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Disruptive ROVA Electropneumatic Valve Technology for Satellite-Delivering Rocket Applications

Luis Teia[1]

[1] Rocket Factory Augsburg AG, Berliner Allee 65, 86153 Augsburg, Germany

Correspondence: Dr Luis Teia, Rocket Factory Augsburg AG, Berliner Allee 65, 86153 Augsburg, Germany. E-mail: luis.teia@rfa.space; luisteia@sapo.pt

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Abstract

This article presents a novel design for a Rotational Valve (ROVA) electro-pneumatic (pilot+main) valve combo developed for our rocket RFA ONE, where rotation governs the internal piston movement (in commercial valves, translation is the traditional movement). The need for such a new design comes from two facts: (1) commercial valve design operational pressure at maximum 10bar limits some rocket applications, where higher pressures are used to drive larger purelypneumatic both actuators and valves; (2) dents and scratches cause pistons to get stuck, leading to maintenance downtime and costs. It is the thesis of this study that a valve design employing rotation may alleviate this jamming problem. The 10bar limit problem (emerging from a seal being lift-off due to excessive pneumatic pressure) is resolved by making that seal insensitive to driving pressure. The ROVA valve combo internal operation is explained in detail, being visualized using Computer-Aided Design (CAD) and free to download at an open-source repository. Physical calculations show that the pressurization of internal paths plus the piston's rotation is achieved with times comparable to commercial valves. This new design pushes the envelop on the electro-pneumatic valve capability to handle larger piloting pressures (that commercial options), and potentially extends valve life by using rotation as a preferred means of operation.

Keywords: rocket, space, electro-pneumatic, valve, rotation

1. Introduction

Rocket vehicles that deliver satellites into space have an internal dynamic operation that depends on pneumatic technology. Figure 1a pictorially represents the process of pressing the propellant tanks with an inert gas (e.g., helium or nitrogen), controlled by a combination of a main pneumatic valve driven (in itself by a smaller electro-pneumatic valve) that together, regulating the pushing of propellants into the main engines for combustion, and subsequent generation of propulsive thrust (Turner 2005, Hedayat et al 2007). The pneumatic pressure system (like the ROVA valve in Figure 1b actuators) can be regarded as the muscle-system of a body in an analogy to the human body, whilst the electric cabling conducting outputs to drive them (the actuators, and receiving inputs from sensors) can be regarded as the nervous system. Whilst electrical-driven motors and actuators are developing at an astounding pace, its integration into space rocket is still limited (with some exceptions as the electric-pump of the Rutherford engines being powered by electric motors). In many applications, it is still more reliable and robust to choose pneumatic solutions. Electric networks transmit power virtually instantaneously, but with the downside that conversion into a force/torque often requires motors and actuators with large and heavy coils. Also, electric connectors can have intermittent contact, and cables can be severed during an onboard fire.

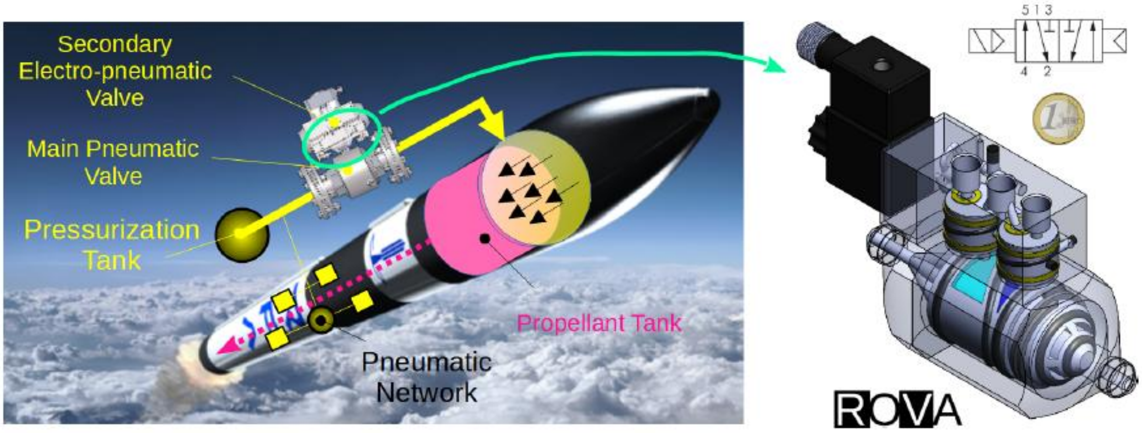

Figure 1. RFA One rocket showing the pneumatic tank pressurization systems driven by ROVA valves

