Low Power Arcjet Application for End of Life Satellite Servicing

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ABSTRACT

In this paper the results of a low-power arcjet study for satellites beginning-of-life and end-of life servicing by de-orbit is presented. Two distinct use cases were analysed while considering the common propellants hydrazine and ammonia, as well as the green alternative ADN based propellants. The first case allows for a stand-alone arcjet system, while the second case is hybridized with the main propulsion system. Both cases come with their individual challenges, which are high number of ignitions, long-time operation time and the necessity to cope with tank pressure blow down. Low power arcjets from the Institute of Space Systems at the University of Stuttgart serve as design reference. A number of various feeding system approaches are explored, a trade-off for minimal mass is made and an estimation on the technological readiness is given.

1 INTRODUCTION

As part of the CleanSpace initiative [1] in collaboration with ESA, Airbus Defense and Space, OHB and TAS, a study has been conducted to create a preliminary design for deorbit-modules for satellites in low earth orbit using electric propulsion. The Institute of Space Systems (IRS) at the University of Stuttgart has a long-standing heritage in the development of electric propulsion systems [2, 3] and the development of advanced propulsion concepts [4-6]. The study is strongly based on the experiences with ammonia and hydrazine arcjets that have been developed and tested at the IRS. An example of this is shown in Fig. 1, where the arcjet ATOS is depicted in operation.

Mission requirements and the respective compliance of the existing arcjets, the resulting necessary developments and the proposed system design are described briefly here. For a more detailed information on the designed systems and considered thrusters, please refer to the public version of the final project report [7].

2 REQUIREMENTS

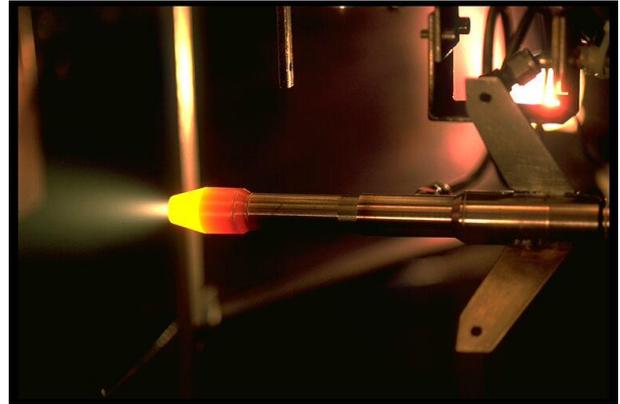The arcjet based de-orbit system had to be developed as

Figure 1 ATOS Arcjet thruster in operation at the Institute of Space Systems University of Stuttgart

a standalone system, operating independently of the main propulsion system of the satellite, named Case 1, and as a hybrid system, that uses components of the already existing main propulsion system (chemical) of the satellite, named Case 2. The requirements in terms of size, power, specific and total impulse, thrust, ON/OFF cycles, propellant, and target satellite mass are briefly shown in the following section. It is evident that the significant high total impulse motivates the additional application of orbit raising i.e. at begin of life when the satellite is placed in a very low Earth orbit, and then raised by the arcjet based system. At end of life, the same system performs the deorbit in order to fulfil the European Code of Conduct for Space Debris Mitigation [8].

In the following the relevant design parameters for each case are given in table 1 and table 2 respectively.

Table 1. Case 1 - De-Orbit Stand-alone System

Satellite mass	800 kg
Minimum Isp	400 s
Minimum Thrust	0.1 N
Maximum power consumption	750 W / (1000 W)
Total impulse	200 kNs

Propellant	Ammonia, hydrazine, ADN (ammonium dinitramide)
Minimum lifetime	10 years
Maximum functional thruster mass	1.2 kg
Minimization of non-demisable materials/components.	

The total impulse requirement of Case 1 will result in over 10000 ON/OFF cycles, which is associated with most wear occurring during arcjet operation.

