Propulsion System Development for the Iodine Satellite (iSAT) Demonstration Mission

Joint Conference of 30th International Symposium on Space Technology and Science, 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium, Hyogo-Kobe, Japan
July 4 – 10, 2015

K. Polzin, S. Peeples, J. Seixal, S. Mauro, B. Lewis, G. Jerman, D. Calvert, J. Dankanich
NASA Marshall Space Flight Center

H. Kamhawi, T. Hickman
NASA Glenn Research Center

J. Szabo, B. Pote, L. Lee
Busek Co., Inc
Motivation

• iSAT – iodine satellite

• 12U (20x20x30-cm) CubeSat flight demo of a 200-W iodine-fed Hall effect thruster

• Purpose here is to describe development and testing of the propulsion system that will be flown
Motivation - continued

- Why iodine?
  - Stores as a dense solid with a low vapor pressure
  - High $\rho \cdot I_{sp}$ making it an enabling technology for near-term small satellite applications
  - Also provides potential systems-level advantages for mid-term higher power spacecraft propulsion
  - Propellant flow can be thermally-regulated, subliming at low temperature ($<100$ C) to yield a low pressure (~50 torr) gas source
  - Low power performance similar to SOA xenon Hall thrusters
  - Current-Voltage characteristics very similar between iodine and xenon-fed Hall thrusters
  - Cold surfaces in a vacuum chamber can be used to ‘cryopump’ propellant
Propulsion System - General

Aft Looking Forward

Propulsion Plate from Front Side
Thruster & Cathode

• Thruster
  – Version of Busek BHT-200 Hall thruster modified for iodine compatibility (BHT-200-I)
  – BHT-200 was first American Hall thruster to fly in space (US Air Force TacSat-2, 2006)
  – Lab testing at 200-W and higher has shown xenon vs. iodine efficiency approx. equal at same operating conditions
  – Lower measured plume divergence with iodine than xenon

• Cathode
  – Typical BaO cathode cannot be used with iodine propellant
  – Baseline is 12CaO-7Al₂O₃ electride emitter cathode
  – Electride cathode initiated w/little to no heating – systems-level power savings for mission
  – In general, LaB₆ cathode also iodine-compatible, but requires more power to initiate discharge – could be used on less power-starved missions
PPU

• **Thruster Power**
  – Power for main discharge, magnetic circuit, and cathode operation
  – 28 VDC input voltage
  – Efficiency >90% at 200W thruster operation
  – Capability to change magnetic circuit polarity
  – Capability to ignite electride cathode (objective to ignite without heater power)
  – Capability to provide heater power to condition/state a cathode

• **Feed System Control and Monitoring**
  – Control one latch valve
  – Control two proportional flow control valves
  – Monitor 4-10 temperature sensors
  – Monitor 1-3 pressure transducers
  – Feed System heater control for four (4) independent heater ‘zones’
Feed System

- ¼” Hastelloy tubing, welded throughout
- 40 micron Hastelloy filter
- Two (2) Vacco PFCVs (independent control of cathode and anode flowrates)
- Tank loading of 0.7 kg I₂ with starting ullage volume of 20%
Feed System Control and Monitoring

- Auxiliary board to operate valves and monitor systems in lab (in lieu of PPU)
- Power distribution card to provide power at correct voltages
- Functionality to be incorporated into PPU
Reservoir – Thermal Modeling

- Reservoir – cylinder of 85.5 mm height, 31.75 mm diameter
- 100 g of iodine, cylindrical shape, equidistant from all sides
- 2.88 W of heater input power

  - Iodine heated by
    - Radiation-only: ~ 1.5 orbits to heat iodine
    - Conduction-only: > 9 orbits to heat iodine

<table>
<thead>
<tr>
<th>component</th>
<th>material</th>
<th>thermal conductivity (W/(m·°C))</th>
<th>density (kg/m³)</th>
<th>specific heat (J/(kg·°C))</th>
<th>IR emissivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>propellant reservoir</td>
<td>titanium</td>
<td>7.1 @ 25°C</td>
<td>4428.8</td>
<td>539.6 @ 25°C</td>
<td>0.2</td>
</tr>
<tr>
<td>propellant (solid)</td>
<td>iodine</td>
<td>0.449</td>
<td>4940</td>
<td>429</td>
<td>0.8</td>
</tr>
<tr>
<td>propellant (gaseous)</td>
<td>titanium</td>
<td>0.004351</td>
<td>4930</td>
<td>217.6</td>
<td>–</td>
</tr>
<tr>
<td>insulation</td>
<td>aluminized black kapton</td>
<td>0.1557 @ 25°C</td>
<td>1449.6</td>
<td>1001.5 @ 25°C</td>
<td>0.03 Solar Absorptivity 0.12</td>
</tr>
</tbody>
</table>
Materials Compatibility

- Iodine compatibility with feed system, thruster, and spacecraft materials
- Little literature data on iodine exposure at the relevant conditions
- Two sets of experiments undertaken to better-quantify exposure in iSAT conditions

