Feasibility of Developing a Refrigerant-Based Propulsion System for Small Spacecraft

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Outline

• Background
• Propulsion system requirements
• Propellant selection
• Engineering modeling
• Safety assessment
• Design application
  ▪ University of Missouri - Rolla
  ▪ University of Texas at Austin
  ▪ Washington University in St. Louis
Background

- Small spacecraft < 100 kg
- AFRL / AFOSR / AIAA
  University Nanosat Program
- Nanosat 4 competition concluded March 2007
- Research collaboration – Feasibility study / safety assessment:
  - University of Missouri – Rolla
  - University of Texas at Austin
  - Washington University in St. Louis
- Collaboration goals:
  - Assess feasibility of using a refrigerant propellant in space
  - Assess feasibility/safety of exceeding sealed container status
Propulsion System Requirements

UNP requirements:
- **Space Shuttle payload design**
  - Most stringent requirements for spaceflight
- **Sealed container requirements**
  - $P$ – Absolute Pressure $\leq 100$ psia (689.48 kPa)
  - $U$ – Internal Energy $\leq 14,240$ ft-lbs (19,310 J)
  - Otherwise it is categorized as a pressure vessel
- To improve performance and meet objectives it was necessary to violate these sealed container requirements and request a waiver for the UNP competition
- Pressure vessel status can be deemed safe
Spacecraft System Requirements

- Dimensional constraints
  - 47.5 x 47.5 cm cylinder
- Spacecraft mass limitation
  - Total 30 kg
- Team requirements (typical)
  - Orbit control
  - 3 axis attitude control
  - Formation flight time
  - Integration
    - Structural
    - Power
    - Command and control
System Desired Attributes

- Low budget, utilizing commercial off-the-shelf components
- Low storage/operating pressures
- Minimal volume/size envelope
- Rapid development – 2 years
- Proven and easy to implement technology without significant prior research
Desired Attributes for the Propellant

- Nontoxic / non-flammable
- Safe and easy laboratory handling procedures
- Environmentally friendly
- Easily obtainable without the need for licensing or permits
- Simple storage requirements
- Easily transportable
- Compatible and chemically inert with common spacecraft materials
Trade Studies

- Cold gas / chemical / electric system trade off
  - Safe and practical solution → cold gas
- Saturated liquids in space
  - Higher mass storage capability
  - Utilize vapor as a common cold gas
  - SPHERES liquid CO$_2$
  - SNAP-1 liquid butane
  - Can-X liquid sulfur hexafluoride (SF$_6$)
- Refrigerants in space
  - Space Shuttle orbiter: freon-21
  - Pioneer 10 and 12: freon
  - No documented uses of a refrigerant having been used as a spacecraft cold gas propellant
## Propellant Selection Process

Max conditions: 100 psia / 100 °C / 19.31 kJ  
Operating conditions: 30 psia / 20 °C  
Spacecraft mass: 25 kg

<table>
<thead>
<tr>
<th>Propellant</th>
<th>Specific Impulse ($I_{sp}$) s</th>
<th>Change in Velocity ($\Delta V$) m/s</th>
<th>Critical Temperature °C</th>
<th>Saturated Vapor Pressure @ 20 °C psia (kPa)</th>
<th>Liquid Density kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-134a</td>
<td>48.52</td>
<td>1.15</td>
<td>100.9</td>
<td>82.98 (572.1)</td>
<td>1150</td>
</tr>
<tr>
<td>R-123</td>
<td>31.60</td>
<td>1.24</td>
<td>183.86</td>
<td>10.98 (75.71)</td>
<td>1460</td>
</tr>
<tr>
<td>H₂O – Water</td>
<td>132.8</td>
<td>2.02*</td>
<td>374</td>
<td>0.338 (2.33)</td>
<td>998</td>
</tr>
<tr>
<td>SF₆ – Sulfur Hexafluoride</td>
<td>41.79</td>
<td>1.38</td>
<td>45.5</td>
<td>304.72 (2101)</td>
<td>1880</td>
</tr>
<tr>
<td>C₄H₁₀ – Butane</td>
<td>65.09</td>
<td>0.91</td>
<td>134.9</td>
<td>43.8 (302)</td>
<td>556</td>
</tr>
<tr>
<td>Xe</td>
<td>30.44</td>
<td>0.89</td>
<td>16.5</td>
<td>-</td>
<td>3057</td>
</tr>
<tr>
<td>CO₂</td>
<td>64.38</td>
<td>0.63</td>
<td>31.0</td>
<td>830.92 (5729)</td>
<td>763</td>
</tr>
<tr>
<td>Ar</td>
<td>55.53</td>
<td>0.48</td>
<td>-122.3</td>
<td>-</td>
<td>1400</td>
</tr>
<tr>
<td>N₂</td>
<td>75.58</td>
<td>0.47</td>
<td>-146.9</td>
<td>-</td>
<td>809</td>
</tr>
<tr>
<td>NH₃ - Ammonia</td>
<td>101.43</td>
<td>0.39</td>
<td>132.35</td>
<td>124.4 (857.8)</td>
<td>682</td>
</tr>
</tbody>
</table>
Propellant Selection Process

