JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 45, No. 1, January–February 2008

Thruster Plumes: Sources for High Pressure and Contamination at the Payload Location

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DOI: 10.2514/1.30600

The ESA comet mission Rosetta was launched in early March 2004. The goal of this mission is the rendezvous with comet 67P/Churyumov–Gerasimenko in 2014. The spacecraft will then accompany the comet toward the sun for about one year. During this close encounter the evolution of the nucleus and the coma will be monitored and analyzed. One of the instruments onboard is the comet pressure sensor. Two gauges are integrated in the sensor, which allow the measurement of the dynamic pressure and the total neutral particle density in the cometary coma. From these measurements the expansion velocity of the coma can be derived. Starting shortly after launch, during a time period of about two years, several tests and background measurements of the total particle density in the vicinity of the spacecraft were made. Some data were collected during the Rosetta thruster firing cycles, which show a huge pressure increase during thruster operation by several orders of magnitude above the background pressure. After a two-year flight duration, the background pressure around the spacecraft is about 2×10^{-11} mbar, whereas values up to 1×10^{-5} mbar have been recorded during the thruster operation. Such high pressures might induce, in the worst case, high-voltage discharges as well as be responsible for a contamination layer on sensitive exposed surfaces of the payload.

Nomenclature

b_{ref} = fit parameter for the particle fluence, multiplier in the exponential term
f_1 = correction factor for the pressure measurement corresponding to the thruster operation time
f_2 = correction factor for the pressure measurement corresponding to the comet pressure sensor time interval
k_1 = fit coefficient
M_{av} = averaged molecular mass of the exhaust gas
m_{ex} = mass of the exhaust inside the nude gauge ionization volume
m_{prop} = propellant mass (fuel and oxidizer)
$\dot{m}_{prop}$ = propellant mass flow rate
N_a = Avogadro constant
N_0 = nozzle particle production rate
n = local particle density
p_a = ambient pressure on Rosetta
p_0 = pressure offset
r = distance nozzle comet pressure sensor nude gauge
S = surface area of a zone of a sphere per degree
t_B = thruster operation time
v_{ex} = gas expansion velocity
y = relative particle fluence from the nozzle
y_{ref} = fit parameter for the particle fluence, multiplier
y_0 = fit parameter for the particle fluence, offset
β = angle between the comet pressure sensor nude gauge and the thruster nozzle figure axis
τ_{COPS} = comet pressure sensor time constant for the response to a pressure increase
τ_2 = fit coefficient in the exponential term

Received 5 March 2007; revision received 27 June 2007; accepted for publication 3 July 2007.

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I. Introduction

THE ESA mission Rosetta was launched on 2 March 2004 toward comet 67P/Churyumov–Gerasimenko. Also onboard this spacecraft is the ROSINA instrument package, which will perform an in situ composition analysis of the cometary coma. It consists of two mass spectrometers and a pressure sensor [1]: one is a reflectron-type time-of-flight mass spectrometer (RTOF) with a mass range of 2–300 amu/e (atomic mass units per elementary charge), and the second one is a double-focusing mass spectrometer (DFMS) with a mass range of 12 to 140 amu/e. The total neutral particle density will be determined with the nude gauge (gauge without enclosure) of the comet pressure sensor (COPS). A second gauge (the ram gauge) of COPS is pointing toward the cometary nucleus and is measuring the dynamic pressure of the cometary coma. The expansion velocity of the coma can then be derived from both results.

The COPS instrument operates also as a safety device for the ROSINA mass spectrometers and for other pressure-sensitive instruments onboard Rosetta. At high pressure values or at high pressure gradients a warning signal is distributed to the other instruments.

Figure 1 shows the Rosetta spacecraft with the instrument platform on top. COPS and DFMS are mounted on this instrument platform, whereas the RTOF sensor is integrated closer to the rear edge of the spacecraft. Only the attraction grid of the ion source is visible in Fig. 1. The numbered items are some of the Rosetta thruster pairs. Please note the close proximity of thruster 1 to the COPS instrument.

Most of the time during the commissioning phase of the ROSINA instrument package, COPS was running in a monitoring mode

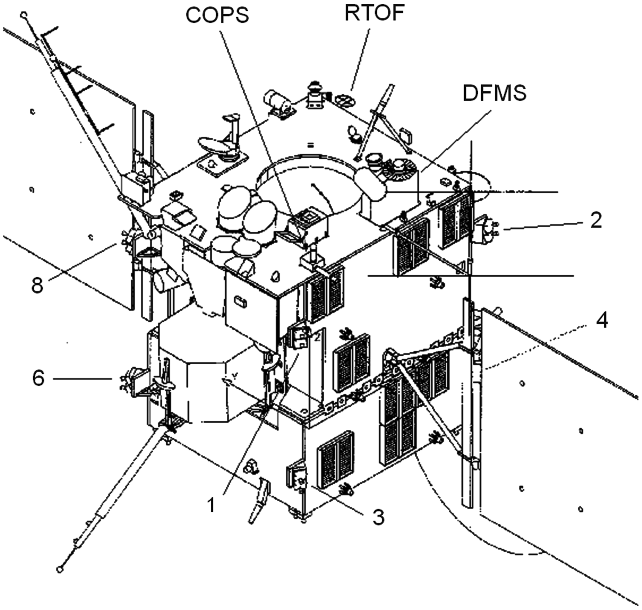


Fig. 1 Drawing of the Rosetta spacecraft: the payload platform with COPS, and the ROSINA mass spectrometer DFMS is on the top. The RTOF instrument is mounted along the rear edge of the spacecraft and therefore only the attraction grid of the entrance system is visible. The solar panels are pointing toward the upper left and the lower right. Also given is the labeling of some thruster pairs.

measuring the total particle density. Early in the mission (24 May 2004) there was an opportunity to have COPS running during a Rosetta thruster firing. Because this first set of data showed an unexpected high pressure increase, which even put the instrument into saturation during the firing sequence, it was decided to do some more measurements. Within the next year a total of three more data sets during thruster firing could be acquired. Although the thrusters are equipped with a special shield designed to minimize contamination via droplets generated by a fuel film on the rim of the thruster nozzle, we could detect a significant gas contamination during the thruster firings.

