A CONTINGENCY IN THE ROSETTA REACTION CONTROL SYSTEM: ALTERNATIVE CRUISE TRAJECTORY STRATEGIES TO COPE WITH DEGRADED DELTA-V RESOURCES.

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ABSTRACT

Since August 2006 a pressure transducer of the Rosetta Reaction Control System (RCS) shows anomalous telemetries indicating a possible leak in a pressurant line. The future operation mode of the RCS may be affected by this problem, resulting in performance degradation. The current propellant budget and its future evolution are evaluated to show the possible states w.r.t. the required mission delta-V. Alternative cruise trajectory strategies are analyzed, providing delta-V savings, to compensate for the expected performance loss of the RCS.

Rosetta was successfully launched by Ariane-5/G1+ on March 2, 2004. The spacecraft's destination is comet 67P/Churyumov-Gerasimenko, which Rosetta will orbit on its journey around the Sun with the goal of researching the comet nucleus during its active period. Rosetta will dispatch the lander Philae, which will touchdown to the nucleus in order to perform in-situ measurements. Swing-by maneuvers at Mars (2007) and Earth (2005, 2007, and 2009) will increase the velocity of Rosetta and turn it, such that the comet can be encountered in 2014 at a sun distance of 4 AU. During this journey Rosetta will enter the asteroid belt twice and perform two asteroid fly-bys, at Steins on September 5, 2008, and at Lutetia on July 10, 2010, in order to increase the scientific outcome of the mission.

The Rosetta Reaction Control System contains a high pressure section with two Helium tanks aimed at maintaining the pressure in the propellant tanks at the required range for the operation of the thrusters. A complex system of pipes and valves allows performing two pressurizations of the propellant tanks during the mission. At pressurization, Helium flows from the high pressure segment to the propellant tanks, the pressure downstream being stabilized at 17 bar by a pressure regulator. For safety reasons the high pressure section has to be isolated from the propellant tanks latest 40 days after pressurization. Hence, with the exception of the two short pressurization periods the RCS is operated in blow-down mode.

The first pressurization was conducted on the occasion of a deep space maneuver, which took place in May 2004. The second and last pressurization is foreseen to be executed in 2011 on the occasion of a large trajectory correction maneuver.

In August 2006 a pressure transducer located at the pressure regulator section, which is currently isolated from both the propellant tanks and the high pressure section, showed a drop of pressure to zero bar. Since then, and despite several reconfiguration attempts of the pressure transducer and interface units, the pressure measurements show consistent zero readings. At this point it cannot be excluded that a Helium leak has occurred in the pressure regulator section.

This situation raises serious concerns as the affected section needs to be re-opened for the next pressurization. Moreover it is considered that the failure might have been caused by a pyrovalve of the same type as those that need to be operated for the second pressurization and later isolation of the RCS system. Therefore a second pressurization of the RCS is considered risky and shall be avoided if possible.

Without a second pressurization, the operation pressure of the RCS will decay far beyond the operational range. It is assumed that the thrusters will still provide thrust with this inlet pressure, but a significant degradation of performance is expected. Due to expected loss of RCS performance it is likely that it will not be possible to achieve the current mission baseline if the second RCS pressurization does not take place.

After a more detailed explanation of the RCS system we present the propellant evolution to be expected with and without pressurization and results of our search for alternative delta-V saving mission options which fit into the expected budget.

1. THE ROSETTA REACTION CONTROL SYSTEM

Rosetta is equipped with a bi-propellant propulsion system using tetra-oxide of nitrogen as oxidizer (N2O4) and mono methyl hydrazine (MMH) as reductor. The system is pressurized with Helium gas (He), in order to guarantee operation conditions of the thrusters in the nominal range between 10.5 and 19 Bar. Normally the system operates in blow down mode, but a high pressure section integrated by Helium tanks and a system of pipes, valves and pressure regulators allows to replenish the propellant tanks with He at the nominal regulation pressure of 17 Bar twice during the mission.

Downstream the propellant tanks, the RCS contains two branches of each 12 thrusters to provide torques for attitude control and forces for trajectory correction maneuvers.

Figure 1 provides a schematic overview of the Rosetta RCS. For simplicity several elements of the RCS of little relevance for the exposure of this paper have been omitted. These are for instance fill and venting valves, test ports, filters and drain valves.

