Electric Propulsion Developments at Rafael

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Abstract: **During the past couple of decades, Rafael is developing Electric Propulsion Systems (EPS) and components. Venus is a program to demonstrate superspectral imaging and precise orbit keeping using Electric Propulsion. In the scope of this project, Rafael developed HET thrusters, the HET-300 to suit a small satellite providing sub-kilowatt power. To operate two such thrusters, PPU-600 was developed, which can supply up to 600W continuously to one thruster. A 16 kg fuel tank supplies the Xenon for the mission. All these components were developed, manufactured and qualified. The Venus Propulsion Base Assembly (PBA) was integrated and fire-tested as a whole All-In-One system in a large vacuum chamber. In order to support the mission's demand for high precision orbit maintenance, a dedicated Technological Mission Module (TMM) was developed. Another recent project is MEPS (Microsatellite Electric Propulsion System). This cooperation with ESA and European companies is aimed to produce a novel low power system for microsatellites. In the frame of this project, a low power high efficiency thruster, a heaterless cathode, PMA, and fuel tank will be developed and qualified. Other EPS components are also developed, such as valves based on Shape Memory Alloy (SMA) technologies. Electric Propulsion Systems are taking a major role in Rafael programs and R&D activities. As such, they are supported by intensive activities for tailoring a suitable EP system to a variety of missions and programs. The goal is to meet the demands of commercial satellites at LEO missions and utilize newly developed technologies for Low-Thrust HETs that are required for operational flexibility. All this will be achieved by using All-In-One concept, of propulsion systems assembled on the same Base-Plate or LRU (Line Replacement Unit) to be incorporated as a self-sustained module to the satellite. This approach can dramatically shorten the Satellite design phases and can be used as cost saving driver for the propulsion and AOCS systems.**

I. Introduction

RAFAEL is a system house in which space equipment and systems are developed and manufactured. During the past couple of decades, Rafael is developing Electric Propulsion Systems (EPS) and components. In the nineties, Rafael started development on Hall Effect Thruster, then considered a new technology to overcome the limitations of the traditional chemical propulsion, in which Rafael was involved from the eighties.

The research and development was carried out in cooperation with Israeli Soreq NRC. Later, Technion's Asher Space Research Institute (ASRI) became the academic support and research partner for EP activities.

After the first successful HET models that were designed for medium power (~800W anodic power), Rafael started developing EP for the Venus project, for a real mission.

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II. Venus Program

A. Venus Missions

Venus is a program initiated between Israel's ISA and France CNES space agencies, to demonstrate two novel missions: Scientific and Technological (Ref. 3, 4, 9).

The scientific mission is earth imaging in a superspectral mode and its objectives are the provision of data for scientific studies dealing with the monitoring, analysis, and modeling of land surface functioning under the influences of environmental factors as well as human activities. The scientific mission will be carried out by a superspectral camera acting as the scientific payload. It will provide a two day revisit rate, which will enable the scientists to carry out research on a temporal basis of images taken at a constant viewing angle and a constant sun angle.

Figure 1. HET-300 flight model

The technological mission is about electrical propulsion for space. As its technological payload, Venμs will incorporate the Israeli Hall Effect Thruster (IHET). The IHET is a recently developed electrical thruster by Rafael. It's designed specifications suit well the use onboard micro and small satellites. The Venus technological mission has a few goals. In its first mission phase, code-named VM1, it will check IHET performance in space by initiating a series of firing experiments, in which the orbit deviations will be recorded and later decoded in off-line mode, to determine the thruster's parameters. These experiments will occur once a month, and in these occasions, the IHET will correct the orbit to a nominal value, which is crucial to achieve the sun-synchronous earth-repeating characteristics. Between the experiments, Venus will perform the imagery dedicated to scientific mission. VM1 orbit is a locked sun-synchronous orbit at a mean Semi Major Axis (SMA) of 720 km altitude. This orbit has an earth-repeating characteristic that is crucial to the scientific mission, with a revisit of exactly two days.