On the other hand, whilst pneumatic networks have challenges in transmitting power, namely slower reaction times (than electrical) due to piping impedance, and also pneumatically-driven pistons have leaks and are difficult to control (i.e., when balanced by an opposing spring, it can result in rebound and harmonic oscillations) — specially for high force or torque efforts — electric valves tend to have larger masses and volume footprints (than pneumatic equivalents) on the rocket. Moreover, pneumatic actuators have the advantage of having much shorter response times (for a given power level) (Pustavrh et al., 2023).

Various components are used in rocket pneumatic systems, some are pressure regulators (Parker, 2003), pressure-compensated needle valves (Danfoss, 2024), and both internally-piloted and externally-piloted valves as well as electro-pneumaticoperated valves (Landefeld/YPC, 2024). This research focuses primarily on the last of these valve types. There are various types of electro-pneumatic-operated valves in industry. Many companies supply these valves with overall equivalent characteristics (i.e., only with slight differences in their design), with some of them being Norgren, Landefeld, Hafner Pneumatik, Festo and Emerson.

To minimize electric power requirements, it is often preferred the selection of valves that transform a small electric input (via pneumatic means) into a large mechanic output. An often adopted approach is the domino coupling of ever growing pneumatic displacement of pistons, which materializes as the small displacement of a ferromagnetic piston via a solenoid coil, that triggers a pneumatic loading of a pilot piston (inside a pilot valve, like the NAMUR type 5/2 electropneumatic-operated valve) [as illustrated in Figure 2a], that subsequently controls the pneumatic-loading of a large piston inside a larger pneumatic valve. For example, this is often a electro-pneumatic system adopted to control the hydraulic extension/contraction of excavator arms via small electric inputs from a joystick (driven by an operator) (Eaton, 2019). Sometimes, the pilot 5/2 valve is coupled to drive a larger valve, like for example in the case of Coax valves (Coax Muller Group, 2024).

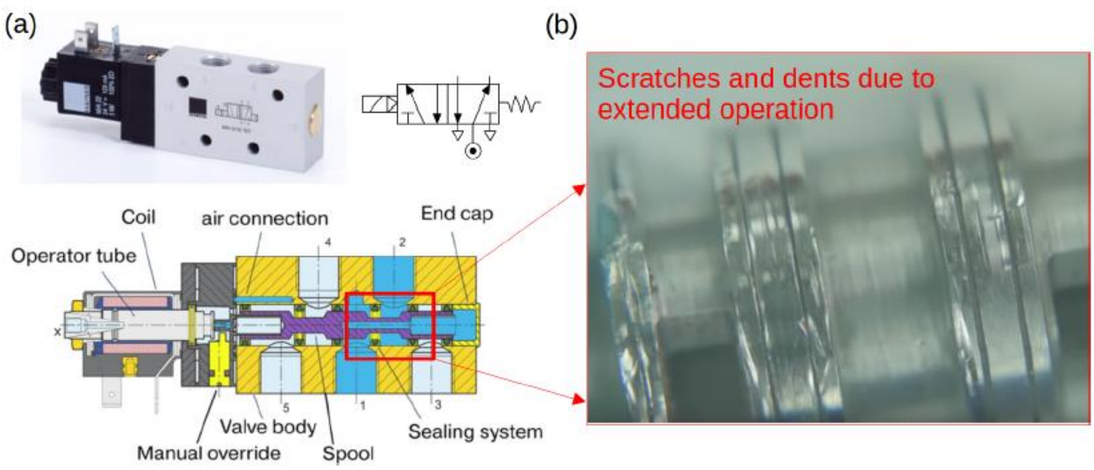

Figure 2. Pilot 5/2 valve (a) photo, functional drawing and crossection (Hafner Pneumatik, 2024), and (b) damaged piston (Global Electronic Services, 2016)

The functional need of our rocket that triggered the present research is as follows. In order to operate a cluster of small 5/2 electro-pneumatic valves distributed around the rocket, it is required a pressure network operating at a maximum pressure of 10bars, because this is the limiting pressure stated by the suppliers to which the valve responds (Festo, 2024). On the other hand, larger valves (like the main valve in example Figure 1a) require larger pressures to open/close, and thus to operate.

