XMM fuel estimates

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• XMM Reaction Control System
• Fuel estimation
  – Book-keeping
  – PVT (Pressure-Volume-Temperature: applying the Ideal Gas Law)
  – Thermal Propellant Gauging Technique (TPGT) (thermal knocking)
• Review and Way Ahead

• Reference Documents
Background

- On July 15, 2009, DP TM TD057 (tank temps. range) went OOL HH with a value of 10.41 degC. Spacecraft Anomaly XMM_SC-60 raised
- Tank1 Thermostat failed
- OOL triggered because Tank1 temperature was more than 10 degC lower than Tanks 2, 3 and 4

- Conclusion from Industry (Astrium) was that this excursion had no impact on Reaction Control System
  - No possibility of pressurant gas entering pipes downstream of Tank1 unless Tank1 nearing empty (< ~6Kg)
  - Total fuel then ~80Kg (or 20Kg per tank)
  - Lower temp encourages more fuel into Tank 1

- Recommendation
  - Maintain Tank1 temperature control using time-tagged commands keeping temperature range between tanks <5degC
  - Try to gauge fuel distribution between tanks to better determine when a tank is near empty
XMM Reaction Control System

- 4 Tanks
  - Hydrazine Fuel
  - Helium Pressurant
  - T1 Main Tank
  - T2, T3, T4 Aux

- Latch Valves
  - LV-1 feeds Branch A
  - LV-2 feeds Branch B

- Pressure Transducers
  - PT-1 System Pressure
  - PT-2 Branch A Press.
  - PT-3 Branch B Press.

- Reaction Control Thrusters
  - 4x Branch A
  - 4x Branch B
Book-keeping: Principles

- Specific Impulse (Isp) of thrusters known
  Isp ~ 2250Ns/kg but varies with inlet pressure

- Thrust known
  - Nominally 25N (at 25bar)
  - Now <10N (<7bar)
  - Can measure with flight calibration

- Fuel mass flow through thrusters can be derived
  \[ \text{Thrust} = \text{Isp} \times \text{m} \]
  
  One firing:
  \[ \Delta \text{m} = \text{m}_f \]
  
  
  
  
  Keep running count of thruster activations (On-times)
  \[ \text{mmfuelfuel} = \text{m}_f \text{loaded} - \sum \Delta \text{m} \]

- Diagram of fuel flow and thruster activation.
**Book-keeping: Running figures**

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remaining fuel (March 2010)</td>
<td>76.3 [kg]</td>
</tr>
<tr>
<td>Consumption last 12 month</td>
<td>5.29 [kg]</td>
</tr>
<tr>
<td>average fuel consumption (since 2003-03-01)</td>
<td>0.48 [kg]</td>
</tr>
<tr>
<td>residual lifetime in month</td>
<td>116 [-]</td>
</tr>
<tr>
<td>extrapolated milage</td>
<td>Sep 2019</td>
</tr>
</tbody>
</table>
Book-keeping: Errors

- BOL = 5% (<11 Kg), EOL = 20% (18 Kg) [RD-2]
- Actually EOL is when Inlet Pressure = 8 bar. PT-01 < 7 bar So we are already past EOL!!
- No calibration for Thrust and Isp below this pressure. Also calibration data is based on constant thrust. Momentum dumping is via short pulse firings.
- PT-01 reading need to be corrected for Temperature variations and also converted to correct inlet pressure to use these calibrations.
PVT: Principles

\[ P_{He} V_{He} = n_{He} R T_{He} \]

where

\[ P_{He} \sim PT-01 \]

\( n_{He} \) number of moles of He is constant. Assume 165 moles loaded (~660g)

\( R \) gas constant

\( T_{He} = \) average temp of He from tank thermistors

\[ V_{He} = V_{tank} - \frac{m_{fuel}}{\rho_{fuel}} \]

\[ m_{fuel} = \rho_{fuel} \left( V_{tank} - n_{He} R T_{He} / P_{He} \right) \]
PVT: Spot Checks

- PVT figures (first est. from FCT) follow the book-keeping (Flight Dynamics figures)
- No evidence of leakage
- Error bars for Book-keeping set at +/- 18Kg
- PVT errors estimated to be 12Kg [RD-2]
Thermal Gauging: Principle

- The thermal response of the propellant tank when heated is related to the propellant load.

