Experimental Feasibility Study of the Conical Pump as a Satellite Propulsion Booster Final Report

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Acronyms

Tag	Description
ADAMP	Ascent and Descent Autonomous Manoeuvrable Platform
AReS	Affordable and Revolutionary Space
CNC	Computer Numerical Control
CRC	Conical Rotary Compressor
CRB	Conical Rotary Booster
DDP	Detailed Development Plan
DstL	Defence Science and Technology Laboratory
FFT	Fast Fourier Transforms
FREP	Final REPort
HTP	High Test Peroxide
JPL	Jet Propulsion Laboratory
PEEK	Polyether Ether Ketone
RoCS	Rotary Cryocooling System

1 INTRODUCTION

1.1 Scope of the document

The present document describes the findings of the Experimental Feasibility Study of the Conical Pump as a Satellite Propulsion Booster, providing a brief overview of the whole program, major findings, conclusions and further study areas

1.2 Background

This study investigates the potential of adapting VERT's proprietary Conical Rotor Compressor (CRC) for use as Conical Rotary Booster (CRB). Aimed at replacing the existing blowdown systems commonly used in satellite propulsion systems, this de-risking project is tasked with proving that the CRC technology can be modified so that it can be used as a pump, capable of meeting the specified inlet and outlet pressure, flow, and longevity requirements.

Electrically driven pumping permits the propellants to be stored at much lower pressure, permitting a lighter, thin-walled tank structure that is less likely to survive re-entry. The mass optimisation benefit of such systems has been modelled in detail. A NASA study [2] predicted a 39-44% increase in payload capacity on the NEAR mission and a 35% increase on the Cassini mission. A JPL study [3] evaluated similar technology for a Mars Ascent Vehicle, predicting a saving of 4.18kg on a dry vehicle mass of 68.55kg – permitting the avionics payload to double.

2 AIM OF THE STUDY

There were two key objectives to this de-risking project. The first one was the development of a benchtop demonstrator to prove that a representative fluid could be pumped by the conical rotary booster at the required pressure. The second technical objective was the development of a plan for further development to TRL9 and Flight Qualification, providing a list of follow-on activities required to produce a flight ready CRC-based pump.

For the development of the CRC-based demonstrator the technical requirements were defined by ESA, based on representative technical targets of a 1kN thruster. The system was required to deliver pressurised fluid up to 20 bar(g) and at a flow of 8 litres/min as standard and be able to demonstrate stable performance for the operating duration test requirements. While a flight ready model of the pump could run with a variety of different propellants, for the purpose of this initial de-risk activity de-ionised water was selected as a simulant for testing since the focus at this stage was on evaluating the pumping of low viscosity liquids using VERT's conical rotor technology. Material compatibility, while crucial for further TRL progression, is to be explored in more detail as part of a follow-on activity. An additional reason for selecting water as the simulant was its similar dynamic viscosity and density to hydrazine, as well as its ease of handling.

The purpose of the second objective is to suggest the potential path for development of a CRC-based pump from the current stage of development all the way to TRL9. Building on the outcomes of the pump prototype development, a Detailed Development Plan was created which was used to define the follow-on activity to further develop the pump.

3 FINDINGS

3.1 Testing

The key objective of the de-risk activity is to prove that a representative fluid, in this instance de-ionised water, can be pressurised by the conical pump at the required pressure of 20 bar(g) while achieving a target flow of 8 litres per minute. An open vented re-circulating demonstration rig was designed to facilitate testing. The specific pump flight requirements are presented in Table 1.

Table 1: Pump Flight Requirements

Parameter	Requirement
Inlet Pressure Range [bar(g)]	4
Outlet Pressure [bar(g)]	20
Volumetric Flow [lpm]	8
Operating Temperature [°C]	40
Operating Temperature Range [°C]	5 - 50

The overall acceptance test of the demonstration rig was set to 1.5 hours, which is representative of the max burn time of the 1 kN thruster, without significant drift on the test pressures (inlet / outlet). Table 2 provides an overview of the demonstration and flight requirements.

