Electric Propulsion Activities at Rafael in 2019

IEPC-2019-600

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

Dan R. Lev[1], Raul Zimmerman[2], Boaz Shoor[3], Leonid Appel[4], Mor Ben-Ephraim[5], Jacob Herscovitz[6] and Oren Epstein[7]
Rafael ADS Ltd., Space Division, Haifa, Israel, 3102102, Israel

For over a decade Rafael has been developing and qualifying Hall thruster based electric propulsion components and full systems, specially designed for the SmallSat category. The focus on the activities conducted at Rafael are the development of low power Hall thruster technologies covering a discharge power range from 100 W up to 900 W. In this paper we overview the electric propulsion technologies developed at Rafael and their current development status. We present a flight operation status of the R-400EPS aboard the VENµS satellite mission in LEO, operating in the 300-600 W power range. Subsequently, we overview the qualification status of the R-200 and R-800EPS, two low power Hall thruster based systems operating in the 150-350 W and 450-900 W power ranges, respectively. We then present the heaterless cathodes developed to couple with these thrusters. We survey the development and qualification status of the PPU developed to serve all Hall thrusters. We review the components of the Propellant Management Assembly (PMA) and present some of the activities conduced to qualify the PMA components. Finally, we briefly overview the infrastructure at Rafael and its capabilities.

I. Introduction

In the past two decades Rafael has been involved in the research and development, manufacturing, qualification and in orbit operation of Rafael's family of Hall thruster based propulsion systems, tailored for a variety of spacecraft and missions. Specifically, in the past five years the Electric Propulsion (EP) related activities intensified, while leveraging the experience and know-how gained including design for manufacturing that enables low cost/high rate of production tailored solutions for the new space era.

Presently, Rafael is working on several Electric propulsion programs, that span over all technology readiness levels (TRL), from basic conceptual designs of low power electric thrusters, through engineering and qualification models, and up to concurrent in-space operational missions.

In this paper we briefly review the EP activities at Rafael, starting with a review of the VENµS EP mission, successfully operating in orbit since 2017. We then present two propulsion systems presently under advanced stages of development – the R-200 EPS and the R-800 EPS. We do so by listing the system characteristics and elaborating upon the system components; specifically the Hall thruster, hollow cathode, PPU and Propellant Management Assembly (PMA). We then overview the infrastructure developed at Rafael, that includes a large capacious state-of-the-art vacuum chamber dedicated for low power Hall thruster operation, and, numerous cathode development and qualification vacuum chambers.

[1] Ph.D., Electric Propulsion R&D Responsible, Manor Division, Space Department
[2] Ph.D.,Senior Engineer, Space Propulsion Department
[3] Senior Engineer, Space Electronics Department
[4] Head of Electric Propulsion group, Space Propulsion Department (leona@rafael.co.il)
[5] Head of Mechanics and Additive Manufacturing Section.
[6] Chief R&D and Venus Project Manager, Space Directorate.
[7] Electric Propulsion Project Manager, Space Directorate. (orenp@rafael.co.il)

II. The R-400 Electric Propulsion System (R-400EPS) - Heritage on-board the VENµS Satellite

The VENµS program (acronyms of Vegetation and Environment monitoring on a New Micro Satellite) is a joint program of the Israeli and French space agencies[1]. The VENµS satellite is designated for super-spectral Earth imaging and Electric Propulsion System (EPS) demonstration.

VENµS includes a full on-board electric propulsion system, denoted R-400EPS (see Figure 1) based on two low power Hall effect thrusters. The Hall thrusters, denoted IHET-300, operate in the 300-600W power range according to mission requirements. Key characteristics of the IHET-300 are listed in Table 1. The electric propulsion system, and components, were designed, manufactured, qualified, integrated, tested and loaded by Rafael. These include the Hall thrusters, PPU, flow controller, propellant tank and other propellant management components.

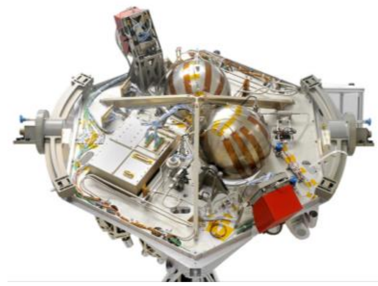

Figure 1. Picture of the electric propulsion system on-board the VENµS satellite.