Section II will give an overview of COPS and its operation modes, followed by the presentation of the measurements in Secs. III and IV. The experimental data set will be compared with theoretical estimates in Sec. V.

II. Comet Pressure Sensor

A. Instrument Overview

Figure 2 shows a picture of the flight model of COPS without its multilayer insulation. Both gauges are mounted to the electronics housing, and the power and communication connections are shown on the right-hand panel of the housing. The nude gauge is an open source gauge that is used to measure the total particle density. The second gauge, the ram gauge, points upward. On top of a short boom is the equilibrium sphere with a small entrance aperture visible. This gauge measures the ram pressure. Together with the total particle density, the coma expansion velocity can be evaluated.

A schematic view of the nude gauge with the applied potentials is given in Fig. 3. Free electrons are generated with a hot filament (tungsten–rhenium), which are used to ionize the neutral gas particles via electron impact ionization. The ions are then extracted toward the collector cathode and the ion current is measured by a highly sensitive electrometer. Because of noncircular motions of the electrons inside the grid volume, the electron impact energy varies between 40 and 150 eV. Further details of this instrument, including some calibration results, can be found in [1,2]. The ram gauge will not be further discussed here, because all the presented results are from nude gauge measurements.

COPS can be operated in different sensitivity modes that are defined by the electron emission current and the measurement range

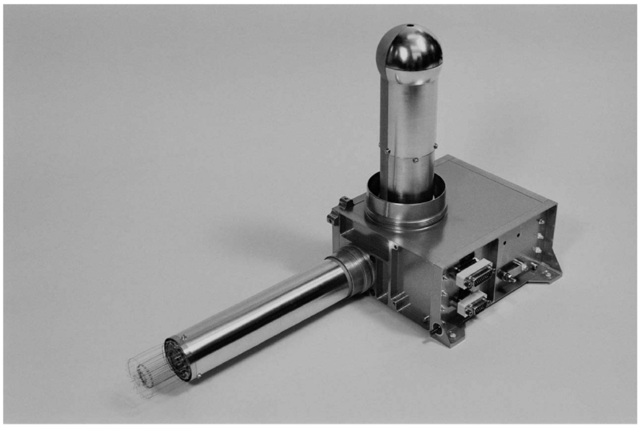


Fig. 2 ROSINA COPS flight spare model. The nude gauge is pointing to the left and the ram gauge is mounted on the top of the electronics housing. Inserted in the right panel are the power and data connectors (with attached connector savers) and the electrical grounding latch.

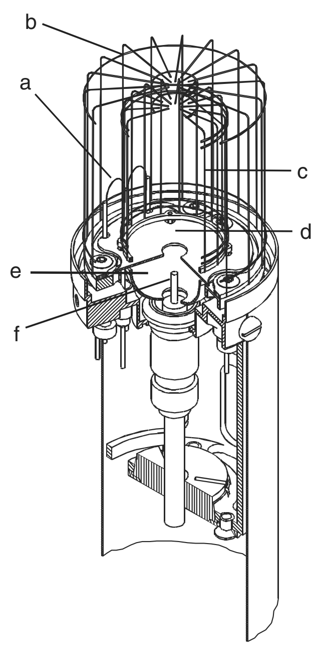


Fig. 3 Schematics of the COPS nude gauge: a) two filaments, 28 V; b) outer grid, −12 V; c) inner grid, 180 V; d) base plate, 0 V; e) reflector, 180 V; and f) ion collector.

of the electrometer. Pressure values between 2×10^{-11} mbar and up to 3×10^{-5} mbar can be recorded. This is achieved by a combination of two electrometer measurements ranges (less than 100 pA or less than 10,000 pA ion current) and two different electron emission settings: 15 and 100 μA. These electron emission settings are not fixed and could be changed if the necessity arises during the mission. Even a higher emission than 100 μA would be possible, but this may shorten the lifetime of the filament.

During normal operation COPS acts as a safeguard instrument for the ROSINA mass spectrometers. If the pressure rises above 10^{-6} mbar, an alarm flag will be set and the data processing unit (DPU) switches the other two instruments off. A second alarm flag will be set if a steep pressure gradient is detected by COPS. The state of these two flags is also distributed on a special data channel to the other Rosetta instruments. If the pressure rises above 10^{-5} mbar, COPS will be switched off too. After a delay of 1 h a switch-on will be tried. During this switch-on a preliminary pressure value at very low electron emission is calculated to detect an ongoing high-pressure situation and the filament can be switched off again.

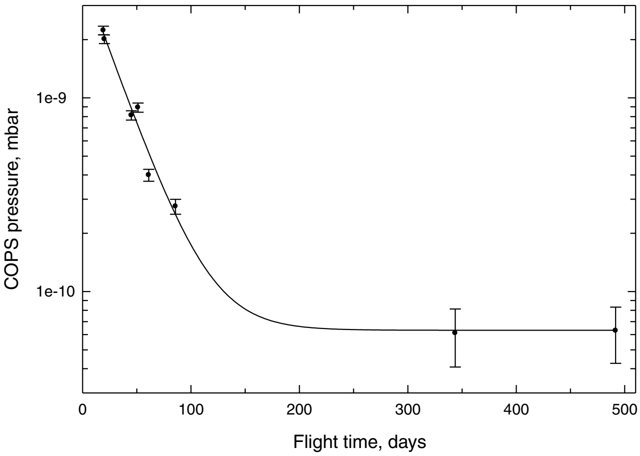


Fig. 4 COPS pressure measurements onboard Rosetta. Error bars are the sum of a 5% error on the measurement value and a 2-bit error from the ADC. The solid line shows an exponential fit to the data points (see Sec. III).

