk3/XR-5 Thrust (mN)	ΔThrust	Heritage Qual Isp (s)	Mk3/XR-5 Isp (s)	ΔIsp
4.5kW, 300V	289	273	-5.4%	1800	1692	-6.0%
4.5kW, 400V	254	251	-1.3%	2010	1939	-3.5%
3.0kW, 300V	202	196	-3.1%	1730	1652	-4.5%
3.0kW, 400V	173	172	-0.9%	1930	1927	-0.2%

A magnetic field mapping test (Fig 6) was done to characterize the variation in thrust with different magnetic field strengths. This was done at 3.0kW, 400V for a range of magnet currents. As shown there was only a small variation in the thrust over the measured magnet range. The overall result correlates very well to heritage XR-5 magnet performance.

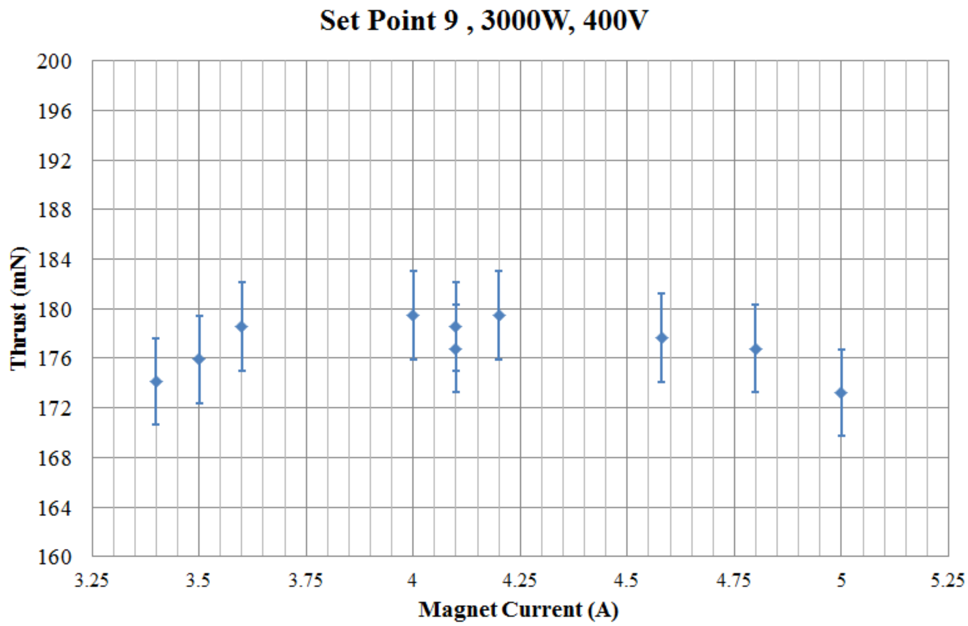

Figure 6. Magnet Map Results Consistent with Heritage Performance

B. XR-5 Thruster Ignition

A number of tests were performed with the aim of optimizing the cathode ignition conditions. These tests showed that all ignitions occurred after a single pulse period and indicated that a higher cathode xenon flow gives a higher cathode ignitor peak current. A flow rate of 1.5 mg/s was sufficient to ignite. Following reliable cathode ignition at low flow rates, ignition was demonstrated at flow rates comparable to a fully open heritage AR XFC (~4 mg/s). An example of a successful cathode ignition is shown as a screenshot from the TAS-B oscilloscope in Fig. 7.

A typical thruster start showed a cathode ignitor pulse peak of typically around 3 A but as high as 14 A with an ignitor current stabilizing after ~250 ms. Thruster start normally occurs at ~100 V but a higher discharge current initially forces the voltage down before reducing to achieve discharge voltage of 100 V or higher.

The PPU Mk3 operated within nominal parameters to drive the thruster without an automated flow controller. The controller PC used prewritten sequence files that were used to command the set points were a hybrid mix of automated scripts with remote commanding from the PPU console to account for the manual operation of mass flow controller. This was necessary as the fully automated scripts required the addition of a close-loop flow controller. The PPU responded as expected to manual changes in flow rate corresponding to an increase in anode discharge current.