After two years in VM1 phase, the satellite will transfer its orbit to a lower one, of 410 km altitude. This transfer phase, codenamed VM2 is quite demanding since it must provide a ΔV of about 350 m/s and insert the satellite into the third mission phase, VM3 in about a six-month duration. The new VM3 orbit is also sun-synchronous earth-repeating, and it was chosen to allows a two day revisit too with similar characteristics to VM1 orbit (see Ref. 8).

VM3 phase lasts one year, during which the IHET is operated more densely, once every forth revolution to compensate for the high drag in this altitude. The other three revolutions are used for imaging. In this phase, the technological mission is highly interleaved with the scientific one, to enable imaging in this high drag environment. The IHET will demonstrate its mission enhancement capabilities. Such a task is not suitable for chemical propulsion due to the Isp characteristics and propellant consumption.

The IHET will gain heritage and will prove Electric Propulsion necessity in such demanding missions of small spacecrafts in low orbit.

B. Venus EPS

Venus technological payload, the EP system is designed to support and operate two HET-300 thrusters. Its main components are the Propellant Management Assembly (PMA), Digital Xenon Flow Controller (DXFC), Power Processing Unit (PPU), and 2 Filter Units (FU). The main part of the IHET, is the Hall Effect Thruster (HET), codenamed HET-300, shown in Figure 1. It operates on Xenon, which is ionized by electrons emitted from the cathode and accelerated as plasma using a high electrical field (Ref. 3, 5).

Table 1. HET-300 Main Characteristics

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

HET-300 useful power range of operation is between 250 to 600W. Thus, it can utilize the instantaneous available power from the satellite. HET-300 performance at 300W is listed in. HET-300 mass is about 1.5 kg and its dimensions are 170x120x90 mm.

Recent laboratory tests results of thrust and Isp of the qualification model at EOL are plotted in Figure 2.

The PMA is composed of a high-pressure tank storing 16 kg of Xenon and a set of valves, pressure reducers and manifolds to transport the gas.

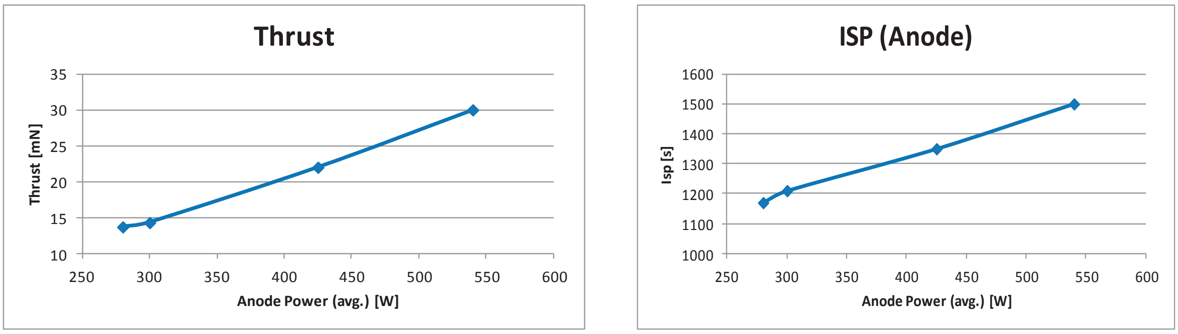

Figure 2. HET-300 thrust (left) and Isp (right)

The PMA feeds the pressure and flow conditioned propellant to thrusters. All these components were developed, manufactured and qualified. Most of them incorporate COTS components, which were modified and adapted to the system. One particular component, the DXFC was specifically developed and manufactured to support Venus mission that requires flexibility in operating the satellite's thrust in a flexible manner, which depends on the instantaneous power produced by the solar panels. Unlike other HET systems with constant operating power - the IHET system incorporates a single DXFC that serves as the "throttling" device to both thrusters. This device allows digital control of the Xenon flow rate through the HET-300 anode. The DXFC (see Figure 3) uses four flow restrictors to control the total Xenon flow. Gas flow through each restrictor is controlled by a latch valves. In addition, it has two backup restrictors to act as redundant flow paths, in case of failure. The variable flow causes controllable variable thrust and power consumption. The DXFC and the embedded PPU control algorithms enables Venμs to utilize whatever power is available from its solar panels, thus exhibiting maximum efficiency.