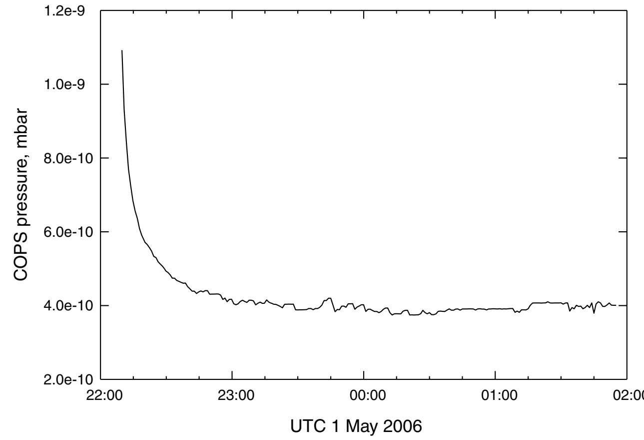


Fig. 5 Pressure characteristics after a switch-on of the nude gauge. At the beginning, the hot filament shows outgassing of condensed materials. Stable conditions are reached within 1 h of operation time.

B. Data Acquisition

Although the generated electron emission and ion currents are continuous, the data are polled by the ROSINA DPU in a fixed 2-s time interval. Thereby all instrument housekeeping values are collected and the actual pressure value is calculated. After the electrometer offset correction, the particle density is proportional to the ratio of the ion current to the electron emission current. Depending on the operating mode of COPS, the ROSINA DPU calculates a running average over five measured values. This averaged pressure result is then stored in a normal housekeeping package that is reported back to Earth once every minute. In the so-called science mode no averaging is done and all individual measurements during 5 min are buffered in the DPU memory. This set of 150 data points is then transmitted as a single science packet.

The analog ion current measurements are converted by a 14-bit ADC that allows a maximum resolution of 0.028 pA in the highest-sensitivity mode. The electron emission measurements are also converted by a 14-bit ADC with a 1-bit resolution of 0.0059 μA in low-emission mode and 0.278 μA in high-emission mode.

III. Rosetta Background Pressure

Roughly two weeks after launch, COPS was switched on for the first time. The Rosetta background pressure is shown in Fig. 4. The initial reading was around 2×10^{-9} mbar after settling of the instrument into a stable pressure reading. This pressure dropped during the first year in space to values of $\sim 6 \times 10^{-11}$ mbar. Simultaneous measurements with the mass spectrometer ROSINA-DFMS showed that the main part of the outgassing is due to water and organics [1].

Table 1 Result of the exponential fit to the measured background pressures of Rosetta

Fit parameter	Value
p_0	6.31×10^{-11} mbar
k_1	4.21×10^{-9} mbar
τ_2	0.0363 days^{-1}

The measured pressure values p_a can be fitted to an exponential decay:

$$p_a = p_0 + k_1 \times e^{-\tau_2 t} \tag{1}$$

Table 1 lists the values for the fitted parameters for Eq. (1). The offset pressure p_0 represents either the residual background pressure of the instrument platform or the measurement limit of the COPS gauge. The inverse τ_2 corresponds to the time constant for the outgassing process on Rosetta in the beginning of the mission, $1/\tau_2 = 28$ days.

Please note that the data points in Fig. 4 represent an averaged pressure value taken after COPS has achieved a constant pressure situation. Because of the implementation of a hot filament as the electron source for the impact ionization, there is always some outgassing existing when the gauge is switched on. A typical situation is given in Fig. 5 for a nude gauge switch-on made during the ROSINA commission phase. A few seconds after the switch-on of the filament, very high pressures values are reported. Because of the steep temperature increase of more than 1500 K, all the condensed material on the filament is vaporized and also measured by COPS. Parts close to the filament (grid and base plate) will also show a slower temperature increase with corresponding outgassing effects. After about 1 h of operation time, no additional outgassing occurs and stable measurement conditions are available.

IV. Thruster Firing Events

A set of reaction wheels inside the Rosetta spacecraft is used for attitude control. This method is preferred over changing the attitude via direct thruster firing because much less vibration throughout the instrument platform is generated. But about once a week, the reaction wheels have to be set to a nominal rotational speed. This is done by a so-called wheel-offloading sequence that consists of two basic steps:

1) It starts with an active phase to spin up or spin down the reaction wheels, with several thruster pulses to balance the torque impulse introduced by the wheels.

2) The damping phase is used to damp out any attitude and rotational speed disturbances and to decide whether the wheels are at their nominal speed or another active step is needed.

Table 2 Nozzle geometry relative to the COPS nude gauge; distances and angles are given for the thruster mounted on the same spacecraft side as the nude gauge

			Rel. particle density contributions		
Thruster no.	Distance r, m	Angle β, deg	Distance	Angle	Product
Thruster 1	0.62	93.3	1	1	1
Thruster 2	2.18	113.5	0.080	0.31	0.025
Thruster 3	2.79	102.3	0.049	0.59	0.029
Thruster 4	3.49	114.2	0.031	0.30	0.0094

