Iodine Satellite Propellant Feed Clog-Clearing Demonstration Testing

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December 2018
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1. INTRODUCTION

The utilization of solid iodine as a propellant in Hall-effect thrusters is being investigated for small-satellite applications. The Iodine Satellite (iSAT) mission aims to demonstrate this technology on board a 12U CubeSat. In the iSAT propellant feed system (PFS), solid iodine is sublimed through heating to produce gaseous propellant that is conducted through tubing to the thruster and cathode. The sublimation process is governed by the iodine vapor pressure, which is shown as a function of temperature in figure 1. As iodine vapor flows out of the tank, the gas pressure in the volume around the solid iodine propellant is reduced until a balance between the flow of iodine out of the tank and the sublimation rate of solid iodine at the equilibrium gas pressure and chosen tank temperature is reached.

![Figure 1. Vapor pressure curve for molecular iodine.](image)

One of the possible issues that can arise in an iodine PFS is that the vapor can redeposit to form a blockage/clog if a cold spot develops in the propellant lines. This occurred in the first integrated propulsion system test in 2016. A combination of high thermal inertia of the materials comprising the propellant tank exit and a lower-than-required level of heating resulted in a cooler
spot at the tank exit, leading to a clog that ended the test. In general, to keep iodine from redepositing in the propellant lines, the lines should be kept significantly warmer than the solid iodine. In a flight system, the heaters will be designed to ensure that, during normal operation, the lines are always at a greater temperature than the tank. However, if a heater fails, the line could cool, leading to the formation of a solid iodine propellant clog.

The line heaters in iSAT have a secondary heater trace that can be used as a backup in the event that a primary heater fails. Such a failure would be detected by the iSAT power processing unit as either an open circuit (no current) or a short circuit (lower circuit resistance/higher current). Detection of such a fault provides the opportunity to switch to the backup system and continue the mission. In the present demonstration test, the goal was to purposefully create and clear an iodine clog in a tube, quantifying the timescale and relative difficulty of clearing. This Technical Memorandum (TM) serves to document the testing that was performed to show that, in the event of a primary circuit heater failure, the system could recover using the secondary heater circuit.
2. TEST SETUP

2.1 Testing Facility

Testing was performed using a 3-ft-diameter, 6-ft-long vacuum vessel. The chamber can be evacuated to high vacuum levels of $10^{-5} - 10^{-6}$ torr using either a turbomolecular pump or, when iodine is flowing, a diffusion pump backed by a mechanical roughing pump. In addition, a Polycold PFC-1100-HC refrigeration unit (Polycold Systems, Inc., San Rafael, CA) pumps chilled refrigerant (–150 °C) through an in-vacuum cooling coil. The coil condenses the iodine vapor, which provides a significant increase in the iodine pumping speed during a test. The vacuum chamber pressure is measured using an MKS Instruments (Andover, MA) 390 Micro-Ion® ATM gauge with a recordable analog voltage output.

2.2 Flow System

The iodine flow system is shown schematically in figure 2 with an as-built image of this system presented in figure 3. The propellant tank is a simple cylindrical geometry with no internal mechanisms and the lines are 0.25-in-diameter tubing. In the system, iodine loaded in the tank flows along the main line into the vacuum chamber. At the end of the line, the iodine exits into vacuum through an orifice with a 0.028-in diameter. The pressure is measured at four different locations within the system ($P_1$, $P_2$, $P_3$, $P_4$). The measurements $P_1$ and $P_2$ are within the MKS 1152 vapor phase flow meter, measuring the pressure at the ends of a laminar flow element to monitor the flowrate.

Figure 2. Iodine clog-clearing test flow system schematic.
The pressures $P_3$ and $P_4$ are monitored by two Honeywell (Morris Plains, NJ) 2-psia Hastelloy® pressure transducers. Flow is controlled using hand-operated valves (HOVs). HOV2 makes it straightforward to evacuate the tubing upstream of the vapor-phase flow meter. The solenoid-operated valves seen in figure 3 were not installed for this experiment series.

