Status Update on the Electric Propulsion Subsystem of TURKSAT6A Communication Satellite

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B. C. Aydin, D. Ulusen, Y. Yurttas, A. Tsybulnyk, S. Neugodnikov, B. Cal, S. K. Gullu, O. Cherkun
TUBITAK UZAY Space Technologies Research Institute, Ankara, Turkey

Abstract: Turkey's first indigenous communication satellite TURKSAT6A (T6A) is under development since 2014. Structural-thermal model of the platform has successfully been integrated and tested in 2018. Integration phase of the satellite engineering model begins in March 2019. The platform houses an experimental Electric Propulsion Subsystem (EPS) whose equipment are direct outcomes of Turkey's first electric propulsion development project, HALE. The EPS is responsible for performing east-west station keeping maneuvers and transferring the satellite to graveyard orbit in case sufficient propellant remains at the end of mission. This paper presents detailed information on the subsystem being developed.

T6A	=	TURKSAT6A Communication Satellite
STM	=	Structural Thermal Model
EM	=	Engineering Model
HALE	=	Hall Effect Thruster System Development Project
EPS	=	Electric Propulsion Subsystem
HET	=	Hall Effect Thruster
PPCU	=	Power Processing and Control Unit
XPT	=	Xenon Propellant Tank
XFU	=	Xenon Feed Unit
GSU	=	Ground Support Unit

I. Introduction

Turkey has its own communication satellites since the year of 1994, starting with TURKSAT1B satellite due to the unsuccessful launch of TURKSAT1A. The series of TURKSAT satellites are procured from various different foreign contractors until TURKSAT6A which will be the first indigenously designed communication satellite platform of Turkey. TUBITAK UZAY is the main contractor of this development project and working with local partners since 2014. Structural-thermal model (STM) of the platform, which is given in Figure 1, was successfully integrated and tested in 2018. Integration phase of the satellite engineering model (EM) begins in March 2019 and is still in progress. In T6A project, not only the platform but also satellite subsystems are designed, manufactured, and tested by Turkish engineers. The platform houses an experimental Electric Propulsion Subsystem (EPS) whose equipment are direct outcomes of Turkey's first electric propulsion development project, HALE [1].

Figure 1 T6A STM

HALE project is initiated by TUBITAK UZAY in the aim of conducting research activities in the field of electric propulsion for the first time in Turkey in 2010. The project is financially supported by Turkish Ministry of Development. The main objective of the project is to establish a facility in order to carry out research and development activities on this key technology and to develop a laboratory model Hall thruster electric propulsion systems for potential national space missions. The project has been successfully completed achieving all of its goals in 2018 [1,2]. The laboratory established within this project is shown in Figure 2. The HALE project outcomes; Hall Effect Thruster, Power Processing & Control Unit, Xenon Feed Unit and Propellant Tank form T6A Electric Propulsion Subsystem (EPS) and all equipment are designed and customized according to TURKSAT6A platform requirements.

Figure 2 HALE Electric Propulsion Laboratory

II. Subsystem

The EPS on board T6A is responsible for performing east-west station keeping maneuvers and transferring the platform to graveyard orbit in case sufficient propellant remains at the end of mission. All EPS equipment of T6A are subjected to qualification test campaign. Qualification test types, loads and durations are compliant with the ECSS-E-ST-10-03C testing standard. This paper is a follow up study for the previously published paper [3], and therefore it first presents a brief overview of each subsystem equipment design and then provides status update for their development. The architectural design of the subsystem is given in Figure 3.