At launch the high pressure He tanks are isolated from the pressure regulator and also the pressure regulator is isolated from the propellant tanks. The system operates initially in blow down mode.

The first pressurization of the RCS is conducted with the following steps: the lines from the He tanks to the primary pressure regulator are opened by firing a pair of Pyro Valves Normally Closed (PVNC), PVNC2 and PVNC32. These valves are disposed in parallel, such that even if one valve fails the line is opened. In the same way, firing PVNC12 and PVNC13 opens the lines between the pressure regulator and the M2O4 tank. Firing PVNC18 and PVNC19 opens the lines to the MMH tank. This stabilizes the pressure of the propellant tanks at 17 Bar.

To minimize migration of N2O4 vapor upstream, which is highly corrosive and might attack components of the RCS (specially the pressure regulator) the RCS shall not remain pressurized for longer than 40 days. Isolation of the pressure regulator from the He tanks is achieved by firing a pair of Pyro Valves Normally Open (PVNO), disposed in series, PVNO1 and PVNO31. Also upon a failure of one of the two valves the line is closed successfully. The lines from the pressure regulator to the tanks are closed in a similar way by firing PVNO11, PVNO27, PVNO17 and PVNO28.

A second pressurization is achieved nominally by firing PVNC3, PVNC4, PVNC14, PVNC15, PVNC20 and PVNC21. Final isolation is achieved by firing PVNO5, PVNO16, PVNO29, PVNO22 and PVNO30.

In the event of a failure of the pressure regulator it is possible to isolate it and open the lines to a second pressure regulator by firing PVNO5, PVNO6, and PVNC7-10.

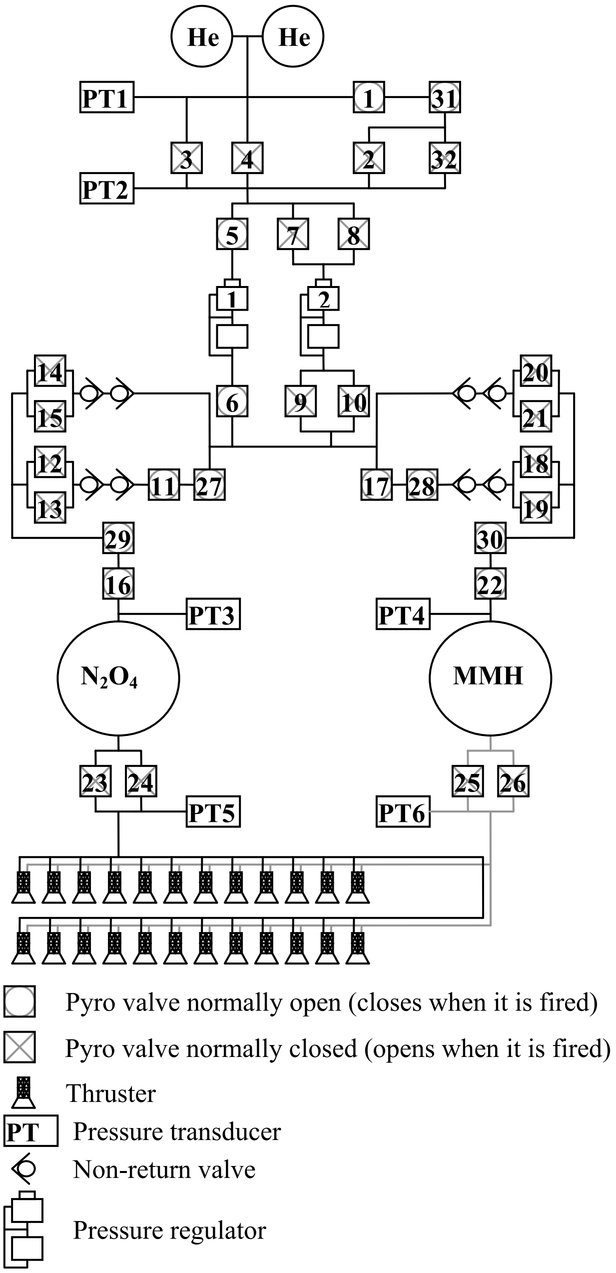

Figure 1: Rosetta Reaction Control System

The slots for the two pressurization periods are selected such that the pressure evolution is in the nominal range of operation of the thrusters (10.5 to 19 Bar). This has to be assessed for extreme conditions in the propellant consumption profile for the mission (i.e. cases with worst case propellant consumption, e.g. for attitude control and navigation, and cases with minimum possible consumption), and also taking into account opposite cases for temperature profile predictions (cold and hot cases).

