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Space Station Cathode Ignition Test Status at 32,000 Cycles

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A plasma contactor system has been baselined for the International Space Station for structural potential control. An ignition procedure was developed for the plasma contactor hollow cathode assembly (HCA). To demonstrate the required 99% HCA ignition reliability over 6,000 cycles, an ignition test was conducted. An accelerated test procedure was employed to rapidly accumulate ignition cycles. The test procedure minimized the differences between accelerated and non-accelerated test results. The development HCA used in this test has achieved 32,000 ignitions to date. The HCA has been qualified for cyclic operation, which could reduce xenon consumption and extend the life of the plasma contactor system.

Introduction

The International Space Station (ISS) requires a plasma contactor system for structural charge control. The plasma contactor system consists of a hollow cathode assembly (HCA), xenon gas feed system, and power electronics. There are two HCA requirements specific to its ignition.[1] The HCA is required to ignite a minimum of 10 times, taking less than 6.0 minutes for each ignition. The HCA is also required to demonstrate a minimum of 6,000 ignition cycles with at least 99% reliability.

An ignition test of a prototype HCA was previously conducted.[2] The ignition procedure employed by this test utilized a pre-heat phase and a pulsed ignitor to initiate the HCA discharge. This accelerated ignition test was voluntarily terminated after demonstrating a total of 3,615 cycles.

In order to demonstrate the HCA ignition requirements, a test using a new ignition procedure on a high fidelity development model HCA was conducted. This test has achieved, to date, 32,000 ignition cycles with 99.98% reliability.

Test Article

A hollow cathode assembly is shown in Figure 1. The test article was a development unit hollow cathode assembly,[1] designated HCA.014.

The HCA consists of a hollow cathode containing a low work function electron emitter. A heater is helically wound about the exterior of the cathode tube. At its downstream end, the cathode tube is terminated by an orifice plate. Enclosing the cathode is a cylindrical anode, terminated with an orifice plate. The design of the test article is identical to that of the flight HCAs,[1] except for the wire gauge of one of its three power leads.

Test Equipment

Vacuum Facility

The ignition test was performed in an 84 liter cryopumped chamber, with a xenon pumping speed of 2,100 liters per second.[2] The facility had a base pressure of 2.0×10^{-5} Pa and an operating pressure of 3.0×10^{-2} Pa at normal test conditions.

Laboratory Gas Feed System

A laboratory gas feed system, visible in Figure 2, was used to deliver xenon gas to the HCA. The xenon flow rate was measured and controlled with a mass flow controller. A mass flow meter was located upstream of the flow controller to provide a redundant flow measurement.

The mass flow meter and controller were calibrated prior to the start of the test using a volumetric flow calibrator, traceable to a primary standard. Feed system protocols[2] appropriate for HCAs were used to mitigate xenon gas contamination.

Power Supplies

The HCA power supplies provide heater power, anode power, and the ignitor pulse train. The output specifications of the power supplies were identical to the ISS plasma contactor power electronics specifications.[1]

A heater power supply provided a constant current of up to 8.5 ADC to the heater. The anode power supply provided a constant current of 3.0 ADC to the cathode at a maximum voltage of 40 VDC. Details on the breadboard power supplies have been described elsewhere.[3,4,5]

The anode power supply also provided ignition pulses used to initiate the discharge. The output filter inductor was used as a pulse transformer for the ignition circuit. Additional turns were added to act as the primary winding of the pulse transformer. This winding was charged by applying a voltage across the winding by means of a transistor. The transistor was then turned off causing a large flyback pulse on the primary winding which was then amplified by the turns ratio of the transformer. The turn off time of the transistor controls the duration of the start pulse while the on time of the transistor controls the voltage magnitude. This starting technique has been used in other applications.[3,6]

The output pulse had a peak value of approximately 750 ± 100 V and a pulse width of about 14 μs. The energy in the pulse was approximately 200 mJ and the pulse frequency was 10 Hz.