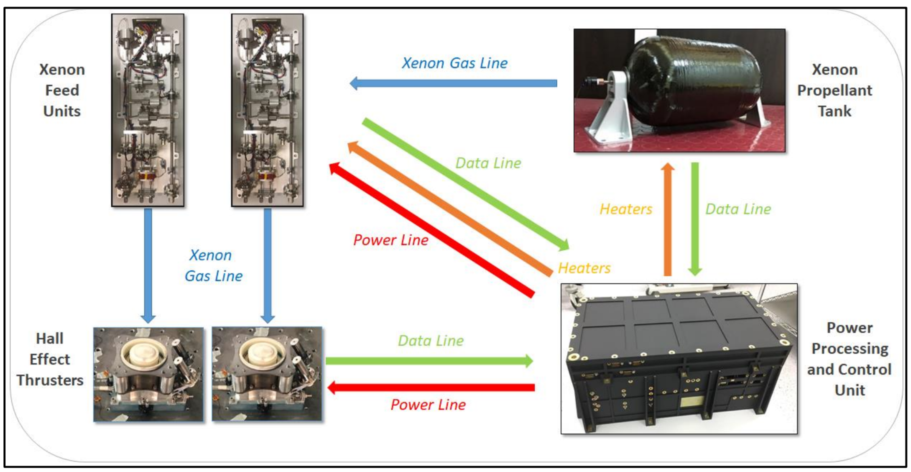

Figure 3 Electric Propulsion Subsystem

A. Hall Effect Thruster

The EPS has two identical Hall Effect Thrusters, each having two Cesium based hollow cathodes (one redundant) [4]. Each thruster has a power level of 1500W and does not operate simultaneously during the mission due to the power limitations of the platform.

After accomplishing all functional and performance tests on the prototype [3], a qualification test model of the Hall Effect Thruster (HET) is manufactured. In the frame of qualification test campaign; functional-performance, vibration, thermal-vacuum, shock and final functional-performance tests of HET are carried out successfully. In the following sections of this paper, details of each test are presented.

Figure 4 Functional Test Setup

Functional Tests

For the functional tests, the biggest vacuum chamber at the HALE facility is used, which has a diameter of 2.3 m and a length of 4.5 m (Figure 4). The tests are performed in July 2018. During the tests, thruster electrical characteristics and overall performance are checked by measuring the thrust and plume parameters. Thrust measurements carried out by an inverted pendulum type of thrust stand [1,5,6]. Figure 5 shows the calibration process and the measured thrust. Considering the plume diagnostics, a set of Faraday probes [7] are utilized which are positioned inside the vacuum chamber on a semi-circular rake with a 1m radius. The rake is rotated by a rotary table run via a stepper motor. During the operation of the thrusters, this rake traces the plume by 1^0 steps, taking ion current density measurements covering whole 180^0 angle. An example of the obtained plume distribution is given in Figure 6. Specific impulse and efficiency of the thruster are calculated based on these measured parameters. The measured thruster performance characteristics are listed in Table 1 are perfectly matching with the performance requirements.

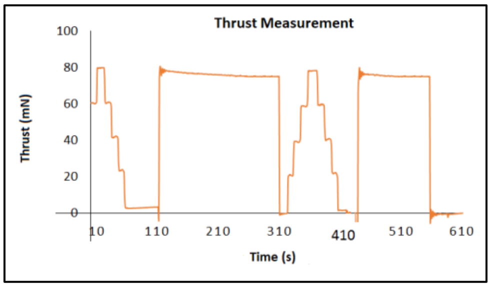

Figure 5 Thrust Measurement

Table 1 HET Functional Test Results

Performance Parameters	Measured Values
Thrust	76 mN
Anode Xenon Flow Rate	47 sccm
Anode Voltage	300 V
Anode Current	4.41 A
Specific Impulse	1760 s
Efficiency	% 47.39
Full Plume Angle (Full) Half Plume Angle	71^0 $35,5^0$

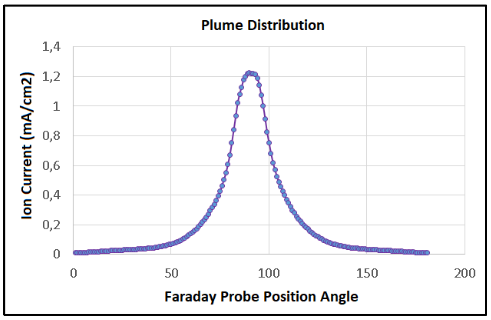

Figure 6 Plume Measurement

Vibration and Shock Tests

After completion of functional tests, the thruster is subjected to structural tests. Vibration tests are carried at the vibration & shock test facility at TUBITAK UZAY in August 2018. The qualification level load profiles applied are given in Table 2. Accelerometer allocations can be seen in Figure ***7***. In order to evaluate the equipment integrity, a resonance search is performed before and after the vibration tests with a sweep rate of 2 oct/min. Considering all axes, the sweep rate for sinus vibration tests is 2 oct/min and the durations for random vibration tests are 2 min. The calculated shifts in amplitude and frequency regarding the before-after resonance searches are in the limits of the ECSS-E-ST-10-03C testing standard in all axes.