This poses a problem, as then it is required two pressure networks — one low (i.e., maximum 10bar) and one high (e.g., sometimes in excess of 30bars). Therefore, in order to avoid the added complexity, mass and cost of two pressure supplies (i.e., more regulators, more piping, etc), it is required a new small electro-pneumatic valve that can operate reliably at such high pressures (thus removing the need for the lower pressure network).

Maintenance of these valves has shown that after sufficient usage damaging occurs in the piston (Global Electronic Services, 2016), whether due to a single harsh actuation or due to many cycles, which eventually leads it to operate inefficiently or even get stuck. Cylindrical pistons (under loading) that slide inside structures can both develop features that generate friction to sliding (e.g., scratches or dents) or even get jammed (e.g., bent piston inside a sleeve). A piston that is not translating, but is rotating is less susceptible to the two aforementioned problems.

1.1 Hypothesis

The assumption of this study is that it should be possible to create the functionality of a electro-pneumatic pilot plus main pneumatic valve operating entirely based on rotational motions.

2. Theory

The new design for the ROVA valve, shown in Figure 3, is in fact a combo of a larger ROVA main rotational valve driven by a (smaller) ROVA pilot rotational valve (with a different piston rotational orientation). Each will be described now in turn using this proof-of-concept computer-aided design (CAD) [done only to express the functionality of the valve; detailed features like screw orifices for attachment, and exact split and screwing of the front/rear cap to the main valve center body is not shown here]. First, we shall give a general description, and then a functional explanation on how each valve operates.

The general dimensions of the valve are 150mm x 94mm x 44mm. The main body is 120mm in length, with a square cross sectional width of 44mm. The pilot body is around 70mm in length (without the solenoid), with a square cross sectional of width 30mm. The main piston is 60mm long and has a cylindrical section with a diameter of 34mm. The pilot pistons are 15mm in height and have a diameter of 20mm. The valve was constructed in CAD using the opensource software FreeCAD, and is accessible for download at this author's opensource profile in Figshare by clicking here. The assembly was exported from FreeCAD and rendered using the photorealistic OpenCascade engine CADRays, to provide a more professional visual look to the valve.