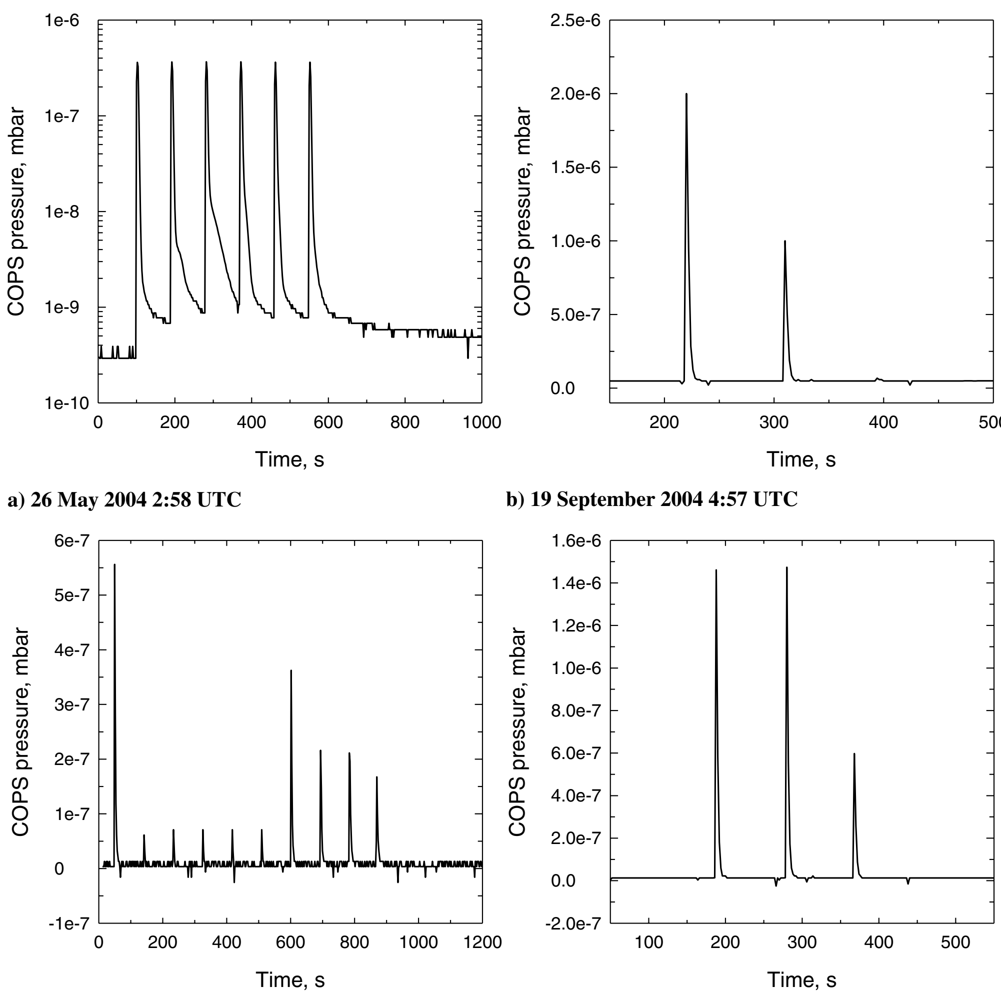
The Rosetta spacecraft is equipped with a set of 12 pairs of 10-N thrusters. Eight pairs are mounted on the four spacecraft edges perpendicular to the instrument platform, and the remaining four pairs are mounted on the opposite side of the instrument platform. Positions and numbering for some thrusters are given in Fig. 1

During the observed thruster firings only thrusters one to eight were used, and due to geometrical constraints we expect to see a contribution to the pressure increase only from thrusters one to four, which are mounted on the same side of the spacecraft as COPS. The contribution should roughly depend on two basic geometrical parameters: distance r between the thruster nozzle and COPS and the angle β between COPS and the nozzle figure axis. A collection of these values is given in Table 2 for the four closest neighboring thrusters. The relative particle density contribution is assumed to be proportional to $1/r^2$. The major part of the exhaust particle fluence is below an angle of 90 deg. At high angle values the particle fluence decreases exponentially and drops to zero at around $\beta = 140$ deg. The dependence of the particle fluence with respect to β will be presented in Sec. V.

Because of its close proximity to the nude gauge, thruster 1 will dominate the contribution to any measurements. Table 2 shows that thruster 1 has the lowest β value and the shortest distance to COPS, which results in the highest gas contribution. The products of the relative particle density contributions indicate that thruster 1 should contribute about 95% to the gas contamination.

Since the launch, COPS was able to observe four thruster firing events. An overview of the results is shown in Fig. 6. For each event, COPS collected data points in the science mode with a 2-s time resolution. Figure 6a shows the data set measured on 25 May 2004. The six different thruster pulses can be easily identified and a pressure increase up to 3.6×10^{-7} mbar was detected. As the electrometer was measuring in the ion low mode, it was saturated at this point by the ion current. For the other three events, COPS was switched to a mode with lower sensitivity. Because the electrometer was no longer saturated, different peak heights are now visible (see Figs. 6b–6d). Figure 6b shows two pressure peaks at times of about 220 and 310 s. Depending on thruster position and how long the thrusters were on, the measured pressure increase is different. A complicated firing sequence is given in Fig. 6c. In this case, 10 different thruster operations could be detected by the COPS nude gauge. The last recorded event shows a sequence with three pressure peaks (see Fig. 6d).

To analyze some of the measured peaks, spacecraft data about fuel consumption and thruster firing times were extracted from two spacecraft data channels. Unfortunately, the time resolution in these data streams is quite low (between 60 and 120 s). With this time resolution it is impossible to make a detailed analysis for each thruster pulse. An example is given in Fig. 7, showing a superposition of the COPS pressure curve with the firing times of thrusters 1–4 as vertical step plots. The width of a single step marks the time interval between the spacecraft data points (in this case, 64 s). If the thruster was fired within this time interval, the operation time is summed and at the end of the interval the total value is recorded. With access to only this data set it would be impossible to differentiate between a single or multiple firing of the corresponding Rosetta thruster unit. The number of firing cycles for each thruster is counted in another data channel. Therefore, it was possible to select the time interval with only one thruster firing pulse for further



a) 26 May 2004 2:58 UTC

b) 19 September 2004 4:57 UTC

c) 10 February 2005 2:59 UTC

d) 7 July 2005 1:40 UTC

Fig. 6 Pressure changes observed by COPS during four different thruster firing events. All data sets were taken during wheel offloading maneuvers. The time scales in the plots are given with respect to the starting points.