Table 2. Case 2 - De-Orbit Hybrid System

Satellite mass	1500 kg
Minimum Isp	600 s
Minimum Thrust	0.1 N
Maximum power consumption	1000 W
Total impulse	670 kNs
Propellant	Hydrazine
Minimum lifetime	10 years
Maximum functional thruster mass	1.2 kg
Operating pressure at beginning of life (BOL)	24 bar
Operating pressure at end of life (BOL)	7 bar
Minimization of non-demisable materials/components.	

3   LOW POWER ARCJETS

The IRS has a significant heritage with regards to the development of arcjet thrusters ranging from 750 W to high 100 kW power consumptions [3]. The thrusters
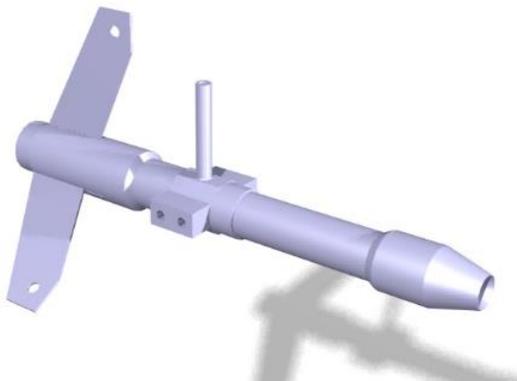

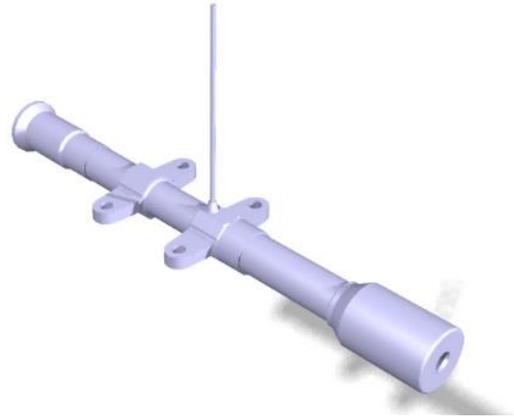*Figure 2 CAD model ATOS thruster - flight model*

Figure 3 CAD model ARTUS thruster – engineering model

ARTUS (Arcjet Thruster University of Stuttgart) and ATOS (Arcjet Thruster on Oscar Satellite) are of particular interest for this study and are briefly described here.

a.   ARTUS

The ARTUS thruster, shown in Fig. 3, has a mass of 0.4

1 - Fill/Drain valve
2 - Presure transducer
3 - Diaphragm Tank
4 - Pyrovalve
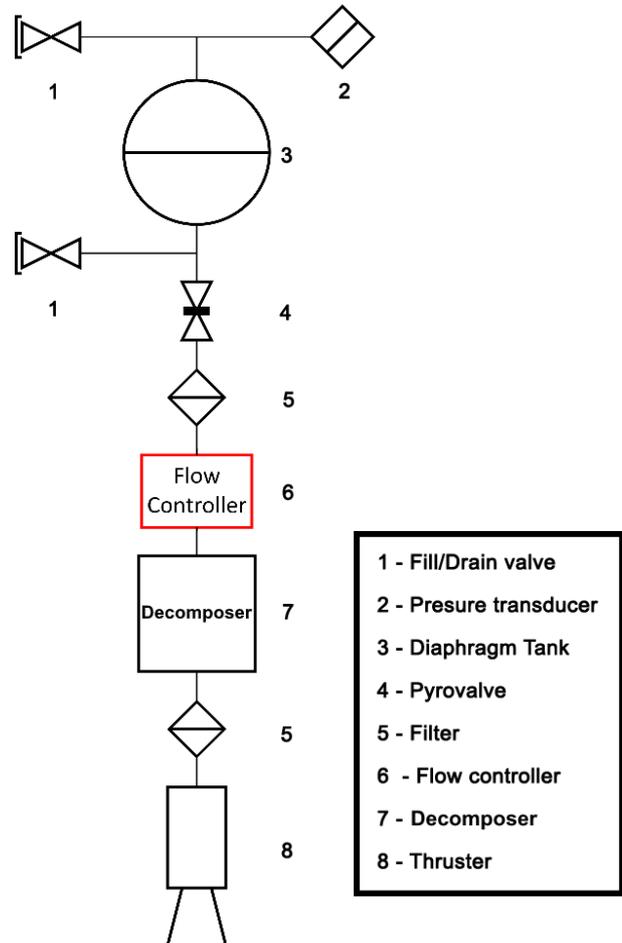5 - Filter
6 - Flow controller
7 - Decomposer
8 - Thruster