Data Acquisition and Control System

The test was computer controlled to facilitate unattended operation. Controlled parameters included heater and anode currents, xenon flow rate, ignitor operation, and sequencing. Test chamber pressure, heater and anode currents and voltages, xenon flow rate, and cathode tip temperature data were automatically acquired. Data were displayed and stored electronically.

The breadboard power supplies provided heater and anode telemetry, which were verified using digital multimeters. An oscilloscope was used to observe high frequency data, such as the ignitor pulse form and the AC components of the heater and anode voltages. The test article environment pressure was measured with a Bayard-Alpert gauge.

The HCA cathode orifice plate temperature was measured with an electronic pyrometer. This pyrometer reading was automatically recorded by the data acquisition system. Independent measurements of the HCA cathode orifice plate temperature were manually obtained with a disappearing filament, optical pyrometer.

Test Procedures

Test Plan

The test plan consisted of cyclic operation of the HCA using two profiles. Most of the cycles were accumulated using an accelerated profile, which was defined after an initial test period that accumulated 125 ignitions. During these initial ignitions, the HCA operation and dormant times were varied to assess their impact on the ignition behavior.

The accelerated profile consisted of one minute HCA operation followed by twenty minutes dormancy. The HCA is considered on when the anode current reaches its nominal 3.0 A value. One minute was sufficient for the anode voltage to reach 90% of its steady state value. The twenty minutes dormancy was the minimum off time required to prevent the HCA from immediately igniting upon application of the 40 V anode voltage without ignitor pulses.

At 3,000 cycle intervals, ignition cycles were performed using a nominal mission profile, which simulated on-orbit operation. The mission profile consisted of fifty minutes operation followed by forty minutes dormancy.[7] Table I lists the operating profiles during the test. The HCA was operated with these two profiles to establish a correlation between the accelerated profile and mission profile ignition characteristics over the course of the test.

The xenon flow range specified for the flight HCAs is 5.8 to 7.5 sccm.[1] During both accelerated and mission profile operation, the nominal xenon flow rate was set to 6.0 sccm.

Test Article Preparation

After installation, and whenever the HCA was exposed to air, the HCA was conditioned with a timed heater sequence. The purpose of this conditioning is to remove adsorbed contaminants from the electron emitter.

Characterization tests were performed on the HCA over a range of xenon flow rates. The characterization tests consisted of igniting the HCA, systematically varying the xenon flow rate, and recording the HCA parameters. Such tests were conducted prior to the ignition test and subsequent to unscheduled test interruptions.

Ignition

The ignition procedure was as follows. Heater power of 73 to 76 W was applied. After 3.4 minutes, a xenon gas flow of 6.0 sccm was initiated. After a 4 second flow stabilization period, the anode open circuit voltage and ignition pulse were applied. The heater power was maintained until an anode current of greater than 2.5 A was detected. Subsequently, the heater and ignitor were shut off.

For the purposes of this test, if ignition did not take place within thirty minutes, the ignition was considered a failure. Figure 3 shows the HCA parameters during a typical ignition cycle.

Results and Discussion

Test Article Characterization

Data from the pre-test and the most recent characterizations, performed after 29,277 ignition cycles, are shown in Figure 4. Over the flow rate range of 5.8 to 7.5 sccm, specified for the flight model HCAs, the anode voltage has remained between 12.0 and 15.0 V. As indicated in Figure 4, the characteristic of the test article did not change appreciably over the duration of the ignition test.

The anode voltage of the HCA at the end of each operating period is shown in Figure 5. This parameter, which averaged 13.8 V, began with a minimum value of 11.6 V and reached a maximum value of 17.4 V. Based upon HCA performance assessments performed elsewhere,[1] these values are well within acceptable limits.

Ignition Behavior

One vital parameter measured during the ignition test was the time required to ignite the HCA. Ignition time is plotted in Figure 6. The average ignition time was 4.4 minutes with a population standard deviation of 0.45 minutes.

