Development of a Helium Cryopumped Facility to Evaluate Hall Effect Thrusters

Christopher H. McLean*
Olaf Lesky**
TRW
Space and Technology Division
Redondo Beach, CA

Abstract

TRW has developed a facility dedicated to the evaluation of Hall Effect Thrusters (HET's) and integration issues associated with these thrusters, their major sub-systems, and the spacecraft interface. This facility includes a high altitude vacuum chamber, a Programmable Logic Controller (PLC) driven mechanical and cryogenic pumping system, a laboratory model xenon propellant feed system, a laboratory power supply with a variable start circuit, and a dedicated Data Acquisition and Control System (DACS). The facility is capable of integration and evaluation of flight and flight type propellant flow control units and power processors. Laboratory support systems allow thruster operation with or without flight and flight type subsystems to resolve issues of each major subsystem individually. Development of this facility was critical to defining and resolving HET system and spacecraft integration issues. The facility will be fully operational in the fall of 1997.

Introduction

During 1996 TRW contracted a study from NYMA, Inc., to develop preliminary specifications for a facility suitable to evaluate HET's. The aim of this facility was to provide a working environment to evaluate integration issues associated with HET's, including thruster, propellant feed system (PFS), and power processing interfaces.

Progression of the project, and the expansion of TRW's interest in thruster development, lead to increasing facility capacities for higher pumping speed, thrust measurement, and a greatly expanded DACS. Development of in-situ insulator erosion measurement techniques is also underway.

Support for the fabrication and development of the thrust stand was provided by NASA Lewis Research Center. Additional support and recommendations were provided by the Jet Propulsion Laboratory and various component suppliers.

Test Facility

The high altitude facility consists of a non-magnetic, cylindrical stainless steel tank, 7 feet in diameter by 17 feet long, employing a mechanical blower roughing system and three 48 inch diameter helium cryopumps (Figures 1.1, 1.2, 2.0). A hinged, 7 foot diameter door allows access to the chamber at one end of the tank. The three cryopumps are located on the sides of the tank. Thrusters will be mounted on a NASA LeRC thrust stand located immediately inside the chamber door.

Mechanical pump oil is the greatest potential source of organic contaminant in the test facility. The helium cryopumps adsorb gas onto activated carbon elements, which are sensitive to oil contamination. Oil contamination of the carbon elements greatly reduces their pumping speed. For this reason, extreme care was taken to keep pump oil from backstreaming into the vacuum chamber.

Complete pump down of the facility takes approximately 10 hours, mainly due to the cool down period associated with the cryopumps. Pump down of the facility is fully automated using a Programmable Logic Controller (PLC).
The PLC allows for the system to be pumped down overnight, minimizing downtime during normal working hours.

The facility is lined with graphite to minimize the effect of backspattering from energetic xenon ions. A 36 inch by 36 inch by one inch thick graphite target is mounted in the rear of the chamber, directly in line with the thruster plume. The lining is made from 0.020" thick graphoil. Both the lining and the target are made from high purity, high density carbon.

Pressure during the pump down phase is monitored using two compensated thermocouple pressure gages. High vacuum pressure is measured using two ion gages. Both types of gages were calibrated for xenon.

**Roughing System**

Roughing of the chamber is accomplished with a Stokes 1722 two stage mechanical blower. The second stage of the pump is a rotary oil sealed vacuum pump backing the first stage, a positive displacement high vacuum booster. Stokes low vapor pressure oils are used in both stages of the pump to reduce backstreaming. The gas exiting the second stage is routed through a vent pipe with a drain to capture moisture and prevent it draining back into the pump. The vent pipe exhausts out the facility roof and is turned downward to prevent the entrance of ram water.

The mechanical pump is connected to the rear of the chamber via an eight inch diameter stainless steel line. The inlet of the mechanical pump is isolated from the line by a mechanical bellows. An LN₂ cold finger is positioned between the mechanical pumps and the vacuum chamber. An electro-pneumatic gate valve is located at the entrance of the eight inch line into the chamber. This valve closes when the crossover pressure of the cryopumps is achieved.

Nitrogen gas injection is used to assure viscous flow in the roughing pump line, and a LN₂ cold finger to trap oil backstreaming from the mechanical pump.

The cold finger was designed to have minimal pressure drop. The cold finger has an outer diameter of ten inches, surrounded by a 15 inch inner diameter jacket. The finger flow annulus is approximately twice the flow area of the eight inch pump line to account for turning and boundary layer flow losses in the finger.

**Helium Cryopumps**

Cryogenic pumping is a clean form of pumping. Since gas is pumped to the cold surfaces of the pump, there is no introduction of oil contaminants typical of mechanical or diffusion pumped systems.