Figure 4 Hydrazine based flow controlled feeding concept

kg and is qualified for operation with secondary hydrazine ($N_2 + 2 H_2$) and ammonia (NH_3).

For the operation with decomposed hydrazine, powers from 660 to 1640 W have been tested, for a mass flow rate of 23 to 45 mg/s, which result in a thrust of 105 to 231 mN and a specific impulse of 382 to 548 s.

When operated with ammonia powers from 800 W to 1850 W have been tested, with a mass flow rate of 22 to 36 mg/s. This results in a thrust of 107 to 221 mN, while the specific impulse varies between 472 to 632 s accordingly.

b. ATOS

The ATOS thruster, shown in Fig. 2, has a total mass of 0.7 kg and is fully flight qualified for launch with an Ariane 5 as it has flown on the Oscar P3-D satellite [9]. It is operated with ammonia at a power level of 750 W and a mass flow rate of 24 mg/s. Under these conditions, a thrust of 115 mN and a specific impulse of 484 s was achieved.

4 SYSTEM DESIGN

The final design of the arcjet based propulsion system is highly dependent on the propellant feeding concept
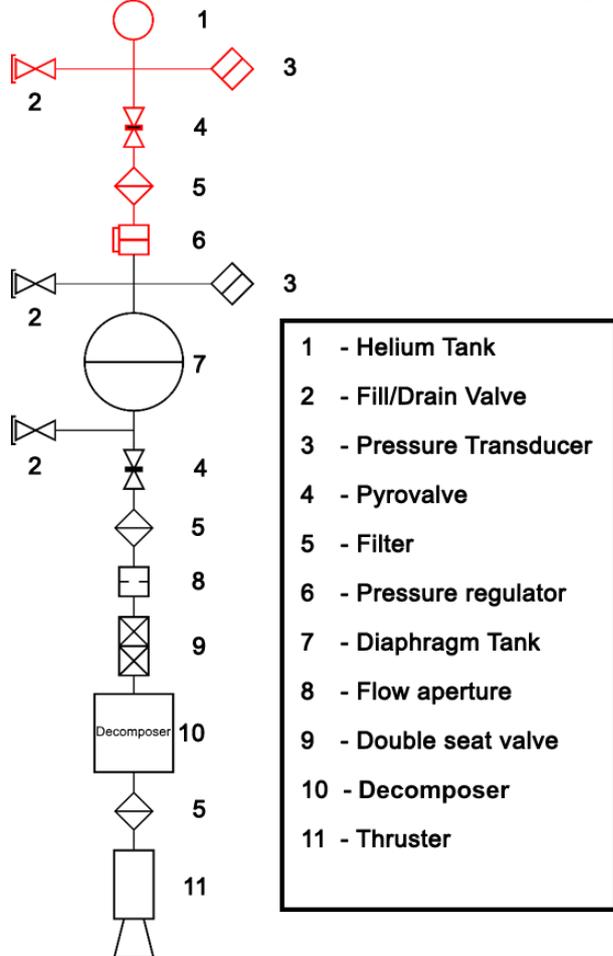