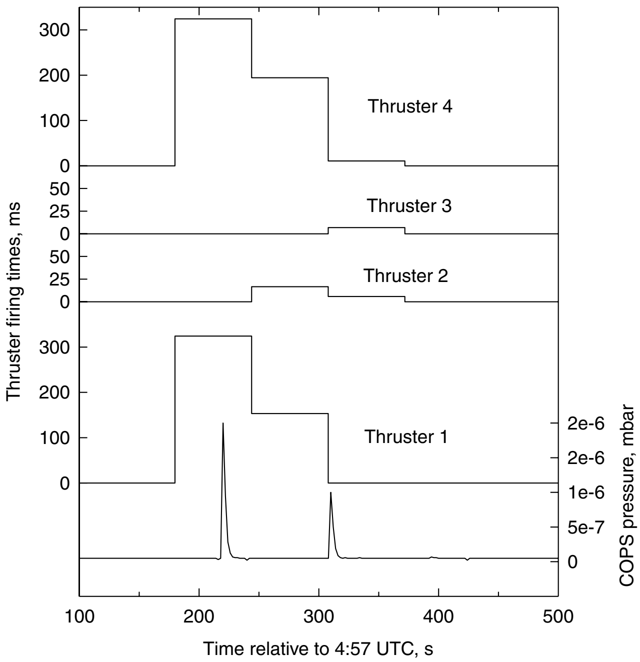


Fig. 7 Thruster firing from 19 September 2004. The thruster firing times are superimposed over the COPS pressure data set. The spacecraft data channel recorded the thruster operation times every 64 s. Please note that the thruster firing time scales for thruster 2 and thruster 3 are enhanced by a factor of 2.

analysis. In the case in which a single pressure peak from a single thruster pulse falls into a spacecraft data report interval, a corresponding evaluation was possible. But during intervals in which two or more thruster firings occurred, an unambiguously analysis was impossible. Within the preceding constraints a data evaluation for only the first pulse in Fig. 7 would be possible. The second pulse consists of more than one thruster operation cycle, and the third pulse shows now significant pressure increase in the medium-sensitivity mode of COPS. Most probably, this is because only thrusters 2 to 4 were operational.

Within the given constraints an evaluation for eight thruster pulses was possible, which are given in Table 3. One can see that most events include thruster 1 and only two firings are without thruster 1. Comparing results between these two sets can give an estimate of the ratio between thruster 1 and the others with respect to the contamination.

V. Model Calculation

A. Correction Factors

This section compares the measured pressure increases to a model calculation. The pressure values given by the COPS measurements are not real particle densities around the nude gauge during a thruster firing. Because of the following two reasons, they represent only a lower limit for the true pressure value:

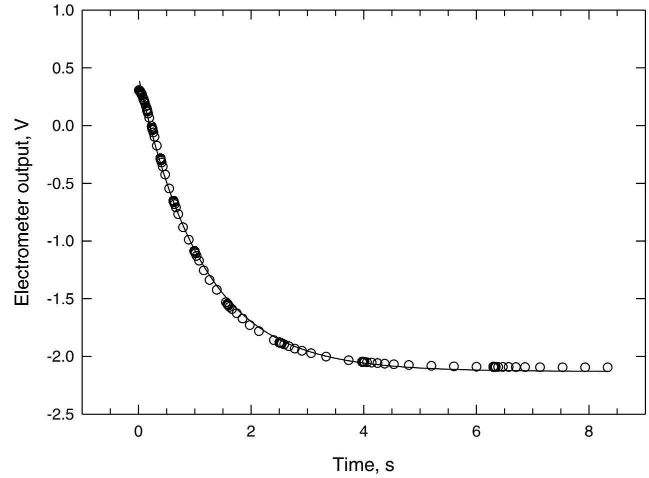


Fig. 8 COPS nude gauge electrometer response curve to an input current increase from 0 to 2500 pA at the time $t = 0$. The open circles represent the results from the electronic circuit simulation and the solid line corresponds to an exponential fit.

1) Because the thruster burn duration is much shorter than the response time of COPS, the measured peak particle density is too low.

2) Every 2 s the COPS housekeeping values are collected by the ROSINA DPU. The pressure is calculated inside the DPU from these housekeeping values. The timing of COPS is not correlated with the thruster firing. The data collection happens some arbitrary time after the end of the thruster firing. Therefore, the reported pressure values are again too low.

To correct the results for point 1, an electronic circuit simulation for the COPS electrometer was performed.

Figure 8 shows the response to an input current increase. An exponential fit yields a time constant of about $\tau_{\mathrm{COPS}} = 1.125$ s. Therefore, the first correction factor is $f_1 = (1 - e^{-(t_B/\tau_{\mathrm{COPS}})})^{-1}$, where t_B is the thruster operation time.

The second problem cannot be corrected easily. One has to know the time delay between the thruster switch-off and the pressure measurement. Unfortunately, the exact thruster firing times are not known and the time delay can be anywhere between 0 and $(2.0 - t_B)$ s. The two situations are given in Fig. 9. The lower panel shows the thruster pulse at the beginning of the 2-s time interval. On the upper panel, the thruster pulse is activated close to the end of the time interval. The assumed intensity is 1×10^{-5} mbar over a period of 150 ms. In the first case, a pressure value of 2.53×10^{-7} mbar is reported. The second case results in a much higher value of 1.26×10^{-6} mbar. The measured pressure value in the first case is five times lower compared with the second one. Because the relative position of a thruster pulse inside this 2-s time frame is not known, the second correction factor f_2 is somewhere between 1 and 5. The true pressure p_f during a thruster firing can be calculated according to the following formula:

Table 3 Pressure peaks assigned to corresponding thruster operations; if thruster 1 was operational, the pressure values were corrected only with the firing times of thruster 1; for the upper limits in the last column, f_2 was set to 5.0