Table 2: Demonstrator and Flight Requirements

Test Parameter	Demo Requirement (Key Goal)	Flight Requirement
Duration	1.5 hrs	1 hrs
Inlet Pressure	4 bar(g)	4 bar(g)
Outlet Pressure	20 bar(g)	20 bar(g)

To optimise the CRC for pumping as opposed to compression, the effective volume of the “compression” chamber was progressively reduced, thus optimising the compressor for pumping incompressible fluids. To do this the base helical profile was not changed but the length of the rotors was reduced by progressively cutting back the helical surface and thereby reducing the built-in compression ratio for the rotor pair.

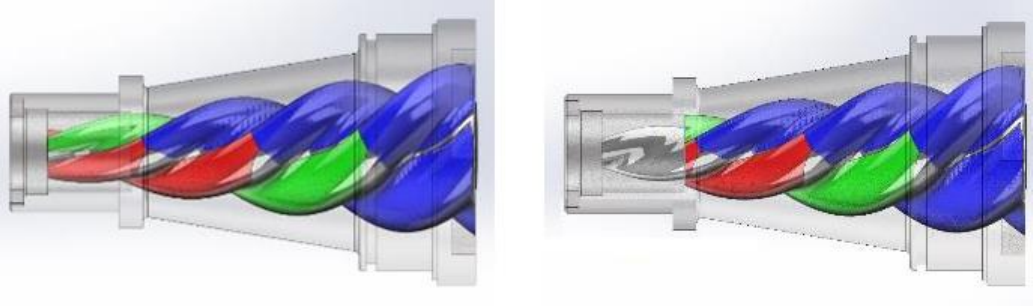

Figure 1: Rotor Cutback

A rotor with a 20% cutback was selected for, following initial evaluation which found that it yielded better results compared to the longer versions (17% and 14%), both in terms of high-pressure performance and low-pressure fluctuation, with the shorter (22%) rotor length producing significant flow and pressure fluctuations.

Evaluation of the pump was performed over a range of speeds and discharge pressures. Speed ranged from 3000 to 3500 RPM and outlet pressure from 14 bar(g) to 20 bar(g). Inlet pressure was initially fixed to 1.0 ± 0.2 bar(g).

An effort was made to match the testing parameters as closely as possibly with the specified potential flight parameters for such a device. As such the inlet pressure was set at 4.0 ± 0.2 bar(g) during testing. The main aim of these test runs was to prove that the pump can cope with higher than ambient inlet pressures without a drop-off in performance. Tests were performed at both 3000 and 3500 RPM to better evaluate how performance scales with increased speed.

The rotary booster was found to be capable of delivering the performance required, producing more than the minimum required flow at a discharge pressure of 20 bar(g). A linear performance drop-off was noted, which was expected as it was known from prior experience that PEEK rotors exhibit increased wear, which increases internal leakage and in turn leads to flow and pressure loses.