The shock tests are conducted in October 2018. The applied shock profile given in Table 3 is determined according to the shock sources on the T6A platform and the location of thrusters on the satellite. The tests are repeated 3 times for each axes. A detailed visual check is carried out to check for damage since no functional test is performed between structural and thermal vacuum tests.

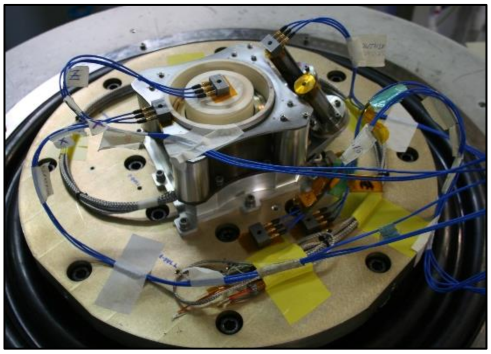

Figure 7 Vibration Test Setup

Table 2 Qualification Level Sinus and Random Vibration Load Profiles

Sinus Vibration Profile		Random Vibration Profiles			
All Axes		Z Axis		X and Y Axes	
Frequency (Hz)	**Level (g^2/Hz)**	**Frequency (Hz)**	**Level (g^2/Hz)**	**Frequency (Hz)**	**Level (g^2/Hz)**
5-20	11mm (0-peak)	20	0.0085739	20	0.0085739
21-60	20g (0-peak)	100	0.212	100	0.212
61-100	6g (0-peak)	400	0.212	200	0.212
		2000	0.042634	2000	0.009944

		Total	14,418 grms	Total	9,843 grms

Table 3 Shock Load Profile

Frequency (Hz)	SRS (g)
100	45
1000	1700
10000	1700

Thermal Vacuum Test

The vacuum chambers used for the thruster functional tests in the HALE facility are not equipped with a shroud and, therefore, do not have a thermal testing capability. For this reason, thermal vacuum tests are performed at TUBITAK UZAY's newly established thermal vacuum chamber (Figure 8). This facility, however, does not allow for thruster operation during the tests and, therefore, firing tests under thermal vacuum environment are planned to be performed at a suitable foreign test facility next year.

The thermal tests are conducted for 8 vacuum cycles according to the ECSS-E-ST-10-03C testing standard as shown in Figure 8. Qualification temperature interval of the thruster is determined to be -40^0C / $+80^0$C. During the third cycle, one of the pump goes through an error state. After removing the error, the test is successfully completed. A final functional test is performed following the structural and thermal vacuum tests and it is reported that the thruster is functioning with its nominal electrical characteristics and qualified.