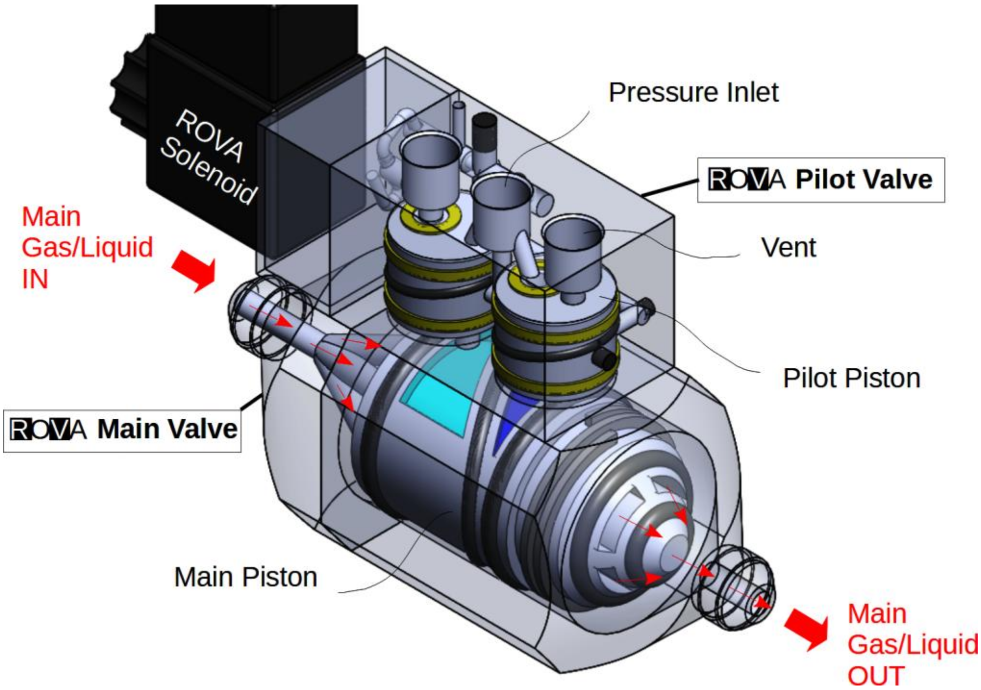

Figure 3. The ROVA electro-pneumatic pilot + main valve combo

The *ROVA main valve* (Figure 3) comprises of a rotating piston threaded within an enclosure caped on either side. The main piston is composed of both a cylindrical section and a conical section, and encompasses an inner path along which the main gas/liquid flows, providing fluid communication between the inlet of the valve (back cap) and the outlet (front cap). This path exists at front conical section of the main piston in between two o-rings. When the main piston is rotated closed, the male conical section presses the o-rings against the female conical counterpart, closing the path access downstream. The cylindrical part of the piston has at each extreme o-rings that isolate it from the main gas/liquid. A third o-ring is present in-between (the aforementioned o-rings) disposed in an elliptical path (i.e., at a section inclined to the axis of the cylinder) — the purpose being to isolate two diagonally-opposing portions of the cylindrical sections. These opposing sections hold recesses, forming enclosed cavities possessing a side interfacing with the diagonal o-ring. When pressurized gas agent is released into one of these cavities (while the opposing is at ambient pressure), a pressure differential is generated that pushes and rotates the main piston.

The *ROVA pilot valve* (Figure 3; explained further in Figure 4) comprises of a block holding two small rotating pistons side-by-side. The holding block has three threaded holes (also common to other 5/2 pilot valves), forming the traditional central pressure (Port 1) with two adjacent discharge vent or dump (Port 3 and 5). The difference is more present with the rest of the features. These threaded holes (Figure 4a) have smaller holes that link to two deep cylindrical cavities located lower along the height of the block. Namely, two small diagonal holes link the central pressure port to the closest extreme of each of the two deep cylindrical cavities. While, one vertically straight and centred small hole on each of the vent/dump ports connects to the other extreme of each of the cylindrical cavities.