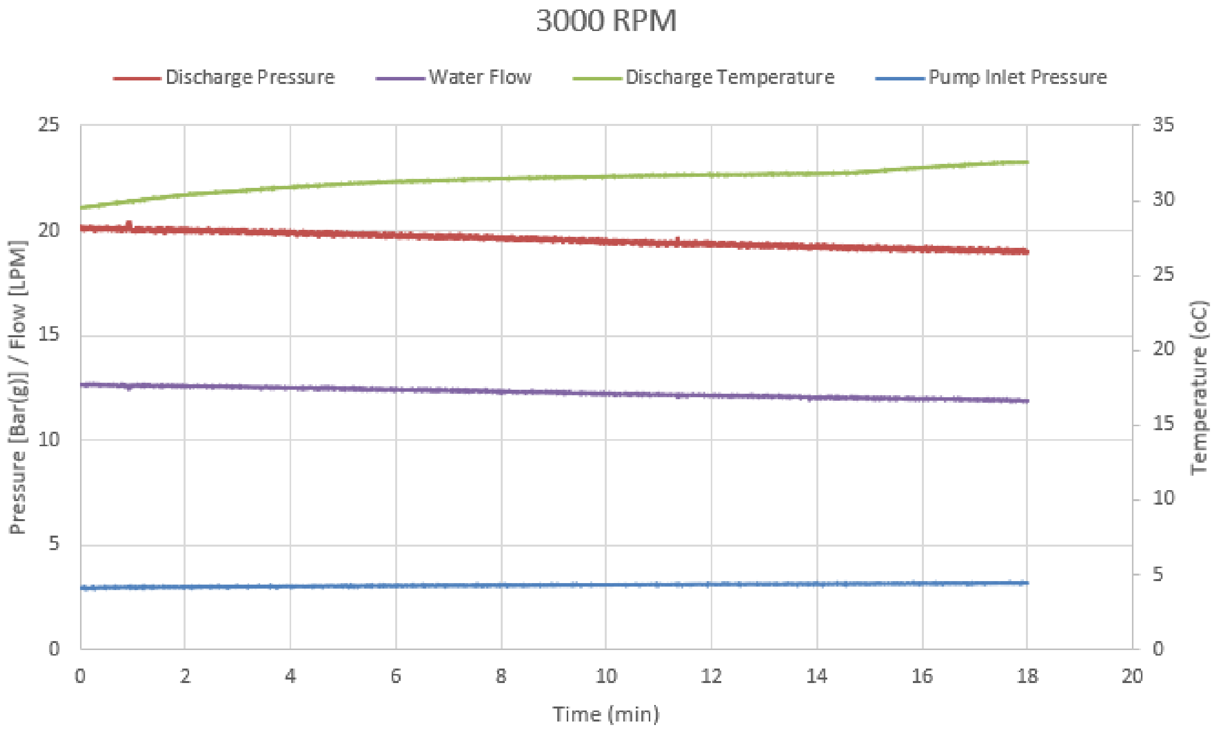

Figure 2: Performance Monitoring - 3000 RPM - 20 bar(g)

Endurance performance evaluation of the pump was performed as per the requirements presented in Table 2. In total two endurance test runs were performed. During the first run the pump ran uninterrupted for 1 hour at a fixed speed of 3000 RPM. The water flow was actively cooled throughout the run, with the heat exchanger fan running at a fixed speed.