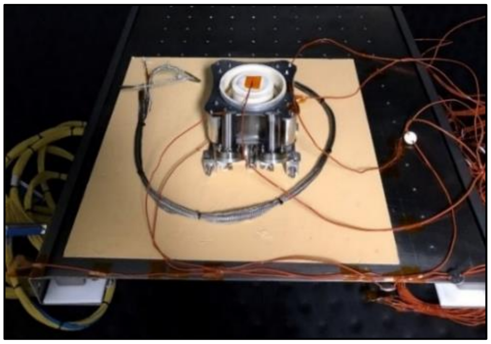

Figure 8 Thermal Vacuum Tests

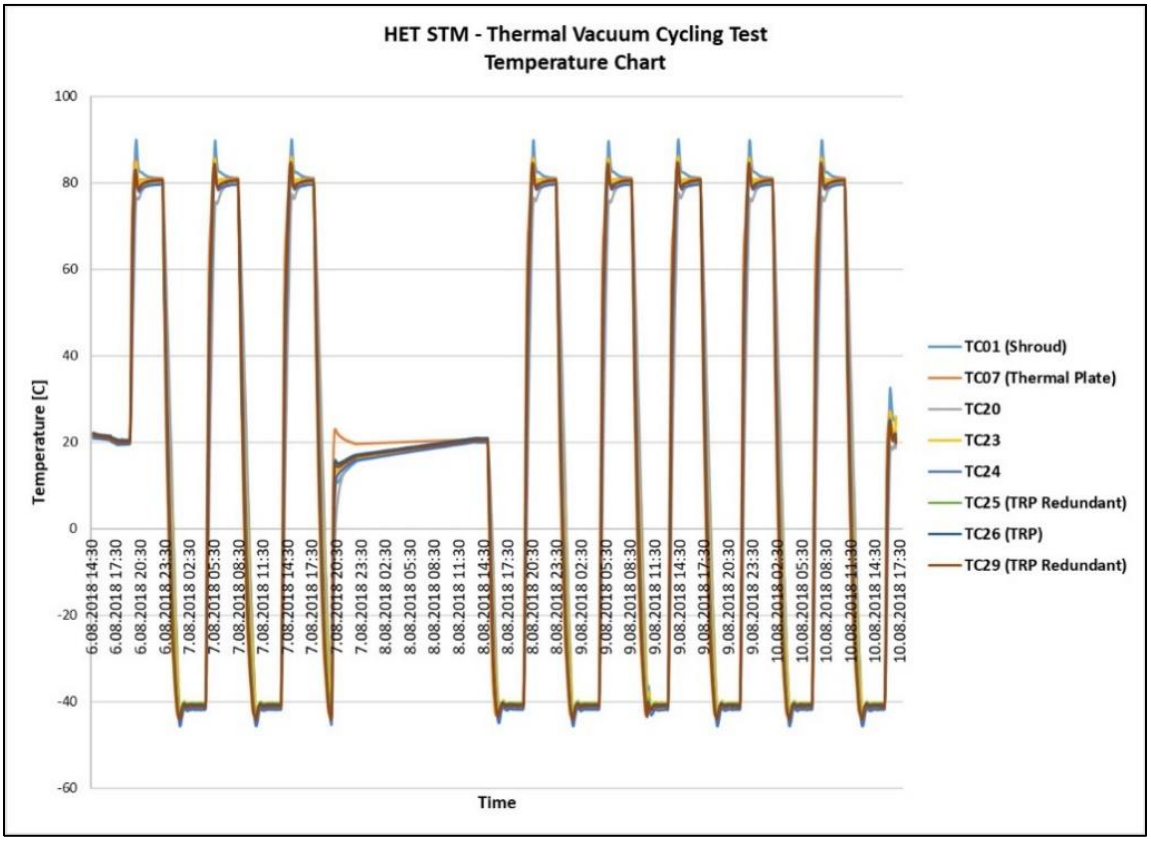

Figure 9 Thermal Vacuum Cycles

B. Power Processing Unit

In the subsystem, Power Processing and Control Unit (PPCU) is responsible for controlling the thruster operation, supplying necessary power to each subsystem equipment (including heaters on XFU and Propellant Tank) and establishing an interface with the satellite. The PPCU characteristics are summarized in Table 4 and the detailed design description of the PPCU can be found in [8,9,10]. The equipment consists of power processing, control, DC-DC and filter boards and a mechanical body The qualification test model of the PPCU in Figure 10 is manufactured and the unit is subjected to functional-performance and EMC tests.

Table 4 PPCU Characteristics

Features	Values
Bus Voltage	100 V
Max Input Power	1750 W
Inrush Current	< 25 A (max 50 ms)
Mass	16 kg
Efficiency	> 90
Communication Interface	MIL-STD-1553B, Discreet Line

Figure 10 PPCU Qualification Model

Functional Tests

Functional test of the PPCU is conducted at the 10,000 class clean room environment at TUBITAK UZAY facility in April 2019. Before equipment level functional test, each board inside the PPCU is tested alone. Since the power processing board is a high-power unit, its testing and verification is possible only with a heat sink imitating the radiator structure on the satellite panel. For this purpose, a special ground support unit (GSU) is developed specifically for the functional tests. The objective of the GSU is to provide heat dissipation and easy access to all components on the power processing board.

During the equipment level functional tests all internal and external interfaces are tested. Electronic loads are utilized for the interfaces with the anode and cathodes of HET. A special test board is manufactured for representing electronic valves, pressure sensors, heaters and thermistors of Xenon Feed Unit. Considering the interfaces with the Satellite Management Unit, a MIL-STD-1553 simulator and a test board for the discreet line interface are used. Finally, a commercial power supply is utilized representing Power Subsystem of the satellite with 100 V and 18 A ratings. Considering the max operation time on the satellite, the unit is operated for one hour. The functional test setup is seen in Figure 11.