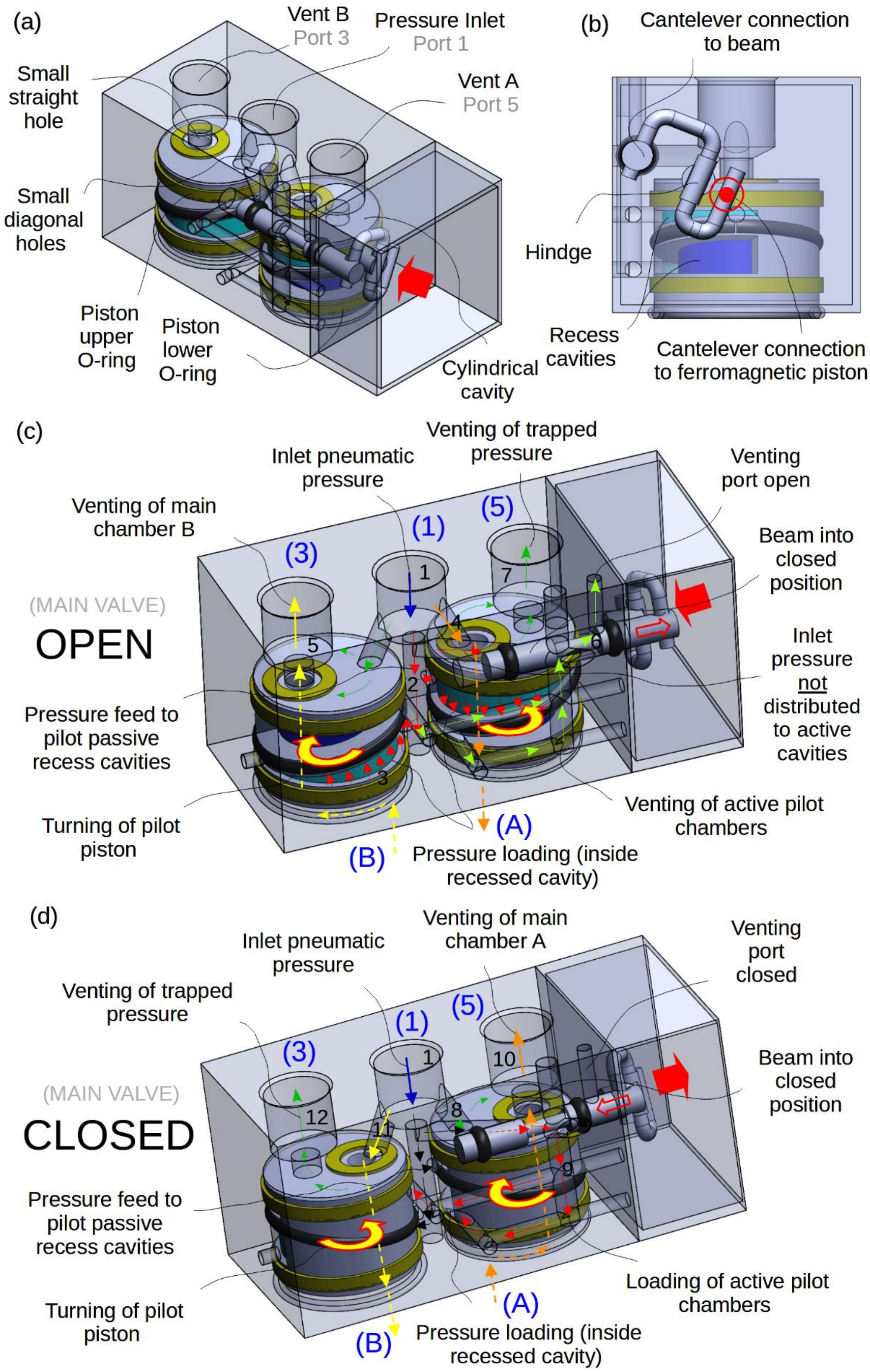

Figure 4. ROVA Pilot Valve views: (a) isometric, (b) side, (c) open and (d) closed

Each of the cylindrical cavities holds rotational pistons. The flat faces of each piston have specific features that enable the passage of the pneumatic air/gas, in and out. The cylindrical face of the pistons has two circular cavities to hold o-rings, at the most upper and lower positions, and in between there is an additional diagonal o-ring. This follows on the principle previously adopted for the main rotational piston. Each cylinder has an off-axis hole that goes through it (top-to-bottom), being the outlets pneumatically insulated via dedicated smaller o-rings located at the upper face (of each of the piston). The lower face of the pistons forms a enclosed cavity. When aligned, these piston through-holes connect the central pressure port to the inlet port of the main valve (who in turn connects to one of the recessed cavities on the surface of the main piston). In an 180 degree rotation (locked in place between protrusions in the pilot pistons, and arc recesses in the cylindrical chambers — not shown in Figure 4), the same through-holes connect the vent ports to the same inlet port of the main piston. Each of the pistons is at 180 degrees phase to the other. That is, at any given time, one of the discs is rotated to load one of the main piston cavities, while the other disc is rotated to connect the opposing main piston cavity to one of the dump ports (in ambient conditions).

The *functioning of the ROVA pilot valve* (Figure 4) occurs as follows. The rotation of the pilot pistons is achieved by pneumatic loading of the triangular recess cavities (adjacent to the diagonal o-ring, and located at the surface of the cylindrical face). Initially, the ferromagnetic piston is pressed via a spring that keeps the small cantilever in the closed position (pushed against the pilot block). When a current is passed through the solenoid, the electromagnetic field generated passes imperfectly aligned through the dislocated ferromagnetic piston. This induces a polarization effect of the ferromagnetic piston opposite in polarity to that produced by the coil. These weaker ferromagnetic piston poles are attracted by the stronger inverse magnetic poles generated by the coil generating attraction (pushing against the spring). The ferromagnetic piston then displaces back until its and the coils magnetic field is aligned, effectively pulls the small cantilever into the open position (pushing against the spring). This pulling of the cantilever has a moment effect that pulls (an opposing) small rod on the far corner of the pilot valve. This small rod has some o-rings along it, and a small detent to allow the pressurized gas to pass.

The rod is inserted into a cylindrical cavity that has three ports: (1) channel that connects to the pressure in port, (2) vertical path that links to the side recesses in the small piston cylinders, and (3) a small vertical path that links to the top and ambient surrounding air.