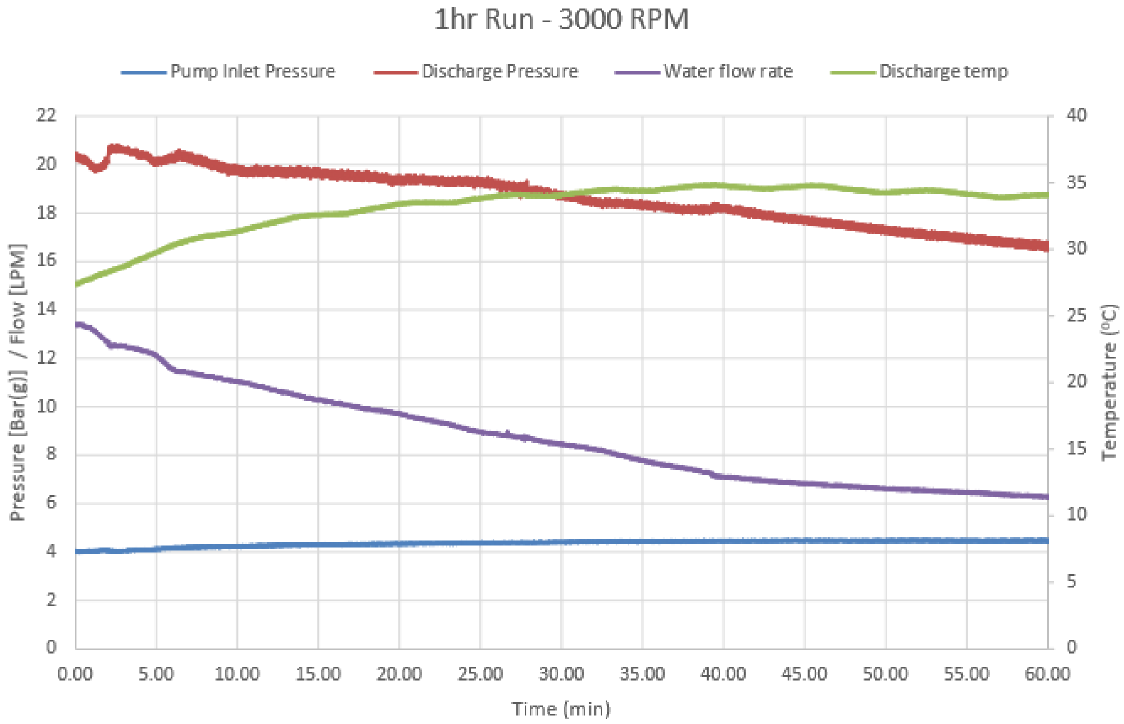

Figure 3: Endurance Run#1 - 1 Hour - 3000rpm - 20 bar(g)

Results were in-line with previous findings, confirming that while it is clear that the pump can provide the required amount of flow at the desired pressure of 20 bar(g), performance drops off linearly through the run. The second endurance run attempted to mitigate the performance drop off by implementing a variable speed protocol, where the motor speed was increased from 3000RPM to 3300RPM, 3500RPM, 3700 RPM and finally 4000RPM, each time the flow dropped below 10 lpm. The implementation of this protocol proved to be an effective way of compensating for pressure and flow loses. Average discharge pressure for the run was 20 bar(g), while average flow was 10 litres/min.

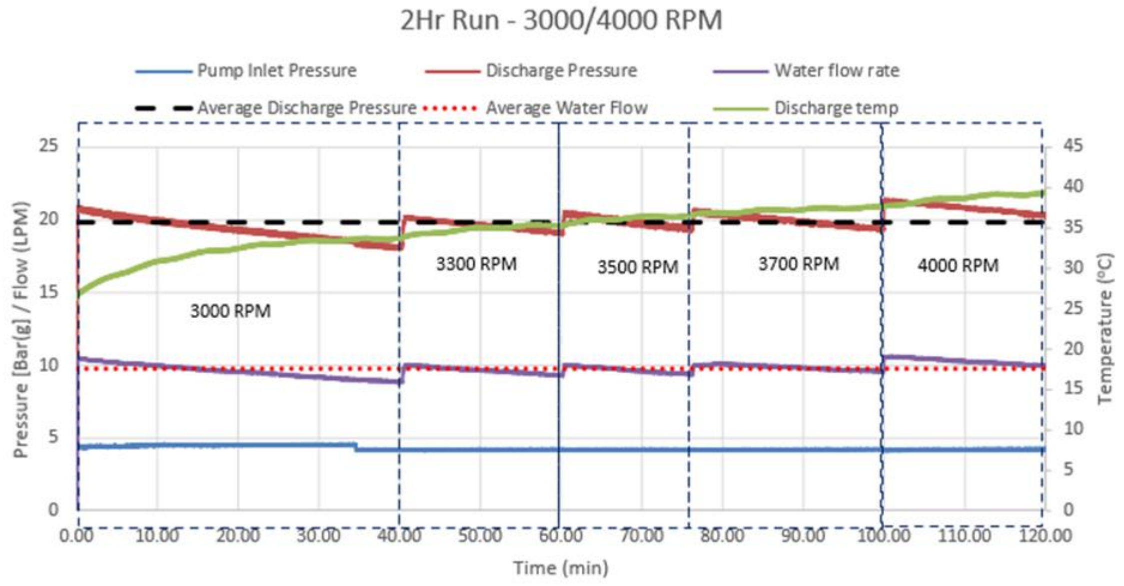

Figure 4: Endurance Run #2 - 2 Hours – Variable Speed [3000-4000RPM] - 20 Bar(G)

The pump was also characterised in terms of pressure pulsations produced, with the use of a high bandwidth pressure sensor recorded 32 samples sets were recorded at a rate of 50 kH, analysed using FFT analysis. During the initial performance evaluation stage, highest-pressure spike was recorded around 100Hz. This corresponds to the expected opening of the rotor chambers twice per full revolution of the inner.