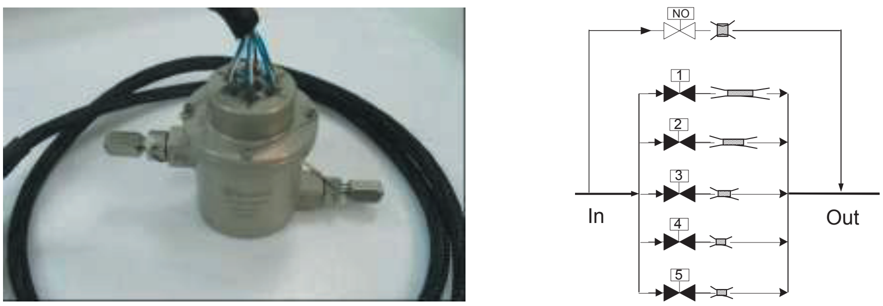

Figure 3 - Digital Xenon Flow Controller (DXFC): flight model (left) and block diagram (right)

Another important and crucial component is the PPU (see Ref. 6). It contains two sub-assemblies: the Power Supplies Unit (PSU) and the Sequencer Control Unit (SCU).

The PSU contains the diverse power supplies and control and management signals. These power supplies are feeding the HETs' power requirements and provide power for auxiliary units, such as valves and sensors. A Thruster Selection Unit (TSU) selects the active thruster to operate. The thruster selection causes connecting the selected thruster to the PSU supplies, upon selection command received from the On Board Computer (OBC) prior to each operation. The SCU is the control section of the PPU. Its main function is controlling the ignition and operation of the HETs. It also implements the communication with the satellite OBC, monitors all signals being traced during mission, handling and acquisition of data, manages the sequence of the thruster's operation, redundancy management and powers and controls EPS components. The PPU block diagram is shown in Figure 4 herein with its main connections to the EPS sub-assemblies.

PPU block diagram and main characteristics are shown in Figure 4. The upper part, where the electrical connectors are located, is placed in the satellite hull. The bottom part is exposed outside the satellite and the flat radiator cools the PPU. Table 2. shows its main characteristics.

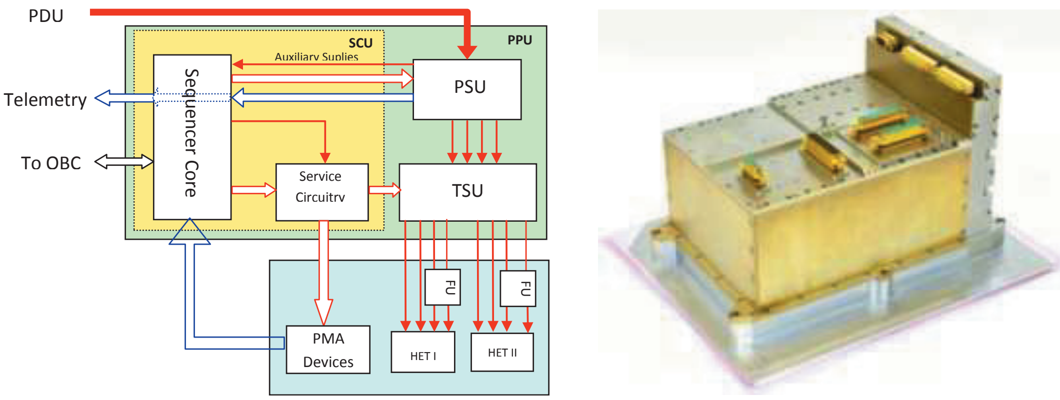

Figure 4 - PPU block diagram in EPS environment (left) and flight model (right)

EPS development posed a big challenge on the design team because it must perform all Venus missions within the allocated performance and reliability requirements. A systematic reliability approach was adopted (see Ref. 7) in order to deliver the required mission reliability. All subsystems are redundant, except the Xenon tank. The design has no single point of failure. PPU has dual power supplies and twu redundant SCUs. All solenoid and latching valves are redundant. The two thrusters are also functionally redundant, although the mission budgets are based on consecutive operation of both.