The role of the electric propulsion system on-board VENµS is (1) to maintain satellite orbit in a 720 km Orbit, (2) to transfer the satellite to a 410 km orbit, and (3) to maintain the satellite's orbit in a precise 410 km earth repeating locked orbit. To perform all of the above the satellite must operate both of its thrusters at different power levels.

The VENµS satellite was launched in August 2017 on-board the Vega launcher. Following the launch the electric propulsion system performed a set of In-Orbit Tests (IOT) in which full system functionality was assessed and its propulsion system was found fully functional. Subsequently the propulsion system started performing a periodical orbit maintenance operations[2]. The second phase, which includes de-orbit transfer to a 410 km orbit, is planned to initiate in 2020.

Table 1. Key characteristics Rafael's IHET-300 @300 W

Property	Value
Thrust @ 300W (EOL)	> 14.3 mN
Specific Impulse @ 300W (EOL)	> 1210 sec
Power Operation Range	250W to 600W
Operating Life	> 1100 hours
Number of Operation Cycles	> 2000
Total Impulse	> 135 kNs

As of June 2019, the electric propulsion system was activated 147 times. Thus far, the propulsion system has been successful and proven to operate properly at a variety of system power levels of 250-600 W.

III. The R-200 Electric Propulsion System (R-200EPS)

Recently, Rafael has been developing the R-200EPS, a full Hall thruster based electric propulsion system in the 150-350 W power range. The R-200EPS is an improved derivative of the R-400EPS (In orbit onboard the VENµS satellite) and consists of a low power Thruster Unit (TU), based on Hall thruster and hollow cathode, Power processing Unit (PPU) and a Propellant Management Assembly (PMA). The propulsion system is designated to operate with either xenon or krypton propellants. The main propulsion system characteristics are presented in Table 2.

Table 2. Key characteristics of R-200 EPS

Property	Value
Power	150-350 Watt
Thrust (Xe)	5-15 mN
Isp (Xe)	800-1200 sec
Propellant	Xe, Kr
Total Impulse (Xe)	> 200 kNs

Numerous activities have been conducted in order to couple the R-200 EPS components and to examine its performance. The various coupling tests included (1) thruster-cathode coupling in a wide range of discharge power levels, (2) PPU-thruster-cathode coupling in steady state operation, (3) PPU-thruster-cathode coupling in for thruster unit ignition, (4) pyro valve-pressure regulator-flow controller-solenoid valve, (5) thruster-cathode-PPU-flow controller coupling, (6) full system coupling test.

RAFAEL's heritage and experience in high volume of production was implemented in the R-200EPS. i.e. Design-For-Manufacturing that enables high quality/low cost production in high volumes as required for large constellations in the new space.

The propulsion system is suitable for a variety of applications aboard a wide range of spacecraft platforms – orbit maintenance/change/deorbit of satellites in LEO, orbit transfer for LEO satellite constellations, attitude control of large LEO and GEO satellite platforms and the main means of propulsion for small deep space spacecraft.

We hereby overview the system components, their specifications and the main development activities.

A. The R-200 Hall Thruster (HT)

The R-200HT is a low power Hall thruster designed to operate in the 100-300 W discharge power range. To overcome the low mass utilization efficiency issues associated with low power Hall thrusters[3,4] the R-200HT includes a non-conventional configuration. The thruster consists of co-axial anodes and an elongated discharge channel. The co-axial anode configuration creates radial electric field in the near anode region. This electric field pattern repels the ions towards the discharge channel center in the ionization region and lowers the ion flux into the walls. The elongated discharge channel assures a relatively high degree of ionization even for relatively low density plasma, as with low power operation of the R-200 thruster.

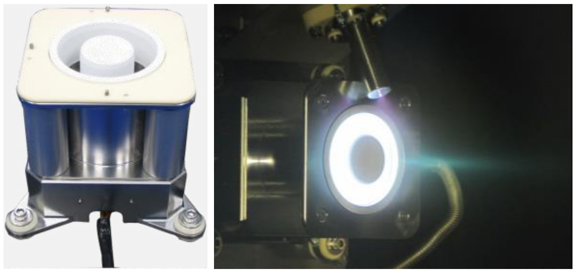

Figure 2. Picture of the R-200 Hall thruster.