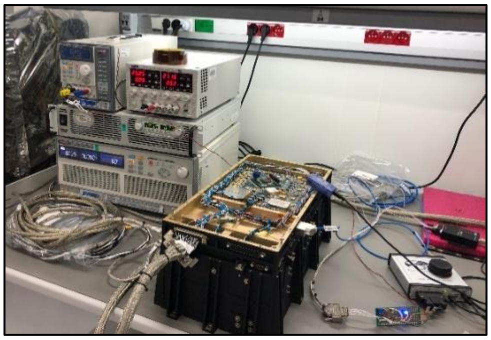

Figure 11 PPCU Functional Test Setup

Electromagnetic Compatibility Tests

The EMC tests are performed according to MIL-STD-461F and tests and limits for space systems are applied. The conducted tests are carried out in clean room environment at TUBITAK UZAY. The radiated tests are conducted in EMC chamber of Turkish Aerospace Space System Integration and Test (USET) facility. The list of applied tests are given in Table 5. Figure 12 shows both conducted and radiated EMC test setups.

Table 5 Applied EMC Tests

Tests	Frequency	Limit
CS101	30Hz-150kHz	$6V_{rms}$
CS114	10kHz-200MHz	curve 3 (MIL-STD-461F Figure CS114-1)
CS115	30 pulse per minute(impulse excitation)	5A
CS116	10kHz,100kHz,1MHz,10MHz,30MHz,100MHz	MIL-STD-461F Figure CS116-2
RE102	2MHz-1GHz	70dBμV/m
RS103	2MHz-18GHz	20V/m

In CS101 test, hot power leads are subjected to interference voltage. The level given in standard is tailored to system requirements and increased to 6Vrms for the whole frequency interval. In MIL-STD-461F, CS114, CS115 and CS116 tests are intended to simulate the environmental effects in space. The interference signal levels for space systems are injected to all interconnected cables including power cables. Radiated tests are performed in semi anechoic chamber of EMC test facility. RE102 limit is tailored to 70dBμV/m due to neglect the ambient noise of auxiliary equipment. System level analyses show that 20dB RE/RS margin which is defined in ECSS-E-ST-20-07C for safety critical equipment is still satisfied with the tailored limit. Emission level of the equipment does not exceed 70dBμV/m. RS103 test is implemented and the equipment is sustaining its operational functions properly during and after the test period. Although the electric field level for equipment which is located inside the main frame is specified as 1V/m in ECSS-E-ST-20-07C, PPCU is subjected to 20V/m radiated electric field according to MIL-STD-461F RS103 test. PPCU withstands with the exaggerated electric field level even though it is expected that it shall not be exposed to this radiated field in space environment. The EMC test results ensure that the qualification test model of PPCU can function and perform nominally without any malfunction and deviation beyond the tolerances and does not interfere with the satellite system.

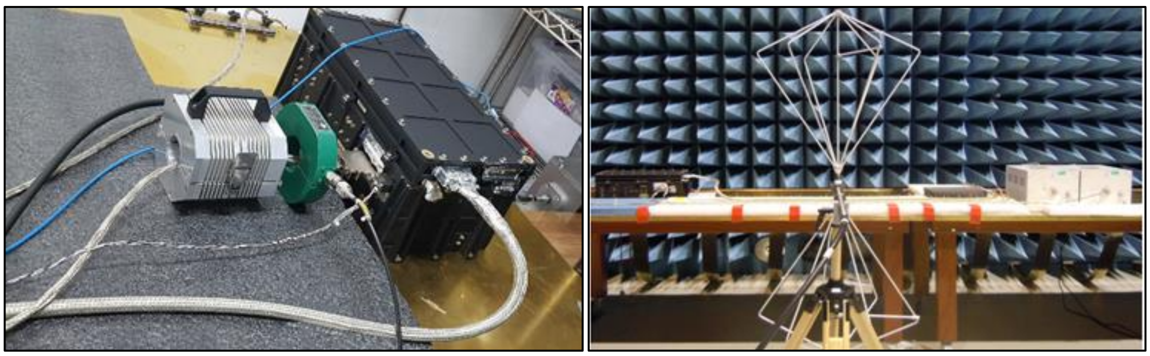

Figure 12 PPCU EMC Conducted and Radiated Test Setups at TUBITAK UZAY and USET, respectively

C. Xenon Propellant Tank

Xenon Propellant Tank (XPT) is designed, manufactured, and qualified in collaboration of TUBITAK UZAY and IZOREEL Composites Ltd. Detailed description of the XPT designing, manufacturing, and qualification testing activities can be found in [11]. The XPT is capable of storing approximately 13 kg of Xenon under 150 bar pressure. XPT's features are given in Table 6.