Table 2. PPU main characteristics

Characteristic	Value
Mass	Less than 12kg
Efficiency at max. power	91%
Anodic power	up to 600W @ 300 VDC
Thermal control	Autonomous, through bottom radiator
Anode voltage PS	300 VDC
Magnetic Field PS	0.6 - 2.6A, variable control for optimal performance
Cathode Heater Current	Selectable up to 11 ADC
Cathode keeper Voltage	60 VDC
Auxiliary PS	5 VDC, 16 VDC and 28 VDC
Redundancy	Full cold redundancy, reconfigurable in space
Interface	Power: Unregulated bus, 34 to 42 V Communications: Dual redundant CAN-Bus

Fault Tree Analysis (FTA) and Failure Modes and Effects Analysis (FMEA) tools were selected to analyze the reliability of the whole system, as can be seen in Figure 5.

C. Qualification and End-to-End Fire Tests

An extensive qualification campaign was carried on to qualify all EPS equipment for the mission environment conditions (see Ref. 5, 6).

The thrusters had gone to a full life test of 2000 hours, which is twice (a factor of 2.0) as needed for Venus mission. Life test was performed on various power level and on various firing durations, but mainly on the representative mission figures of about 425 W and less than a hour operation (representing the sunlight period of a LEO revolution). The lifetime test was carried along with the qualification cathode, in an identical as possible setup to satellite one.

Many tests were performed to qualify for the environment conditions. To mention

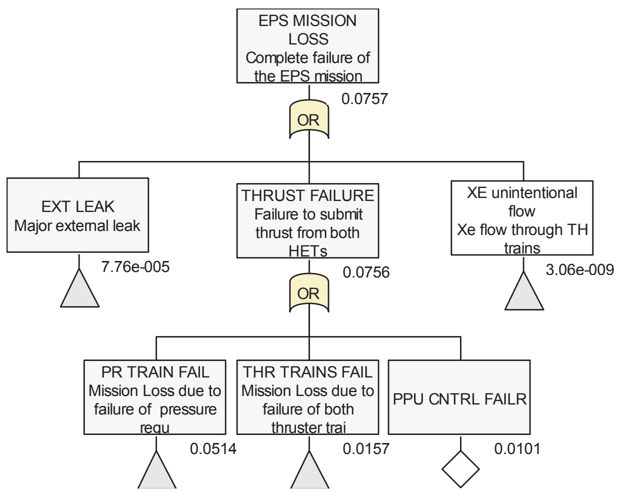

Figure 5 – Example of Failure Fault Trees and Results

some: Random vibrations, Sine vibrations, Shock, Thermal Vacuum and Static acceleration. PMA components were tested together as a sub-system on a base plate. While it enabled easy pre and post functional testing – it saves a lot of time and proved effective. Figure 6 shows a typical environment test of the PPU.

In addition to environment testing, the PPU was tested for EMC / EMI tests, according to MIL-STD-461D.

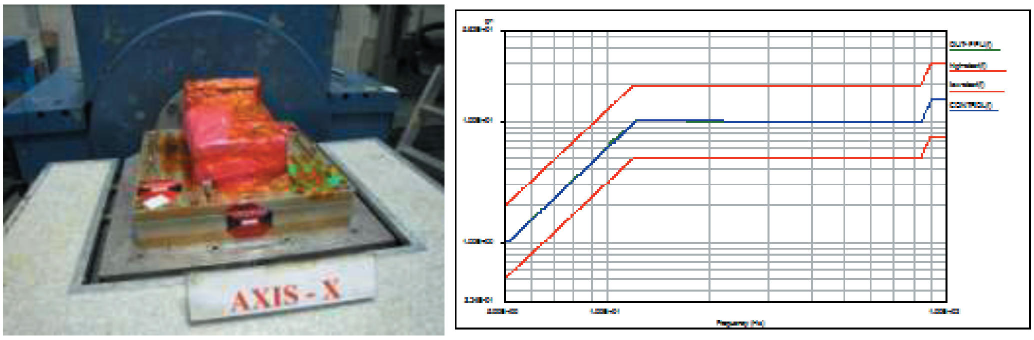

Figure 6. PPU in Vibrator tests configuration (left) and sinusoidal results (right)

The concluding test was an end-to-end fire test. The Venus Propulsion Base Assembly (PBA) was integrated and fire-tested as a whole All-In-One system in a large vacuum chamber, as shown in Figure 7. The whole flight assembled baseplate was installed in a large vacuum chamber. External interfaces, providing power and commands were set outside the chamber, representing the satellite. During this test, each thruster of the EPS was fired and the test proved that the system is operable.