At the test section (TS) locations, a piece of bent glass tubing is inserted into the line in the manner depicted in figure 4. The flowpath is broken, and the routing directed downward where it is mated to a glass tubing section using a Cajon O-ring sealed fitting (Swagelok®, Solon, OH). The glass section has two bends directing the iodine flow back upward to continue flowing towards the vacuum chamber. During the test, the glass section is first heated to the same temperature as the rest of the line, after which it is immersed in an ice water bath cooling the walls to produce an iodine clog at that location. The use of glass tubing permits visual verification that clogging is occurring.
2.3 Data Acquisition and Control

Experiment control and data acquisition are performed using a National Instruments (Austin, TX) Compact FieldPoint system. The system has two 8-channel analog voltage input modules, three 8-channel thermocouple measurement modules, an 8-channel analog voltage output module, and two 16-channel digital output modules. The system is controlled and data are recorded using LabVIEW sampling at a rate of 1 Hz.

2.4 Thermal Regulation

The system is divided into three independently controlled heater zones for this test. The tank comprises one heater zone; a second zone is comprised of a short run of tubing inside the vacuum tank. The third heater zone runs the entire length of tubing between the tank and the vacuum chamber. (The MKS 1152 has an independently powered and regulated heater system that maintains it at an elevated temperature throughout the test.) Each zone is heated using heater rope, and the temperature is monitored using type-K stick-on thermocouples. The LabVIEW program controls an alternating current relay for each heater zone, switching the relay using a digital output signal. The heaters are active until the target thermocouple temperature for each zone is reached. After that, the relays are switched on when the temperature drops below the set point and are switched off again after the temperature exceeds the set value.

Figure 4. Glass tube: (a) inserted into the flowpath and (b) test section schematic.
3. TEST PROCEDURE

The iodine was loaded using the following process:

1. The chamber was evacuated with HOV1 and HOV2 open to permit removal of the air within the feed lines and propellant tank.

2. HOV1 and HOV2 were then closed, and the lid was removed from the iodine tank.

3. After loading the tank with iodine, the lid was replaced, and the tank was evacuated by opening HOV2.

4. HOV2 was closed, HOV1 and HOV3 were opened, and a purge of several (<10) sccm of xenon gas was performed for roughly 1 hr to remove impurities and remaining trace gases.

5. The purge flow was stopped, and HOV1 and HOV3 were closed.

The following steps were performed during each test:

1. The propellant lines (both outside and inside the chamber) were heated to 125–130 °C.

2. Once the lines reached the target temperature, the tank was heated to a target temperature of 90 °C.

3. Upon reaching temperature, the valves were opened to permit flow of iodine vapor from the tank into the vacuum chamber.

At this point, the system was ready to test. The valve opening sequence varied for the different tests conducted and reported in this TM. After each test was completed, the following steps were performed:

1. If it was opened, HOV1 was closed to stop further iodine flow.

2. If it was not already off, the tank heater was turned off permitting the tank to cool.

3. The remaining heaters were turned off when the tank was less than roughly 50 °C.
4. TEST RESULTS

The illustration in figure 2 showed two possible locations where an iodine clog could be produced in the present setup. When there is an iodine flow, the largest pressure drop in the system occurs across the MKS 1152 vapor flow meter. Consequently, the two TSs correspond to a lower-pressure location (TS1) and a higher-pressure location (TS2). The following subsections report the testing conducted in each section.

4.1 Case 1: Test Section 1

In Case 1, a glass tube section was inserted into the flow line at TS1 located between pressure gauge P₄ and the orifice at the end of the flowpath where iodine exhausts into vacuum (see fig. 2). The iodine pressure in this region is usually low (typically well below 10 torr throughout the test). During Case 1, an iodine flow was initiated by opening valve HOV1. After flow was established, the overwrapped aluminum foil and heater rope were removed from the glass tubing in TS1. The section was submerged into an ice bath, which produced the start of a clog in a matter of seconds.

