LIFE TESTING OF THE HOLLOW CATHODE PLASMA CONTACTOR FOR THE ProSEDS MISSION

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ABSTRACT

The Propulsive Small Expendable Deployer System (ProSEDS) mission is designed to provide an on-orbit demonstration of the electrodynamic propulsion capabilities of tethers in space. The ProSEDS experiment will be a secondary payload on a Delta II unmanned expendable booster. A 5-km conductive tether is attached to the Delta II second stage and collects current from the low Earth orbit (LEO) plasma. A hollow cathode plasma contactor (HCPC) emits the collected electrons from the Delta II, completing the electrical circuit with the ambient plasma. The current flowing through the tether generates thrust based on the Lorentz Force Law. The thrust will be generated opposite to the velocity vector, slowing down the spacecraft and causing it to de-orbit in approximately 14 days compared to the normal 6 months. A 10-km non-conductive tether is between the conductive tether and an endmass containing several scientific instruments.

Extensive testing of a development unit for the HCPC has been performed at the Marshall Space Flight Center. The purpose to the testing was to examine the HCPC design and ensure that the design would meet the unique requirements of the ProSEDS mission. Because of the science requirements to measure the background ambient plasma, the HCPC must operate on a duty cycle, where the HCPC is shutdown once every minute while on orbit. Because of this unique requirement, the development unit for tested for a simulated ProSEDS mission where the HCPC was cycled on and off for 10,095 cycles.

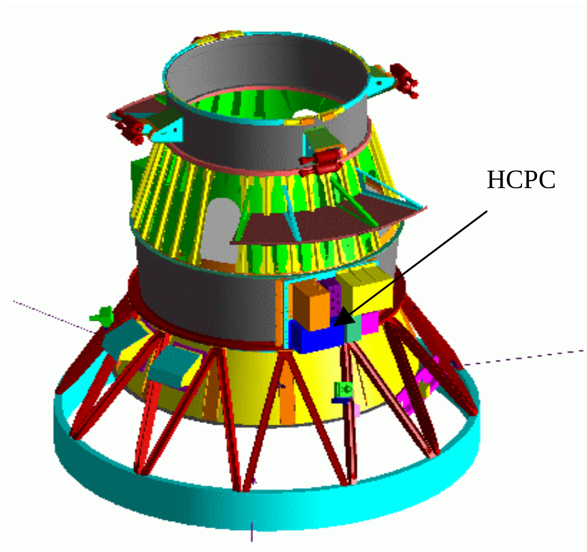

Figure 1 ProSEDS attached to Delta II second stage

INTRODUCTION

ProSEDS will be attached to the Delta II second stage (fig. 1) and will demonstrate the use of electrodynamic tethers as a thrust-generating device. The generated force is either in the direction of the velocity vector or opposing the motion. In the case of ProSEDS, the force is opposing the motion and will cause the Delta II second stage to de-orbit in about 14 days compared to the normal six months.

After the third stage firing, the tether will be deployed. The tether deployer will remain attached to the second stage. The section of tether closest to the second stage is electrically insulated to prevent arcing back to the Delta. Five kilometers of electrically conductive tether and up to 10 km of non-conductive tether will be deployed and are attached to an endmass with scientific instruments. Kevlar is used as needed at transition points for strength, snag prevention, and protection from third stage exhaust.

As the tether cuts across the Earth's magnetic field, a voltage is induced across the wire. Electrons are attracted to the positively biased end of the wire farthest from the Delta. Current flowing through the tether experiences a drag force because of interaction with Earth's magnetic field. This drag force is coupled mechanically to the stage via the tether, which lowers the orbit. The Hollow Cathode Plasma Contactor (HCPC) on ProSEDS will emit electrons back to space. The HCPC was designed and built by Electric Propulsion Laboratory of Monument, CO.

The HCPC emits electrons to the ambient space plasma using improvements in standard hollow cathode technology[1]. These improvements allow the HCPC to consume less power and operate using lower gas flowrates than standard hollow cathodes. The HCPC unit uses xenon as the expellant of the system and is capable of 10-A emission current at 2 standard cubic centimeters per minute (sccm) flowrate.