- Apply the Energy equation

\[ Q \Delta t = m \cdot C_p \Delta T \]

- Where:
  - \( Q \) is applied heat rate minus heat loss to the environment (J/s)
  - \( \Delta t \) is the change in time (s)
  - \( m \) is the mass of the tank system (kg)
  - \( C_p \) is the specific heat of the tank system (J/kg.K)
  - \( \Delta T \) is the change in temperature (K)

- I.e. A full tank should have greater heat capacity, therefore requires longer heating time to reach a given \( \Delta T \) than an empty tank.
Tank Duty Cycle

Over lifetime
- Temperature gradient increases
- Temperature cycle time (peak-to-peak) reduces
- Heater Off-time (or On-time) reduces
For any tank

\[ m \cdot C_p = [m \cdot C_p]_{\text{tank}} + m_{\text{fuel}} \cdot C_p_{\text{fuel}} + m_{\text{He}} \cdot C_p_{\text{He}} \]

If \([m \cdot C_p]_{\text{tank}}\) and \(m_{\text{He}} \cdot C_p_{\text{He}}\) neglected

If \(Q\) considered constant (ca. 14W steady heat input)

Then

\[ \frac{[m_{\text{fuel}}]_{\text{rev-1}}}{[m_{\text{fuel}}]_{\text{rev-n}}} = \frac{[\Delta t/\Delta T]_{\text{rev-1}}}{[\Delta t/\Delta T]_{\text{rev-n}}} \]

Or if \(\Delta T\) is constant (thermostat set-points fixed)

\[ \frac{[m_{\text{fuel}}]_{\text{rev-1}}}{[m_{\text{fuel}}]_{\text{rev-n}}} = \frac{[\Delta t]_{\text{rev-1}}}{[\Delta t]_{\text{rev-n}}} \]
Try Tank 1

\[ \frac{\Delta t}{\Delta T} \text{rev-100} / \frac{\Delta t}{\Delta T} \text{rev-1000} \]

- prove of concept: data from rev 100 compared to rev 1000
- In reality due to the quantization of HK data the method is highly dependent on the data selection for the determination of the slope
Fuel Ratios: Cycle Time Measurement

• Method 1
  – Spot checks of Tank cycles over 10 days at 1 year intervals

![Graph showing tank heater cycles over time]
Fuel Ratios: Cycle Time Measurement

• Method 2
  – Statistical analysis of all temperature data over 230 days in 2000 and in 2008

Example of Cycle times
  – Green - with angle correction
  – Red - without angle correction
Compare to Book-keeping

<table>
<thead>
<tr>
<th></th>
<th>Tank1</th>
<th>Tank 2</th>
<th>Tank 3</th>
<th>Tank 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method 1 Spot checks</td>
<td>38% ± 12</td>
<td>25% ± 13</td>
<td>43%* ± 8</td>
<td>54% ± 8</td>
</tr>
<tr>
<td>Method 2 Statistical Analysis</td>
<td>47% ± 6</td>
<td>33% ± 6</td>
<td>48% ± 6</td>
<td>52% ± 6</td>
</tr>
</tbody>
</table>

* Data taken from 2009 for Tank 3

- Methods agree within error margins
- Tank 2 supplying more Fuel?
- But 30Kg fuel missing?
Thermal Gauging: Method 3

- In the simplest form a single tank system can be described as
  - a Capacitance \( m.Cp \)
  - with a Conductive coupling to the environment (the XMM base plate).

- In the steady state condition with heater off the system will be at \( T_{\text{min}} \).

- When heat is applied at a constant rate \( Q_{\text{in}} \) the tank temperature will increase.