Early Development Models (DM) and Engineering Models (EM) of the R-200 underwent a development program that included proof-of-concept tests, experimental and numerical validation of physical mechanisms, wall material selection, performance testing, thruster engineering model structural, thermal and magnetic simulations followed by an engineering model production as well as full performance mapping[5]. Following these development phases a Qualification Model (QM) of the thruster was produced.

The R-200-QM Hall thruster is presently at the end of a meticulous qualification program that included steady state performance characterization, ignition tests, Shock and Vibration (S&V) test and post S&V test operation. To date the thruster successfully passed all qualification tests.

The R-200 thruster, as part of the R-200 EPS, is scheduled for launch in 2021/22.

B. The R-200 ARC-1A Hollow Cathode

During recent years Rafael is engaged in heaterless hollow cathode (HHC) development[6]. Heaterless hollow cathodes are a subclass of hollow cathodes that do not require external heating for cathode ignition[7]. In this type of cathodes the heating process is by plasma discharge generation inside the cathode cavity, in the emitter-keeper gap.

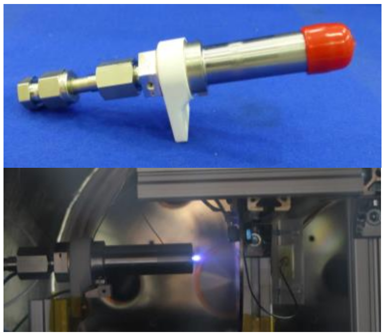

Figure 3. Pictures of R-200 heaterless hollow cathode (ARC-1A) operating in diode mode configuration.

The cathode, denoted R-200 ARC-1A (see Figure 3), is designed to operate at the low current regime (0.5-1.1 A) and couple with low power Hall Thrusters (100-300 W). The cathode was designed following a rigorous mechanical and thermal design process and is made of a combination of refractory metals and other conventional materials with geometry that maintains the required temperatures throughout the cathode parts and components[8]. A barium oxide impregnated tungsten emitter (also referred to as the insert) is utilized to generate electrons during operation. The cathode is structured in such a way that alternative emitters can be integrated in it and still operate at the required cathode discharge current range. The leading characteristics of the R-200 ARC-1A cathode are presented in Table 3.

Table 3. Key features of the Rafael R-200 heaterless Hollow Cathode (ARC-1A).

#	Requirement	Value
1	Discharge Current	0.3-1.2 A
2	Xenon Mass Flow Rate	0.1-0.25 mg/s
3	Lifetime	>4,000 A×hr
4	No. of Startups	3,500
5	Ignition Voltage	< 400 V
6	Mass	170 gr

The various development activities included early technology study, the development of manufacturing processes, study of cathode failure mechanisms, the construction of thermal and power models, the manufacturing of the engineering model of the cathode, performance characterization, cold ignition test, 5,000 hours endurance test, manufacture repeatability, performance at very low discharge current levels (below 0.5A), which allows for sub-100W Hall thruster operation, and the coupling with two Hall thrusters[9]. During the cathode-thruster coupling experiments, cathode ignition and steady state operation were proved successful and compatible with expected low power electric propulsion system requirements.

The ARC-1A will soon start a lifetime experiment with the R-200 Hall thruster. The cathode will undergo steady state operation of over 1,000 hours and perform several hundred ignitions.

IV. The R-800 Electric Propulsion System (R-800EPS)

For over a year Rafael has been developing the R-800EPS, a full Hall thruster based electric propulsion system in the 450-900 W power range. The R-800 EPS is an improved derivative of the R-400EPS (In orbit onboard the VENμS satellite) and consists of a low power Thruster Unit (TU), based on Hall thruster and hollow cathode, Power processing Unit (PPU) and a Propellant Management Assembly (PMA). The R-800EPS is designated to operate with either xenon or krypton propellants. The main propulsion system characteristics are presented in Table 2.

Rafael's heritage and experience in high volume of production was implemented in the R-800EPS. i.e. Design-For-Manufacturing that enables high quality/low cost production in high volumes as required for large constellations in the new space.

Numerous activities have been performed in order to couple the R-800 EPS components and to examine its performance. The various coupling tests included (1) thruster-cathode coupling in a wide range of discharge power levels, (2) PPU-thruster-cathode coupling in steady state operation, (3) PPU-thruster-cathode coupling in for thruster unit ignition, (4) PPU-flow controller- pyro valve-pressure regulator, (5) thruster-cathode-PPU-flow controller coupling, (6) full system coupling test.

We hereby overview the system components, their specifications and the main development activities.