The ProSEDS mission lifetime was set at 1 day because most of the primary objectives can be met in that time. The extended ProSEDS mission will be for as many days as possible, until the Delta II second stage burns up or the tether is severed by a micrometeoroid or space debris particle. The HCPC unit has been designed for a 12-day mission. Because of the science requirements to measure the background ambient plasma and open circuit tether voltage, the

ProSEDS hardware is cycled off and on depending on the time during the mission. During the first seven orbits after launch, ProSEDS will employ a 60-second cycle, and for the remainder of the mission, ProSEDS will employ an 80-second cycle to allow charging of the secondary battery. Consequently, the HCPC operation will be shut down for 30 seconds of both these cycles to allow for the ambient plasma measurements.

LIFE CYCLE REQUIREMENTS

The number of cycles for the HCPC lifetime test was calculated based on a 12-day mission. Early in the mission, the HCPC will operate in a pulsed 60-second cycle, 30 seconds off and 30 seconds on. During the off cycle, the xenon flow is completely shut down, the keeper is disabled, but the heater is enabled to heat the hollow cathode for the next ignition. Twenty-nine seconds into the cycle, the keeper power supply is turned on, and the heater power supply is turned off. At thirty seconds, gas flow is enabled, allowing the unit to start. When ignition occurs, the keeper draws current, thereby placing the power supplies into constant current mode and the keeper voltage drops. ProSEDS plans to operate using the 60-second cycle during the first 7 orbits on the primary battery.

After the first seven orbits and for the remainder of the 12-day mission, the HCPC will operate in an 80-second cycle. During the 80-second cycle, the HCPC is off for 30 seconds and on for 50 seconds. After the normal 30 seconds of being shut down, the HCPC is turned on and ProSEDS data collected. The first 15 seconds during this period is used to measure the tether performance and the remaining 35 seconds are used to charge the secondary battery. Also during this cycle, when the tether current is greater than 1.5-A, the keeper power is turned off, reducing power draw on the secondary battery. This reduces the time the secondary battery is in the complete recharge mode, providing a greater amount of science data returned. When the secondary battery reaches a 60% state of charge, the mission will go into a battery recovery phase where all the current collected by the tether will be used to charge the secondary battery. This occurs about 30% of the time during the 80-second cycle.

During every cycle of the ProSEDS mission, the HCPC is turned off and on one time. For the entire ProSEDS mission, it was calculated that the HCPC would undergo a total of 9,371 on/off cycles. This number takes into account the time employing the 60-second cycle, the 80 second cycle, and the time in battery recharge mode where no cycle occurs. The goal of the lifetime test of the development unit of the HCPC was to complete 10,000 on/off cycles. These cycles were entirely 60-second cycles primarily to save time. During the 60-second cycle, the keeper power was on part of the time and off part of the time. Several tests were done on the 80-second cycle for software verification prior to beginning the life test.

TEST SET-UP AND PROCEDURE

The HCPC development unit was placed into a 1.2-m by 3-m diffusion pumped vacuum chamber (fig. 2). The vacuum chamber is capable of a base pressure of 2×10^{-6} Torr and 6×10^{-5} Torr when the HCPC is operating. The chamber is equipped with a plasma source that produces a diffuse ambient plasma to simulate LEO space conditions. The ambient plasma source was not used during the lifetime tests.

A large stainless steel anode plate, which was isolated from ground, was placed in the chamber to collect the electrons from the HCPC. The electron collection was facilitated using a 100 V, 10 A power supply. Also, during initial testing of the HCPC we determined that adding a resistor to the circuit helped to stabilize operation of the HCPC. The entire experiment was powered using a 28 V, 10 A power supply, and the power was fed through the ProSEDS Data System Electronics Box (DSEB) prototype. The DSEB was used to control the HCPC cycling using test software. The experiment was monitored during operation using computer software, and if a problem occurred, the experiment was shut down via a relay. The experiment set-up is detailed in figure 3.

