The Development and Qualification of the STAR Resistojet System for Telecommunications Applications

Federico Romei¹, Matt Robinson¹, Chris Ogunlesi¹, Dave Gibbon²

and

Angelo Grubišić¹ (1981 - 2019)

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UK Space Agency Flagship

- Super-High Temperature Resistojets for All-Electric Telecommunication Satellites (STAR)

- National Space Technology Programme (NSTP) Flagship project: 2-years TRL innovation (KO in April)

- Consortium:
  - Developed High-Temperature Resistojet (HTR) AM design
  - Proved first AM resistojet prototype in 316L†
  - Goal: design and testing of STAR EM model in high-temperature materials

†Manufacturing of a high-temperature resistojet heat exchanger by selective laser melting F Romei, AN Grubišić, D Gibbon – Acta Astronautica, 2017
UK Space Agency Flagship

- Super-High Temperature Resistojets for All-Electric Telecommunication Satellites (STAR)
- 2-years TRL innovation project (KO in April)
- Consortium:
  - Global supplier of refractory metal powders for AM
  - Developer of advanced refractory metal alloys
  - Custom SLM powder including Ta/W alloys
Super-High Temperature Resistojets for All-Electric Telecommunication Satellites (STAR)

2-years TRL innovation project (KO in April)

Consortium:

- Market leader in additive manufacturing
- Produced parts in nickel alloys and pure Ta. Next will produce parts in Ta/W alloys
UK Space Agency Flagship

- Super-High Temperature Resistojets for All-Electric Telecommunication Satellites (STAR)
- 2-years TRL innovation project (KO in April)
- Consortium:
  - Independent innovation and technology company
  - Develop standardization processes and secure supply chain strategy for the STAR thruster
UK Space Agency Flagship

- Super-High Temperature Resistojets for All-Electric Telecommunication Satellites (STAR)
- 2-years TRL innovation project (KO in April)
- Consortium:
  - World's leading small satellite manufacturer
  - Extensive heritage with Xe and butane resistojets
  - End user requirements and guidelines for the STAR
State of the Art Xenon Resistojets (SSTL)

- Small satellite orbit correction and station keeping
- Heater 28V DC bus voltage at 15W and 30W

<table>
<thead>
<tr>
<th>Variant</th>
<th>Redundant heater power</th>
<th>Propellant</th>
<th>Thrusters</th>
<th>Typical operation temperature</th>
<th>$I_{sp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T30</td>
<td>30 W</td>
<td>Xe</td>
<td>10 launched on 10 S/Cs, 2 waiting launch</td>
<td>530°C</td>
<td>48 s</td>
</tr>
<tr>
<td>T15</td>
<td>15 W</td>
<td>C$<em>4$H$</em>{10}$</td>
<td>19 launched on 10 S/Cs, 4 waiting launch</td>
<td>250-350°C</td>
<td>&gt; 100</td>
</tr>
</tbody>
</table>
Concept of the STAR Thruster

- Maximise specific impulse, hence stagnation temperature

\[ I_{sp} \approx \frac{1}{g_0} \sqrt{\frac{2c_{p,m}T_0}{M}} \]

- 3D printed monolithic regenerative heat exchanger

- 316L prototype \((T_0 = 1,000 \text{ K})\) demonstrated†

- Refractory metals \((T_0 > 2,500 \text{ K})\) to reach \(I_{sp} > 80\) s with Xe

†Validation of an Additively Manufactured Resistojet through Experimental and Computational Analysis F. Romei, A. Grubišić – Acta Astronautica, 2019
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\(\dagger\)Validation of an Additively Manufactured Resistojet through Experimental and Computational Analysis F. Romei, A. Grubišić – Acta Astronautica, 2019
Application 1: Stand-Alone Propulsion

- **Small Satellites:**
  - Limited resources
    - Volume (0.75 m³)
    - Mass (200 kg)
    - Power (100 W)
  - Dependence on:
    - High storage density – \( I_{sp} \) product
    - Inert propellants
    - Lower cost of AIT

- **Resulting system:**
  - Low \( I_{sp} \)
  - Low total impulse/ low \( \Delta v \)
  - Limited on-orbit/deorbit capability
  - +70% \( \Delta v \) from STAR thruster = game changer

RapidEye constellation, SSTL (Xe resistojet)

Disaster monitoring constellation AISAT-1, SSTL (Butane resistojet)
Application 2: All-Electric Spacecraft