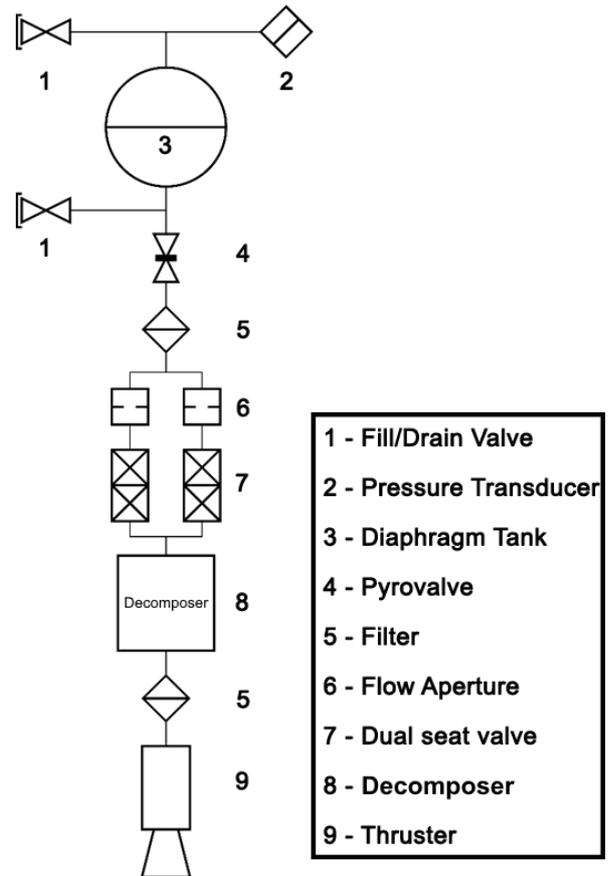*Figure 5 Hydrazine based pressure controlled feeding concept*

1 - Helium Tank
2 - Fill/Drain Valve
3 - Pressure Transducer
4 - Pyrovalve
5 - Filter
6 - Pressure regulator
7 - Diaphragm Tank
8 - Flow aperture
9 - Double seat valve
10 - Decomposer
11 - Thruster

Figure 6 Hydrazine based dual branch / blow down feeding concept

1 - Fill/Drain Valve
2 - Pressure Transducer
3 - Diaphragm Tank
4 - Pyrovalve
5 - Filter
6 - Flow Aperture
7 - Dual seat valve
8 - Decomposer
9 - Thruster

utilized and the propellant used. These system design options are explored here.

a. Case 1 – Stand-alone system

For the stand-alone Case three distinct concepts for feeding systems are proposed and detailed here. The technological readiness level (TRL) of hydrazine based feeding systems is seen as 2-3, as the direct use of hydrazine still needs to be qualified.

i. Hydrazine Flow Control

The system shown in Fig. 4 uses a diaphragm tank for storage of the hydrazine propellant, which is pressurized with helium. A flow controller for liquid hydrazine throttles the hydrazine to the desired flow rate before it enters a decomposer that generates hydrogen and nitrogen from the hydrazine to operate the arcjet.

ii. Hydrazine Pressure Control

The system shown in Fig. 5 uses a diaphragm tank for storage of the hydrazine. The tank is pressurized by a helium tank that pressurizes the propellant tank to a constant pressure using a pressure regulator. With the propellant being at constant pressure no active flow

regulation is required anymore. A flow constrictor reduces the flow to the required flow rate at given tank pressure before it enters a decomposer that generates hydrogen and nitrogen from hydrazine to operate the arcjet.

iii. Hydrazine Blow Down

The system shown in Fig. 6 uses a diaphragm tank for storage of hydrazine. The tank is pressurized with helium. The tank pressure variation and the resulting change in flow rate is partially compensated by having two flow branches with different flow resistances. One branch, having a high flow resistance, is used at the beginning of the mission when the tank pressure is still high, while the other branch, having a lower flow resistance, is used at the end of the mission when the tank pressure is lower. The respective flow resistance is achieved by using a flow constrictor for liquid hydrazine. After passing these branches the flow enters a decomposer that generates hydrogen and nitrogen from the hydrazine to operate the arcjet.