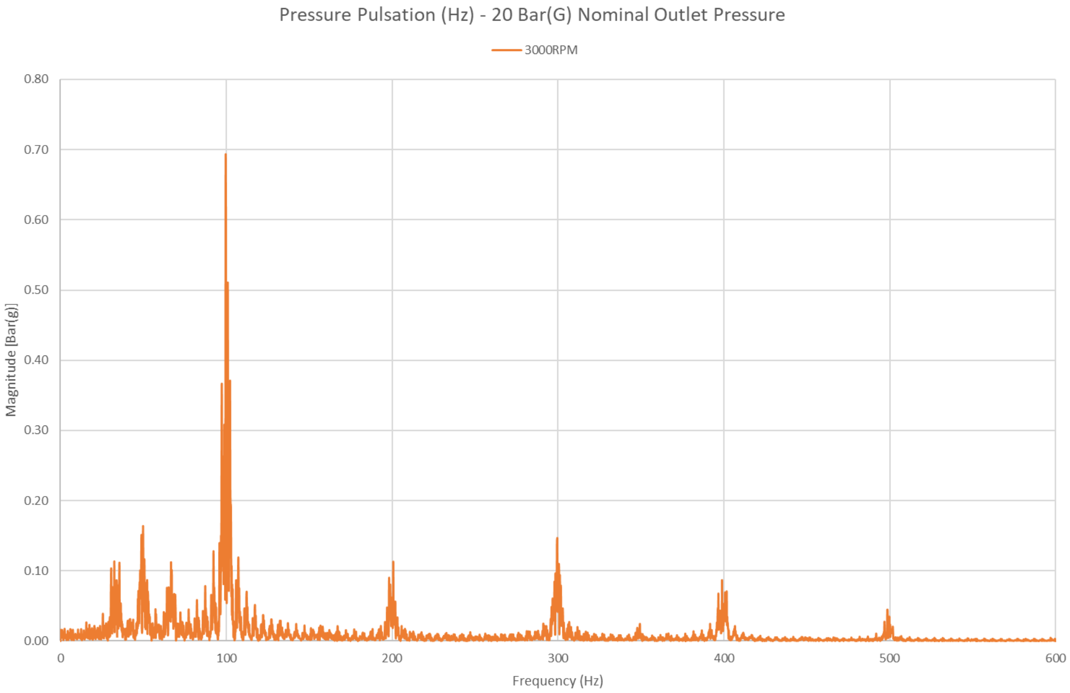

Figure 5: Pressure Pulsations at 20 bar(g) and 3000 RPM

Similar results were recorded during the second endurance run. As expected, the highest peaks are at 2-events-per-revolution (100/110/117/123/133Hz), throughout the speed range.

While the magnitude of pulsations, especially at the frequency of 100 Hz, is high, it is encouraging that the magnitude of pulses is significantly lower at frequencies of 300Hz and above, which are noted to be critical for the engine design. Of interest is the fact that the area of graph below 100 Hz has high magnitude pulses for most speeds tested, the 3700RPM one being the exception. At this point it is not clear what is causing these high pulses at lower frequencies.

3.2 Follow-On

In this test program it has thus been demonstrated that this technology has reached a maturity of TRL 4: Component and/or breadboard functional verification in laboratory environment in respect to the following critical functions:

Table 3: Project Critical Functions

#	Critical function	Target	Achievement
1	Pressure	20 bar(g)	20 bar(g)
2	Flow rate	8 lpm	11 lpm @ 3000rpm
3	Fluid	Kerosene, MMH, MON	Water simulant used
4	Material compatibility	Compatibility	Limited/low compatibility
5	Test environment	Laboratory	Laboratory

A follow-on project would look into addressing the growing market for satellites commissioned for governmental research and commercial purposes. Recent years have seen significant developments in both these areas, with an increasing tempo of robotic lunar and planetary exploration, and an acceleration of commercial exploitation of space resources, primarily between low Earth orbit and the moon.