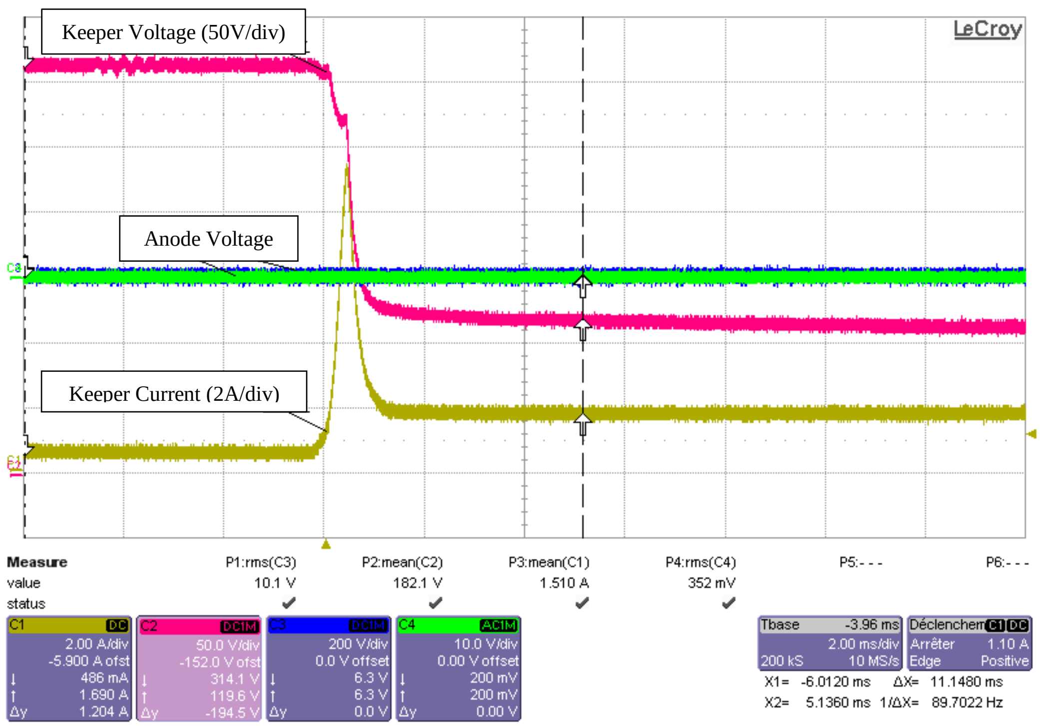

Figure 7. Example of a Successful Cathode Ignition

C. XR-5 Thruster Discharge Oscillations

The main frequency of discharge current oscillation was around 25kHz, except at lower voltages (during thruster start up) where it can be much lower (~7kHz). Amplitude was between 0.14 and 2.0 A_{rms} during set points and up to 2.6 A_{rms} during magnet mapping test. The XR-5 discharge oscillations were considered very smooth with no appreciable perturbations observed. Thruster noise was very low throughout the test. A sample of the discharge current oscillation is shown in Fig 8 for the 4.5 kW at 300 V. A comparison between discharge current oscillations from a test that NASA JPL [6] conducted and this test is shown in Table 3. The comparison shows that there were similar thruster oscillations from two different facilities and test setups.

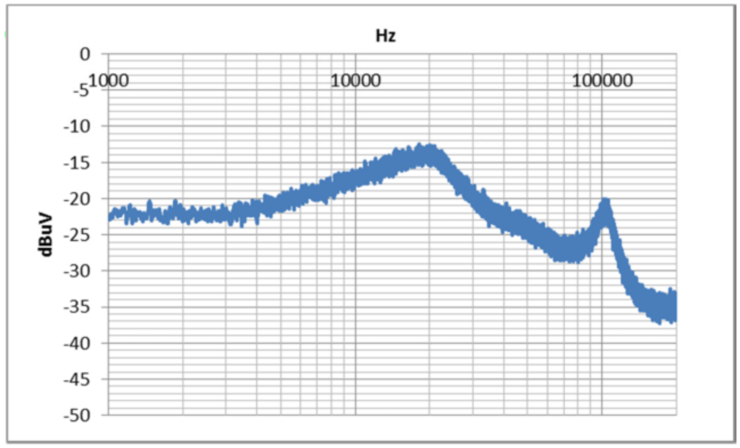

Figure 8. Smooth Discharge Current Oscillation at 4.5kW,

Table 4. Comparison of Discharge Current Oscillations

Anode Current	300V, 15A JPL	300V, 15A QQ
Osc.Amp. (A_{rms})	1.09	0.88
f (kHz)	22	21

D. XR-5 Thruster Thermal Stability

A long duration test run of set point 9 (3kW, 400V) was done to validate that thruster performance remained stable as thermal equilibrium was achieved. The plot of thermocouple data is shown in (Fig 9). Set point 9 was chosen because its low flow rate (<9.76 mg/s) would result in acceptably low chamber pressures (i.e., would not flood the pumps after running for multiple hours). The test was concluded 3.5 hours after the magnet voltage had stabilized. Performance measurements taken at regular intervals showed that performance variation was less than 3% over the 3.5 hour duration. Discharge voltage oscillations decreased after approximately 30 minutes of operation and then remained constant after 2 hours.