iv. Ammonia

The system shown in Fig. 7 uses a PMD tank to store the

1 - Ammonia tank

2 - Fill/Drain Valve

3 - Pyrovalve

4 - Filter

5 - Dual seat valve

6 - Gas generator

7 - Flow controller
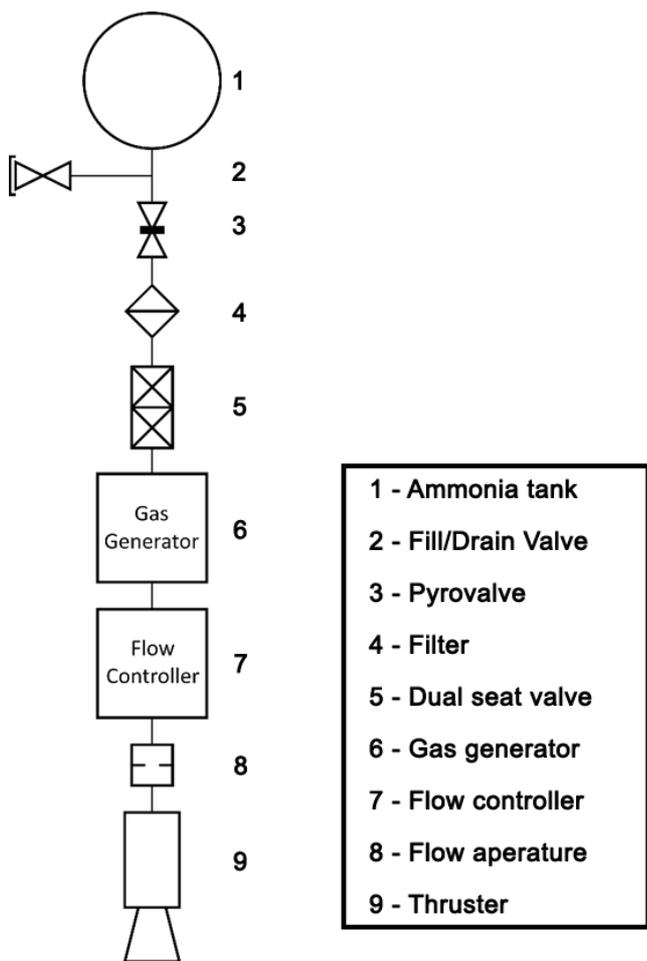
8 - Flow aperature

9 - Thruster

Figure 7 Ammonia based stand-alone flow controlled feeding concept

ammonia propellant. The pressure in the tank stays relatively constant throughout the mission as ammonia is stored at vapour pressure. Small changes in pressure and thus flow rate are compensated by the use of a flow controller for gaseous ammonia. A gas generator between tank and flow controller ensures, that all ammonia is in the gas phase when passing the flow controller and thruster. The TRL of the ammonia based feeding system is seen as 3-4.

v. System Mass Comparison

In the following the total wet mass of the propulsion system of Case 1 are compared, the details for each system differentiated for power level and propellant are given in Table 3. For the propellant tank, as one of the heaviest system components, a comparison to commercially available tanks from Orbital ATK [11] were compared to a tank mass estimate of a custom tailored solution to identify a potential for system mass reduction. The results of this are given in Table 3.

It is evident that a custom made tank solution allows for a total system mass reduction of 0.6 kg to 2.7 kg dependent on the specific case.

As expected the system mass is reduced, when the arcjet is operated at higher power levels as the additional energy leads to a higher specific impulse resulting in a smaller propellant mass requirement.

For the hydrazine based systems a flow controlled concept is estimated to require the lowest total wet mass. However, an ammonia based system consistently outperforms the hydrazine approach, due to the inherently simpler design concept and the higher specific impulse for the ammonia thrusters at IRS.