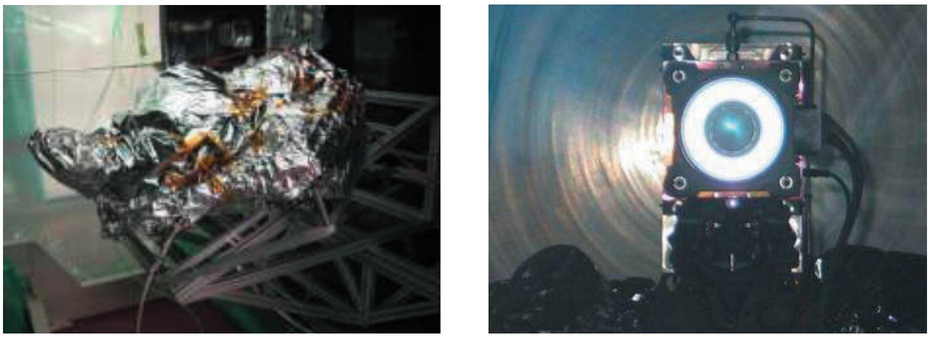

Figure 7. PBA configuration for fire test (left) and firing thruster #1 (right)

D. Orbit Control and Technological Mission Center

In order to support the mission's demand for high precision orbit maintenance, a dedicated Technological Mission Module (TMM) was developed. It comprises of diverse autonomous orbit control algorithms that are integrated into the satellite's On Board Computer (OBC). A Technological Mission Center (TMC) was also developed to be in charge of EP and orbit control during the mission. The TMM and TMC are driving the EPS autonomously, thus providing an advanced tier of EPS functionality. Unlike the traditional orbit control schemes, where the satellite provides orbit data to ground station, which computes the necessary maneuvers – Venus orbit control works differently. The TMC commands the TMM with the nominal orbit. The TMM estimates the orbit on-board and autonomously computes the adequate EPS firing sequence taking into consideration the desired correction and the satellite constraints. The TMM decides the required maneuver duration, EPS power needed and desired satellite attitude. Thus a new paradigm of autonomous orbit control will be proved, thanks to the synergy between the EPS hardware and TMM control algorithms.

III. Microsatellite Electric Propulsion System (MEPS)

E. MEPS Missions

Another recent project is MEPS (Microsatellite Electric Propulsion System). This cooperation with ESA and European companies is aimed to produce a novel low power system for microsatellites. In the frame of this project, a low power high efficiency thruster, a heaterless cathode, PMA, and fuel tank will be developed and qualified.

MEPS program started in late 2013, jointly supported by the European Space Agency (ESA) and the Israeli Space Agency (ISA) and is aimed at the qualification of a newly developed propulsion system (Ref.1). MEPS is based on a low power, low cost Hall Effect Thrusters for a minimum power level of 100W. The system consists of two Truster Units (TU), a Power Processing Unit (PPU), Propellant Management Assembly (PMA), feeding lines and a Xe tank. This system is intended to be a "plug and play" system that can be easily installed on a number of small space platforms, such as Microsatellites. It is intended to provide a prompt, effective response to the market needs, where small microsatellite platforms can highly benefit from a low-cost, low-mass propulsion system. MEPS is a very effective solution for drag compensation, orbit maintenance and end-of-life de-orbit for LEO satellites.