The HCA took slightly longer to ignite when operated using the mission profile. The ignition time using the mission profile averaged 0.8 minutes longer compared to accelerated cycle ignition times. The cause of this discrepancy is related to the temperature of the HCA at the beginning of each cycle. During the accelerated testing, the HCA is dormant for twenty minutes, whereas the HCA is dormant for forty minutes during mission profile operation. Hence, during mission profile operation, the HCA takes longer to reach the temperature required to establish sufficient thermionic emission to ignite the HCA.

On five occasions, the ignition time exceeded 12 minutes. The longest ignition time was approximately 23 minutes. These singular, long ignitions were indicative of restarts after a prolonged dormant period.

After 27,000 cycles, the HCA failed to ignite within 30 minutes upon changing from the accelerated test mode to the mission profile operation. No malfunction was detected in the test equipment. A continuity test of the HCA wiring revealed no problems with the HCA. During the attempted restart of the test, the HCA ignited in 4.3 minutes. A succeeding characterization test showed no anomalies in the HCA operation. Since that time, HCA.014 has achieved a total of 32,000 ignition cycles without further ignition failures.

One consequence of cyclic HCA operation is increased life of the plasma contactor system. The on-orbit life of the plasma contactor is limited to two years of continuous operation by the size of the xenon tank. The ISS plasma contactor system life could be extended to three years, requiring approximately 11,800 HCA ignition cycles,[8,9] which the test article has surpassed.

A phenomenon observed periodically during the test were oscillating ignition times. An example of this behavior is shown in Figure 7. This behavior could not be attributed to the test support equipment and appears to be associated with the test article. However, this behavior does not effect the ability of the HCA to perform its function.

The effect of heater input power on ignition time was investigated on two separate occasions. Figure 8 shows the results of these tests. The ignition times are shorter at higher values of heater power. Over the heater power range of 70 to 78 W, this effect is approximately linear. After approximately 4,480 cycles, the ignition time with 70 W heater power was 5.62 minutes, decreasing 0.17 minutes per additional watt. At 21,090 cycles, the ignition time with 70 W heater power was 4.72 minutes, decreasing 0.10 minutes per additional watt. The heater power of the flight HCAs is limited to the range of 73 to 76 W. Over the entire heater power range investigated, the HCA ignition times were acceptable.

Heater Characteristics

The heater performance is reflected in the cathode tip temperature data and the heater power measurements. These data are depicted in Figures 9 and 10, respectively. The HCA cathode tip temperature was measured 3.5 minutes after the start of each ignition cycle. The average cathode tip temperature was 1,030 °C. The maximum heater power applied during each cycle averaged 74 W.

There appears to be a correlation between the heater power, cathode tip temperature, and HCA ignition time. Changes in the maximum heater power result in like changes in the cathode tip temperature measurements. The exception to this appears to occur during the first 4,000 cycles, where the cathode temperature decreases independent of the heater power. This change may indicate an irreversible change in the heater properties, or a change in the cathode surface emissivity.

The decreasing HCA cathode temperature results in an increasing ignition time, from an initial value of 3.9 minutes to 5.0 minutes. After 4,000 cycles, these trends ceased.

Conclusions

Since HCA.014 is essentially identical to the flight HCAs, the reliability demonstrated by the test article is believed to be representative. The ignition test of a high fidelity development model HCA has attained 32,000 successful ignition cycles, demonstrating the International Space Station requirements, which include a 6,000 cycle capability with at least 99% ignition reliability. The test will be continued until the HCA no longer functions.

Acknowledgments

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Table I - Test profiles.