<table>
<thead>
<tr>
<th>Systems</th>
<th>Metal or Alloy</th>
<th>Base Elements</th>
<th>Dry Iodine Vapor @ 25°C</th>
<th>Dry Iodine Vapor @ 100°C</th>
<th>Dry Iodine Vapor @ 300°C, 0.53 atm (Corrosion Rate mm/year)</th>
<th>Dry Iodine Vapor @ 450°C, 0.53 atm (Corrosion Rate mm/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>Pure Nickel</td>
<td>Ni</td>
<td>Resistant</td>
<td>Resistant</td>
<td>0.27</td>
<td>1.2</td>
</tr>
<tr>
<td>Alloys</td>
<td>Inconel 600</td>
<td>Ni-Cr-Fe</td>
<td>Resistant</td>
<td>Resistant</td>
<td>0.107</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>Inconel 625</td>
<td>Ni-Cr-Mo</td>
<td>Resistant</td>
<td>Resistant</td>
<td>0.057</td>
<td>No Data</td>
</tr>
<tr>
<td></td>
<td>Hastelloy B</td>
<td>Ni-Mo</td>
<td>Resistant</td>
<td>Resistant</td>
<td>No Data</td>
<td>0.464</td>
</tr>
<tr>
<td></td>
<td>Hastelloy C</td>
<td>Ni-Cr-Mo</td>
<td>Resistant</td>
<td>Resistant</td>
<td>0.056</td>
<td>No Data</td>
</tr>
<tr>
<td>Noble</td>
<td>Pure Platinum</td>
<td>Rt</td>
<td>Resistant</td>
<td>Resistant</td>
<td>0</td>
<td>0.006</td>
</tr>
<tr>
<td>Metals</td>
<td>Pure Gold</td>
<td>Au</td>
<td>Resistant</td>
<td>Resistant</td>
<td>0</td>
<td>0.024</td>
</tr>
<tr>
<td>Refractory</td>
<td>Pure Tungsten</td>
<td>W</td>
<td>Resistant</td>
<td>Resistant</td>
<td>0</td>
<td>0.008</td>
</tr>
<tr>
<td>Metals</td>
<td>Pure Molybdenum</td>
<td>Mo</td>
<td>Resistant</td>
<td>Resistant</td>
<td>0.003</td>
<td>0.033</td>
</tr>
<tr>
<td></td>
<td>Pure Tantalum</td>
<td>Ta</td>
<td>Resistant</td>
<td>Resistant</td>
<td>0.005</td>
<td>0.88</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Pure Aluminum</td>
<td>Al</td>
<td>Unusable</td>
<td>Unusable</td>
<td>Unusable</td>
<td>Unusable</td>
</tr>
<tr>
<td></td>
<td>Pure Copper</td>
<td>Cu</td>
<td>Resistant</td>
<td>Unusable</td>
<td>Unusable</td>
<td>Unusable</td>
</tr>
<tr>
<td>Copper</td>
<td>Brass</td>
<td>Cu-Zn</td>
<td>Resistant</td>
<td>Unusable</td>
<td>Unusable</td>
<td>Unusable</td>
</tr>
<tr>
<td>Alloys</td>
<td>Iron, Cast Iron, Steel</td>
<td>Fe</td>
<td>Resistant</td>
<td>Unusable</td>
<td>Unusable</td>
<td>Unusable</td>
</tr>
<tr>
<td>Iron</td>
<td>316 Stainless Steel</td>
<td>Fe-Cr-Ni</td>
<td>Resistant</td>
<td>0.4 (Estimated*)</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>Alloys</td>
<td>304 Stainless Steel</td>
<td>Fe-Cr-Ni</td>
<td>Resistant</td>
<td>0.6 (Estimated*)</td>
<td>3.2</td>
<td></td>
</tr>
</tbody>
</table>

* Estimated corrosion rate at 300°C based upon extrapolation from 450°C data.
Materials Compatibility

**Active Iodine Flow Test Setup**

- Vacuum Chamber
  - Test Samples
  - 75 Torr

**Passive Iodine Bath Test Setup**

- Heating Element
  - Solid Iodide
  - Iodine Vapor

<table>
<thead>
<tr>
<th>Material Category</th>
<th>Material Identification</th>
<th>1 Week Surface Condition</th>
<th>1 Week Thickness Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel Alloys</td>
<td>304 Stainless Steel</td>
<td>Minor Darkening</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>316 Stainless Steel</td>
<td>Minor Darkening</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>4130 Alloy Steel</td>
<td>Minor Darkening</td>
<td>None</td>
</tr>
<tr>
<td>Aluminum Alloys</td>
<td>6061 Aluminum</td>
<td>Minor Darkening</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>7075 Aluminum</td>
<td>Minor Darkening</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>7075 Aluminum, Anodized</td>
<td>Minor Darkening</td>
<td>None</td>
</tr>
<tr>
<td>Copper Alloys</td>
<td>110 Copper</td>
<td>White Layer</td>
<td>Swelled</td>
</tr>
<tr>
<td></td>
<td>Brass</td>
<td>Blackened</td>
<td>None</td>
</tr>
<tr>
<td>Titanium Alloys</td>
<td>Titanium 6-Al-4V</td>
<td>Minor Darkening</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Commercially Pure Ti</td>
<td>Minor Darkening</td>
<td>None</td>
</tr>
</tbody>
</table>
Propellant Loading / 80-hr Test

- Loading procedure – heating (before loading) followed by neutral gas purge to drive out oxygen, water vapor, and other volatile compounds

- 80-hr test at NASA-GRC to operate total mission throughput (anode on iodine)
- Performance measurements on xenon initially (baseline)
- Iodine feed to anode operated with reservoir, Vacco PFCV, and MSFC-developed auxiliary board
- Plume plasma measurements (Faraday probe, Langmuir probe) and materials coupons
Acknowledgements

• This work is sponsored by NASA’s Space Technology Mission Directorate and is managed by the Small Spacecraft Technology Program at the NASA Ames Research Center.