Table 3 Total system wet mass comparison Case 1

	COTS tank	Custom tank
N_2H_4 ARTUS Flow control, 750 W	59.0 kg	56.3 kg
N_2H_4 ARTUS Flow control, 1000 W	53.6 kg	52.5 kg
N_2H_4 ARTUS Pressure control, 750 W	58.5 kg	57.2 kg
N_2H_4 ARTUS Pressure control, 1000 W	56.0 kg	54.5 kg
N_2H_4 ARTUS Blow down, 750 W	60.3 kg	59.6 kg
N_2H_4 ARTUS Blow down, 1000 W	56.9 kg	55.4 kg
NH_3 ATOS, 750 W	53.5 kg	52.4 kg
NH_3 ATOS, 1000 W	**48.5 kg**	**46.6 kg**

b. Case 2 - Hybrid system

For the hybridized system the flow control is generally simpler, as the synergy with the main propulsion system

is used, which removes the necessity of a dedicated tank and pressurisation system.

i. Flow Controlled

The system shown in Fig. 8 assumes that an upstream flow control is present in the satellite reducing this system to a flow constrictor for mass flow adjustment, dual seat valve, decomposer and filter.

ii. Blow Down

The system shown in Fig. 9 system includes two branches with different flow resistances for operation with high and low tank pressure. Respective dual seat valves, a filter and decomposer are included in the propellant feed system.

iii. System Mass Comparison

In the following the total wet masses of the propulsion systems of Case 2 are compared, the details for each system are given in Table 4.

A flow controlled hybridized system reduces the overall system mass by approximately 10 kg compared to a dual branch system.
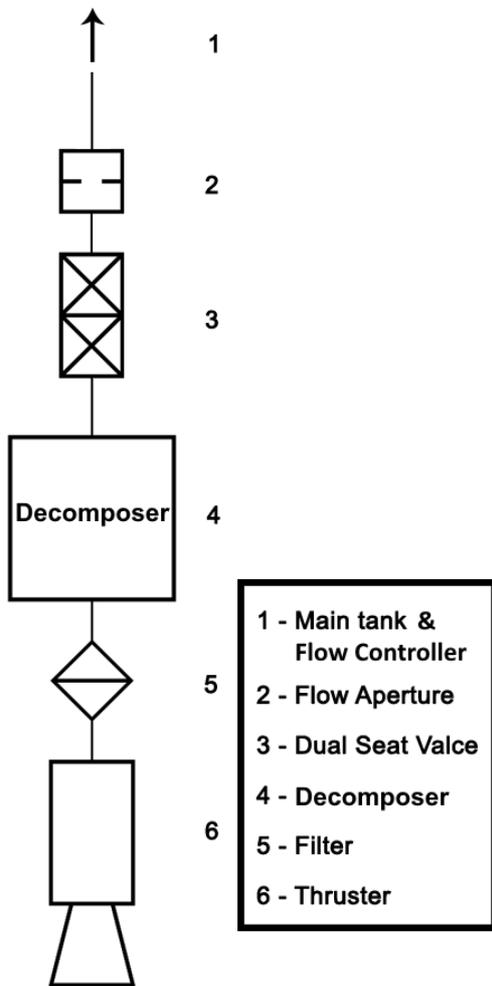
Figure 8 Hybrid system flow controlled feeding concept
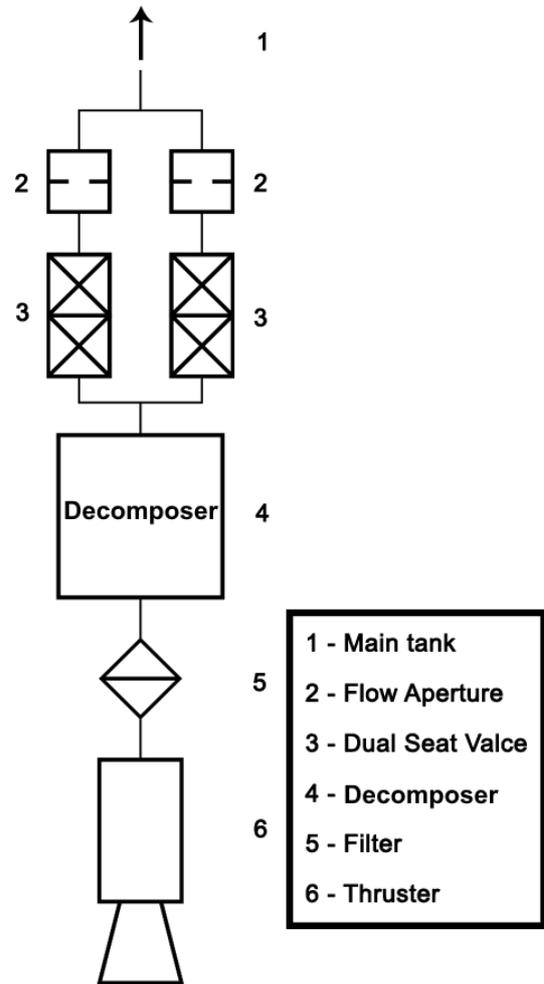
Figure 9 Hybrid system blow down / dual branch feeding concept

