Factors Affecting the Efficiency of Krypton Hall Thrusters

Richard R. Hofer, Peter Y. Peterson
QSS Group, Inc., Cleveland, OH

David T. Jacobson, David M. Manzella
NASA Glenn Research Center, Cleveland, OH
Payload Advantage – Mars

- Nuclear electric propulsion delivers greater payloads than chemical propulsion at the expense of trip time.
- Specific impulse of 4000 s balances trip time with delivered payload.
  - Typical specific impulse for ion thrusters
  - More than twice the typical specific impulse of xenon Hall thrusters
- Compared to ion thrusters, Hall thrusters offer benefits in terms of volume, mass, and cost

The Question:
How can Hall thrusters achieve high-specific impulse AND long lifetime?

One (possible) answer:
Krypton Hall thruster
# Krypton vs. Xenon

<table>
<thead>
<tr>
<th></th>
<th>Xenon</th>
<th>Krypton</th>
<th>Relative to xenon...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Weight (g/mol)</td>
<td>131.3</td>
<td>83.8</td>
<td>$\uparrow I_{sp}$, $\downarrow T$, $\uparrow$Lifetime @ Constant Voltage and density</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; Ionization Potential (eV)</td>
<td>12.1</td>
<td>14.0</td>
<td>$\downarrow$Mass utilization efficiency, $\downarrow$Multiply-charged Ions ($\uparrow$Lifetime)</td>
</tr>
<tr>
<td>Cost ($/L)</td>
<td>$4.50</td>
<td>$0.38</td>
<td>$\downarrow$Qualification &amp; On-orbit Costs, $\uparrow$Availability, $\downarrow$Price Volatility</td>
</tr>
<tr>
<td>Density (at 190 bar, 340 K, kg/m&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>1.66</td>
<td>0.67</td>
<td>$\uparrow$Storage tank mass/volume</td>
</tr>
</tbody>
</table>

In general,

Xe $\rightarrow$ high-$I_{sp}$, high-$T$

Kr $\rightarrow$ high-$I_{sp}$, long life
Efficient krypton operation requires increasing the propellant utilization, which is affected by several design variables.

The challenge is to achieve high-propellant utilization without sacrificing thermal margin, stability, and lifetime.
GRC-developed Hall thrusters have demonstrated efficient operation over a wide range of conditions.

**Power:** 1-100 kW  
**Thrust:** 0.1-3 N  
**I_{sp}:** 1000-5000 s  
**Efficiency:** 40-70%  
**Propellant:** Xe, Kr
Performance – Xenon vs. Krypton

- At constant current density, efficiency increases with thruster size (power)
- Compared to xenon, krypton efficiency is typically 5-15% less
- Both trends are primarily due to differences in the mass utilization

![Xenon Performance Graph](image1)
![Krypton Performance Graph](image2)

46th Meeting of the APS Division of Plasma Physics, Savannah, GA, Nov. 15-19, 2004
Glenn Research Center at Lewis Field
Hall Thruster Efficiency

By accounting for the effects of a multiply-charged, partially-ionized plasma, Hall thruster efficiency can be expressed as a function of the charge-, voltage-, current-, and mass-utilization efficiencies.

Anode efficiency

\[ \eta_a = \frac{T^2}{2m_a P_d} = \eta_q \eta_v \eta_b \eta_m \]

Charge utilization efficiency

\[ \eta_q = \left( \frac{\sum \Omega_i \sqrt{Z_i}}{\sum \Omega_i / Z_i} \right)^2 \]

Voltage utilization efficiency

\[ \eta_v = \frac{V_a}{V_d} = 1 - \frac{V_l}{V_d} \]

Current utilization efficiency

\[ \eta_b = \frac{I_b}{I_d} \]

Mass utilization efficiency

\[ \eta_m = \frac{\dot{m}_b}{\dot{m}_a} \]
Hall Thruster Efficiency (2)

Electron current and utilization efficiencies can be computed if the following quantities are known:

✓ Anode efficiency – measured with thrust stand
✓ Loss voltage – measured with RPA
✓ Ion species fractions – measured with ExB probe

\[
\eta_a = \left(1 - \frac{V_i}{V_d}\right) \left(1 - \frac{I_e}{I_d}\right)^2 \left(\sum \frac{\Omega_i}{\sqrt{Z_i}}\right)^2 \frac{m_{xe}I_d}{m_a e}
\]

XENON

- Charge utilization = 98-99%
- Voltage utilization = 89-97%
- Mass utilization = 86-90%
- Current utilization = 77-81%

XENON

\(I_E\) constant with voltage \(\sim 2.1\) A
Plasma Diagnostics in Vacuum Facility 12

46th Meeting of the APS Division of Plasma Physics, Savannah, GA, Nov. 15-19, 2004
Glenn Research Center at Lewis Field
NASA-173Mv2 Operating Conditions

- NASA-173Mv2 Hall thruster
  - Magnetic circuit optimized for high-Isp
  - Designed for xenon

- Xenon conditions
  - 800 V, 9.84 A
  - 10 mg/s anode, 1 mg/s cathode
  - Thrust 324 mN
  - Anode Isp 3310 s (Total Isp = 3000 s)
  - Anode efficiency 66.7% (Total Efficiency = 59.6%)

- Krypton conditions
  - 800 V, 8.27 A
  - 6.4 mg/s anode, 0.64 mg/s cathode
  - Thrust 215 mN
  - Anode Isp 3410 s (Total Isp = 3100 s)
  - Anode efficiency 54.7% (Total Efficiency = 48.8%)
**NASA-173Mv2 – Xenon vs. Krypton**

<table>
<thead>
<tr>
<th></th>
<th>Xenon</th>
<th>Krypton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vd = 800 V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss voltage (V)</td>
<td>25</td>
<td>64</td>
</tr>
<tr>
<td>Species Fractions (%)</td>
<td>88, 11, 1</td>
<td>96.1, 3.4, 0.5</td>
</tr>
<tr>
<td>Divergence angle (degrees)</td>
<td>61°</td>
<td>67°</td>
</tr>
<tr>
<td>Breathing-Mode Frequency (kHz)</td>
<td>25</td>
<td>31</td>
</tr>
<tr>
<td>Oscillation magnitude (% of $I_D$)</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>Electron Current (A)</td>
<td>2.09</td>
<td>2.04</td>
</tr>
</tbody>
</table>
NASA-173Mv2 – Xenon vs. Krypton Efficiencies

Vd = 800 V

10.5% decrease in Mass utilization

<table>
<thead>
<tr>
<th></th>
<th>Anode</th>
<th>Charge</th>
<th>Voltage</th>
<th>Current</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xenon</td>
<td>66.7%</td>
<td>97.6%</td>
<td>96.9%</td>
<td>78.7%</td>
<td>89.6%</td>
</tr>
<tr>
<td>Krypton</td>
<td>54.2%</td>
<td>98.9%</td>
<td>92.0%</td>
<td>75.3%</td>
<td>79.1%</td>
</tr>
</tbody>
</table>

50% decrease in Mass utilization
Conclusions

• **The krypton-fueled Hall thruster offers the possibility of high-specific impulse and long lifetime**

• **NASA’s series of Hall thrusters have demonstrated krypton efficiencies only 5-15% less than xenon**
  – Larger thrusters have smaller differences in efficiency

• **Plasma measurements have demonstrated that efficiency is reduced due to a decrease in mass utilization**

• **Current efforts are considering the implications of these results, and how design changes can be made to increase the efficiency of krypton Hall thrusters**