The measured iodine pressures and iodine flowrate are presented in figure 5 for the beginning of the test, with the time when the glass tubing was submerged in the ice bath denoted as Cooling Applied. The reduction of the gas pressure as measured by gauges P₂, P₃, and P₄ was immediate, as was the appearance of iodine deposits on the glass tubing walls, preferentially appearing where the iodine flow in the glass first goes below the waterline. The clog evolution as a function of time is shown in figure 6 with (a) representing an image just after the tubing was submerged in the ice bath and the image in (e) representing 2.75 hr later, just before heating is reapplied to clear the clog.

![Figure 5](image)

Figure 5. For Case 1, while the clog was formed: (a) gas pressures measured along the flowpath and (b) iodine flowrate measured by the MKS 1152 flow meter.
Figure 6. For Case 1, sequence of images of the iodine plug as it was forming: (a) immediately after immersion in the ice water bath (0 min), (b) 1 min after immersion, (c) 7 min after immersion, (d) 17 min after immersion, and (e) immediately after removal from the ice water bath, approximately 2.75 hr after immersion.

Figure 7 presents pressures and iodine flowrate while heating was reapplied to TS1, and the clog was cleared. At an experiment time of approximately 16,650 s, the pressure trend reverses, indicative of clog clearing. Within 5 min of applying heat, the clog was completely gone from this section. At no time during this testing did the flow meter indicate flow reduced to zero; in fact, flow mostly remained steady between 0.8 and 1 mg/s.
4.2 Case 2: Test Section 2, Trial 1

In Case 2, a glass tube section was inserted into the flow line at the location of TS2 (see fig. 2), located between the iodine tank and pressure gauge P1 at the entrance of the flow meter. When the flowpath is clear, the pressure P1—plus any small line losses—is roughly equal to the pressure in the tank. The time histories of the pressure and iodine flowrate for this trial are presented in figure 8.

Figure 8. For Case 2, time histories showing: (a) gas pressures and (b) iodine flowrates measured by the MKS 1152 flow meter. Data span the clogging and clog-clearing process, with the time of discrete events indicated.
For Case 2, Trial 1 in TS2, the iodine tank was heated to the target temperature of 90 °C. Then, the TS was immersed in the ice water bath with HOV1 closed. With no iodine flow yet established, only a faint ring of iodine was observed depositing on the glass tube where it entered the water (fig. (9(a)). This ring formed from iodine that moved from the iodine tank into the tube through diffusion. Once HOV1 was opened, permitting convective iodine flow, the formation of a clog was very rapid as shown in (b) and (c). The flowrate was almost immediately reduced to a no-flow condition. Comparing figure 6(e) from Case 1, TS1 and figure 9(c), the plug appearing in Case 2’s TS2 is observed to be much more extensive and appears to more completely fill the tubing in the latter image.

![Figure 9. For Case 2, sequence of images of the iodine plug as it was forming: (a) immediately after immersion in the ice water bath, (b) just after the opening of HOV1, and (c) immediately after removal from the ice water bath, approximately 15 min after initial immersion.](image)

In Case 2, Trial 1, the clog-clearing process was accomplished with HOV1 open throughout the duration of the test until the clog visually disappeared. The clog took much longer to disappear in this test, and the limited thermal conductivity of glass made it difficult to heat the glass tubing from an initially cold condition. Iodine underneath the path of the rope heater was observed to disappear first, while iodine farther away remained longer. Midway through the test, a heat gun was added to supplement the rope heater on TS2 (Added Clog Heating in fig. 8), so the test could be completed in a reasonable amount of time. The significant amount of iodine in the clog actually served as a second iodine sublimation source, and as it was elevated in temperature up to the level of the rest of the flowpath, the flowrate increased dramatically between 5,000 and 6,000 s. The flowrate out generally decreased after the tank heater was turned off, limiting the supply of iodine to that being sublimed from the clog. Many of the intermediate ups and downs in the pressure and flowrate were due to outside events, such as the moving of a rope heater to give it better thermal contact, the addition of the heat gun to increase the temperature of the entire TS more quickly, or the removal of insulating foil to visually observe the clog-clearing progress.
4.3 Case 3: Test Section 2, Trial 2