Figure 8. MEPS model installed in a Micro-Satellite

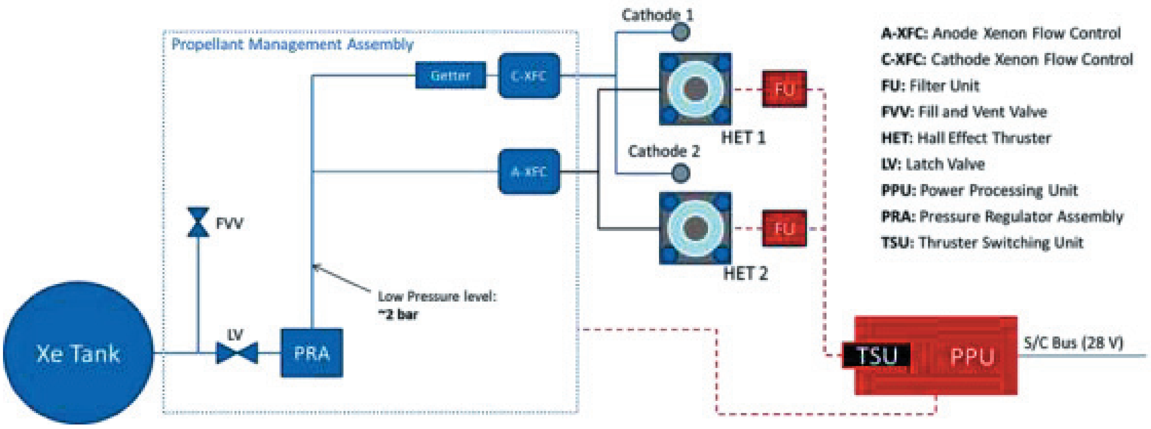

Figure 9. MEPS system architecture

MEPS is going to pave the way to a new class of affordable and capable small space missions, adopting the "All-In-One" paradigm (Ref. 1). Figure 9 shows MEPS model as installed in a Micro-Satellite of 100 kg class.

After the successful completion of Phase 1, the program has now entered Phase 2, where the full EM propulsion system will be assembled and tested to verify the functionality of all the components and the compliance with the specifications defined in Phase 1.

MEPS is a dual thruster system, as shown in Figure 9. Only one thruster can be operated at a time, thus providing diverse functionality and redundancy.

Two existing thruster concepts are being evaluated for the target system: Alta's HT-100, a Hall Effect Thruster based on permanent magnets, and Rafael's CAM-200, a Hall thruster with an innovative topology of the magnetic field. Thrust provided is between 5.5 and 14 mN, with a maximum specific impulse of 1250s and a discharge power between 100 and 250W.

Conceived with a design-to-cost approach, MEPS can be an affordable system to significantly extend the capabilities of micro and mini satellites operating in Low Earth Orbit or even enable new classes of missions which are feasible only by means of electric propulsion.

F. MEPS CAM200 Thruster

Rafael's CAM200 Hall effect thruster, presented in Figure 10, is a unique and unconventional Hall thruster as it consists of a co-axial anodes. The use of co-axial anodes in low power Hall effect thrusters has already been proven to overcome the associated limitations such as ion loss to the inner thruster walls and insufficient degree of ionization [3,4]. As such Rafael's CAM200 Hall thruster exhibits unparalleled performance in terms of thrust, specific impulse and efficiency.

Development on the thruster, that is a derivative of the Simplified-CAMILA Hall thruster [5], commenced in 2012 with the design, manufacture and experimentation of several development models (CAM200-DM) [6]. Recently, in 2014, Engineering Models (EM) of the thruster were fabricated and are currently undergoing extensive experimentation to prove thruster capabilities. Representative measured thruster performance parameters are presented in Table 3.

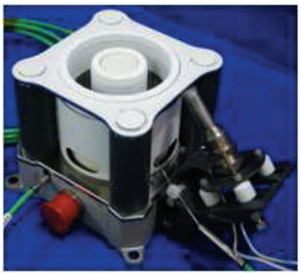

Figure 10. CAM200-EM

Table 3. CAM200-EM measured performance

Power [W]	Thrust [mN]	Isp [sec]	η [%]
100	5±0.15	850±50	21±2
200	10.5±0.3	1500±60	40±3
300	16.2±0.5	1650±70	44±3

G. Rafael Heaterless Hollow Cathode (RHHC)

In recent years, Rafael has been investigating low current Heaterless Hollow Cathode HHC physics for igniting and neutralizing low power Hall Effect Thrusters which are particularly developed by Rafael. Great attention and efforts are invested in proper thermally efficient designs, Manufacturability and versatile designs that are able to operate with various commercially available emitters.