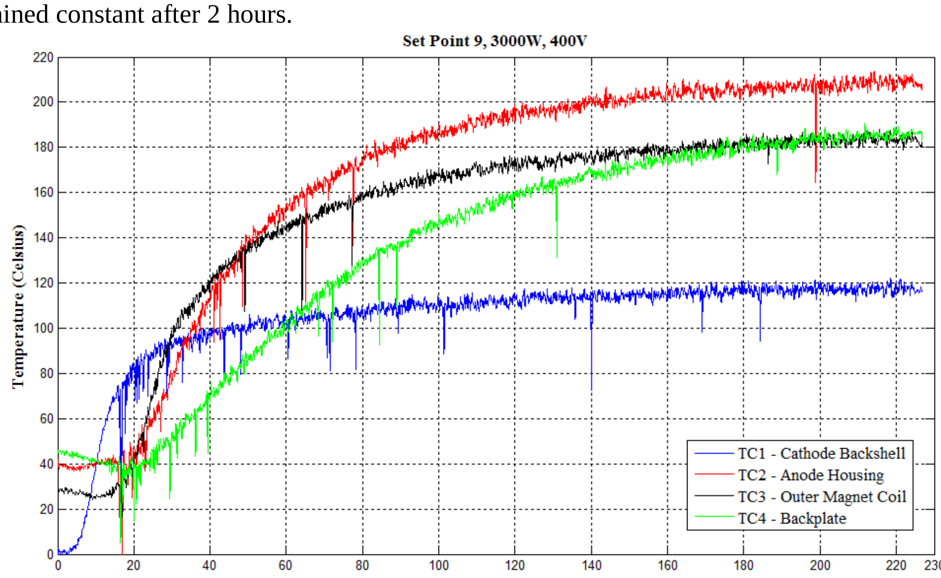

Figure 9. Thermal Steady State reached after 3.5 hours

IV. Conclusion

Aerojet Rocketdyne in collaboration with TAS-B and the greater European space community has successfully completed the first XR-5 HET with a PPU Mk3 firing at the LEEP2 vacuum facility at QinetiQ. This represents a significant and important step in the development of a joint venture between AR and TAS-B in future electric propulsion products.

The primary aim of this test was to demonstrate the operation of the AR XR-5 thruster with the TAS-B PPU across a number of operating conditions, validate electrical interfaces and characterize the PPU output. An EM XR-5 HET, was safely and successfully initialized, operated and shutdown in response to the PPU commands using the TAS-B PPU Mk3 without an automated flow controller. All planned target operating conditions were achieved in this test as expected.

Comparing the thrust measurements to the heritage qualification values, the PPU Mk3 performed very well despite the lack of an automated flow controller. The measurements showed good correlation to the qualification test values with deviations within ±5.4% and the thruster operated with an efficiency of ~50% across those operating conditions.

After successful cathode ignition, a series of tests were done to optimize ignition at various flow rates, comparable to heritage values. The thruster operation was considered to be very smooth with no appreciable perturbations on the primary bus. Noise levels were low and no error events were observed. The cathode was started with heritage ignition sequence with minor deviations from the PPU commands. The discharge current oscillation was observed to be approximately 25kHz and consistent with heritage values. A final long duration test run achieved near thermal steady state after several hours with the thruster.

Future work would focus on further characterization of the performance of the XR-5 with the PPU Mk3 and harness impedance characterization of the ignitor transient peak at the thruster to evaluate any potential optimizations to the PPU Mk3.

This test has provided the basis for further development of the system as a whole for an XR-5 to operate with a 100V bus PPU Mk3. The inclusion of a xenon flow controller and further testing at higher power operating points would improve the applicability of this system.

Acknowledgments

We would also like to thank the PPU team at TAS-B for their input into this study particularly Caroline Dessauvages, Stephane Fraselle and Clement Marlier, Mars Space's Michele Coletti, Simone Ciaralli, facility support at QinetiQ with Andrew Stapleton, Neville Coombs and the operational support from HET experts at Aerojet Rocketdyne, Justin Pucci and Erica Richards. Thanks to ESA for their support in this test campaign. Any opinions, findings, and conclusion or recommendations expressed in this material are those of the authors and do not necessarily reflect the view of ESA. Also a special thanks to the hard work and efforts at European Space Propulsion with Glenn Sheppard and the rest of the team.

References

[1]Eric Bourguignon, Stéphane Fraselle and Thierry Scalais (2013), "Power Processing Unit Activities at Thales Alenia Space Belgium (ETCA)," The 33rd International Electric Propulsion Conference, IEPC-2013-213.

[2]Stephen D. Clark and Andrew W. Stapleton (2015), "Development and Commissioning of an Electric Propulsion Test Facility," The 34th International Electric Propulsion Conference, IEPC-2015-391.

[3]Randolph, T., Kim, V., Kaufman, H., Kozubsky, K., Zhurin, V., and Day, M., (1993) "Facility Effects on Stationary Plasma Thruster Testing," The 23rd International Electric Propulsion Conference, IEPC 1993-093.

[4]D. King, D. Tilley, R. Aadland, K. Nottingham, R. Smith, C. Roberts, V. Hruby, B. Pote, and J. Monheiser. (1998) "Development of the BPT family of U.S.-designed Hall current thrusters for commercial LEO and GEO applications," The 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA-98-3338.

[5]Kristi de Grys, Alex Mathers, Ben Welander (2010), "Demonstration of 10,400 Hours of Operation on a 4.5 kW Qualification Model Hall Thruster," The 46th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. AIAA 2010-6698.

[6]Richard R. Hofer, Dan M. Goebel, John Steven Snyder, and Izabela Sandler (2009), "BPT-4000 Hall Thruster Extended Power Throttling Range Characterization for NASA Science Missions," The 31st International Electric Propulsion Conference, University of Michigan, USA, IEPC-2009-085.