Trial 2 was conducted mostly like Trial 1 except that HOV1 was closed very quickly after the formation of a clog, the heat gun was applied to TS2 at the same time the rope heater was reapplied, and the tank heater was turned off very soon after the formation of the clog. In closing HOV1 after the formation of the clog, the situation was simulated where iodine clogs the tubing as it exits the tank, and the downstream control valves were closed to isolate the higher pressure side of the feed system from the thruster and cathode (similar to what occurred during the integrated system test of 2016). In this case, heating was used to resublime the clog and force it back into the cooler propellant tank (as opposed to allowing it to vent through the system into the vacuum chamber).

As was done for Trial 1, testing in Trial 2 was initiated by opening HOV1, establishing an iodine flow. Immediately after the valve was opened, the clog formed. The pressure and flowrate waveforms for this test are given in figure 10. Visual observations indicate that the clog was cleared by roughly the 6,000 s mark. Images showing the formation of the clog and subsequent clearing are presented in figure 11.

![Figure 10. For Case 3, time histories showing: (a) gas pressures and (b) iodine flowrate measured by the MKS 1152 flow meter. Data span the clogging and clog-clearing process.](image-url)
Figure 11. For Case 3, sequence of images of the iodine plug formation and clearing: (a) immediately after immersion in the ice water bath and opening of HOV1, (b) 20 s after (a), (c) immediately after removal from the ice water bath (≈15 min after initial immersion), (d) during the clog-clearing process, and (e) with the tube completely cleared.
4.4 Post-Test Inspection

The propellant tank and lid were inspected after the final test to ensure that no iodine was depositing on the lid or in the region where the tubing exits the tank (as occurred during the integrated system test of 2016). The tank and lid, shown in figure 12, appeared in good condition with no iodine deposited anywhere but the bottom of the tank.

![Figure 12](image.png)

Figure 12. Images of: (a) the propellant and (b) the propellant tank lid (with a sheathed thermocouple emerging from one port).
5. DISCUSSION

Initially, attempts to clog TS1 were performed several times using a water-cooled thermal heat sink mechanically attached to metal tubing in that section. In that testing, the pressure and flowrate data were similar to those presented in figures 5 and 7. The fact that the flowrate did not go to zero caused an alteration in the approach, using glass tubing immersed in an ice water bath to permit visual observation of the TS.

The formation of solid iodine in TS1 and the initial drop in the pressures measured by gauges P2, P3, and P4 indicated that as the deposit first formed, the cold section was actually removing iodine from the gas phase faster than it was entering the tubing section. Effectively, the tank was producing iodine vapor, and the cold section was redepositing it, ‘pumping’ the gas phase and permitting flow to continue across the flow meter. Later in the testing, the pressures increased to a level greater than when the tube was unclugged, but they did not approach the value of $P_1$, which remained relatively constant throughout the test. The conclusion reached was that the clog, while capturing some of the iodine in that region, is also somewhat porous, allowing some iodine to pass. A comparison of the photographs in figures 6, 9, and 11 shows that the extent and apparent density of the deposit in TS1 was much smaller than the clogs that formed in TS2. Referring to figure 1, the lower pressure in TS1 relative to the propellant tank means iodine in TS2 had to be cooled well below the tank temperature to deposit, and it is reasonable to assume, based on these tests, that some iodine, though cooler, made it through to the vacuum chamber. The clog cleared within a few minutes of the removal of the water bath and the reapplication of heating. The TS1 data, where a clog was formed in the low-pressure section of the feed system (the section directly exposed to vacuum conditions), allow the conclusion that a clog in this area will be small in extent, will not completely block the flow, and will be relatively easy to clear.