▪ Advantages of A-E spacecraft:
  – Common Xenon Propellant Management System
    • System mass saving (1 vs 2 PMS)
    • Complexity reduction and reuse of architecture
    • PPS & RCS mass fraction optimisation (Deep Space 1, SMART 1, Hayabusa)
  – Absence of hydrazine
    • Lower cost of AIT
    • Lower risk of regulation changes
  – Safe mode operations
    • Xe resistojets can operate in cold redundancy for safe mode/de-spin

Boeing – 702SP (ABS-3A and Eutelsat 115 West B, 2015)

OHB System – Electra, SmallGEO Flex platform (http://www.esa.int/)
Low Reynolds number nozzles at high temperature

Need of high nozzle efficiency (>90%), i.e. \( \text{Re}_t > 4000 \)

To size the nozzle based on mission requirements
Nozzle Considerations

- LEO application: primary propulsion for $\Delta v$ manoeuvres (no pulse)
- Material: nickel alloys, temperature range: 1,100 K – 1,400 K

Stagnation pressure (left) and nozzle efficiency (right) colormaps with overlaid nozzle performance in terms of thrust (----) and specific impulse (-----) iso-contours as function of the mass flow rate and propellant stagnation temperature $T_0$. Calculations are made for $d_i = 0.3\, \text{mm}$. 
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Design point:

\[ F = 50 \text{ mN} \]
\[ I_{sp} = 60 \text{ s} \]
\[ p_0 = 5 \text{ bar} \]
\[ P_e < 50 \text{ W} \]
\[ \eta_{ts} > 60\% \]
Nozzle Considerations

- GEO A-E application: RCS, de-spin and momentum damping
- Material: Ta/W alloys, temperature range: 2,100 K – 2,600 K

Stagnation pressure (left) and nozzle efficiency (right) colormaps with overlaid nozzle performance in terms of thrust (———) and specific impulse (———) iso-contours as function of the mass flow rate and propellant stagnation temperature $T_0$. Calculations are made for $d_t = 0.6$ mm.
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Design point:

- $F = 200\, \text{mN}$
- $I_{sp} > 80\, \text{s}$
- $p_0 = 5\, \text{bar}$
- $P_e < 150\, \text{W}$
- $\eta_{fs} > 60\%$
Iterative Heater Design

Low resistance (low risk – high priority)

- Straight cylinders

Medium resistance (medium risk – medium priority)

- Heater with inner helix
- Heater with meshed cylinders

High resistance (high risk – low priority)

- Single track helix
Iterative Heater Design

- **Heater resistance ~ 10 mΩ**

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<th>Resistance Level</th>
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Straight cylinders: first design in 316L (left) and current design in Nickel alloy (right)
Iterative Heater Design

- **Low resistance (low risk – high priority)**
  - Straight cylinders

- **Medium resistance (medium risk – medium priority)**
  - Heater with inner helix
  - Heater with meshed cylinders

- **High resistance (high risk – low priority)**
  - Single track helix

- Heater resistance ~ 100 mΩ

Meshed cylinders design
Iterative Heater Design

- **Heater resistance ~ 1 Ω**

**Low resistance (low risk – high priority)**

- Straight cylinders

**Medium resistance (medium risk – medium priority)**

- Heater with inner helix
- Heater with meshed cylinders

**High resistance (high risk – low priority)**

- Single track helix
STAR PCU development

- **LEO application:**
  - EM model for full STAR system tests
  - low cost, current controlled output

- **A-E GEO application:** BOM and schematics only
Test Campaign

- **Sub-component:**
  - Heater cycling tests of several designs -> selection of heater
    - M. Robinson (A393): Ta - low resistance design: ~ 340 cycles performed, 120 at 80% of $T_{\text{max}}$
  - Selective Laser Melting high temperature properties
    - C. Ogunlesi (A403): surface emissivity and electrical conductivity at high-temperature
  - PCU design + environmental testing

- **Full system (STAR thruster + PCU) tests:**
  - Thermal cycling + vibration + shock tests
  - Leak + performance tests + thruster cleanliness verification
  - Life test + NDT inspection
Summary of STAR project

Phase 1:
- Investigate on resistivity and surface emissivity of SLM custom material
- Iteration of heater design to maximise lifetime/electrical resistance

Phase 2:
- Testing of PCU
- Testing of STAR thrusters in Ta/W and nickel alloys
- STAR system EM model test
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Thank you for your attention

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