- The higher the temperature with respect to \( T_{\text{min}} \) the higher the heat losses \( Q_{\text{out}} \) until eventually the tank system reaches equilibrium again at \( T_{\text{max}} \) with \( Q_{\text{in}} = Q_{\text{out}} \).
Method 3: System Response

**TANK 1 EXT Temperatures during Solar Flare Dec 2006**

When heating from Tmin to Tmax:

\[ T = \text{Tmin} + \Delta T \left(1 - e^{-t/\tau_1}\right) \]

\( \Delta T = \text{Tmax} - \text{Tmin} \)

\( \tau_1 = \) Time constant for heating

When cooling the function is:

\[ T = \text{Tmax} - \Delta T \left(1 - e^{-t/\tau_2}\right) \]

\( \Delta T = \text{Tmax} - \text{Tmin} \)

\( \tau_2 = \) Time constant for cooling
Method 3: Analysis

- For the heating case:

  \[ \frac{d}{dt}(T) = \frac{\Delta T}{\tau_1} \exp(-t/\tau_1) \]

- In the initial condition when temperature \( T = T_{\text{min}} \) and time \( t = 0 \) the gradient is therefore simply:

  \[ \text{Initial gradient} = \frac{\Delta T}{\tau_1} \]

- This initial gradient is shown as the blue line (previous slide)

- If it is assumed that at this instant the heat loss is zero (\( Q_{\text{out}} = 0 \)) and all heater power is therefore applied to the tank (\( Q_{\text{in}} = \text{heater power} \)), then if we apply the energy equation (see Thermal Gauging Principle slide) we have:

  \[ \frac{Q_{\text{in}}}{m \cdot C_p} = \frac{\Delta T}{\tau_1} \]
Method 3: Analysis

- We now have to assume the mass and heat capacity of the Helium gas in the tank can be neglected. If so then we can write:

\[ m \cdot C_p = [m \cdot C_p]_{\text{tank}} + m_{\text{fuel}} \cdot C_{p_{\text{fuel}}} = Q_{\text{in}} \cdot (\tau_1/\Delta T) \]

- or rearranging:

\[ m_{\text{fuel}} = (Q_{\text{in}} \cdot (\tau_1/\Delta T) - [m \cdot C_p]_{\text{tank}}) / C_{p_{\text{fuel}}} \]

- Simply by estimating \( \tau_1 \) and \( \Delta T \) (Graphical best fit), it was possible to arrive at absolute values for the fuel in each tank.

- In practice it was difficult to find times where data was stable enough to make a fit: Best data from periods of Solar Flares where S/C in same pointing for number of days
Method 3: Results

• Surprising Results
  Tank 2 (as before) appears to have least fuel
  Tank 4 has 2 to 3 times more fuel than Tank 1
  Tank 1 (most important) looks OK

<table>
<thead>
<tr>
<th>2001</th>
<th>TANK1</th>
<th>TANK2</th>
<th>TANK3</th>
<th>TANK4</th>
</tr>
</thead>
<tbody>
<tr>
<td>dT</td>
<td>11</td>
<td>5.2</td>
<td>6</td>
<td>8.5</td>
</tr>
<tr>
<td>tau1</td>
<td>18</td>
<td>3</td>
<td>4.3</td>
<td>32</td>
</tr>
<tr>
<td>tau2</td>
<td>13</td>
<td>2.5</td>
<td>4</td>
<td>27</td>
</tr>
<tr>
<td>Q_in/m.Cp</td>
<td>0.61</td>
<td>1.73</td>
<td>1.40</td>
<td>0.27</td>
</tr>
<tr>
<td>Q_out/m.Cp</td>
<td>0.85</td>
<td>2.08</td>
<td>1.50</td>
<td>0.31</td>
</tr>
<tr>
<td>m.Cp</td>
<td>20.95</td>
<td>7.38</td>
<td>9.17</td>
<td>48.19</td>
</tr>
<tr>
<td>Qout</td>
<td>17.72</td>
<td>15.36</td>
<td>13.76</td>
<td>15.17</td>
</tr>
<tr>
<td>Mass fuel</td>
<td>22.49</td>
<td>6.79</td>
<td>8.88</td>
<td>54.52</td>
</tr>
<tr>
<td>Total</td>
<td>92.68 Kg</td>
<td></td>
<td></td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>2009</th>
<th>TANK1</th>
<th>TANK2</th>
<th>TANK3</th>
<th>TANK4</th>
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</thead>
<tbody>
<tr>
<td>dT</td>
<td>13</td>
<td>6.5</td>
<td>6</td>
<td>6.4</td>
</tr>
<tr>
<td>tau1</td>
<td>9.5</td>
<td>1.4</td>
<td>3</td>
<td>16</td>
</tr>
<tr>
<td>tau2</td>
<td>5.8</td>
<td>1.3</td>
<td>2.8</td>
<td>12</td>
</tr>
<tr>
<td>Q_in/m.Cp</td>
<td>1.37</td>
<td>4.64</td>
<td>2.00</td>
<td>0.40</td>
</tr>
<tr>
<td>Q_out/m.Cp</td>
<td>2.24</td>
<td>5.00</td>
<td>2.14</td>
<td>0.53</td>
</tr>
<tr>
<td>m.Cp</td>
<td>9.35</td>
<td>2.76</td>
<td>6.40</td>
<td>32.00</td>
</tr>
<tr>
<td>Qout</td>
<td>20.97</td>
<td>13.78</td>
<td>13.71</td>
<td>17.07</td>
</tr>
<tr>
<td>Mass fuel</td>
<td>8.93</td>
<td>1.38</td>
<td>5.64</td>
<td>35.58</td>
</tr>
<tr>
<td>Total</td>
<td>51.53 Kg</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Thermal Gauging vs Book-keeping