EPA Regulations and Legality

- **R-123 – HCFC**
  - EPA definition: Class II substance
  - Sale and production illegal after 2015
  - License restrictions

- **R-134a – HFC**
  - EPA definition: Alternate refrigerant
  - Friendlier to environment and humans
  - No restrictions on small quantity purchases
  - Release as a refrigerant must be recaptured

Hardware Compatibility

- Seals need to be compatible and meet outgassing regulations
- Use seals only when absolutely necessary
- R-134a has limited compatibility data
Two-Phase Dimensional Application

R-134a Pressure and State Envelope – 2.5 L Tank
# Refined Engineering Model (R134a)

<table>
<thead>
<tr>
<th>Maximum Tank Pressure at 70 °C (psia (kPa))</th>
<th>Propellant Mass (g)</th>
<th>Internal Energy (kJ)</th>
<th>Total Thrust Exhaust Duration (min)</th>
<th>Change in velocity (\Delta V) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 (689.5)</td>
<td>67.6</td>
<td>19.1</td>
<td>7.9</td>
<td>1.05</td>
</tr>
<tr>
<td>200 (1379.0)</td>
<td>152.7</td>
<td>42.0</td>
<td>17.9</td>
<td>2.38</td>
</tr>
<tr>
<td>300 (2068.4)</td>
<td>277.0</td>
<td>72.9</td>
<td>32.5</td>
<td>4.33</td>
</tr>
<tr>
<td>307.2 (2118.2)</td>
<td>1388.9*</td>
<td>229.0*</td>
<td>162.9*</td>
<td>22.2*</td>
</tr>
</tbody>
</table>

Spacecraft mass: 25 kg  
Operating conditions: 30 psia / 20 °C  
*Calculated with an initial tank propellant quality of 10%
Safety Assessment

• **Aim**
  - Ensure the propellant will operate within the guidelines set by the university developers
  - Identify and classify hazards associated with the propellant, the risks assessed and mitigating solutions found

• **Identification**
  - Qualitative analysis of a general system using a two-phase propellant
  - Focused on worst-case conditions

• **Classification**
  - **Catastrophic** - A catastrophic hazard is defined as any single or multiple system failure which has the potential to cause damage/harm not only to the spacecraft, but to surrounding equipment/personnel as well
  - **Critical** - A critical hazard is defined as any system failure which results in damage/harm to the spacecraft and/or has the potential to negatively impact mission objectives to the point of failure
  - **Tolerable** - A tolerable hazard is defined as any system failure which results in minimal damage to the spacecraft/mission
Safety Assessment

• Acceptable Risk for Flight
  ▪ Defined as operating the system with known hazards classified as tolerable or with hazards which can be mitigated by use of the appropriate safety devices and measures

• Catastrophic hazards
  ▪ Temperature rise / latent heat effects
  ▪ Thermal expansion / fatigue

• Critical hazards
  ▪ Propellant freezing
  ▪ Chemical reactivity

• Tolerable hazards
  ▪ Asphyxiation and skin irritation to personnel
University of Missouri - Rolla

- Satellite pair - MR and MRS SAT
- Study autonomous formation flight 50 m ± 5 m
University of Texas at Austin

- ARTEMIS – Satellite pair
- Separate on-orbit and autonomously rendezvous within a target distance of 50 m
Washington University in St. Louis

- Two spacecraft
  - 3 kg free-flyer (Bandit)
  - 29 kg host (Akoya)
- Flight-test proximity operations technologies, including:
  - Repeatable docking
  - Navigation within 5 m of a target
  - Image-based navigation
Summary - Small Spacecraft Propulsion Solution

Universal design methodology
R-134a provides:
• A feasible propellant option for small spacecraft
• Can be safely operated above the sealed container status
• Safe and practical for low-budget developers
• Allows easy system development and test
• Performance comparable to traditional cold gas propellants
Questions ?

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