Cycle Numbers	On Time, min	Off Time, min	Cycle Numbers	On Time, min	Off Time, min
1-25	50	40	12,036-12,065	50	40
26-50	1	6	12,066-15,013	1	20
51-75	1	40	15,014-15,058	50	40
76-100	1	20	15,059-18,033	1	20
101-125	2	20	18,034-18,053	50	40
126-2,207	1	20	18,054-21,009	1	20
2,208-2,293	1	6	21,010-21,042	50	40
2,294-2,999	1	20	21,043-24,319	1	20
3,000-3,025	50	40	24,320-24,347	50	40
3,026-5,996	1	20	24,348-27,032	1	20
5,997-6,026	50	40	27,033-27,072	50	40
6,027-9,000	1	20	27,073-30,006	1	20
9,001-9,030	50	40	30,007-30,036	50	40
9,031-12,035	1	20	30,037-present	1	20

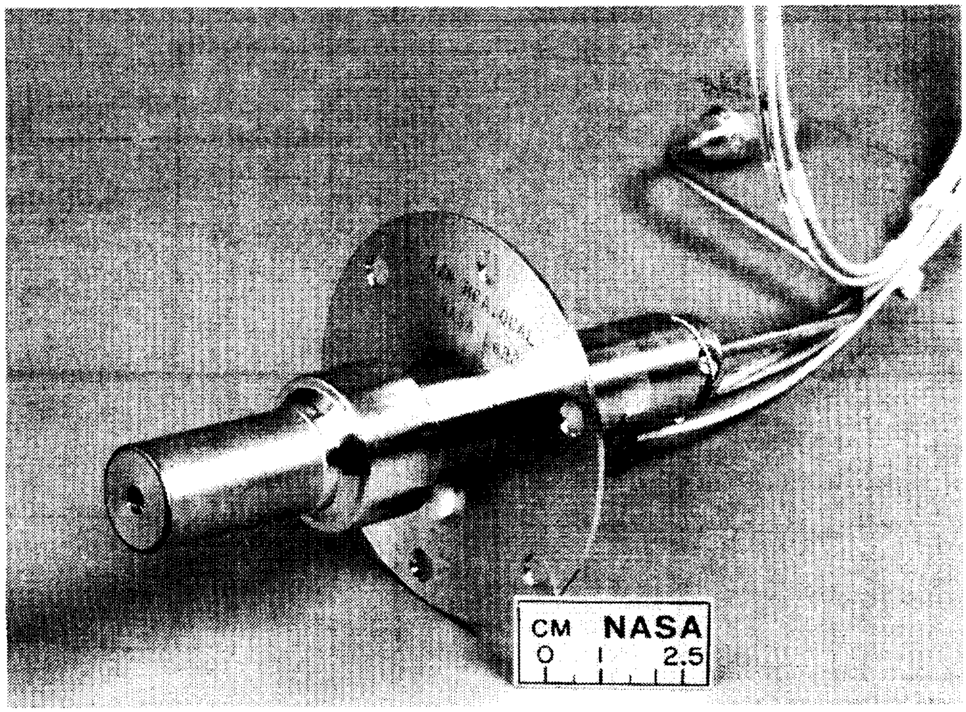

Figure 1 - International Space Station hollow cathode assembly.