The Helium Cryopumps used in this facility are Turbo Molecular-1200 (TM-1200) cryopumps manufactured by CVI of Columbus, Ohio (Figure 3.0). These pumps are two stage, consisting of an outer first (warm) 80 K stage and an inner second (cold) 15 K stage. Actual operational temperatures will be a function of the thermal heat load on the pumps, which is a function of tank geometry and radiative view factors from the engine.

The outer stage has two main functions. First, the outer stage completely surrounds the inner stage, baffling it from external heat sources and heat radiating from the thruster. Secondly, the outer stage acts as a water and hydrocarbon pump by cryocondensing these vapors onto its surface.

The inner stage has two components, a cryocondensing surface and a cryoadsorption surface. The cryocondensing surfaces condenses most of the gas in the pump except for hydrogen, helium and neon. The second component is a bed of activated carbon, the inlet to which is baffled to maximize the cryoadsorption of hydrogen, helium and neon.

**Operating Procedure**

The vacuum chamber is roughed down using the mechanical blower to a background pressure acceptable for cryopump operation (cross-over pressure). After the gate valve is closed, a 10 minute pressure Rate of Rise (ROR) test is conducted. Increasing pressure after rough down is due mainly to water evolution from the activated carbon elements of the cryopumps and the carbon lining of the facility. If the ROR is greater than 15 mtorr/minute, the roughing procedure is repeated until an acceptable ROR measurement is made. After an acceptable ROR
test is completed, LN2 flow is initiated to the cryopumps, and the He refrigerators are turned on.

Cryopump operation can be initiated over a range of acceptable pressures. The highest acceptable pressure is determined by the cryogenic geometry, the heat capacity of the gas, and the refrigeration capacity of the expander. The lowest pressure is one above which oil will not backstream from the mechanical roughing system to the chamber.

The upper pressure boundary for cryopump operation is a function of the pump's inner and outer stage geometry, the heat and refrigerative capacity of the inner stage, and the volume of residual atmospheric gas after the roughing pump is finished. This upper cross-over pressure can be determined from Equation 1:

$$P_{C_{\text{max}}} = \frac{PV_i}{V}$$  \hspace{1cm} \text{Eqn. 1}

In Equation 1, $P_{C_{\text{max}}}$ is the maximum allowable crossover pressure, $V$ is the volume of the chamber, including pump volume, and $PV_i$ is the maximum quantity of burst gas admissible to the pump without irreversibly warming the pump. The value of $PV_i$ is typically supplied by the pump manufacturer. The TM-1200 pumps are rated at $PV_i = 2000$ torr x liters$^3$.

Combining this with the theoretical value for the facility volume results in an upper cross-over pressure boundary of 90 mtorr.

Oil backstreaming from the mechanical pump occurs when flow in the roughing lines transitions from viscous flow to free molecular flow. This occurs when the characteristic Knudsen number (Kn) falls below $Kn < 0.01$, where Kn is defined to be:

$$Kn = \frac{\lambda}{d}$$  \hspace{1cm} \text{Eqn. 2}

In Equation 2 $\lambda$ is the mean free path of the gas and $d$ is the diameter of the pipe. $\lambda$ is defined as:

$$\lambda = \frac{1}{\sqrt{2\pi d^2n}}$$  \hspace{1cm} \text{Eqn. 3}

In Equation 3, $d_o$ is the molecular diameter of the gas and $n$ is the gas density (molecules/unit volume).

Combination of equations 2, 3, and the ideal gas law, assuming an average molecular diameter for air of 0.372 nm and a roughing line diameter of 8 inches, the lower boundary of viscous flow for the roughing system is approximately 25 mtorr. Measurement of the pressure at the inlet to the mechanical roughing pump minimizes the risk of oil backstreaming.

A cross-over pressure of 75 mtorr, as measured at the inlet to the mechanical pump, is used for the HET facility.

**Pumping Speed & Operational Pressure**

The steady state cryogenic pumping speed for each pump is determined by the operational temperature of the second stage, which is dependent on facility geometry and the resultant heat load on the cryogenic surfaces. Pumping speeds for the TM-1200 have been reported from between 16,000 to 27,00 liters/sec for xenon$^6$$^7$.

The ultimate operating pressure of the test facility is dependent on both the pumping speed of the cryopumps and thruster propellant flow rate. Pump down transients and steady state operational pressure can be approximated from:

$$P = P_0e^{-St/V} + \frac{Q}{S}$$  \hspace{1cm} \text{Eqn. 4}

In Equation 4 $P_0$ is some initial tank pressure, $S$ is the speed for the facility pumps (in volume/unit time), $t$ is time and $V$ is the system volume.

$$Q = m\text{dot} \times R \times T$$  \hspace{1cm} \text{Eqn. 5}

In equation 5 $Q$ is the thruster throughput (pressure x volume/unit time), $m\text{dot}$ is the thruster propellant flow rate (mass/unit time), $R$ is the gas constant and $T$ is the gas temperature.
Combining Equations 4 & 5 and assuming a 5 kW HET thruster with a propellant flow rate of 15 mg/sec, the theoretical steady state facility back ground pressure varies between 0.026 and 0.045 mtorr for the two reported pump speeds.