In general it is advantageous to delay pressurization periods as much as possible. In this way, the ullage of the tanks is at maximum and the largest possible amount of He flows from the He tanks to the propellant tanks. However, the RO thrusters are trimmed to operate at 17 Bar. At this pressure they provide the highest specific impulse (ISP). Hence, there is also an interest to try to perform large maneuvers in pressure regulated mode.

Based on these considerations, the first RCS pressurization was performed on the occasion of the first deep space maneuver (150 m/s), in May 2004. The second pressurization is scheduled to take place in 2011, on the occasion of a maneuver of about 800 m/s. Figure 2 shows the nominal pressure evolution and function of mission delta-V, based on this pressurization strategy.

2. AN ANOMALY OF THE REACTION CONTROL SYSTEM

After the isolation of the RCS which followed the first pressurization, the Pressure Transducer (PT) PT2 has shown systematically a reading of about 22 Bar. In August 2006 the pressure measured by PT2 showed a drop to 0 Bar between two consecutive readings. Those two readings were separated by two weeks during which Telemetry (TM) from PT2 was neither recorded nor down-linked. Since then the reading of PT2 measurements has stayed consistently at 0.

Attempts have been undertaken to power cycle and reconfigure PT2 and related units, as the associated Acquisition and Control Unit (ACM) and the Avionics Interface Unit (AIU), which are in the chain of telemetry to the S/C computer. This was done in the hope that the failure could have originated from a temporary electronic corruption which would naturally disappear in the reconfiguration process. This has not been the case and PT2 still shows persistently zero readings. It is also to be noted, that PT2 readings themselves are not digital zero, but correspond to digital numbers which once calibrated correspond to zero pressure.

At this point it must be assumed that a true hardware (H/W) failure is the cause of the anomalous TM of PT2. Such H/W failure could be caused either by a leak in the segment of the pressure regulator or by a failure of PT2 itself. Unfortunately there is no backup PT in the segment, which could provide independent measurements and only at the time of the second pressurization the readings of PT1 and PT2 could be compared.

Hence, a worst case hypothesis of a leak cannot be excluded. Due to the small volume affected and due to the separation of the measurements indicating the anomaly it cannot directly be concluded on the dimension of the leak. However from navigation analysis it can be stated that no anomalous acceleration was detected and from monitoring of the reaction wheels (RW) also no differentiated disturbance torque could be observed. This seems to indicate that if there is a leak at all, it is probably not too large.

On the origin of the possible leak, only conjectures can be made. The leak could be in any item comprised by the segment of the pressure regulator. There are several components in this segment, including pyro valves, filters, non-return valves, fill and venting valves, the pressure transducer and the pressure regulator.

A certain concern was raised upon an alarm given to ESA by the PVNO manufacturer. Valves of the same type of a series mounted on Venus Express were built with a faulty explosive that can cause severe cracks at firing. The valves of Rosetta are not of the affected series and anyway the delay between the firing of some of those valves at isolation and the event of the pressure drop rather speak against a failure related to this.

The consequences of the leak are also widely open. First, it is clear that as long as the regulator segment is isolated from both the He tanks and the propellant tanks there is no direct implication for the operations of the thrusters.

If a leak occurred upstream of the pressure regulator, then the pressure regulator would have been exposed to an inverted pressure gradient, which may have damaged it. In this case the regulator could be isolated and future operations could be based on the redundant unit.

Anyway, when performing the second pressurization the leak point will be exposed to pressure again (unless the leak point is at the regulator, and it is isolated for the reason above mentioned). If the leak point is downstream of the pressure regulator, it will be exposed to a pressure of 17 Bar but if it is upstream of the pressure regulator it will be exposed to the He tank pressure of 180 Bar. Even in the case of a small leak, the reaction to such high pressure raises concerns. In the extreme the leak point may collapse and He may flow uncontrolled through it at high rate, possibly damaging S/C components, possibly such that no significant amount of He reaches the propellant tanks, thus the pressurization being ineffective.

ESA is in contact with the supplier of the Rosetta RCS, to try to assess possible causes and consequences of different failure modes of the components involved.