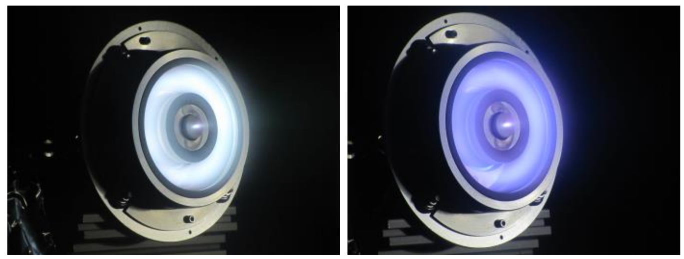

Figure 4. Pictures of Rafael's R-800-DM Hall thruster operating on xenon (left) and Krypton (right).

A. The R-800 Hall Thruster (HT)

The R-800HT is a low power Hall thruster designed to operate in the 450-900 W discharge power range. The thruster has a conventional Hall thruster configuration with the gas distributer serving also as the anode. At the same time, the thruster consists of a unique set of materials and structure that makes it relatively light weight and allows it to operate with both xenon and krypton as propellants. Additionally, the R-800HT consists of permanent magnets and a center cathode, making it energy efficient with low volume signature. Pictures of the R-800 Hall thruster operating on xenon and krypton are presented in Figure 4.

Table 4. Key characteristics of the Rafael's R-800 Hall thruster

Property	Value
Power	450-900
Thrust (Xe)	25-48 mN
Isp (Xe)	1000-1500 sec
Propellant	Xe, Kr
Total Impulse (Xe)	> 560 kNs

Several Development Models (DM) of the R-800 thruster were produced in order to assess thruster performance and test its design features. During this initial development phase an appropriate magnetic field topology and magnitude were selected for performance optimization at different discharge power levels. In addition, new simplified designs of the gas distributer, and thruster body were examined with the purpose of reducing the thruster mass, cost and ease of integration. The design verification activities culminated with a 500 hour thruster operation test, with xenon, after which the thruster lifetime was extrapolated. The estimated thruster lifetime is greater than 560 kNs.

To validate the lifetime estimation, based on the 500 hour experiment, a numerical simulation was conducted that accounts for the thruster's geometry, channel materials, mass flow rate, discharge voltage, and magnetic field topology. To assure simulation validity it was outsourced to an external acclaimed independent electric propulsion laboratory. Simulation results show that the estimated thruster lifetime is approximately 560 kNs. This result is in line with the minimum total impulse calculated by simple extrapolation.

The R-800 main characteristics are presented in Table 4.

An EM of the thruster is currently manufactured and is scheduled to start characterization in the upcoming months.

B. The R-800 ARC-2A Hollow Cathode

In order to meet to actual performance needs of the R-800 Hall Thruster, Rafael has developed and qualified a second class of heaterless hollow cathode (HHC) denoted as the ARC-2A (see Figure 5) beneficing of up-scale characteristics as described in Table 5.

The ARC-2A have been designed to operate at the higher current regime (1.2-3 A) and couple with low-to-medium power Hall thrusters (450-900 W). The cathode was designed using rigorous mechanical, thermal design process

Figure 5. Picture of Rafael's R-800 Heaterless Cathode (ARC-2A)

employing materials with geometry that maintains the required temperatures throughout the cathode parts and components. W-BaO, and/or, Lab6 emitters were alternatively tested for the generation of electrons beam and full cathode operation.

The various early development activities of the ARC-2A cathode included the production of several development models, each differs by geometry, material type, emitter types and sealing techniques. The ultimate goal was to determine the most thermally-effective and cost-effective design that meets all of the cathode's functional requirements. Additionally, the most adequate ignition scheme was sought after, which allows for a short ignition, under one minute.

Table 5. Key features of Rafael's R-800 hollow cathode (ARC-2A).

#	Requirement	Value
1	Discharge Current	1.2-3 A
2	Xenon Mass Flow Rate	0.1-0.2 mg/s
3	Expected Lifetime	>10,000 A×hr
4	Propellant	Xe, Kr
5	Ignition Voltage	< 500 V
6	Mass	150 gr

To validate cathode functionality it was operated at a wide range of mass flow rates (0.1-0.5 mg/s) and discharge current levels (0.8-3.5 A). Additionally, cathode ignition voltage, as a function of cathode mass flow rate was characterized to assure cathode ignition at the nominal mass flow rate below 0.2 mg/s (see Figure 6). Lastly, a dedicated transient operation analysis was performed in order to determine the cathode ignition capabilities and minimize the required power during ignition.