The technology of HHC does not use any heating element to initiate electron emission; therefore providing fast response during thruster ignition, simplicity of the PPU and lower power consumption, which is crucial for low power EP systems that this cathode is designed for.

The development is a part of the MEPS effort, for which the cathode will operate with the CAM200 thruster as well as with Sitael's HT-100 thruster. As part of the development Rafael has designed and fabricated several development models that were used to improve design capabilities and optimize cathode performance and lifetime (Ref. 14). As part of the process speacial manufacturing processes were developed to allow for the use of a variety of materials and geometries for optimal cathode thermal design. In addition, unique startup hardware and corresponding startup schemes were developed to properly initiate cathode operation.

Figure 11. Rafael's Hollow Heaterless Cathode (RHHC)

Current development activities include experimentation and implementation of new materials, startup sequence optimization and additional engineering adjustments as a preparation to engineering model manufacture.

H. Propellant Management Assembly (PMA)

In the frame of MEPS development program, Rafael also develops a PMA to suit the EP system. It is a redundant sub-system consisting of pressure reducing and flow control components, as well as a DXFC to control the anodic power of the active thruster and its cathode.

IV. Advanced Technologies and Equipment

I. Shape Memory Alloy (SMA) Valves

Rafael also develops advanced components, which are based on unique technologies. One such component is the Shape Memory Alloy Valve (SMAV), shown in Figure 12 – patent pending.

The increasing demands for safety in various applications lead Rafael into the field of Shape Memory Alloys (SMA). SMA is well known for its chemical and physical durability. This technology enables the use of inert, reliable and testable actuators, which replace pyrotechnic components thus increasing system reliability and safety.

The actuator, including the heater, can be pulled out and tested before final integration as well as during service.

SMAV is a reliable, inert, testable, compact, low-cost valve that allows integrating the best performance for military and space applications. The SMAV was developed to withstand harsh environmental conditions such as high and low temperatures as well as typical vibrations and shocks for aerospace applications. The SMAV is a hermetic device since the inlet is sealed with a nipple that is sheared by the SMA actuator. The SMA actuator is sealed with a bellows. The SMA Valve exhibits excellent internal and external leakage. Inlet and outlet tubes are 1/4" Titanium. The SMAV is proofed to a pressure of 38 Bar and higher pressure versions are currently on the design phase.

Figure 12. SMAV model (patent pending)

J. Fuel Tanks: Traditional and COPV

Rafael currently acts as a house supplier for in space propulsion system based on chemical, cold gas and electrical propulsion system which is based on Rafael's fully qualified and space proven propulsion components. One of the major components is the propellant tanks in which more than 70 of those are currently in space. Rafael is working more than 30 years on various types of propellant tanks that meet the space industry requirements standards for the different types of the propulsion systems. The novel technology used by Rafael engineering and the state of the art production assembly and testing facility enabled Rafael to establish a fully mature production lines for the propellant tanks and providing them to a variety of satellites constellations.

Figure 13 presents some of Rafael's propellant tanks that are qualified and space proven.

Figure 13. Xe tank (left); GSU-1L High pressure COPV tank (center); PEPT-590 tank (right)

V. From Equipment to System Level: All-In-One System Approach

Electric Propulsion Systems are taking a major role in Rafael programs and R&D activities. As such, they are supported by intensive activities for tailoring a suitable EP system to a variety of missions and programs. The goal is to meet the demands of commercial satellites at LEO missions and utilize newly developed technologies for Low-Thrust HETs that are required for operational flexibility. All this will be achieved by using All-In-One concept, of propulsion systems assembled on the same Base-Plate or LRU (Line Replacement Unit) to be incorporated as a self-sustained module to the satellite. This approach can dramatically shorten the Satellite design phases and can be used as cost saving driver for the propulsion and AOCS systems.

The current development activities leads to modern and compact Electric Propulsion Systems with high operational flexibility and high performances that shall imply a simple integration effort to the Satellite and finally shall lead to much easier task and lower risk in completing mission.

The goals will include an EPS that can be easily adapted to many platforms hence sold in big quantities to cover the high costs of development.