Figure 2 HCPC in MSFC Test Chamber

As much as possible, the HCPC development unit used the same parts as the flight unit design. The hollow cathode used in this test was from the same lot that the flight cathode was produced. In the electrical system, the same DC/DC converters to power the heater and keeper were used. The main difference between the development unit and the flight unit was that the xenon gas tank for the development unit was made of stainless steel. The flight unit gas tank is made of aluminum. Both tanks are of the same volume. Finally, the development unit physically was twice the size as the flight unit (38.8 cm long x 38.8 cm wide x 12.7 cm high).

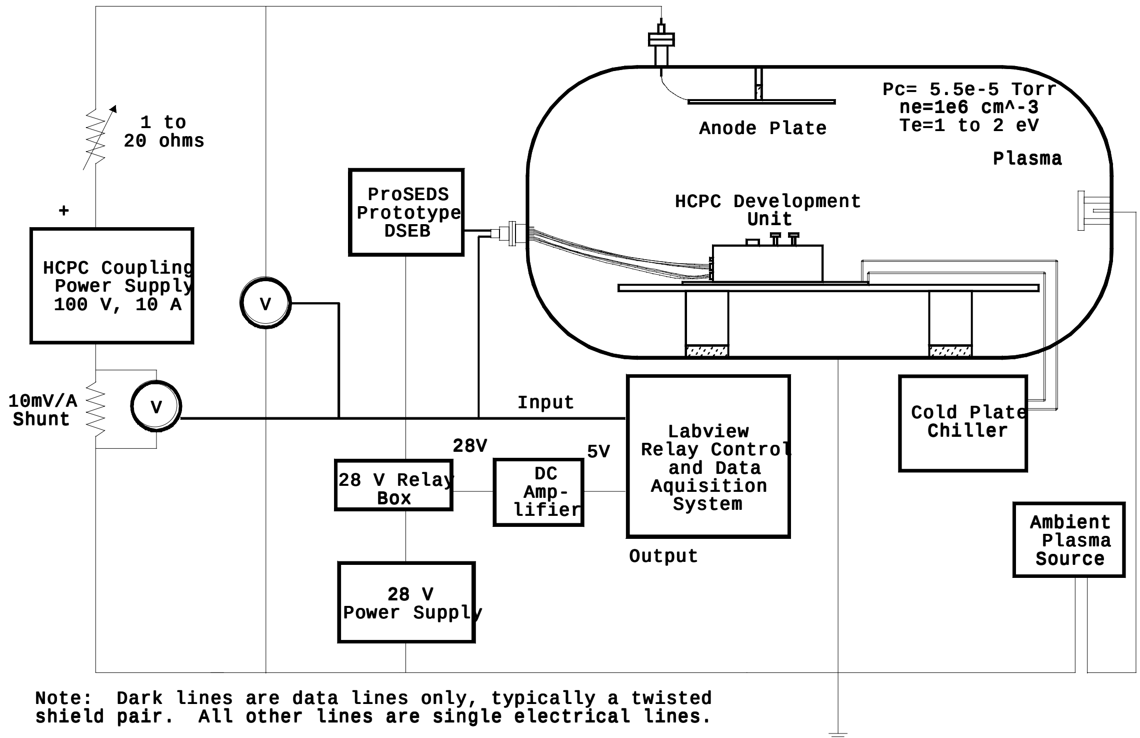

Figure 3. Plasma chamber set-up with HCPC and DSEB

TEST RESULTS

The life test was started by placing the HCPC in the vacuum chamber, pumping the chamber down, and running the conditioning cycle. During the conditioning cycle, the cathode heater voltage as a function of time was recorded and is shown in Figure 4. The conditioning cycle consists of two segments. The first segment is a 15-minute gas purge cycle, and the second segment is a 54-minute heating cycle. The 54 minute heating cycle is broken up into a 9 minute off cycle, 10 minute on cycle, 8 minute off cycle, 10 minute on cycle, 7 minute off cycle, and finally a 10 minute on cycle. During the 10-minute on cycle, the heaters are pulsed on 5 seconds and off 10 seconds continuously during this period.