The current development model of the ARC-2A cathode has successfully operated for several hundred hours, of which 250 hours coupled to the R-800 Hall thruster. The cathode has proved to operate steadily at all discharge current range in a self-sustaining mode (without the need for keeper PS to maintain the discharge). The cathode has proved to ignite several hundred times in a dedicated ignition experiment. The cathode was also operated on krypton in order to demonstrate that no particular design, operation or functional restrictions on the cathode exist when operating on such gas.

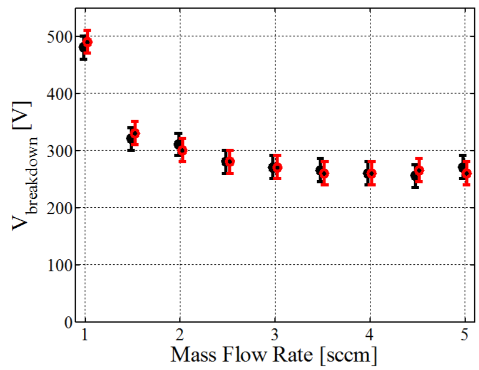

Figure 6. Breakdown voltage vs cathode mass flow rate for the R-800 heaterless cathode (ARC-2A).

Presently, an engineering model of the ARC-2A is under production. The new cathode model will be located at the R-800 thruster center (see Figure 4 above). The new cathode model will undergo a variety of qualification activities including an endurance test.

V. Power Processing Unit

As part of its EPS development, Rafael has developed a power processing units. The first PPU was developed for the Venus mission and is currently operating successfully in space. Presently, two avenues of PPU development are explored – a modular traditional PPU, compatible with all sub-kilowatt Hall thrusters, and a compact affordable PPU intended to meet the needs for large constellations. We hereby elaborate upon the development activities and current status of each PPU.

A. VENμS PPU (R-400 PPU)

Rafael's first generation PPU (R-400 PPU) is now operating successfully in space, since 2017, in a LEO mission onboard the VENμS Micro-satellite. Picture of the Venus PPU is presented in Figure 7. The Venus PPU is capable of supporting all aspects of the electric propulsion system on-board the satellite. According to Satellite On Board Compiter commands, it delivers and control a varying anode power up to 600 W, the necessary current for the cathode heater, the cathode keeper power, controls all the propellant feed components and switches between the two Hall thruster according to the mission needs.

The Venus PPU is fully redundant and thermally independent as it includes a radiation cooling plate facing deep space. Since Venus is a technological mission, its PPU has numerous diagnostic and parametrical capabilities that allow mission operators to monitor propulsion system, assess its performance and change it accordingy.

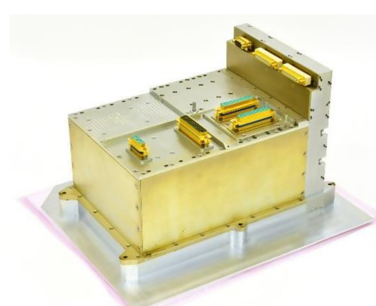

Figure 7. Picture of Rafael's R-400 Venus PPU.

B. Rafael's SmallSat R-400 Mk2 PPU

Rafael's second generation Power Processing Unit (R-400 Mk2 PPU) was derived from the VENµS R-400 PPU and developed to be a common solution for Rafael's Under 1KW Electric Propulsion Systems. The PPU design consists of three development phases, one for each model; Bread Board (BB), Engineering Model (EM) and Flight Model (FM). The PPU is fully compatible with Rafael's R-200 EPS and R-800 EPS. It has a total efficiency above 92% and the ability to support a wide range of thruster operating points up to 900 W. Picture of the PPU Bread Board model is presented in Figure 8.

The modular implementation of the unit enables high flexibility in determining its final configuration according to mission requirements – redundancy policy, with or without a sequencer and adaptation to the desire working point. In other words, the PPU configuration can be easily adapted to the platform and mission needs while reducing the PPU mass and complexity whether desired. The PPU includes a TSU (Thruster Selection Unit) to select the desired thruster unit (if needed). The PPU input voltage is 100V nominal and can be adapted to any required bus voltage.