It operates as follows, when the small rod is pulled back, the o-ring on the far end isolated the pressure inlet path (1), as it links it to a dead-end cavity. The small detent along the rod partially aligns with the vertical path (2) [that links to the recesses in the pistons] and also connects to the path (3) that leads to ambient. This decompresses the piston pressure loaded recesses. When the small rod is pulled forward, detent along the rod becomes aligned with the pressure inlet path (1) linking it to the vertical path (2), thus pressure loading the recesses in the pistons. This leads to the pistons to rotate.

There is also a vertical path (in between the piston holding cavities in the holding block) that connects the pressure inlet to a couple diagonal ports linking to the opposing recesses in the cylinder. The idea is that these are always loading the opposing recesses in the surface of the pistons. What causes them to turn is the loading on the opposite side recesses (as described before, due to the opening of the small rod) that act on a larger surface, that causes a force differential resulting in a torque and thus piston rotations. Remove this, and the pressure coming from the pressure inlet returns the pistons to their original rotational position.

The *functioning of the ROVA main valve* (Figure 5) occurs as follows. The ROVA valve opening and closing is achieved by means of a rotational movement. The ROVA piston is threaded on its outer diameter at the front (Figure 5a). The thread is very similar in shape and functioning to the threads binding a cap to a water bottle inlet, which comprises of only two turns with a thick rail-type thread. Intermittent gaps (not shown) could be added along the thread to minimize friction, and thus facilitate the turning motion. This physically supports the main piston at the front end.