Pulse no. (in fig.)/thruster no.	Raw COPS pressure p_{COPS}, mbar	Pulse width t_B, ms	Corrected pressure $p_{\mathrm{COPS}} \times f_1$, mbar	Upper limit p_f, $p_{\mathrm{COPS}} \times f_1 \times f_2$, mbar
1 (Fig. 6b)/1	1.95×10^{-6}	324.2	7.79×10^{-6}	3.9×10^{-5}
2 (Fig. 6b)/1 + 2	9.51×10^{-7}	153/16.6	7.47×10^{-6}	3.7×10^{-5}
1(Fig. 6c)/1 + 2 + 3	5.48×10^{-7}	60.5/138.6/152.3	1.05×10^{-5}	5.3×10^{-5}
2 (Fig. 6c)/2 + 3	5.31×10^{-8}	162.2/161.1	3.95×10^{-7}	2.0×10^{-6}
5 (Fig. 6c)/2 + 3	6.28×10^{-8}	161.1/161.1	4.68×10^{-7}	2.3×10^{-6}
9 (Fig. 6c)/1 + 2 + 3	2.03×10^{-7}	22.5/34.2/114.3	1.02×10^{-5}	5.1×10^{-5}
1 (Fig. 6d)/1 + 4	1.45×10^{-6}	329.1/329.1	5.72×10^{-6}	2.9×10^{-5}
2 (Fig. 6d)/1 + 4	1.46×10^{-6}	329.1/329.1	5.76×10^{-6}	2.9×10^{-5}
3 (Fig. 6d)/1 + 3 + 4	5.85×10^{-7}	106.5/51.8/67.4	6.48×10^{-6}	3.2×10^{-5}

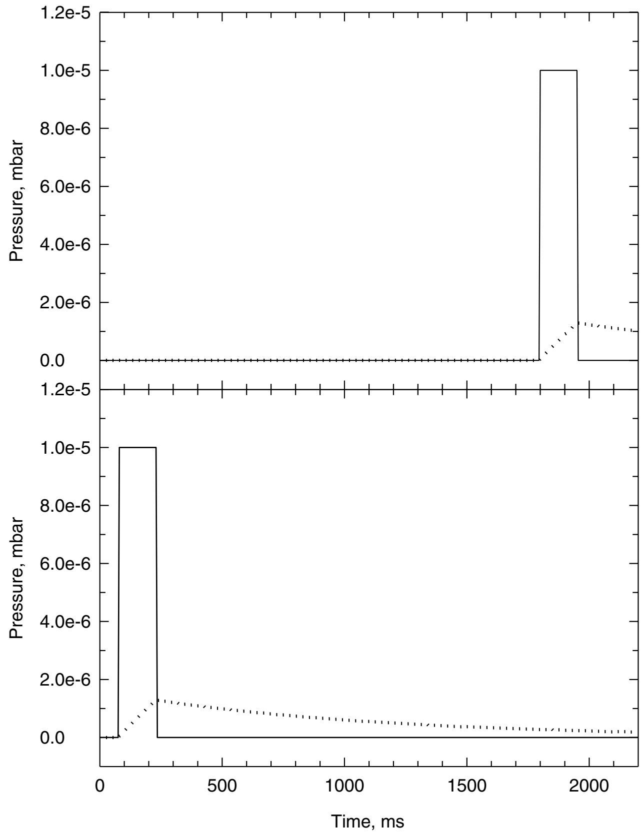


Fig. 9 COPS response curve to a 150-ms pressure pulse, plotted as the solid line. The doted line represents the COPS response to the signal input. The assumed data readout is at $t = 2000$ ms. In the upper panel, the pressure pulse is initiated at 1800 ms resulting in a signal readout of 1.22×10^{-6} mbar. The lower panel shows an early pulse at $t = 80$ ms. The corresponding readout would be only 2.27×10^{-7} mbar.

$$p_f = p_{\mathrm{COPS}} \times f_1 \times f_2 \tag{2}$$

A collection of the evaluated pressure pulses is given in Table 3. The measured COPS pressure is given with the firing times of the contributing thrusters. The factor f_1 has been used to calculate the corrected pressure values, but only with the firing times of thruster 1, except in the case in which thruster 1 was not operational (see pulses 2 and 5 of Fig. 6c in Table 3). The corrected pressure values for pulses with thruster 1 contribution are similar within a factor of 2. If only thrusters 2 and 3 are fired, the corrected pressure value is lower by a factor of 12 to 20. This is expected because these thrusters are further away from the COPS nude gauge and have larger β values. According to Table 2, these thrusters contribute 2.5 and 2.9% to the particle density at COPS.

B. Comparison of Measurements with Model Calculation

To calculate a particle density at the position of the nude gauge of COPS, the following assumptions were made: The thruster exit nozzle acts as a point source for the neutral exhaust gas particles. The Rosetta thruster are bipropellants units that use monomethylhydrazine fuel and mixed oxides of nitrogen as oxidizer [3]. The nominal thrust is 10 N with a flow rate of 3.5 $\mathrm{g\,s^{-1}}$ and a mixing ratio of 1.65. The combustion reactions are constant and therefore the exhaust gases have a constant composition with an assumed mean molecular weight of $M_{\mathrm{av}} = 20.1\ \mathrm{g\,mol^{-1}}$.** Because the experimental data have an uncertainty of around a factor of 5, the choice of the molecular weight is not very critical. The gas velocity for the radial expansion was taken from the thrust equation:

$$F = \frac{\mathrm{d}m_{\mathrm{prop}}}{\mathrm{d}t} v_{\mathrm{ex}} = \dot{m}_{\mathrm{prop}} v_{\mathrm{ex}} \tag{3}$$

With the thrust $F = 10$ N and the measured mass flow rate of the propellant $\dot{m}_{\mathrm{prop}} = 3.6\ \mathrm{g\,s^{-1}}$, the expansion velocity can be calculated as $v_{\mathrm{ex}} = 2.78\ \mathrm{km\ s^{-1}}$. Superimposed to the spherical expansion is an anisotropic particle fluence that depends on the angle β toward the nozzle figure axis. This anisotropy can be represented by an exponential function. Table 4 lists the values for the relative cumulative particle fluence for the Rosetta thrusters and their corresponding β positions. The listed values were estimated from Fig. 5-3 in [2].