The unit is fully redundant up to 600W anodic power and uses graceful degradation for power levels from 600W up to 900W. The ability to cross branches and using a combination of power supplies and sequencer units from different branch makes the PPU highly reliable.

To date, the BB phase was successfully completed and coupling tests with the R-200EPS and R-800EPS were successfully performed. Presently an Engineering Model (EM) of the PPU is in production. The EM will contain a configuration that matches the flight model configuration in terms of electronic circuit design, as well as mechanical and thermal design. The only difference between the modules will be the EEE parts; the EM will contain commercial on the shelf electronic components while the Flight Model (FM) will contain space grade components.

Figure 8. Picture of the R-400Mk2 PPU breadboard model and sequencer.

C. Compact and Affordable PPU

With the recent trend of reducing the mass, volume and cost of space systems Rafael engaged in a dedicated activity of developing and producing a compact and affordable PPU. The top goal is to design a system that can be easily adapted by many satellite platforms, where each platform may be mass produced.

To date, two development models (DM) of the compact PPU have been produced. The first model contains a 300 W anodic power module, on a single string branch with 28v input voltage and total efficiency above 85%. It also contains electromagnets, cathode heater, cathode keeper and an auxiliary power supplies. This first model of PPU is designed and manufactured for lab purposes and tests, based on COTS industrial EEE components, with loose dimensions for ease of troubleshooting and design adjustments. This development model's mechanical dimensions are 360×220×80 mm (see Figure 9).

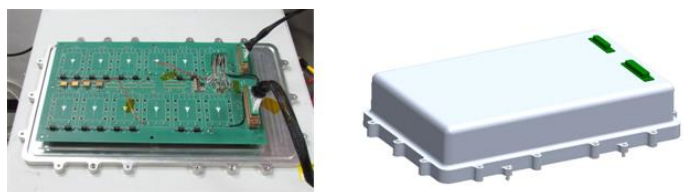

Figure 9. Picture and illustration of the first compact PPU model.

The next compact PPU model is now in its final design phase. It has a single string branch with 46V input voltage, it delivers anodic power of 600W, and its total efficiency is above 85%. It is compatible with Rafael's R-200 EPS and R-800 electric propulsion systems. It contains a magnet, a cathode igniter and auxiliary power supplies. This model also contains a sequencer responsible for PPU control, operation sequences and interface to the On-Board Computer (OBC) via TM/TC communication ports. This model has mechanical dimensions of 120×135×80 mm, and weighs 5 kg.

VI. Rafael's Propellant Management Assembly (R-400PMA)

Rafael's first generation of the Propellant Management Assembly (PMA) is operating onboard VENµS R-400 EPS. In parallel with the above mentioned activities Rafael is developing all components required for the second generation of the propellant management R-400Mk2 PMA, derived from the VENµS R-400PMA. These include pressure regulators, Shape Memory Allow (SMA) valves, Fill and Vent Valves (FVV), a thermal flow controller and a solenoid valve. All components were developed and are manufactured and tested in house at Rafael. All PMA components are compatible with xenon and krypton and have a maximum activation temperature of 50°C. The pressure regulator has maximum inlet pressure of 186 bar and weighs less than 700 gr. The SMA valve is a Normally Closed (NC) valve – it is activated at the beginning of the mission and stays open. It has maximum inlet pressure of 186 bar and weighs less than 150 gr. The FVV has maximum inlet pressure of 186 bar and weighs less than 100 gr. To assure high reliability it includes two seals.

The Solenoid valve has maximum inlet pressure of 25 bar and weighs less than 150 gr. Valve operation requires power of no more than 2 W.

Figure 10. Pictures of the Propellant Management Assembly (PMA): pressure regulator, SMA valve, fill and vent valve.

The flow controller is based on the thermal throttle technique. It has a maximum inlet pressure of 25 bar and a wide mass flow rate span of 5-36 sccm (Xe) – compatible with both the R-200 and R-800 Hall thrusters. The flow controller weighs less than 200 gr. Dedicated flow control tests were conducted where the flow controller successfully operated Rafael’s Hall thrusters at a variety of operational points. Additionally, a dedicated TU-PPU test was performed, in which the PPU successfully controlled the flow according to the required thruster discharge current in a closed-loop control scheme.

A. Rafael's Shape Memory Allow Valve (R-400SMAV)

Targeting SMA as a leading technology for innovative space applications, Rafael’s space directorate selected SMA NC valves for the flow barrier between the propellant tank and the electric propulsion system.