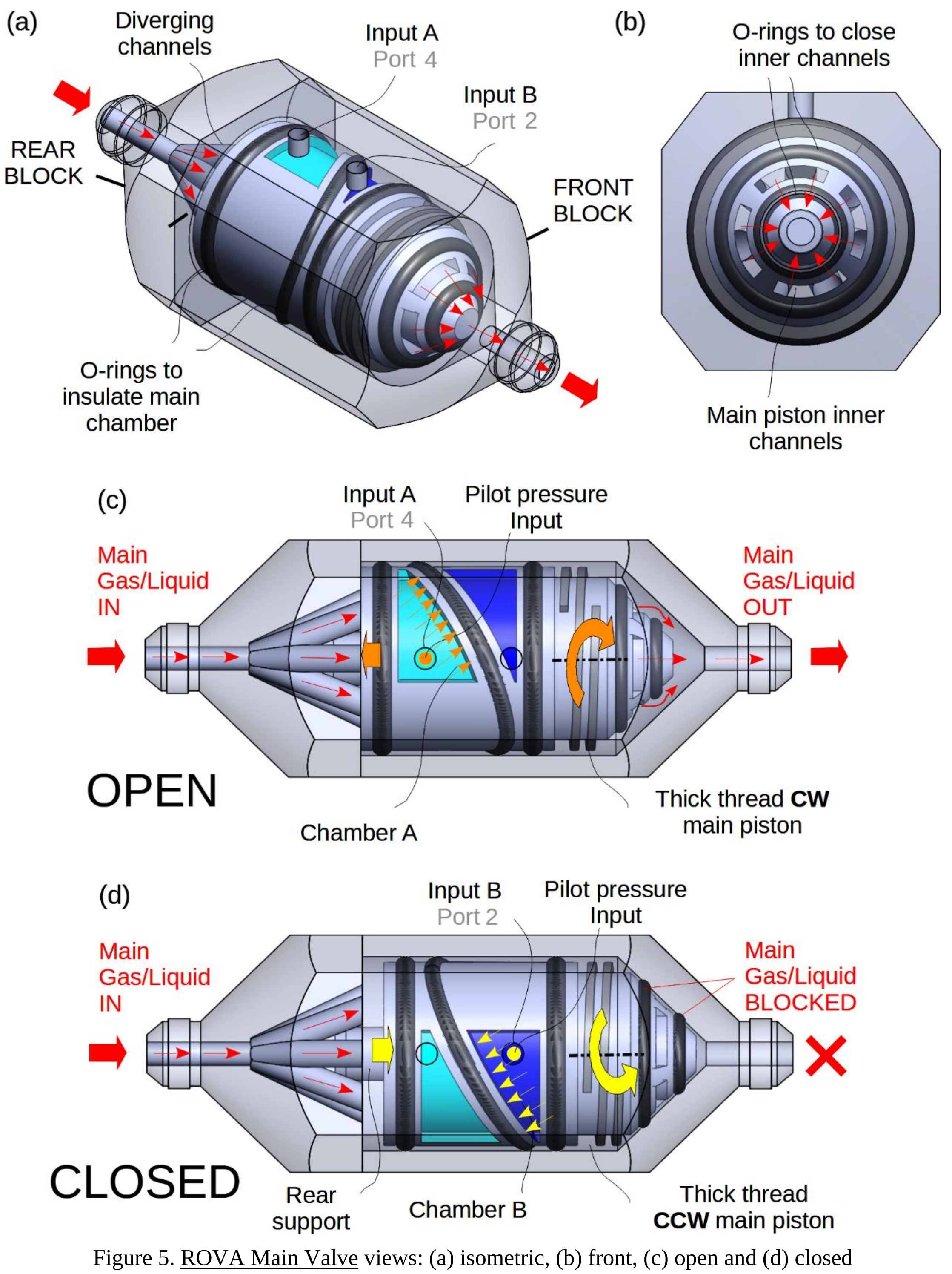

Figure 5. ROVA Main Valve views: (a) isometric, (b) front, (c) open and (d) closed

At the back end, the main piston has a cylindrical protrusion aligned with its axis of rotation, that extends back. When the back block threads into the main block, the cylindrical protrusion slides inside a corresponding hole at the centre of the back block, thus providing rear support to the main piston.

The clockwise and anti-clockwise motion of the main piston is achieved by loading one of the recess chambers in the cylindrical section (adjacent to the diagonal o-ring) [Figure 5b], and unloading the opposing the other recess chamber, thus creating the pressure differential that generated the torque that turns the main piston. The opening rotational motion has an opposite pressure loading to that of the closing rotational motion.

Supported at both ends, any torque rotates the main piston left and right, which via the front thread translates the piston back and forth. The rotational interval is linked to the axial translation interval via the threading setting. When it rotates towards the open position, the main piston hist the back block, and gets locked in place (enabling the gap at the front to provide a flow path for the gas/fluid to flow to the exit at the front) [better shown in Figure 5c].

Similarly, when the main piston rotates towards the closed position, the main piston hits the front block, and the conical male section of the piston presses against the conical female section of the front block, creating insulation of the mid-path in between the corresponding o-rings, thus essentially closing the communication path for the gas/liquid to flow.

Since the inlet and outlet have the same cross sectional area as equivalent commercial valves (G1/4), the number of liters per minute the ROVA valve should be the same.

3. Analysis

The analysis starts with decomposing the different fluidic and mechanical mechanisms that contribute to the opening of the ROVA valve. The first is a fluidic study, which determines the rate of loading the path plus chamber to the supply pressure. The second is a mechanical study, which determines the speed of rotation of the pilot and main valve cylinders or pistons.

There are five steps that occur during the opening of the ROVA combo valve, where the fluidic process occurs partially overlapped to the mechanical process (with the pilot being followed by the main), and are defined as follows:

1. *Electromechanical process:* In order to avoid transient electromagnetic simulations on how the ferromagnetic piston gets accelerated and then asymptotically locked into the magnetic poles generated by the coil (reacting against the spring), it is assumed that this part of the process lasts around 20% of the whole period from electric signal input to main valve full open. A future study will cover this simulation with a dedicated publication.

2. *Pilot fluidic process:* under no electric input into the solenoid, the pilot pistons are rotational locked in placed by a continuous pressure loading onto one of its recessed cavities (in the cylindrical face). Only after solenoid actuation, and subsequent pressure release into the opposite side recessed cavity (of the said cylindrical face), will the force differential (driven by the delta area between the two sides) cause the pilot piston to rotate completely to the opposite position (i.e., here selected to 180 degrees).

3. *Pilot mechanical process:* comprising of the rotation of the pilot pistons, that initially are held in place due to the continuous inlet pressure loading on one of the recess chambers on the cylindrical sides. Upon arrival of the aforementioned pressure loading via path (2), the pressure loading of the opposing recess chamber (with a larger loading are) causes the pilot pistons to turn by 180 degrees (then halted due to a mechanical indentation that prevents further rotation).

4. *Main fluidic process:* the main piston is rotated via a similar mechanism, in that the pressure build up in one of the cavities generates a differential pressure (the other side is at ambient), producing a torque. There is always one side holding the recessed cavity loaded at any given time, and the other is vented.