Beyond these concepts the wet system masses are given for cases where advanced concepts to further increase the specific impulse are given. To achieve a specific impulse of at least 600 s beyond the implementation of advanced concepts the supplied power needs to be increased to 1.5 kW.

Table 4 Total system wet mass comparison Case 2 and advanced concepts

	Hybrid system wet mass
N_2H_4 ARTUS Dual branch, 1000 W	152.2 kg
N_2H_4 ARTUS Flow control, 1000 W	**142.2 kg**
N_2H_4 ARTUS , I_{sp} 528 s, 1000 W	134.1 kg
N_2H_4 ARTUS I_{sp} 600 s, 1500 W	119.9 kg

5   DESIGN CHALLENGES

The given requirements are overall met by the proposed

arcjet de-orbit systems due to the heritage of respective arcjets available at the IRS. Among the remaining challenges are the large number of ON/OFF cycles and the long lifetime requirements resulting in not yet performed qualification demands. The design challenges are listed below, including the required actions for alleviation:

- Especially case 1 requires a large number of operating cycles which is one order of magnitude above the currently tested maximum of cycles. Consequently additional lifetime testing will be required and further additional measures may be taken to reduce electrode erosion, which are discussed and assessed in more detail in the final project report [7].
- For case 2 the I$_{sp}$ of 600 s can be achieved by extending the thrusters operational envelope to lower gas flow rates. This requires further qualification, and an increase of the power supply from 1000 W to 1500 W.
- Neither ADN nor other green propellants or propellants containing oxygen have been tested with existing arcjet thrusters of the IRS. Consequently, additional electrode development and thruster characterization is required to assess such propellants.
- To date hydrazine was used indirectly by utilizing a representative mixture of hydrogen and nitrogen (secondary hydrazine). If hydrazine is chosen as propellant respective tests and preparation will be required.
- A preliminary analysis of the demisability of critical module components suggests that the propellant tanks alone may not sufficiently demise, which needs to be assessed in further analysis.

6 ARCJET GREEN PROPELLANT USE

The suitability of using green propellants for use in arcjets is discussed here.

Ammonium dinitramide H$_4$N$_4$O$_4$ (ADN) is currently seen as green candidate for replacing the highly toxic hydrazine [10]. When fed through an arcjet molecules will fully decompose, which will result for ADN in a mean molar mass for the decomposition products of $M_{ADN,decomposed} = 24.8$ g/mol.

The relation between mean molar mass M and effective exhaust velocity c_e is given by:

$$c_e \propto \frac{1}{\sqrt{M}} \tag{1}$$

This proportionality implies that a minimal molar mass is desired to achieve a maximum exhaust velocity and efficiency of propellant use.