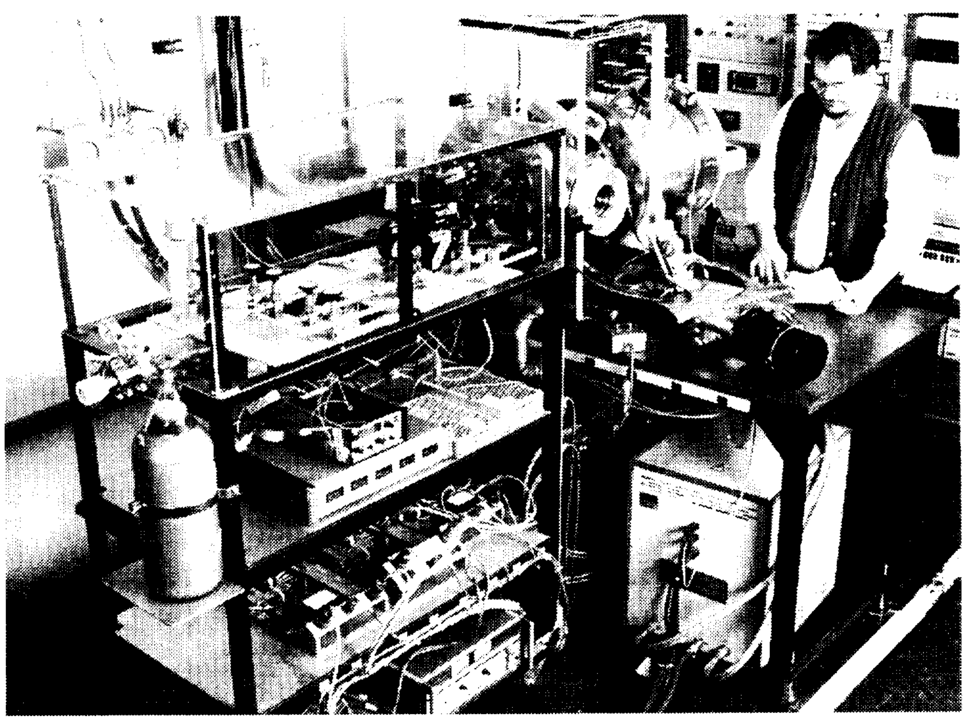

Figure 2 - HCA ignition test stand.

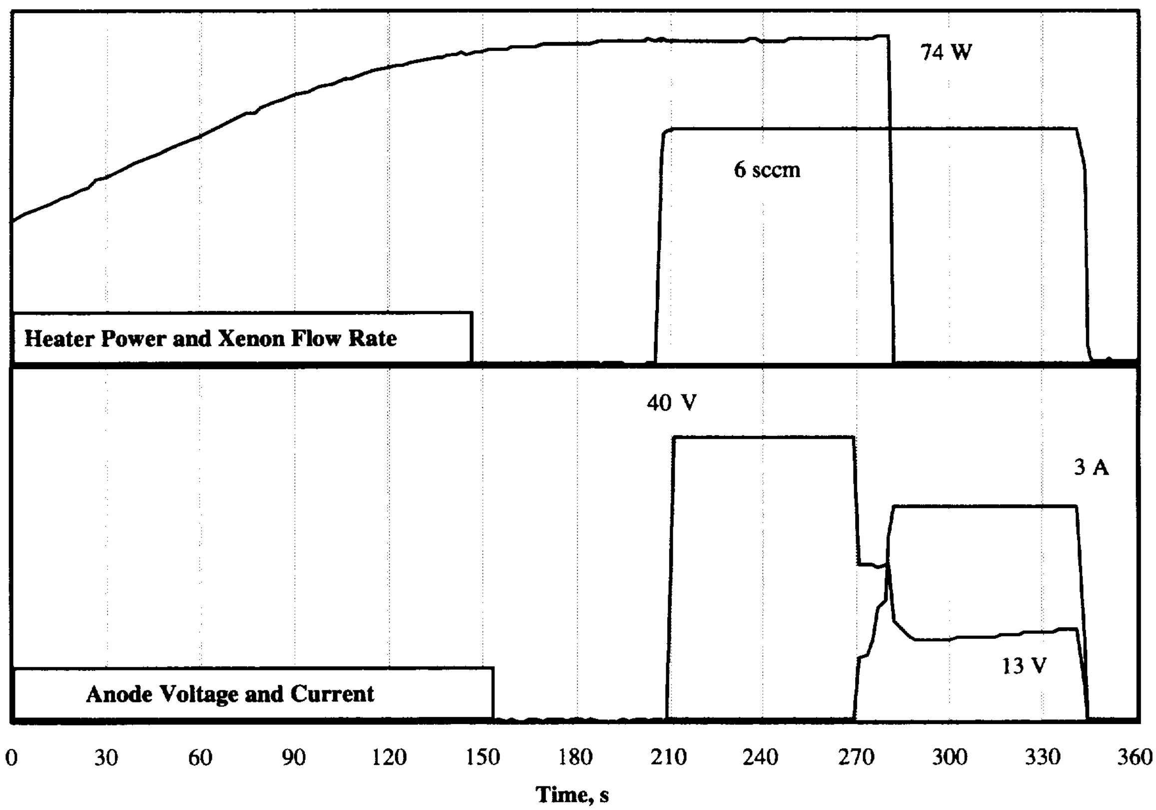

Figure 3 - Typical HCA ignition cycle data.