Table 4 Relative particle fluences and corresponding β values; maximum extension of the gas plume is around $\beta = 140$ deg

Angle, β, deg	Relative cumulative particle fluence
30.0	0.900
70.0	0.990
112.0	0.999
143.4	1.000

The particle density at the position of the nude gauge is determined by the local particle fluence, which is the derivative of the cumulative particle fluence with respect to β. To calculate the derivative, the relative cumulative particle fluence has been fitted to an exponential curve:

$$y = y_0 + y_{\mathrm{ref}} \times (1 - e^{-\beta/\beta_{\mathrm{ref}}}) \tag{4}$$

The resulting fit and the calculated parameters are given in Fig. 10. Please note that the results given in Fig. 10 are only valid for high β values. The particle density at the position of the nude gauge is proportional to the relative local particle fluence y' in the corresponding direction from the nozzle to the gauge. This particle fluence can be calculated as the derivative of y with respect to β:

$$y' = \frac{\mathrm{d}y}{\mathrm{d}\beta} = \frac{y_{\mathrm{ref}}}{\beta_{\mathrm{ref}}} \times e^{-\beta/\beta_{\mathrm{ref}}} \tag{5}$$

Please note that Eq. (5) calculates the particle fluence through a zone of a sphere centered on the nozzle exit. Therefore, to obtain the particle density, the particle fluence has to be divided by the surface area of the zone S and multiplied by the expansion velocity v_{ex}:

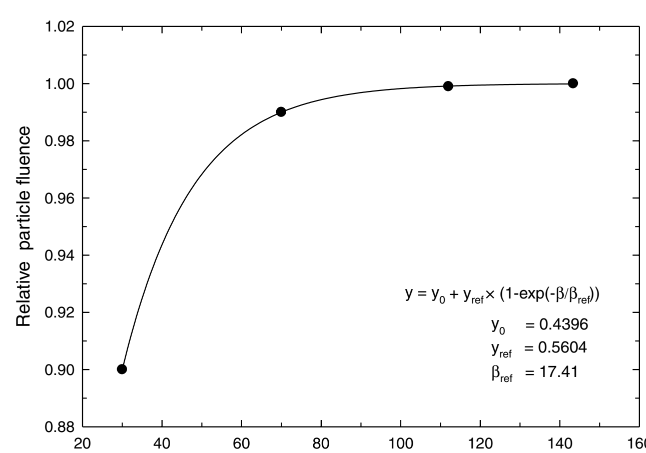


Fig. 10 Fit to the relative particle fluence of the Rosetta thrusters. The resulting fit is represented by the solid lines. The data points from Table 4 are marked with full circles. The fit formula and the results for the fit parameters are also given in the figure.

**According to Delft University of Technology, the mean molecular weight depends somewhat on the mixing ratio; that is, it increases from 19.1 to 21 $\mathrm{g\,mol^{-1}}$ for a mixing ratio range of 1.4 to 1.8. Properties available online at http://www.lr.tudelft.nl/live/pagina.jsp?id=3ad4fc8f-7dea-4701-9b61-d0ed633fbbf3&lang=en [retrieved 6 June 2007].

Table 5 Some intermediate and final results of the model calculation

Variable	Value
Angle between COPS and the nozzle, β	93.3 deg
Distance between COPS and the nozzle, r	0.62 m
Particle fluence at the nozzle exit, N_0	1.08×10^{23} s^{-1}
Relative local particle fluence, y'	1.51×10^{-4} (deg)$^{-1}$
Surface area of the zone per degree	0.0397 m^2 (deg)$^{-1}$
Calculated particle density	1.48×10^{17} m^{-3}
Calculated pressure for 300 K	6.1×10^{-6} mbar

$$n = \frac{N_0 y'(\beta)}{S(\beta, r) v_{ex}} \tag{6}$$

with

$$S(\beta, r) = 2\pi r^2[1 - \cos(\beta)] \times \frac{\pi}{180} \tag{7}$$

and

$$N_0 = \dot{m}_{prop} \times \left(\frac{M_{av}}{N_a}\right)^{-1} \tag{8}$$

The calculated particle density and the corresponding pressure value are reported in Table 5.

The calculated pressure value shows a good agreement with the corrected pressures measured by the COPS nude gauge. Because the model calculation includes only thruster 1, the result is compared with firings in which only thrusters 1 or $1 + 4$ were operational. These experimental values are between 5.7×10^{-6} mbar to 3.9×10^{-5} mbar for the pulses 1 (Fig. 6b) and 1 (Fig. 6d). For the second pulse, one can neglect the contribution from thruster 4 because of the geometry (see also Table 2). According to this table, the particle density ratio between thruster 1 and thruster 4 is about 100:1. Unfortunately, with the recorded firings it is not possible to calculate an experimental value for this ratio. On the other hand, comparison between thruster 1 and thrusters 2 and 3 is possible. Comparison between the second pulses from Figs. 6b and 6c shows a pressure ratio of 18:1. This is very close to the prediction calculated from the values of Table 2: $(0.025 + 0.029)^{-1} = 18.5{:}1$. The sum of thrusters 2 and 3 was taken because pulse 2 (Fig. 6c) shows equal firing times for thrusters 2 and 3.

VI. Long-Term Effects

During previous analyses of contamination of the payload by thruster firing it was always assumed that fuel droplets staying on the nozzles give the main contribution to the contamination of the payload [4]. In [4] the authors describe a detection limit of 8 ng cm^{-2}. Because the used quartz crystal microbalance system allows accumulation of the contamination over time, a direct comparison with COPS, measuring a particle density, is not possible. To give an impression of the detection limit of COPS, we have calculated the corresponding mass of the exhaust in the ionization volume of the nude gauge at a pressure of 1×10^{-6} mbar and $m_{ex} = 9.5$ pg. Please note that the lower limit for the pressure measurement is around $2\text{–}3 \times 10^{-11}$ mbar, therefore the mass detection limit will again be four orders of magnitude lower. The measurements by COPS made it very clear that the pressure in the vicinity of the payload increases by several orders of magnitude during thruster firing, not due to droplets but due to the expanding exhaust gas, even for payload that is outside the 180-deg cone of the nozzle direction. These pressure peaks are potentially harmful for all payloads that use high voltages. The decrease of the pressure at the end of the firing has two components, shown in Fig. 11: a fast component similar to the increase that reflects the exhaust gas pressure and a slow decrease. Even at the end of the measurement period (more than 1 h after the thruster firing), the reported pressure is still almost 50% above the Rosetta background pressure. This slow decrease could be indeed due to droplets.