While this is still taking place, there are strong indications that it will not be possible to fully exclude risks of a second pressurization. Hence it is important to assess in how far mission objectives could be achieved without a second RCS pressurization.

3. RCS PERFORMANCE IN THE ABSENCE OF A SECOND PRESSURIZATION

The first question is what is to be expected in terms of RCS performance in case a second pressurization does not take place.

Without a second pressurization no further He will be filled into the propellant tanks. Thus from the current tank pressures it is straight forward to see that at about end of mission, when all propellant is depleted the pressure of the MMH tank will reach a value of about 6.7 Bar and the pressure of the M2O4 a value of about 7.5 Bar (the difference is explained by the higher vapor pressure of M2O4).

These pressures are far below the operational range of the thrusters, which is between 10.5 Bar and 19 Bar. As there was no evidence on whether the thrusters can operate under these conditions, and if so, what will be the resulting performance, ESA requested the RCS manufacturer to perform an initial series of tests with a spare thruster at different inlet pressures and operation conditions. The results of these tests show that the thrusters can operate at low pressures.

The resulting thrust levels, especially for pulsed mode at small duty cycle is very noisy. The effect on this for the S/C controllers needs to be assessed by simulations. There is a high thrust on the controllers, because so far they have proven in simulations and in real flight to be very robust, which leads to the assumption that the implication of the roughness of the thrust level may be easily compensated by adjusting a few deadbands and Failure Detection Isolation and Recovery (FDIR) thresholds.

It is obvious that the accuracy of small delta-V maneuvers, that are implemented on-board by impulse counting, will be negatively impacted. This is severe for navigation around the comet, for which analysis has shown a need for very accurate, small maneuvers, in particular in the phase leading to lander delivery.

Also the overall performance of the thrusters in terms of ISP will be lower than at nominal operation conditions for which the thrusters have been trimmed. It may be significantly below the expectation from extrapolation of performance models available for the nominal range of operation.

The tests performed were intended to provide an indication on the overall feasibility of avoiding a second pressurization. If this option is retained a comprehensive test (with many more test conditions) will be needed to provide full evidence of the consequences of no pressurization.

4. PROPELLANT BUDGET

One of the key issues for a decision on a second pressurization is the state of the propellant budget.

First it has to be pointed out that the original Rosetta mission to comet Wirtanen was designed with very generous propellant reserves. The launch of Rosetta in January 2003 was suspended due to the failure of ARIANE-5/P1, which occurred just a few weeks before begin of the launch window.

The opportunity for the Wirtanen mission was lost. A backup mission to comet Churyumov-Gerasimenko could be found which had formally a marginally negative propellant budget.

After a perfect launch the propellant allocations for launcher dispersion were saved, turning the propellant budget positive. Part of the margin gained was taken to modify the Rosetta cruise to achieve fly-bys of Steins in September 2008 and of Lutetia in July 2010, to increase the science return of the mission.

Currently, after 3 years of cruise, small additional propellant savings have been achieved with respect to the post-launch budget. The total mission delta-V requirement, accounting for the savings already achieved in the past, but retaining the contingency delta-V allocations for the future is 1971 m/s. The propellant resources on the S/C, are sufficient to provide the mission delta-V requirement with a margin of 54 m/s.

In the case of no second pressurization the thrusters have a lower performance. The available performance models for the thrusters have been adapted according to the results of the tests at low pressure. Based on this the propellant budget has been redone (without a second pressurization) resulting in a negative margin of about 146 m/s (i.e. propellant exhausted 146 m/s before the total mission delta-V requirement is achieved). Note, that the number given here has a large uncertainty. Figure 2 and Figure 3 show the evolution of the propellant mass as function of mission delta-V, for the nominal case and for the case without second pressurization.

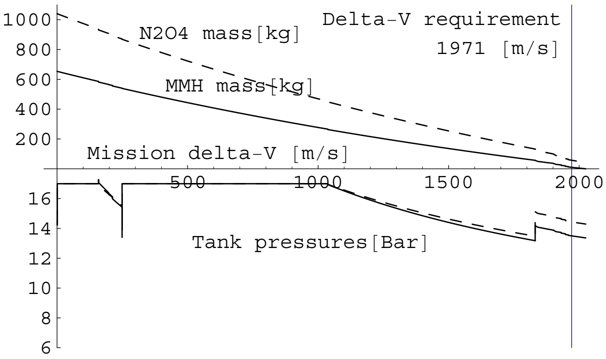

Figure 2: Propellant evolution (nominal)

The upper part of the plot shows the evolution of the remaining N2O4 mass and MMH mass as function of the mission delta-V. In the lower part the evolution of the tank pressures are shown in parallel. The two pressurization periods show constant pressures at 17 Bar.