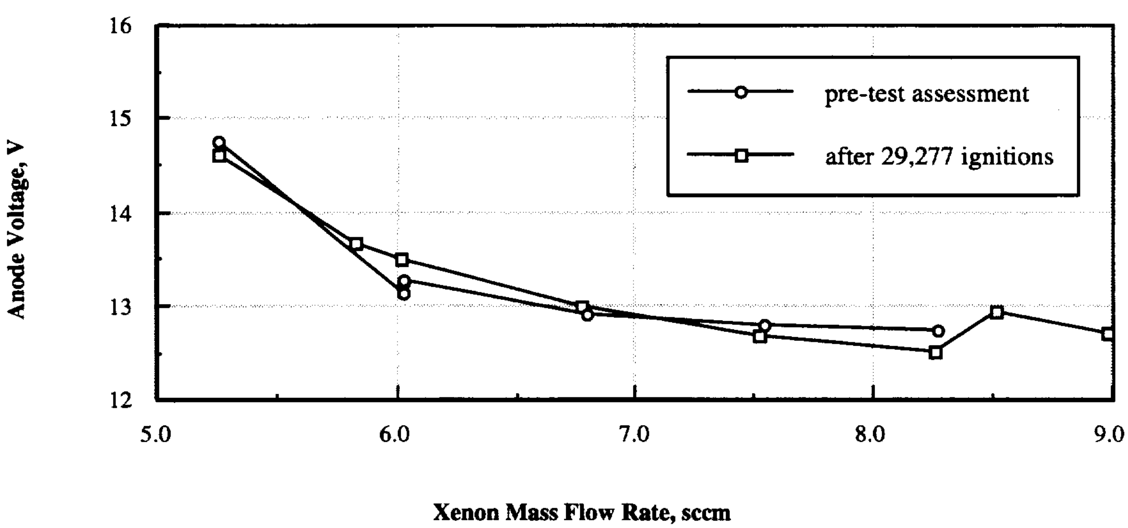

Figure 4 - HCA characterization test results.

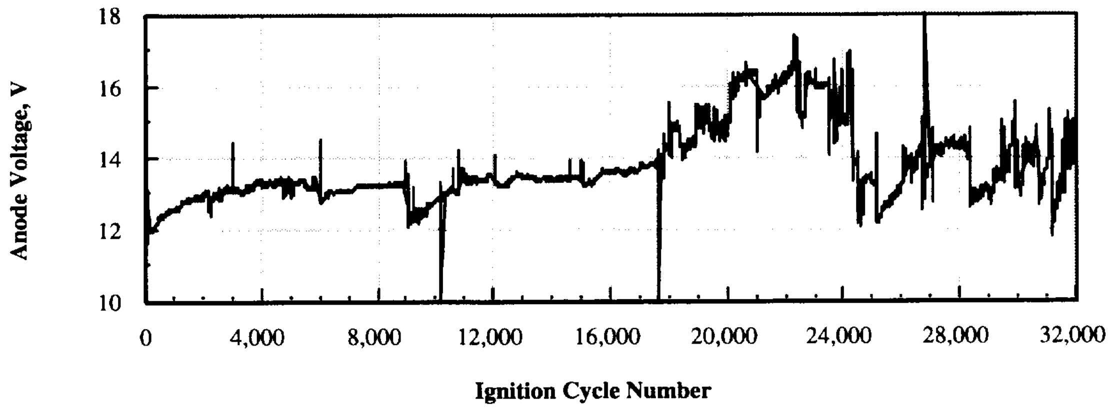

Figure 5 - Anode voltage versus ignition cycle. The anode voltage measured at the end of each cycle is shown.