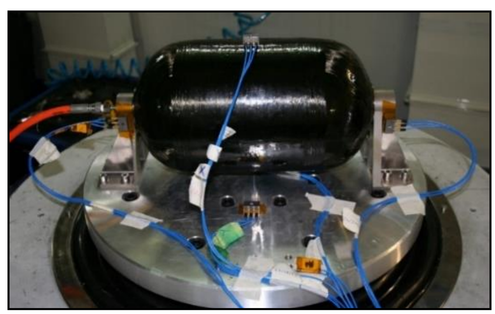

Figure 13 Tank Vibration Test Bench

The tank is mounted on the satellite panels via two brackets. One bracket is free in motion through a bearing structure in order to compensate the increase in the Tank's length when it is fully loaded. The other bracket is fixed. Due to the updated thermal analyses, the need to isolate the XPT from the satellite structure is arisen, therefore the brackets' material is changed as Titanium, which are previously Aluminum. Due to this modification in the bracket material and design, it is considered the vibration tests have to be repeated. Since the qualification model of the XPT is exposed to destructive test (burst test) [11], the vibration tests are repeated on the engineering model of XPT (Figure 13). Shock and thermal vacuum tests are not performed at equipment level, since the XPT is subjected the mentioned tests at system level on engineering model of the satellite in 2020 when the tank is fully loaded with 13 kg of Xenon.

Both engineering and flight models are manufactured and successfully tested at acceptance test levels. The proof and leak tests are performed at IZOREEL infrastructure. The random vibration tests are conducted at TUBITAK UZAY test facility. During the proof tests, the tanks is exposed to 225 bar (1.5 x operation pressure) for 5 minutes. The leak tests are repeated models after vibration tests for both engineering and flight. The tank is loaded with Helium gas at 150 bar and placed into a vacuum chamber. After reaching the suitable vacuum level, leak measurements are taken at least 30 minutes (Figure 14).

Table 6 Xenon Propellant Tank Characteristics

Parameters	Requirements for T6A Platform
MEOP	150 bar
Proof Pressure	225 bar
Burst Pressure	min 300 bar (1:2)
Operation Cycle	min 50 cycles
Tank Size	Ø204.5 mm OD x 382 mm long, boss to boss
Propellant Weight	min 10 kg Xenon gas
Tank Weight	3.7 kg
Tank Capacity	min 8.3 lt
Compatibility	Xenon, Argon, Helium
Leakage	<1x10-6 std cc/s He @ MEOP
Operating Temperatures	-5 ˚C to 65 ˚C
Natural Frequency	>140 Hz, filled

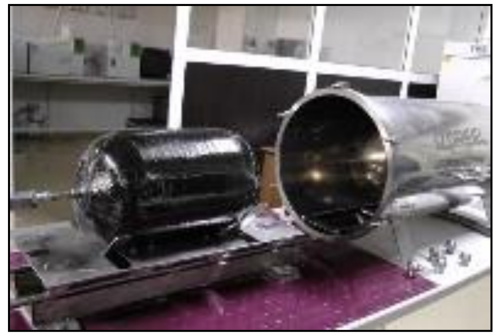

Figure 14 XPT Leak Test Setup

D. Xenon Feed Unit

Xenon Feed Unit regulates the pressure of Xenon gas stored in the XPT and provides variable and constant flow rates to the HET's anode and cathodes, respectively. There are two XFU units in the subsystem, supplying propellant to the HETs independently. The design of this unit has been extensively explained in [12]. The characteristics of the unit is given in Table 7. In the integration of tıe unit, orbital welding is applied at most of the connection points to keep the total leakage as minimum as possible. Each welding type considering tube thicknesses, cross-sections, material type etc., is carefully investigated [13] and proper welding parameters are determined by a staff who received special orbital welding training. Welded samples are exposed to destructive and non-destructive tests. As a result, a fully qualified welding and assembly processes are attained. To ensure the cleanliness of the tubes, IEST-STD-CC1246D is applied for related procedures [14].