**Regeneration**

Regeneration of the cryopumps occurs whenever the flow of LN2 is terminated from the first stage, and power is removed from the compressor for the second stage. For the HET facility, there are three scenarios when regeneration occurs.

1. testing of an engine is completed and the chamber is to be opened
2. the maximum amount of propellant that the cryogenic surfaces can mechanically support has been adsorbed. CVI recommends than no more than 20 lbm of xenon be adsorbed per pump at any time
3. power fails in the facility, stopping the compressors and the flow of LN2

The first two scenarios are controlled warming cycles of the pumps. A nitrogen gas purge warms the second stage first, followed by the first stage. In doing so the water desorbed from the first stage is not condensed on the second stage’s charcoal element. The mechanical roughing system is turned on to remove the evolved gases and the nitrogen purge. The flow rate of the nitrogen is set to maintain viscous flow in the roughing lines.

In the event of a power failure, the cryopumps will warm without the benefits of a warm N₂ purge or mechanical roughing. The evolved gas will increase pressure in the test chamber, potentially risking overpressurization of the facility. A relief valve is placed on the facility to relieve overpressure if the facility pressure increase to 0.07 psi above ambient. At this pressure, a resultant force of 400 lbf is placed on the chamber door, which is secured by an arrangements of clamps.

**Carbon Lining and Backsputtering**

Impingement of a surface by energetic ions results in surface heating and sputtering of material from charge exchange and transfer of kinetic energy between the ions and the target surface. For a constant ion flux density impinging on a surface, the sputter rate of a substance is proportional to:

\[
\frac{dh}{dt} \approx \frac{M \times S_j}{\rho} \times I_{flux}
\]

Eqn. 6

In Equation 6, \(h\) is the eroded target thickness, \(t\) is the target exposure time, \(M\) is the target material atomic weight, \(S_j\) is the target material sputter yield for specific target material and ion type (atoms sputtered/ion), \(I_{flux}\) is the angular dependent ion flux per unit area on the impinged surface and \(\rho\) is the material's density. Higher values of \((M \times S_j)/\rho\) yield higher sputter rates of the impinged material for a given \(I_{flux}\).

Table 1.0 compares the relationship of \((M \times S_j)/\rho\) for iron and carbon for 300 eV xenon ions impinging at normal incidence:

<table>
<thead>
<tr>
<th>material</th>
<th>((M \times S_j)/\rho)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.4</td>
</tr>
<tr>
<td>Fe</td>
<td>4.0</td>
</tr>
</tbody>
</table>

The sputter yield of carbon is an order of magnitude smaller that that of iron for a given flux of xenon ions. Use of the carbon lining of the HET facility reduces the amount of material sputtered and prevents erosion of the facility walls.

**Instrumentation**

Instrumentation for the HET facility is a combination of several pressure transducers to monitor propellant pressures at various points in the feed system, a linear transducer for thrust measurement, thermal mass propellant flow control units/meters, numerous thermocouples, and ion gages to measure facility pressure during thruster operation. Thruster operation, data acquisition and reduction are controlled from the main data acquisition system (DACS). This system was developed as an independent, mobile system to facilitate transition of laboratory thruster testing to full scale spacecraft integration
evaluation in TRW's M1 Space Simulator facility.

**DACS**

The DACS architecture is composed of a National Instruments VXI bus. An industrial computer running LabVIEW interfaces to the VXI components using National Instruments high speed MXI interface connection. The VXI bus controls data synchronization, thermocouple and transducer signal conditioning, and provides discrete analog output voltages to control accessory thruster devices.

A GPIB IEEE 488.2 interface is also included in the industrial computer. This interface controls thruster power supplies, monitors power supply output voltages and currents, monitors facility background pressure, and is used to trigger and monitor the laboratory oscilloscope.

The VXI architecture was chosen for its low noise, flexibility, expandability, and to minimize integration issues typically associated with DACS using multiple components and vendors.

Data reduction is accomplished by the computer using the LabVIEW software. Real time test measurements are displayed on the computer monitor. Test data can be printed as required. Large data files are transferred to a workstation using the building LAN for manipulation. Using National Instruments Internet Developers Toolkit, a password protected website is established allowing remote access to real time data and test control.

**Thrust Stand**

The facility includes thrust measurement capability utilizing a water cooled, inverted pendulum thrust stand design of the type developed by NASA Lewis, used previously to evaluate various HET's. The thrust stand is capable of in situ calibration. 1 thrust resolution is between 20 and 200 mN with an accuracy of +/- 1.5%.