By contrast, visual observations of the clogs formed in TS2 showed them to be much larger in extent and apparent density, forming to that size very quickly (tens of seconds), while it took hours to form the much smaller plug-like clog in TS1. The clog could be cleared, but it took significantly longer to do so relative to TS1. The unclogging problem was exacerbated by the poor heat transfer properties of glass, which did not reheat quickly after the tubing was removed from the water bath. Note that the TS heaters were part of the heater zone consisting of all the tubing outside of the vacuum tank. This heater zone was regulated based upon a temperature measurement at a different location, which was always hot, so the heater power applied during the unclogging phase was actually a fraction of the power applied during initial heating of the system. This lower level of average power was not effective in reheating the glass tubing section in a timely manner, necessitating the use of the heat gun to supplement the overall heating.
The times it took to clear the clog in TS2 during Trials 1 and 2 are comparable, with Trial 1 taking the longest. However, in Trial 1, most of the heating and subsequent iodine resublimation occurred after the heat gun was applied. Comparing the time it took to clear the blockage after additional heating was applied, it is clear that it took much longer to clear all the iodine in Trial 2. The conclusion reached was that a clog formed in the (relatively) high-pressure section of the feed system (e.g., at the propellant tank exit) can appear very quickly. This clog will totally block the flow; and, while it can be cleared with the application of heat, clearing takes significantly longer than for a clog in the low pressure section. It was demonstrated in Trial 2 that the iodine comprising the clog can be cleared by reheating the line and forcing the iodine back into the cooler iodine propellant tank.
6. CONCLUSIONS

The iSAT PFS can be rendered unusable if an iodine blockage/clog forms at a cold spot in the propellant lines. The integrated propulsion system test (2016) suffered this issue when a cooler spot at the propellant tank exit produced a clog at that location that ended the test. A clog in this higher-pressure location forms easily and quickly, as is now recognized through the present testing. In general, to keep iodine from redepositing somewhere else within the system, the propellant lines should be kept significantly warmer than the solid iodine that is subliming to produce the iodine vapor. In the flight system, while the heaters are designed to ensure that the lines remain hotter, a heater failure could cause a propellant line to become clogged with iodine propellant.

A test apparatus was assembled to purposefully clog tubing and then attempt to clear the blockage through the application of heat. The flight system possesses a set of redundant heaters, so during the iSAT mission, recovery in this manner is possible. Testing showed that the manner in which the clog forms and is cleared is highly dependent upon the location where the clog forms.

The low-pressure section near the exit to vacuum is relatively difficult to completely clog, with clog-clearing through the application of heat being very easy and quick. The timescale of clearing is on the order of minutes.

The high-pressure section near the sublimation source is very easy to clog completely, but much more difficult to clear as it requires significantly more time and heat. With the application of significant auxiliary heating, the timescale for clog clearing was \( \approx 30 \) min.

The testing successfully demonstrated that a clog occurring anywhere within the feed system could be cleared if necessary. Testing also showed that, with the valves closed, the iodine contained within a blockage in the high-pressure section could be forced back into the propellant tank, recovering that propellant for later use.
REFERENCES


Experiments are conducted to quantify the formation and clearing of iodine clogs in an iodine feed system. Deposits in the low-pressure portion of the system near the exit to vacuum appear to be relatively small in extent and incomplete in blocking the flow, and they are relatively easy to remove with the re-application of heating, disappearing in minutes. Clogs forming upstream, nearer to the higher-pressure propellant tank, appear to completely block the flow, are much larger in spatial extent, and form much more rapidly than the low-pressure blockages. Significantly more effort is required to remove upstream deposits.

iodine, propellant, feed, systems, iodine, sublimation
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