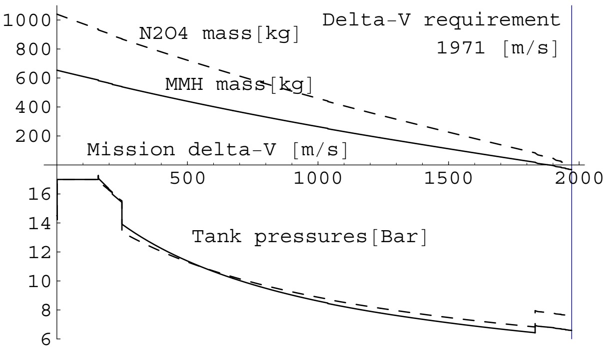

Figure 3: Propellant evolution (no pressurization)

Similar to the previous figure, but omitting the second pressurization phase. The pressure reaches minimum values of about 6.7 Bar. The mass consumption shows a steeper decrease. The tanks are empty before the total mission delta-V requirement is achieved.

An interesting observation that can be made is that in both cases the MMH is exhausted significantly earlier than the N2O4, or equivalently, when the MMH is exhausted, there is still a significant amount of N2O4 that cannot be burned. This residual mass is to all respects equivalent to undesirable ballast mass.

The unbalanced loading had minor implications for the original Rosetta mission, in which the lifetime was mainly dictated by performance degradation of solar array and optical instruments in the comet environment. For the Churyumov mission and in particular for the case without second pressurization this is critical.

It must be noted that the MMH tank was unloaded in the period between the original launch date for Wirtanen and the actual launch date for Churyumov. This was not possible for the N2O4, due to its highly corrosive nature. Hence it was not possible to correct the imbalance.

5. MISSION REDEFINITION FOR DEGRADED PROPELLANT BUDGET

Major fuel savings need to be achieved in case a re-pressurization will be avoided. This will require changes of the current mission baseline. Therefore we analyzed alternative delta-V saving mission options with the following goal and requirements:

- The total delta-v should be less than the currently expected 1787 m/s until rendezvous (RDV) (sum of deterministic delta-V from now until comet arrival plus the actual accumulated delta-V, but neglecting the duration of the approach phase and the split of the RDV delta-V into several maneuvers).
- Minimum distance to Sun of 0.8 AU because of thermal constraints
- Maximum distance to Sun of 5.5 AU because of power constraints, where the maximum distance for maneuvers is 4.4 AU
- Minimum distance of 200 (Earth) and 250 (Mars) km for swing-bys

Omitting of asteroid fly-bys

The delta-V allocated after launch for the fly-bys was 111 m/s. Part of this delta-V could still be saved by omitting asteroid fly-bys now. While the Steins fly-by between the 2nd and 3rd Earth swing-bys is relatively inexpensive, much more fuel could be saved by omitting the fly-by at Lutetia on the arc from the 3rd Earth swing-by to the comet. Unfortunately, Lutetia is scientifically more interesting.

Delayed arrival

The nominal rendezvous already takes place at 4.0 AU distance from the Sun in order to have enough margin before start of comet activity for the rendezvous maneuver sequence and approach to the comet, the global mapping and search for a landing site in close observation, the lander delivery preparation and execution. However, Comet activity is expected to start from about 3 AU. Therefore it could be envisaged to shorten this margin by one month, arriving at about 3.8 AU, end of June, 2014, which reduces the stopping delta-V required to join with the comet on its orbit.