A major challenge, during the design phase of such valves, is avoiding contamination of the propellant by particulates from the valve itself. Other design challenges focused on reducing the valve power consumption, valve sealing, pressure drop across the valve, extending the component temperature envelope, reduce shock or vibration effects during valve operation, and achieving all the above while maintaining high component reliability and allowing testability as spacecraft level.

The SMA high pressure (186 bar) valve is composed of a relatively basic mechanism, yet with much innovation. The fluid compartment is composed of an inlet port sealed by a nipple and an outlet port. The outlet port is part of the valve body. Over the nipple we find the SMA actuator placed into a piston. A custom-made heater is placed within the SMA, the latter is surrounded by a preloaded spring.

The working principle of the mechanism is as follows: an electrical current is running through the heater. After a period of approximately 20 sec the SMA actuator reaches its austenitic starting temperature (As) and begins to exert force. This force is applied on the nipple. Perpendicular to its connection to the inlet port, exerting a shearing force where there is a weakening in the form of circumferential groove. As the force overcomes the one required for shearing the nipple, the nipple is pushed downward further and secured by the spring in order to prevent any possible interference with the flow.

To overcome the sensitivity of the propulsion system to propellant contamination, a strict design of the nipple geometry was tested and verified.

The heater is space proven and designed for small dimensions, low weight while having high power and high reliability.

The SMA valve has an all-welded design based on titanium to titanium interface, fully tested and verified with standard non-destructive tests; hence, no unique technologies are involved in this design.

VII. Rafael's Space Propulsion Manufacturing and Testing Infrastructure

To enable all of the above developments and component/system qualification Rafael has an advanced electric propulsion test facility consisting of six vacuum chambers at different sizes. In addition, as part of the space propulsion department infrastructure a 1,000 m^2 class 100,000 (equivalent to ISO-8) clean room is used for propulsion system integration and in-air component testing.

All vacuum chambers are controlled using an automated system that allows for remote control, execution of an automated test program and recording of all data during experimentation. The automated setup allows for vacuum chamber utilization 24/7. Since all chamber parameters are monitored the system has the ability to safely shut down in case of unexpected events such as facility power shutdown or a power supply malfunction.

The largest vacuum chamber, marked ‘Chamber A1’, is a 2.5 m dia. by 6.5 m long stainless steel tank. The chamber is used for Hall thruster testing and entire system integration testing. The vacuum chamber is equipped with a set of dry mechanical pumps, turbo pumps, cold shrouds and cryogenic pumps. The combined measured pumping speed of the chamber is 50,000 l/sec, ultimate pressure is 1×10^{-8} torr, and operating pressure during a 250 W thruster operation is 6×10^{-6} torr (Xe corrected). The chamber also includes graphite sheaths on the chamber walls, as well as a graphite target on the chamber’s rear wall. The graphite surfaces minimize chamber wall sputtering and allow for proper lifetime experiments. A state of the art thrust stand is used to measure thruster performance, The thrust stand has a full measuring span of 0-100 mN and resolution of 0.2 mN. Three pressure gauges are located at different points along the chamber. One of the gauges is located on the thruster side to accurately measure the pressure at the thruster vicinity. An array of seven retarding potential analyzers, positioned on a rotating arc, are used to measure the energy distribution of the ejected ions, and assess the thruster divergence angle.

Figure 11. Rafael's EPS testing facility

Three identical vacuum chambers, marked ‘Chamber C1/2/3’, are 0.45 m dia. and 0.7 m long stainless steel tank. The chambers are used for hollow cathode testing. The chambers are equipped with mechanical and cryogenic pumps. The combined measured pumping speed of the chamber is 4,000 l/sec, ultimate pressure is 5×10^{-8} torr, and operating pressure, during cathode operation, less than 2×10^{-5} torr (Xe corrected). The chambers include all the required electrical, pneumatic and mechanical feedthrus to support diode mode experiments. The setup also includes ten thermocouples for cathode thermal monitoring.

Two additional vacuum chambers are used for cathode and component research. The main cathode research chamber, marked ‘Chamber C4’ has pumping speed greater than 5,000 l/sec and is equipped with a wide set of diagnostics that allow for meticulous exploration of different cathode parameters. These include a thermal camera, electrostatic probes, spectroscopy etc.