Such use case is a lunar landing craft for science and exploration purposes. As a first step to this goal the development of earth atmosphere demonstration vehicle is planned, named “Ascent and Descent Autonomous Manoeuvrable Platform” (ADAMP) [1]. The basic outline of the potential missions for this electric pump would be as follows:

- 6kN nominal thrust
- Green propellant compatible
- Electric pump pressurised
- Re-ignitable and deep throttling engine
- Multi-mission capable

The two fuels being targeted for this project are kerosene and butyl alcohol. Both of these fuels are termed as “green” since in the event of a release to the environment or contact with personnel the adverse effects are greatly reduced compared to hydrazine based bi-propellant systems.

The main aspects of the next phase of pump development of would be as follows:

1. Rotors configured to remove the internal compression of fluid in the pump
2. Integration of the motor into the pump removing dynamic seals to the external environment
3. Increase the displacement/flow to match the stated development project requirements
4. Provide motor cooling via incoming fluid flow
5. Bearings re-arranged to suit integrated motor and new pump rotors

4 CONCLUSIONS

During this de-risk activity, it was demonstrated that it is possible to adapt the Conical Rotor design for use as a liquid pump. The initial prototype developed by VERT, was successful in meeting the requirements set to satisfy the use case scenario of using the pump as part of a 1kN chemical propulsion system for a satellite.

The major conclusions are:

- Rotors made out of aluminium cannot be used with low viscosity fluids, exacerbated the wear of the two-rotor surface, due to the lack of a substantial lubricating film between the contact areas, leading to galling and seizing of the parts. Selecting a polymer material (PEEK) for one of the two rotors allowed the pump to operate normally.
- Reducing the length of the rotors by 20% yielded the best results in terms of flow produced at the target pressure.
- A CRB with a nominal volume of 8cc is capable of delivering over 10lpm at a pressure of 20Bar(g) when operated at a shaft speed of 3000RPM.
- It was noted that pump performance dropped off linearly due to increase of volumetric losses, attributed to increased wear of the plastic rotor. Implementation of a variable speed protocol, in which the speed increased as the flow dropped below 10lpm, enable the pump to maintain a flow above the required target.
- Pressure pulsations were noted to be within acceptable limits (<300Hz), with the highest amplitudes being around 100Hz.
- Further fine tuning of the rotor geometry is required to improve efficiency of the pump and resolve the issue of performance drop off. This will need to be further assisted by appropriate selection of materials, which can also be compatible with the different fuels to be pumped.
- A follow-on project would look into addressing the growing market for satellites commissioned for governmental research and commercial purposes. Recent years have seen significant developments in both these areas, with an increasing tempo of robotic lunar and planetary exploration, and an acceleration of commercial exploitation of space resources, primarily between low Earth orbit and the moon. Such use case is a lunar landing craft for science and exploration purposes. As a first step to this goal the development of earth atmosphere demonstration vehicle is planned, named "Ascent and Descent Autonomous Manoeuvrable Platform" (ADAMP) [4]. The basic outline of the potential missions for this electric pump would be as follows:
    - 6kN nominal thrust
    - Green propellant compatible
    - Electric pump pressurised
    - Re-ignitable and deep throttling engine
    - Multi-mission capable
- The main aspects of the development of this pump are as follows:
    1. Rotors configured to remove the internal compression of fluid in the pump
    2. Integration of the motor into the pump removing dynamic seals to the external environment
    3. Increase the displacement/flow to match the stated development project requirements
    4. Provide motor cooling via incoming fluid flow
    5. Bearings re-arranged to suit integrated motor and new pump rotors.

5 REFERENCES

[1] European Space Agency, “GSTP Element 1 “Develop” Compendium of Potential Activities 2017,” European Space Research and Technology Centre, Noordwijk, 2017.

[2] D. Noake, “Rotary Cryocooling System - Final Report,” VERT Rotors UK LTD, Edinburgh, 2018.