Late arrival

A further delay of arrival leads to higher delta-V savings. Even a late arrival could be considered. The original Rosetta mission foresees comet arrival at 4 AU, allowing a delivery of the lander when the comet is still inactive. It is assumed that comet navigation is much more difficult with the comet active and hence the delivery of the lander with active comet would also be

Table 1: Saving of Delta-V and Fuel by delaying arrival and omitting fly-bys

RDV Distance	Delta-Vand Fuel Saving							
[AU from Sun]	[m/s] and [kg]							
	All Fly-bys		No Steins		No Lutetia		No Fly-bys	
4.00	0.0	0.0	0.2	0.1	26.6	15.3	88.1	51.0
3.83	48.5	27.8	49.8	28.5	69.4	40.0	117.5	68.4
3.50	123.5	71.6	132.5	77.0	138.6	80.7	164.2	96.0

more risky or even impossible, It is however conceivable to rendezvous the comet at close Sun distance in order to perform the science observations rather in the outbound arc, and to deliver the lander when the activity decreases again to an acceptable level. The comet approach from near comet drift phase without previous onboard observation until transition to start of surface mapping is expected to last about 77 days. An arrival at 3.5 AU would lead to a start of the transition to the comet mapping phase at 3 AU. With this option scientists still get a chance to observe comet activity at an early stage while the lander delivery could be delayed based on the observed activity development.

Results

Table 1 shows delta-V and fuel mass savings w.r.t. the current mission baseline for combinations of the options suggested above. The underlying optimizations assume a start of the change to the current mission baseline with a trajectory correction maneuver on 18/10/2007 before the upcoming Earth swing-by on 13/11/2007.

Only abandoning of the asteroid fly-bys in combination with an arrival at 3.5 AU will lead to a delta-V saving of more than 140 m/s. In case communication constraints on the maneuvers are to be respected (e.g. Sun-Probe-Earth angle > 5 Deg), the maximum savings for the cases ‘No Lutetia’ and of ‘No Fly-bys’ at 3.5 AU reduce to 138.1 and 150.5 m/s.

Table 2 shows events of the mission baseline in comparison to the cases for arrival at 3.5 AU. For all events the date is given as [mm/dd]. For orbit control maneuvers (OCM) the delta-V (dve) is given, for swing-bys (SWB) the radius at closest approach (rad), and for fly-bys (FLB) the relative speed at closest approach (vel). Fly-by distances are 800 km for Steins and 3055 km for Lutetia. The Sun-spacecraft-asteroid angles are about 128.5 deg for Steins and 101.1 for Lutetia for all options. The Earth swing-by 2007 and the initial maneuver of the cases where no Steins fly-by is required differ a lot from those of the other options.

Other fly-by options

For the case of a late arrival without 2nd pressurization a positive fuel margin of about 164-146=18 m/s would exist, which could still be used for fly-bys. The current mission baseline with fly-bys at Steins and Lutetia was decided after launch, based on the available fuel budget as known at that time and on a prioritized list of options set up by the scientific community before launch. The list contained options requiring less fuel than for the baseline and there is the question whether it is still possible to achieve a feasible trajectory with other fly-bys.

We re-computed the delta-Vs of the prioritized list for an arrival at 3.5 AU and 1st maneuver (as above) about one month before Earth swing-by. Results are shown in Table 3. As to be expected, most options are now too expensive. A feasible option, however, is No. 15, one fly-by at Fogolin on the arc from Earth to the Comet, which requires only 8 m/s compared to the case without any fly-bys. Option 12, a combination with fly-bys at Luichewoo and Fogolin, requires 26 m/s. This is just out of range of the available budget as noted above, but

Table 2: Events of mission baseline in comparison to cases arriving at 3.5 AU

Year	Event	Baseline 4.0 AU		All Fly-bys 3.5 AU		No Steins 3.5 AU		No Lutetia 3.5 AU		No Fly-bys 3.5 AU		
2007	OCM	10/18	0.1	10/18	0.2	10/18	7.3	10/18	0.1	10/18	10.6	dve [m/s]
2007	SWB Earth	11/13	11678	11/13	11677	11/13	20463	11/13	11678	11/13	20959	rad [km]
2008	FLB Steins	09/05	8.6	09/05	8.6			09/05	8.6			vel [km/s]
2009	OCM	03/18	6.9	06/22	24.4	03/28	18.9	04/20	8.8	03/22	79.6	dve [m/s]
2009	SWB Earth	11/13	8861	11/13	8822	11/12	7424	11/13	8811	11/11	6900	rad [km]
2010	FLB Lutetia	07/10	15.0	07/10	15.0	07/09	15.1					vel [km/s]
2011	OCM	01/23	788.5	04/08	785.6	05/09	782.2	05/19	792.2	05/15	683.4	dve [m/s]
2014	OCM RDV	05/22	793.9	08/23	655.9	08/23	648.7	08/23	649.7	08/23	651.7	dve [m/s]