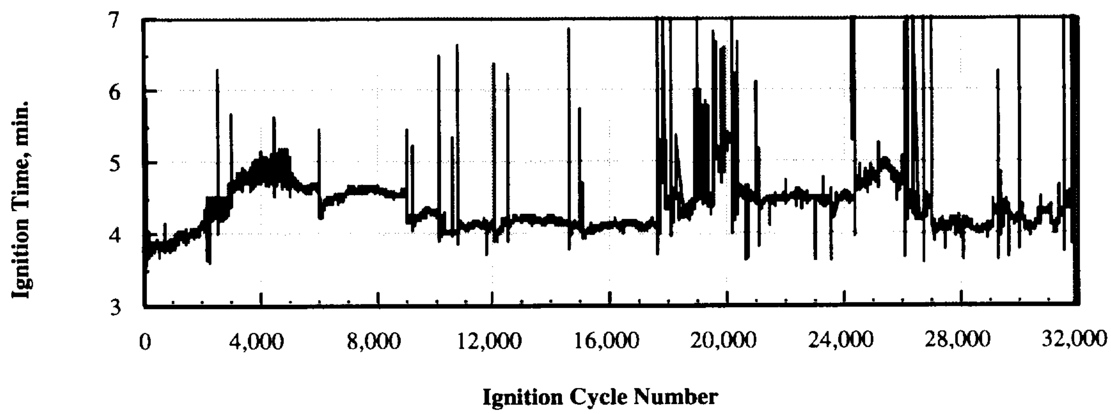

Figure 6 - Ignition time versus ignition cycle.

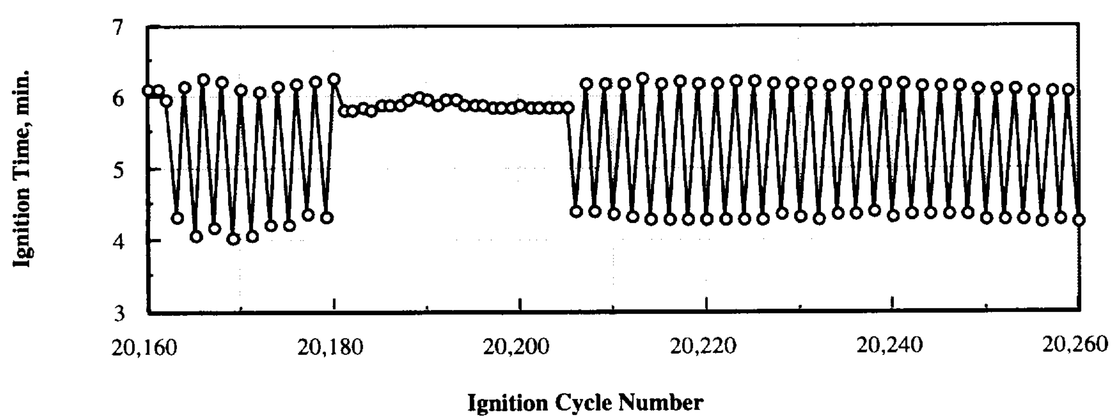

Figure 7 - An example of oscillating ignition times.

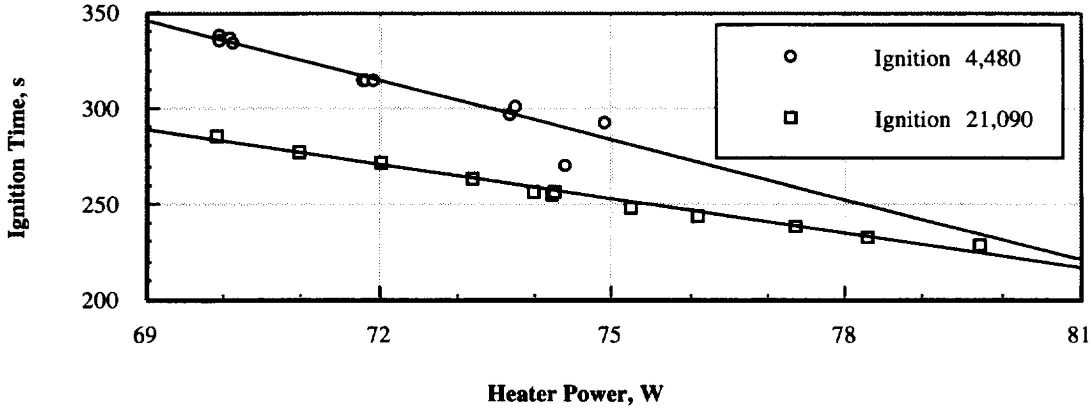

Figure 8 - Heater power versus ignition time.