- Still 30 Kg missing...
Astrium review

- In February 2010 FCT sent Fuel Mass Calculation document [RD-03] to Industry (Astrium) for review
- March 2010 Detailed Analysis received [RD-04]
- No need for alarm, the assymetry in fuel mass could not occur
  - Errors in initial loaded could account for ~2Kg difference between tanks
  - Fuel / pressurant gas migration between tanks during initial fuel orientation manoeuvres (LEOP) could also account for ~2Kg difference
  - Since LEOP the only way to account for more significantly fuel in Tank 4 is a leakage of pressurant gas (loss of 3bar!! Would be observable but is not)
    - This is ruled out since a leakage is not observable in PVT analysis nor in analysis of disturbance torques (Flight Dynamics)
- Two explanations for the assymetry calculated
  - Tank 4 is better insulated (this tank is on the cold side)
  - Temperature measurements are taken from thermistors placed near middle of Tanks (in contact with He) rather than the top (in contact with Fuel)
Way Ahead

- Book-keeping
  - seeking better ground calibration data for thruster performance
  - Which temperatures to use for correcting pressure variations

- Tank gauging (Thermal knocking) requires a better tank model (thermal properties, location of fuel, location of thermistors) and then calibration against flight telemetry

Comparison of Relative Accuracies [RD-7]

<table>
<thead>
<tr>
<th>Method</th>
<th>Accuracy Limitation Drivers</th>
<th>Accuracy Trend</th>
<th>Accuracy 2 years before EOL</th>
<th>Accuracy at EOL</th>
</tr>
</thead>
</table>
| MEASUREMENT DURING THRUSTER FIRINGS Bookkeeping | incomplete maneuver recording  
mission profile has to be known well in advance for on ground calibration testing  
maneuver data measurement accuracy | DECREASING       | < +/- 3 %                     |                                 |
| Flowmeter                   | flowmeter accuracy  
initial tank loading                                                                 | CONSTANT       | < +/- 0.2 % full scale during liquid apogee firing |                                 |
| MEASUREMENT BETWEEN THRUSTER FIRINGS pVT | pressure and temperature measurement accuracy | DECREASING       | < +/- 1.5 %                   |                                 |
| Thermal Knocking            | heater power stability  
stability of thermal environment  
accuracy of thermal model | INCREASING       | +/- 10 to 15 % of remaining propellant mass |                                 |
Way Ahead – Thermal Knocking

- Flight Calibration?
- Perhaps TANK 4 is best suited
References

RD-1 Assessment of XMM Anomaly XMM_SC-60 and Recovery Action, Astrium, 21/07/2009


RD-3 XMM-Newton Fuel Mass Calculation, J.Martin, Draft, 01-02-2010

RD-4 Assymetric Tank Depletion, Astrium, 11-03-2010

RD-5 XMM-Newton RCS Fluid Dynamics Analysis, XM-TN-BPD-0013


RD-7 Comparative Assessment of Gauging Systems and Description of a Liquid Level Gauging Concept for a Spin Stabilized Spacecraft, Hufenbach.B. 1997ESASP.398..561H

RD-8 Flight Validation of the Thermal Propellant Gauging Method Used at EADS Astrium, L. Dandaleix, 2004ESASP.555E...9D