Table 3: Fly-by options for arrival at 3.5.AU

Priority	Asteroid on arc Earth to Earth	Asteroid on arc Earth to Comet	Total Delta-V until RDV [m/s]	Delta-V Cost w.r.t. no fly-by [m/s]
Baseline	Steins	Lutetia	1787	164
	none	none	1623	0
1	Rhodia	Lutetia	1885	263
2	Luichewoo	Lutetia	1660	37
3	Steins	Lutetia	1664	41
4	Baetsle	Izekov	1811	188
5	Baetsle	Fogolin	1878	255
6	Luichewoo	Izekov	1692	69
7	Rhodia	Izekov	1975	352
8	Rhodia	Fogolin	1964	341
9	Steins	Izekov	1812	189
10	Sofala	Izekov	2163	540
11	Steins	Fogolin	1763	140
12	Luichewoo	Fogolin	1648	26
13	Baetsle	none	1754	131
14	none	Izekov	1671	48
15	none	Fogolin	1631	8

Table 4: Details of suggested fly-bys

	Fogolin (only)	Fogolin	Luichewoo
Date	2010/05/24	2010/05/24	2009/04/02
Relative velocity [km/s]	13.556	13.554	5.420
Sun-S/C-Asteroid angle [deg]	90.0	90.0	166.5
Ear-S/C-Asteroid angle [deg]	106.53	106.59	146.3
Sun-S/C-Earth angle [deg]	25.32	25.32	20.72
Sun-Ear-S/C angle [deg]	93.52	93.40	49.6
Sun distance [AU]	2.36	2.36	2.15
Earth distance [AU]	2.07	2.08	2.66
Fly-by distance [km]	2761.0	2761.0	1140.0

again the available budget for the case without pressurization is uncertain. Therefore also option 2 might be considered, a combination of fly-bys at Luichewoo and Lutetia that requires 37 m/s, which is still a bit cheaper than the combination Steins/Lutetia. Table 4 shows details of the fly-bys at Fogolin alone and for the combination Luichewoo/Fogolin. For Fogolin a fly-by distance of 2761 km and a closest approach 90 degree out of the fly-by plane has been selected based on former analysis results. For Luichewoo the selected fly-by distance is 1140 km and the Sun is in the fly-by plane. Table 5 shows the event timeline with a format similar to Table 2.

6. APPROACH FOR SECOND PRESSURIZATION

In case it is finally decided to perform a second pressurization trade-offs shall be established for several options:

Use of secondary regulator

The use of the secondary regulator has the advantage that it isolates the primary one, which is suspect of having itself a leak and may be damaged by being exposed to a inverted pressure gradient. The disadvantage of using the secondary regulator is that it requires firing additional pyro valves and that the redundancy is lost.

Selection of regulation point

Nominally the pressurization would be executed a few days before a large delta-V of about 800 m/s in 2011. At that point there is not a significant ullage in the tanks. Hence, if there is a significant leak the He tank may be empty before the maneuver has actually started and only a small amount will be transferred to the tanks (note that He that is already in the propellant tanks will be retained thanks to non-return valves).

Table 5: Event timeline for alternative fly-by options

Year	Event	Fogolin		Luichewoo/Fogolin		
2007	OCM	10/18	10.9	10/18	7.6	dve [m/s]
2007	SWB Earth	11/13	20850	11/13	20425	rad [km]
2009	FLB Luichewoo			04/02	5.4	vel [km/s]
2009	OCM	03/29	120.1	05/10	140.7	dve [m/s]
2009	SWB Earth	11/09	6900	11/10	7766	rad [km]
2010	FLB Fogolin	05/24	13.6	05/24	13.6	vel [km/s]
2011	OCM	05/13	634.0	05/13	631.9	dve [m/s]
2014	OCM RDV	08/23	668.8	08/23	670.7	dve [m/s]

Alternatively, the maneuver can be split and the pressurization be performed after the first part of the maneuver. The tanks then have a larger ullage, such that in the case of a significant leak, more He can reach the propellant tanks before the He tanks are empty.

For this scenario we assume that the 1st part of the maneuver is 300 m/s, and we allow two days for analysis before the maneuver continues with the 2nd part. In case the pressurization succeeds, the mission continues as foreseen with arrival at 4.0 AU. In case pressurization fails, the arrival can be delayed.