After the HCPC had been conditioned, it was started using a first time cold start procedure. During the first time cold start, the cathode heater is turned on and held for approximately 150 seconds. After this time, the heater is turned off, the keeper voltage is raised to 60 V, and the gas valve is opened, igniting the HCPC. Data from a first time cold start is shown in figure 5. As can be seen from this set of data, the emission current was set at 0.8 A. The HCPC did not experience any problems starting for the first time using this process.

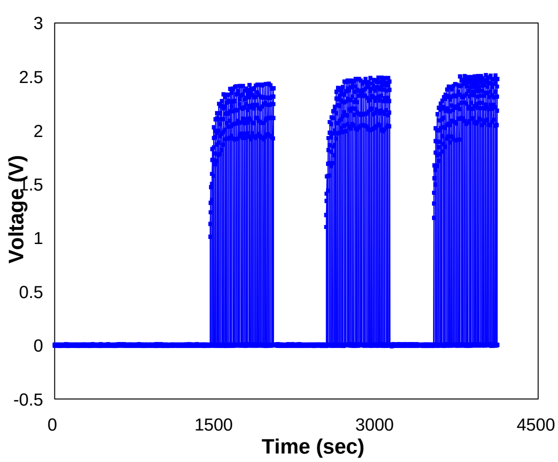

Figure 4 Heater voltage during the conditioning cycle

The second phase of testing was to simulate the HCPC cycling during the duration of the ProSEDS mission. During this test, the 60-second cycle was employed for the sake of time. However, the DSEB software was configured so that the keeper voltage would remain on for part of the test and could be shut down for part of it as well. During the life test, emission current was varied from 0.5 to 5 A. Typical HCPC parameters for a 60 s cycle are shown in figure 6. Throughout the test, the keeper voltage, heater voltage, emission current, coupling voltage, tank pressure, and 28 V input power were measured.

Figure 7 is a comparison of the keeper voltage at various emission currents measured at the beginning of the test and after 10,095 on/off cycles. The data in this figure was collected by holding the emission current at a given level for three complete cycles. When the three cycles were completed, the emission current was increased from 0.5 to 5 A. As Figure 8 shows, only small changes were noted, indicative of the performance of the hollow cathode throughout the test.

Figure 8 shows coupling voltage data at various emission current settings. The coupling voltage is a measure of how effectively the HCPC emits electrons to the stainless steel anode. This figure shows that over the duration of the test, the coupling voltage did not vary significantly throughout the life test.

Figure 9 shows the decrease in pressure in the xenon gas tank due to consumption during the HCPC life test. Thermal variations at the beginning of the test series are apparent because of the spread in the data. The large step change in the middle of the testing is also due to temperature changes. At this point, our liquid nitrogen was used up, and we had to shut down the test until the next day. At this time we adjusted the cooling capacity on our cooling system, lowering the operating temperature from 60 °C to 30 °C. The gas flow rate of the system was estimated to be 1.5 sccm ± 0.5 sccm based on the pressure changes shown in this graph.

CONCLUSIONS

An operational HCPC is vital to the mission success of ProSEDS. Testing of the developmental unit was very satisfactory, showing that the hollow cathode was able to operate in a duty cycle for 10,095 cycles. A slight decrease between the initial and final keeper voltage was noted over the range of emission currents. Also encountered during the test were cooling problems. The HCPC has a temperature limit on the DC/DC converters. Improved thermal interface between the HCPC and the cooling plate resolved this problem.

ACKNOWLEDGMENTS

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REFERENCE

1. G. Aston, M. B. Aston, and J. D. Williams, “Integrated Hollow Cathodes for Space Applications,” 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, AIAA Paper 98-3477, July 1998.