Comparing the mean molar mass of decomposed ADN to other possible propellants with reduced toxicity, like water ($M_{H_2O,decomposed} = 6$ g/mol), methanol ($M_{CH_4O,decomposed} = 5.8$ g/mol) or ammonia ($M_{NH_3,decomposed} = 4.35$ g/mol) shows clearly that no advantage in terms of specific impulse can be expected by using ADN. Furthermore, ADN based propellants like LMP-103s [10] are mixtures of water, ammonia, methanol and ADN. Optimizing the composition of the propellant would, at best, converge to a mean molar mass after decomposition to that of ammonia.

Most green propellant options (like water, ADN and methanol) do contain oxygen, which will be present in atomic form in the thruster nozzle. For the mitigation of expected surface oxidation and erosion additional development effort for surface protection would be required.

7 CONCLUSION

In this paper two cases of an arcjet based system that shall be used for orbit raising and deorbiting of a satellite have been assessed. Correspondingly, the application scenario goes significantly beyond the EoL scenario as motivated by the Cleansat context.

The thrusters used as reference for the performed analyses have already been developed at IRS in the past. Complimentary to these thrusters feeding systems have been designed. The final systems are compliant to the majority of the requirements while few requirements have still to be confirmed in the development phase. However, it is expected that compliance to all requirements can be achieved during development.

Case 1 is a system for an 800 kg satellite, which is independent of the satellite's propulsion system. The system is supposed to provide a total impulse of 200 kNs to the satellite, which can be used for orbit raising and deorbiting of the satellite. For the arcjet power levels of 750 and 1000 W have been considered, where the higher power yields mass savings of over 10 %. Various system designs with propellant hydrazine, ammonia and ADN have been analysed. Generally, all systems have a mass on the order of 55 kg (@1000 W) including propellant. Where variations between the systems are on the order of 10 %. With ammonia as propellant the mass is minimal, which may be attributed to the low complexity of the feeding system and the strong heritage of ammonia thrusters at IRS. Hydrazine, however, promises to yield similar performance, when the system is operated with a mass flow controller, to provide constant feed conditions. Further a flow control by a dual branch system has been proposed, which however, has lower performance due to the variation of feed conditions. In addition, pressure control has been proposed, which, however, results in a high system mass due to the need of a pressurant tank.

Case 2 is a system for a 1500 kg satellite, which needs to

provide a total impulse of 670 s. It uses the synergy with an existing chemical propulsion system. Due to this synergy, no additional tank is required, which leads to a simpler system overall. The thruster is required to operate at 1000 W and provide an I_{sp} of 600 s. As this was found not to be feasible, a power increase to 1500 W was proposed. For the feeding system both a dual branch approach and a single branch approach with flow control have been designed. Assuming the current thruster characteristics, a flow control may lead to mass savings on the order of 7 %. Total system mass with current thruster performance (@1000 W) is on the order of 160 kg, while thruster improvements may reduce this to 150 kg. The proposed power increase to 1500 W will reduce the total system wet mass to 130 kg.

8 OUTLOOK

Development effort to significantly increase the overall system technological readiness level has been proposed.

Improvements of the thrusters need to be investigated to increase the overall efficiency by using recombination chambers, regenerative cooling and use of decomposition enthalpy. Long lifetime and high number of thruster ignition require an additional qualification effort and likely mitigation strategies for arcjet electrode erosions.

To cope with oxygen containing propellants electrode surfaces that are resistant to oxidation effects are required. A possibility for this are compact carbon-carbon electrodes.

After completion of this first phase a bread boarding phase for the chosen feeding system design is envisioned to demonstrate basic functionality of the overall design. Here the development of a gas generator for ammonia or decomposer for hydrazine and ADN is critical.

This is followed by the production of an engineering and qualification model to perform necessary functional. Further mechanical qualification steps and lifetime testing will be performed. An overall technological readiness level of 6 is the objective.

9 ACKNOWLEDGEMENT

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