Table 6 shows the delta-V and fuel mass savings with respect to the current mission baseline in case a decision on a delayed or late arrival is taken shortly before the deep space maneuver in 2011 (un-split) or after attempted pressurization (split) as in the scenario explained above. For the un-split case the savings are smaller than in Table 1 (‘All Fly-bys’) because the trajectory before the decision could not be optimized for the arrival target. Furthermore we find maximum savings of 165 m/s for an arrival at 2.92 AU which is at true anomaly -117.9 deg of the comet orbit.

For the ‘split’ scenario the fuel saving is smaller than for the ‘un-split’ case, because the first maneuver part has not the optimal direction for the targeted arrival distance. For arrival at 3.83 and 3.5 AU the delay until start of the 2nd maneuver part can be optimized, this leads to increased savings. Allowing a free delay and a further relaxation of the arrival distance (not shown in table) leads to a maximum saving of 158 m/s with arrival at 2.96 AU, which is at true anomaly -124.3 deg of the comet orbit.

Influence of approach strategy

The optimization results presented before do not yet reflect the approach strategy, meaning the distribution of the stopping delta-V at arrival into several maneuvers to be performed during the approach phase. We simulated the comet approach phase by six maneuvers distributed over 77 days with delta-v decreasing in steps from around 300 m/s down to 2 m/s until comet orbit insertion. If the arrival at 3.5 AU would be decided with the maneuver before the next Earth swing-by 9 m/s could be saved additionally for the case of Table 1, ‘All Fly-bys’. This additional saving drops to 8 m/s if decision takes place with the deep space maneuver in 2011, as in the ‘split, free delay’ case of Table 6.

SC mode during pressurization

The firing of the pyro valves for pressurization would be done nominally in the S/C normal mode, the attitude being controlled by wheels.

In case there is a large leak, or if it develops to a large leak when exposed to high pressures, it could be that significant torques act on the S/C, such that the wheels are not able to counteract them.

In the extreme overrates could be achieved that cannot be cancelled any more by the S/C controllers.

Pressurization could take place in a thruster controlled mode, in which the torque authority is much larger than in a wheel controlled mode. In this way, the probability of irrecoverably loosing control gets minimized.

Table 6: Saving of Delta-V and Fuel for late decision on arrival and for split of deep space maneuver with pressurization and decision on arrival after first part

RDV Distance	Delta-V and Fuel Saving						
[AU from Sun]	[m/s] and [kg]						
	un-split, but late decision on arrival		split, fix 2 day delay		split, free delay		Delay [Days]
4.00	0.0	0.0	0.0	0.0			
3.83	48.2	27.6	47.2	27.0	48.0	27.5	18.4
3.50	116.9	67.7	106.8	62.0	115.2	66.6	57.6

7. CONCLUSION

The reading of the pressure transducer located in the small, currently isolated volume containing the pressure regulators between the high and the low pressure section of the Rosetta RCS leads to the suspicion of a leak with potential of leading to a premature end of mission in case the section is set under pressure again.

In this situation there are basically two options. If the probability of a leak leading to catastrophic loss of pressure is regarded as high, then a 2nd pressurization should be avoided. This will require massive changes of the current mission baseline. If the probability is regarded as low, the pressurization could be attempted with some precaution against incomplete execution due to pressure losses by the leak.

Without pressurization the thruster performance is reduced and results in a negative margin of the propellant budget, about 146 m/s smaller than the total delta-V requirement of the current mission. A delay of the comet rendezvous to 3.5 instead of the currently planned 4.0 AU distance from the Sun combined with omitting of the currently planned fly-bys at Steins and Lutetia would save 164 m/s if decided with the maneuver on October 18, about one month before the Earth swing-by. In this case a single fly-by at Fogolin with a cost of 8 m/s appears to be feasible without touching the contingency or observation allocations for the future. The next cheapest option would be a combination of fly-bys at Luichewoo and Fogolin with a cost of 26 m/s. Any delay of the decision on a late arrival and on the fly-bys reduces the possible amount of delta-V saved.

If the pressurization will be performed, we suggest increasing the possible amount of He reaching the propellant tank by a split of the deep space maneuver into two parts and pressurizing after the first part. In case of incomplete pressurization it will still be possible to save up to 115 m/s by delaying the comet rendezvous until 3.5 AU distance from the Sun.