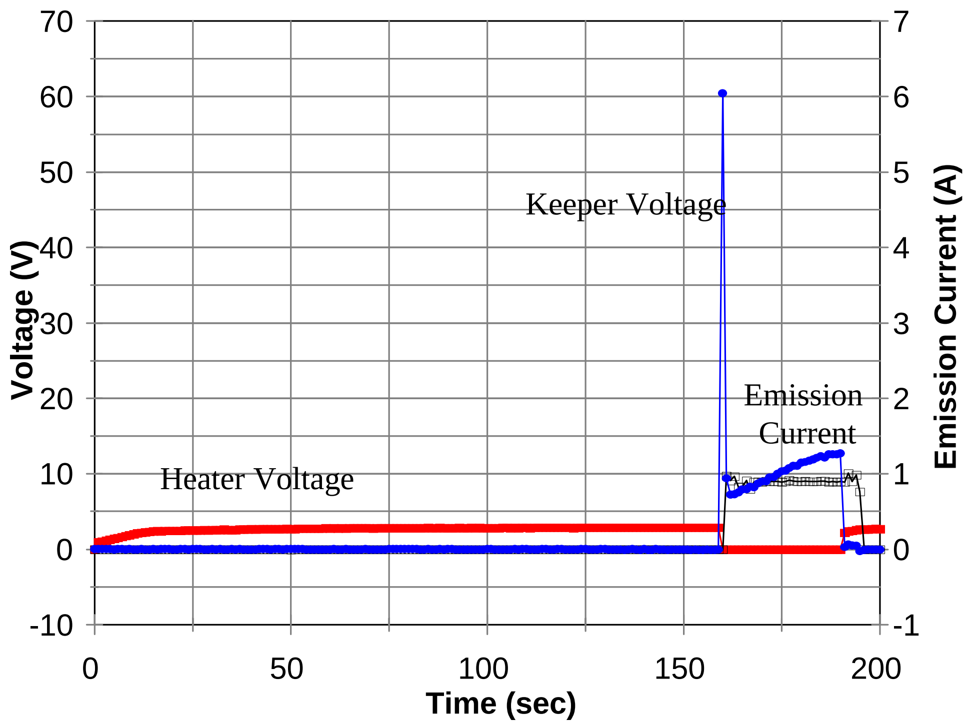

Figure 5. Typical first time cold start characteristics.