A prototype is manufactured with dummy representatives of valves and other components in order to qualify and verify orbital welding process. The prototype of XFU is given in Figure 15. After prototyping process, the qualification model of the XFU (Figure 16) is manufactured and integrated with actual valves, heaters, and sensors. Before the integration of the equipment, all electronic components are subjected to functional tests.

Table 7 XFU Characteristics

Features	Values
Mass Flow Rates	4, 5 mg/s (1-10 mg/s variable) for anode 0,45 mg/s (constant) for cathodes
Mass	2,7 kg
Leak Value	$1x10^{-5}$ scc/s G He
Operation Pressure Values	150 bar @ high pressure section 2-3 bar @ low pressure section

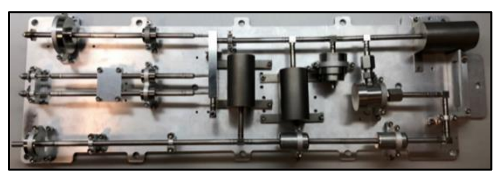

Figure 15 XFU Prototype

Functional Tests (Coupled with PPCU)

For the functional, leak, and proof tests of the XFU, the smallest vacuum chamber at the HALE facility [1] is used which is shown in Figure 16. A booster unit is utilized in order to supply gas for operation and proof pressure. The location of leakage can be determined by means of leak detector sniffer option. Additionally, total leakage of XFU is obtained by integrating leak detector to the vacuum chamber. Besides, thermal vacuum test of the XFU is also planned to be done at this test setup. For this reason, a refrigerated bath circulator is also integrated to the system [15]. In order to have better boundary conditions, vacuum pump is attached to the outlet of the XFU. During the functional tests, the qualification test model of the XFU is electrically coupled with the PPCU. The pressure of the high pressure section is monitored with external pressure transducers. In addition to the thermistors of the equipment, the temperature of critical points on the XFU is tracked via additional temperature sensors. Xenon, Argon and Helium gases are applied at functional, proof and leak tests. Flow meters to measure anode and cathode flow rates are located outside the vacuum chamber.

The coupled tests are initiated by controlling the functions of electronic valves of the XFU by the PPCU. Thermistors are calibrated using heaters on the equipment and external thermocouples. Pressure transducers are also calibrated by applying an inlet pressure starting from 1 to 150 bar. Control valve which provides variable flow to anode is tested and necessary flow rates are attained. Flow restrictors are heated up to 60-65 ^{0}C in order to supply cathodes' constant flow rates. Leak and proof preparations are in progress.

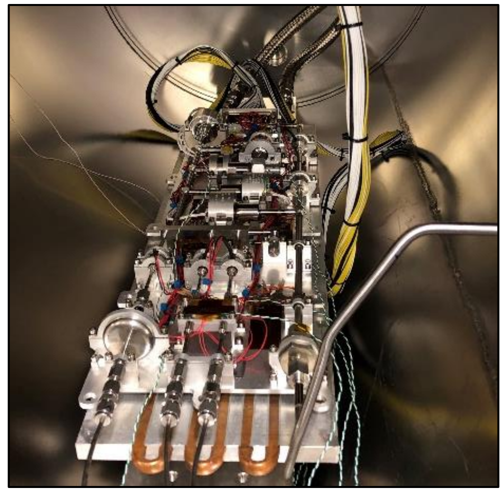

Figure 16 Functional Test Setup of XFU Qualification Model

III.Conclusion and Future Work

The Electric Propulsion Subsystem (EPS) of TURKSAT6A communication satellite are the direct outcomes of the HALE project which is successfully completed in 2018. The EPS consists of four equipment, and all design and testing activity results of each equipment are presented in the paper in detail. The first of four equipment, a 1500 W HET, is already qualified and an engineering model is manufactured ready for acceptance tests. Both engineering and flight models of the Xenon Propellant Tank are manufactured and acceptance test campaigns are accomplished. The qualification test models of Power Processing & Control Unit (PPCU) and Xenon Feed Unit (XFU) are integrated. The PPCU is subjected to functional and EMC tests. The functional tests of the XFU coupled with the PPCU is in progress. After completing coupled tests of the PPCU and XFU, the HET is also planned to be included in the coupled test configuration to finalize the PPCU software. Engineering models of all EPS equipment are planned to be ready for the satellite engineering model integration in March 2020.

Acknowledgments

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