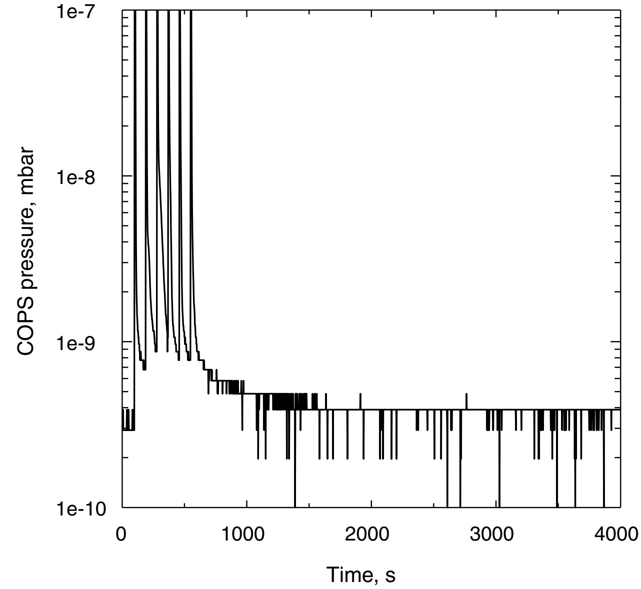


Fig. 11 COPS measurement during the first recorded thruster firing showing a slow decrease of the pressure after the last thruster pulse. Even after 1 h, the pressure is still slightly higher than before the firing sequence.

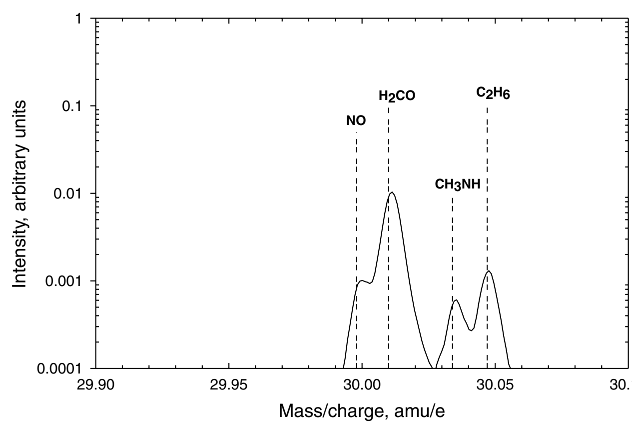


Fig. 12 ROSINA-DFMS high-resolution mass spectrum showing the monomethylhydrazine fragment CH_3NH at the mass/charge = 30.034 amu/e; spectrum was taken during the active checkout phase in December 2006.

ROSINA-DFMS, which is mounted on the payload platform of Rosetta, is a high-resolution mass spectrometer designed to measure thermal neutrals and primary ions [1]. It has a mass range from 12 to greater than 130 amu and a mass resolution of $m/\Delta m \sim 3000$. DFMS is only operated outside of thruster firings for safety reasons (high voltage). During tests in the early phases of the Rosetta mission no signs of monomethylhydrazine were detected by this mass spectrometer. However, during the last checkout in December 2006 there was a clear evidence for hydrazine in the background of Rosetta (see, for example, Fig. 12). Several fragments of monomethylhydrazine could be identified, such as CH_3N, CH_3NH, CH_3NH_2, CH_3N_2H, $CH_3N_2H_2$, and $CH_3N_2H_3$. It is not possible to exactly quantify the partial pressure of the hydrazine because the instrument has not yet been calibrated with this molecule. However, based on other detected molecules in the background of Rosetta and the total pressure measured by COPS (4×10^{-11} mbar), the partial pressure of hydrazine is estimated to be $\sim 2 \times 10^{-12}$ mbar. There are several possibilities why the hydrazine was detected only after more than 1000 days in space: In December 2006 Rosetta was at approximately 1.1 AU from the sun and the temperature around DFMS was 7°C. The measurement was performed about 20 h after the last thruster firing. In July 2005 when the same measurement was last performed, no traces of hydrazine were detected. The temperature of the spacecraft was around $-12°C$, and the time between the thruster firing and the measurement was about 5 days. The time between thruster firing and the measurement could play a role, as could the outgassing rate of Rosetta, which is temperature-dependent. It could also be a long-term effect in the sense that Rosetta accumulates more hydrazine on its multilayer insulation and solar panels with each thruster firing done during the mission, which is not entirely compensated by outgassing into free space. It is also reported in [5] that at 20°C only half of the deposited propellant mass will reevaporate from surfaces. Other residues from incomplete combustion are possible too; that is, methylhydrazinium ($CH_7N_3O_3$) [6]. This will be seen in coming years.

VII. Conclusions

It has been shown that at the location of the COPS sensor, the pressure during thruster firing can be well above 10^{-5} mbar. Because scientific payload instruments very often have high voltages (up to several kilovolts in a very confined space), such a high pressure at the location of the payload can, in the worst case, lead to high-voltage discharges that may damage the payload. It is therefore mandatory to prevent damage to the payload by operational means (switching off the high voltages before thruster firing, even in cases of emergency thruster firing). In the long term, the effect of thruster plumes can additionally lead to a contamination of surfaces by either direct deposition of thruster firing products on sensitive exposed payload surfaces (e.g., mirrors) or by reevaporization from the multilayer insulation or the solar panels. Such effects can only be avoided by using covers.

Acknowledgments

This work would not have been possible without the support of the European Space Operations Centre (ESOC) and especially of the Rosetta spacecraft engineers. The authors would like to thank the following institutions and agencies that supported this work: the State of Bern, the Swiss National Science Foundation, and the European Space Agency PRODEX program. We herewith acknowledge gratefully the work of numerous engineers from the institutions involved in ROSINA who contributed significantly to the ROSINA instrument.

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