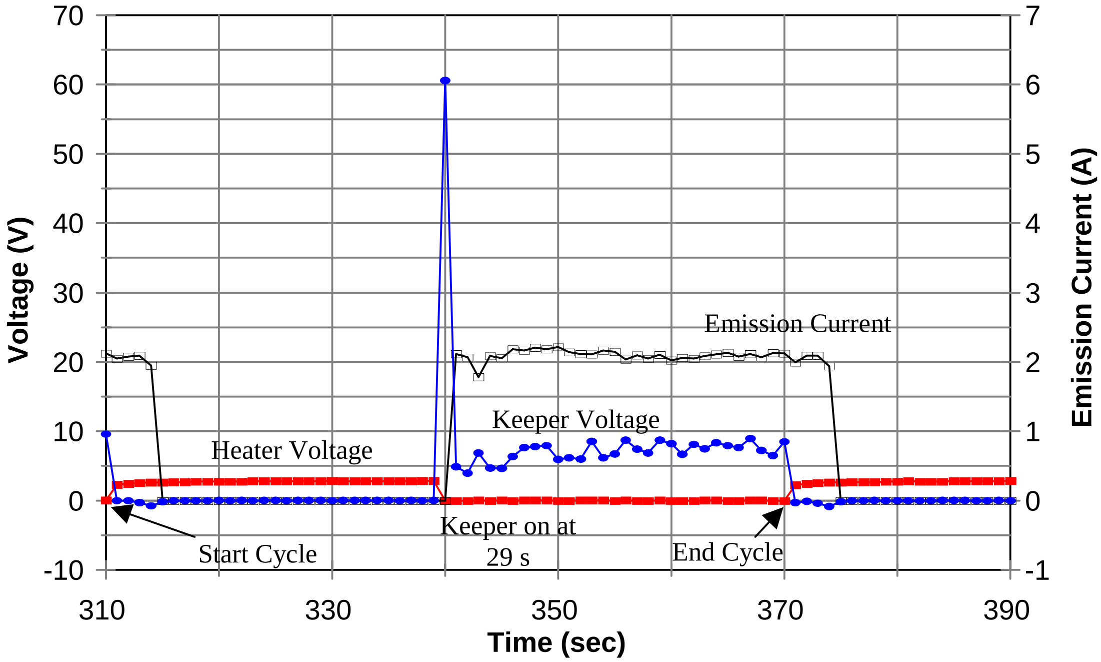

Figure 6. Typical 60-second cycle characteristics

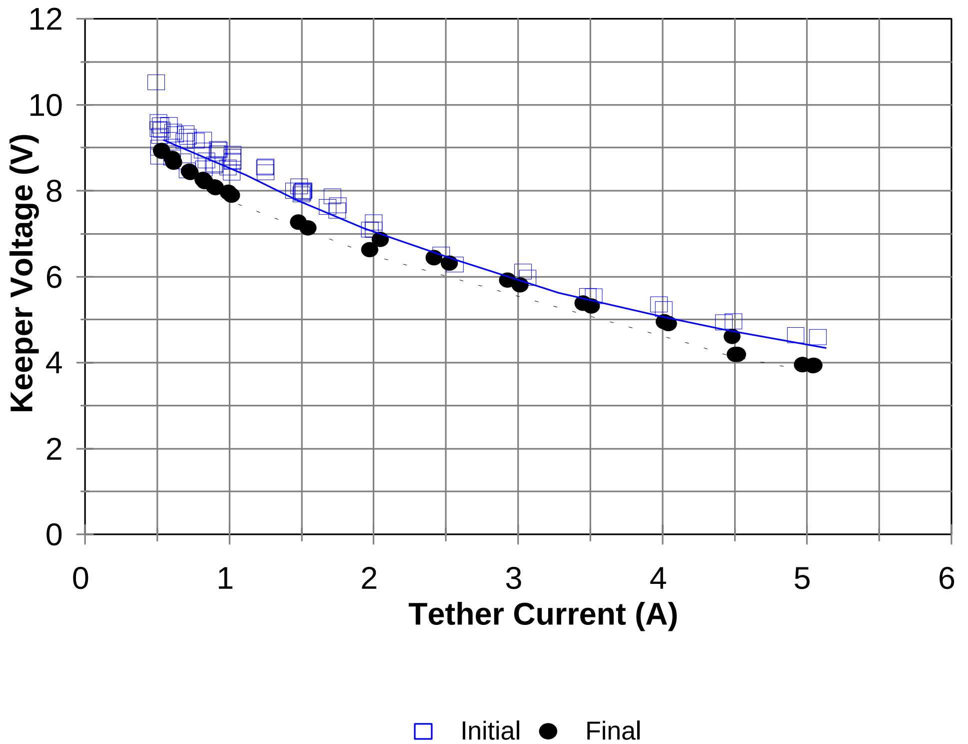

Figure 7. Keeper voltage over life test