All of the cathode vacuum chambers are located in a class 100,000 (ISO-8) clean room to assure cleanliness during integration and installation into the vacuum chambers.

The lab infrastructure is constantly under improvement with the purpose of increasing the lab’s testing capacity and quality. New forms of diagnostics and testing capabilities are constantly under development[10].

Components and subsystem assembly and integration are carried out in special clean room facilities, complying with Federal Std. 209B, ranging from Class 100,000 to Class 100.

Parts, components and subassemblies are cleaned to the highest levels using special equipment (ultrasonic, flushing benches) and checked for level of cleanliness using computerized particle counters (gas and liquid) and UV light. Hydraulic and pneumatic flow benches, equipped with special tools for flow control adjustment, flow calibration and hydraulic response time measurements, have been installed in the clean room. Orbital welding is used for tubing manifolds manufacturing and propulsion system integration in the clean room. The clean room facilities house the propulsion modules production including the components production. The clean room facilities includes assembly, integration and testing (AIT) sections from the components' level through the sub-assemblies level and four stations of propulsion system AIT.

The test and inspection facilities include a wide range of environmental tests (all aspects of dynamic, climatic, thermal, and vacuum) as well as metallurgical, chemical and dimensional inspection and analytical laboratories.

A wide range of NDE capabilities, such as x-ray, dye-penetrate inspection, ultra-sonic are used during development, qualification, production and acceptance tests.

VIII. References

[1]Herscovitz J, Karnieli A., 2008. “VENμS Program: Broad and New Horizons for Super-Spectral Imaging and Electric Propulsion Missions for a Small Satellite” Proceedings of the AIAA/USU Conference on Small Satellites, Coming Attractions, SSC08-III-1, http://digitalcommons.usu.edu/smallsat/2008/all2008/14/.

[2]Jacob Herscovitz, Dan Lev, Leonid Appel, Amoz Davidson, Sapir Berkman, Yonatan Amit-Shapira, Dror Bar-On, Michael Kedem, Ofer Salama, and Shimshon Adler, “Venus - First In-Flight Results of the Electric Propulsion System”, In the *54th Joint Propulsion Conference (JPC)*, 9-11 July, 2018, Cincinnati, OH, USA. AIAA-2018-4464.

[3]Ahedo, E. and Gallardo, J. M.: Scaling Down Hall Thrusters, *In the 29th International Electric Propulsion Conference (IEPC)*, March 2003, Toulouse, France.

[4]Manzella, D., Oleson, S., Sankovic, J., Haag, T., Semenkin, A. and Kim, V.: Evaluation of Low Power Hall Thruster Propulsion, *In the 32nd Joint Propulsion Conference (JPC)*, Jul. 1996, Lake Buena Vista, FL, USA.

[5]D. Lev, R. Eytan, G. Alon, A. Warshavsky, L. Appel, A. Kapulkin and M. Rubanovych. "The Development of CAM200 - Low Power Hall Thruster". *Trans. JSASS, Aerospace Tech. Japan*, 14(ists30), pp. Pb_217- Pb_223, 2016.

[6]J. Herscovitz, Z. Zuckerman and D. Lev. "Electric Propulsion Development at Rafael". *Proceedings of the 34th International Electric Propulsion Conference (IEPC)*, July 4-10, 2015, Hyogo-Kobe, Japan, IEPC-2015-30.

[7]D. Lev and L. Appel. "Heaterless Hollow Cathode Technology - A Critical Review". *The 5th Space Propulsion Conference (SP)*, 2-6 May, 2016, Rome, Italy, SP2016_3125366.

[8]Dan Lev, Gal Alon, Dmytry Mykytchuk and Leonid Appel. "Development of a Low Current Heaterless Hollow Cathode for Hall Thrusters". *Proceedings of the 34th International Electric Propulsion Conference (IEPC)*, July 4-10, 2015, Hyogo-Kobe, Japan, IEPC-2015-163.

[9]Dan Lev, Gal Alon, Leonid Appel, Omri Seeman and Yoav Hadas. "Low Current Heaterless Hollow Cathode Development Overview". *Proceedings of the 35th International Electric Propulsion Conference (IEPC)*, October 8-12, 2017, Atlanta, USA, IEPC-2017-244.

[10]D. Katz-Franco and D. Lev. "Design and Analysis of a Radiation Cooling System for Hollow Cathode Testing". *Applied Thermal Engineering*, 112, 89-99, 2017.