Satellite architects usually design the propulsion system as an embedded subsystem spreading the components throughout the satellite (Spread System).

The Module Approach (MA) recommends to the satellite designer the use of a complete propulsion system module providing the propulsion needs of the mission. After the propulsion mission needs are specified, an existing specific propulsion system module is selected. The advantage of this approach is in having the propulsion section of the satellite at subsystem level, while skipping the component level stage. Modifications, if needed, can be made by the propulsion system provider, such as using different tank or different thrusters.

The module approach can be used on several levels:

- Full independent module: This approach treats the propulsion module as an independent part of the satellite.
- Module as part of the satellite: This approach is similar to the Full independent module but treats the propulsion module as part of the satellite.
- Basic module approach: In this approach the propulsion system is supplied as a mechanically assembled and tested subsystem. It does not include the wiring and the thermal elements.
- Subassembly approach: This approach is not a "system module" approach. The propulsion supplier delivers component assemblies ready to be attached to the satellite.

In addition to the module approach, we recommend to adopt the concept of "All in One Solution". This concept means to use the expertise of a propulsion system provider in the early stages of design. These early stages are crucial to the design, since in these stages, most of the lifecycle cost is committed.

This will enable to include the existing qualified propulsion elements in the satellite design from the structural and performance point of view.

Future propulsion system architectures require modern and compact Propulsion Systems. They must provide high operational flexibility and high performances, while exhibiting simple integration effort with the satellite. Finally, they shall lead to less effort and lower risk.

This approach will shorten delivery lead times and will reduce cost of the propulsion system.

In the propulsion system Module approach, we can distinguish between three main mechanisms that potentially can reduce the cost, as described herein:

- Scope & Quantities advantage - more efficient production methods that reduce the cost per system.
- Transfer from "Spread System" to a Module Approach – to shorten integration time
- "Inherent growing potential" – the ability to enhance performance by replacing leading components.

The outcome of applying those three mechanisms can provide a saving of more than half in the cost.

The presented module approach recommends to the satellite designer the use of a complete propulsion system module based on Electrical Propulsion solutions, providing the propulsion needs of the mission. The advantage of this approach is in having the propulsion section of the satellite at subsystem level, while skipping the component level stage. Modifications, if needed, can be made by the propulsion system provider, such as using different tank or different thrusters

VI. EP Infrastructure

Electric propulsion for space applications is an infrastructure demanding business. Rafael has built the required infrastructure during the past three decades, as seen in Figure 14.

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.

A new clean room, completed in 2010, houses the propulsion modules production including the components production. The new clean room includes assembly, integration and testing (AIT) sections from the components' level through the sub-assemblies level and four stations of propulsion system AIT.

Electrical thrusters hot firing tests are carried out at Rafael facilities in a vacuum chamber. The chamber is capable of testing a wide range of electrical thrusters up to a full propulsion system (diameter of Ø2.5 m). The vacuum chamber can accommodate thrust measurement, from 4 to 120 mN, while evacuating the residual gases and keeping the vacuum environment of up to 2×10^{-5} Torr.

The vacuum chamber is continuously monitored by double set of pressure transducers, a residual gas analyzer and a video recording system.

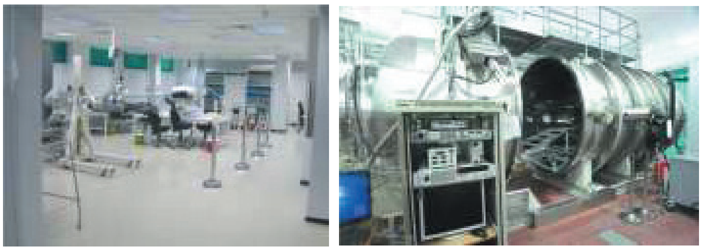

Figure 14. Clean room (left); EP firing and test chamber (right)

VII. Conclusion

RAFAEL designs, develops and manufactures Electrical Propulsion Systems (EPS). It provides EP system to Venus satellite and is developing low power systems to accommodate microsatellites. Rafael has the whole range of solutions, from components up to whole systems and the whole value chain. It has supporting infrastructure as well as experienced designers to provide the whole range of space EP solutions.

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