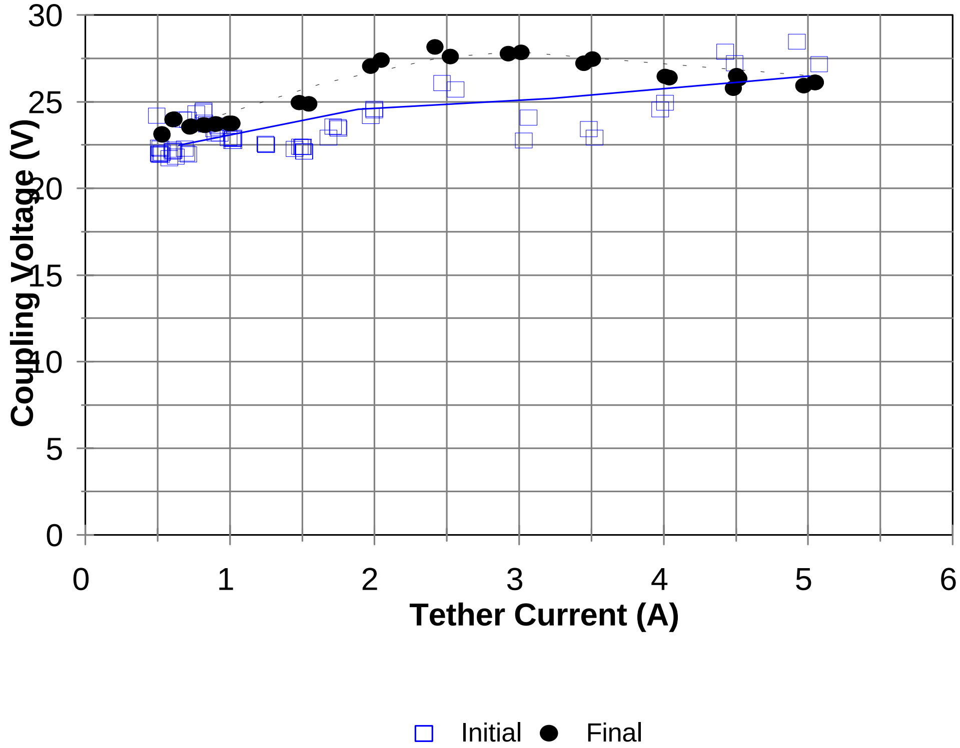

Figure 8. Coupling voltage over life test

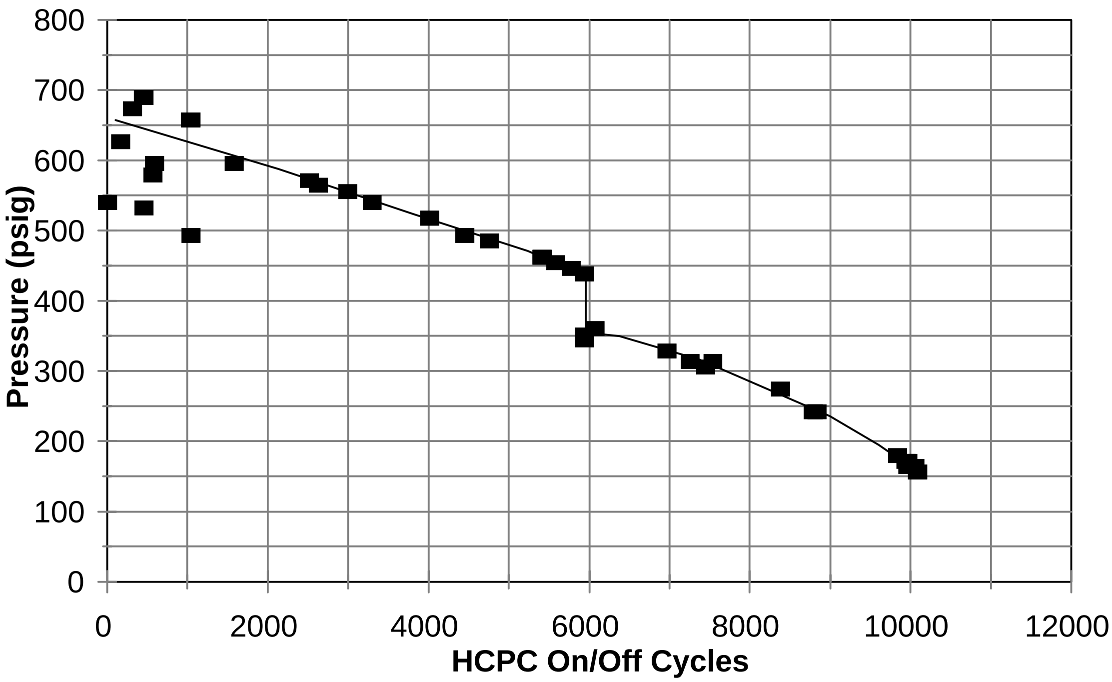

Figure 9. Pressure in xenon gas tank over life test