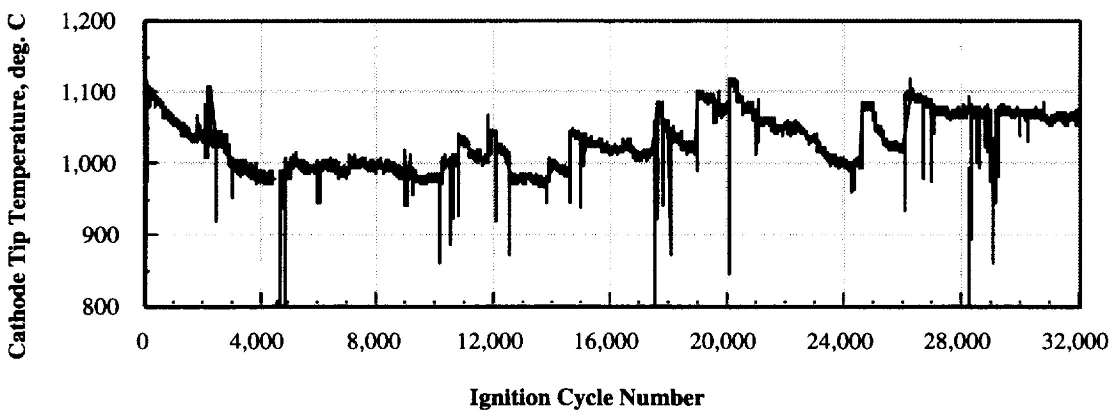

Figure 9 - Cathode tip temperature versus ignition cycle. The temperature is recorded 3.5 minutes after the heater power is applied each cycle.

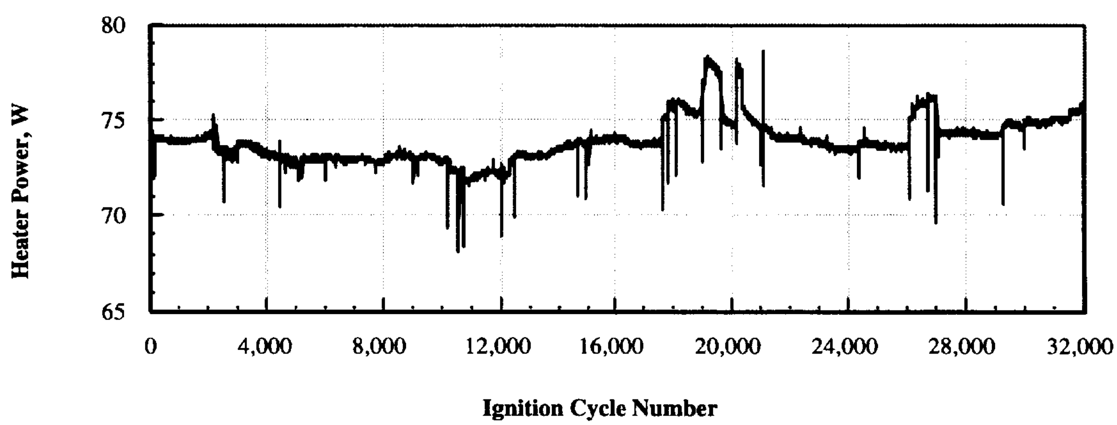

Figure 10 - Heater input power versus ignition cycle. The maximum heater power each cycle is shown.

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13. ABSTRACT *(Maximum 200 words)*

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