**Facility Pressure Measurement**

Measurement of facility pressure is accomplished using a combination of two thermocouple pressure transducers and two ion gages. Both sets of gages are controlled via a Granville Philips 307 Vacuum Gage Controller. A GPIB IEEE 488.2 connection is used by the DACS to record facility background pressure. The complete system of gages and controllers were calibrated for xenon to improve measurement accuracy.

Figure 2.0 shows the location of the four pressure sensing devices. One of the thermocouple transducers is located immediately upstream of the mechanical pump. This measurements is used to maintain viscous flow in the roughing system during pump down of the facility.

The two ion gages are isolated from the facility with gate valves. The gate valves are closed when high vacuum is not present to minimize contamination and prevent burning out the ion tube filaments at higher facility pressure.

**Support Equipment**

The laboratory xenon propellant feed system and laboratory power supply were developed as independent, mobile systems to facilitate transition of laboratory thruster testing to full scale spacecraft integration evaluation in TRW's M1 Space Simulator facility.

**Xenon Propellant Feed System**

The laboratory feed system is a self contained fuel plate capable of supplying xenon propellant from 0 - 200 scem to the main thruster discharge cavity using a thermal mass type flow meter/controller (Figure 4.0). A second flow meter/controller with a range of 0 - 20 scem is provided to regulate the flow of xenon through the cathode. Accuracy of propellant flow measurement is better than 1%.

The thermal mass type flow meter/controllers are digital devices manufactured by UNIT instruments of Yorba, CA. These devices are calibrated specifically for xenon. Flow rate is determined using thermal mass measurement, and an internal feedback loop regulates the flow rate from an externally supplied set point.
Laboratory Power Supply

The laboratory power supply consists of an integrated system of six off the shelf power supplies and a custom control, start and filtering circuit (Figure 5.0). This equipment is integrated into a single, mobile enclosure. Control and monitoring of the power supplies is accomplished using a combination of a Control Printed Circuit Board (CPCB) and a GPIB IEEE 488.2 interface with the DACS. Figure 6.0 shows the CPCB block diagram.

Maximum deliverable discharge power of the power supply is 10 kW. The ignitor supply is capable of starting both heated and non-heated HET cathodes.

Power Supplies

The Discharge Power Supply (DPS) provides the main power to operate the HET. The CPCB monitors discharge current using a Hall sensor. The Keeper Power Supply (KPS) provides DC voltage to the keeper electrode through the isolation diode installed in the CPCB. The maximum voltage is 50 VDC.

The Ignitor Power Supply (IPS) provides the voltage needed to run the high voltage Fly Back Circuit (FBC) installed on the CPCB. The FBC produces the high voltage pulses needed to start the HET. The high voltage pulses and the DC voltage from the KPS are supplied to the ignitor electrode.

The Heater Power Supply (HPS) provides power to pre-heat cathodes prior to attempting engine start. Heating the cathode prior to ignition reduces the work function of the material used for electron emission, enabling the cathode to break down at lower voltages and with greater emission stability and reduces cathode wear.

The Magnet Power Supplies (MPS) are used to supply current to form the magnetic field in the engine. Two supplies are included in the laboratory rack to allow optimization of development thrusters.

Ignition Circuit & CPCB

During start-up, a series of high voltage pulses are supplied to start the engine from the FBC. Multiple pulses may be required to ensure successful cathode ignition. The CPCB contains a Voltage Controlled Oscillator (VCO) with the frequency range of 1 - 20 kHz. The output frequency is adjustable. The VCO drives a slave timer circuit with the range of 4 to 20 micro-sec. The duty cycle is adjustable and is used to adjust the pulse peak voltage.

The slave timer drives the FBC. The FBC produces high voltage pulses at a set frequency and voltage. The high voltage output pulses are added to the DC voltage obtained from the KPS and are sent to a preload circuit.

The preload circuit is used to adjust the pulse width of the pulses. A variable capacitor provides energy storage for the high voltage pulses. The smaller the capacitance, the shorter the output pulse will be. The pulse width adjustment range for an unloaded circuit is 2 to 15 micro-sec. The output voltage will also decrease with the keeper current.

Conclusion

TRW's HET facility will be operational in the fall of 1997. This facility will enable TRW to evaluate the interactions required to understand spacecraft impacts associated with use of HET operating at up to 10 kW for on-orbit propulsion. Facility capabilities include operation of laboratory through flight HET systems and the evaluation of thruster and thruster system performance.

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Figure 1.1 HET Facility - LN2 finger, vacuum pipe, cryocompressors, cryopumps

Figure 1.2 HET Facility - xenon propellant plate, viewport, cryopump