5. *Main mechanical process:* The rotation angle is much smaller than those of the pilot pistons, because less is required to generate the sufficient translation (of the main piston) that creates a crossectional area larger than the choking inlet/outlet area. The front and rear faces of the main valve enclosure halt the rotation, and thus translation of the main piston.

Each *fluidic process* requires the assessment—in discrete time steps—on how much time a cavity takes to be filled with gas. The pressure differential governs how fast the cavity (of volume *V*) gets filled (with mass *M*), and thus how fast the pressure *P* rises inside the cavity, and this how fast it acts on the cylinders surface pushing its rotation. The mass flow of gas entering the cavity is chocked, and is given as the product of three parameters (which can be elaborated into an expanded version) (Turner, 2005):

$$\dot{m} = \rho U A_o = C_d A_o \sqrt{\gamma \rho_t P_t \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} = \frac{dM}{dt} \tag{1}$$

- A_o is the smallest area along the path to the cavity, where the effective area can be even smaller due to fluid dynamic blockages (e.g., vena contracta formation [quantified by the discharge coefficient C_d], flow separation around the corners, formation of recirculating bubble, boundary layer growth, etc) (Teia, 2010)

- *U* is the flow velocity at the smallest area, becoming fixed at chocked conditions.
- *ρ* is the fluid density, which is dependent on both upstream total pressure P_t and temperature T_t

Note that as the pressure inside the path increases, the pressure differential driving the massflow reduces. The incremental gas mass d_M stored each time step d_t inside the volume of the path gradually increases its pressure (here we assume adiabatic process, that is no heat transfer and thus no entropic temperature change). To determine this, we make use of the individual gas constant interlinks any given combination density (i.e., previous mass plus increment divided by the path volume) and temperature into pressure via the perfect gas law, defined as P = RρT (Houghton & Carpenter, 1993).

Each *mechanical process* requires the assessment — in discrete time steps — on how much time a cylinder or piston requires to rotate (via dα angle increments) and accelerate towards its final angular position. This is obtained by applying the rotational version of Newton's Second Law (dependent on the cylinder's rotational inertia I, and thus material property selected) (Walker, 2007), given as

$$T = F.r = P.A_p.r = I\alpha \tag{2}$$

The pneumatic rotational moment is determined from the pressure loading *P* onto the control surfaces of area A_P (with centre at radial position *r*) inside the recessed cavities in the cylindrical region of the piston. This is used in conjunction with the angular position equation as a function of time $\theta = \theta_0 + \omega_i t + 1/2\alpha t^2$, which for a halt start $\omega_i = 0$ at zero angle $\theta_0 = 0$ simplifies to $\theta = 1/2\alpha t^2$. This can be re-arranged and expanded further substituting Eq.(2) into

$$\theta = 1/2\alpha t^2 \quad \rightarrow \quad t = \sqrt{\frac{\theta}{1/2\alpha}} = \sqrt{\frac{2\theta I}{P.A_p.r}} \tag{3}$$

Different combinations of ROVA pilot and main cylinder pistons are considered (namely, stainless steel (Atlas Steel, 2021) and aluminium [NIST Materials Data Repository, 1990]), with their times being computed and compared. Also different operational pressurizing gases—like Helium and Nitrogen are also considered—with their impact on the time taken for the completion of the fluidic processes being also estimated and compared.

4. Results

Figure 6 shows how fast the four process occur (i.e., fluid processes computed from Eq. (1) and mechanical processes computed from Eq.(3) using in both cases discrete time steps). While the pneumatic processes of pressure loading a chamber are asymptotic quickly converging to a final value, the mechanical processes of rotation of the rotational pistons are diverging, with angular velocity and displacement increasing exponential, until abruptly stopped (Figure 6a). The relative partition on time taken to complete each process is shown in Figure 6b, highlighting that the pneumatic processes (with the slowest being the main piston rotation) are much faster than the mechanical ones (with the slowest being — not surprisingly — the rotation of the main valve piston). The added total time taken for the valve to open is thus estimated to be 73ms (i.e., electromagnetic coil 14%, pilot valve 32% and main valve 54%). This result (from the presently non-optimized design) is already comparable (but slightly higher) than traditional 5/2 valves, where reaction times are quoted to fall within the 20ms - 50ms range (Avetics/Emerson, 2021). Future work on streamline the piston's mass will reduce its rotational inertia, thus potentially unlocking an even faster response time.

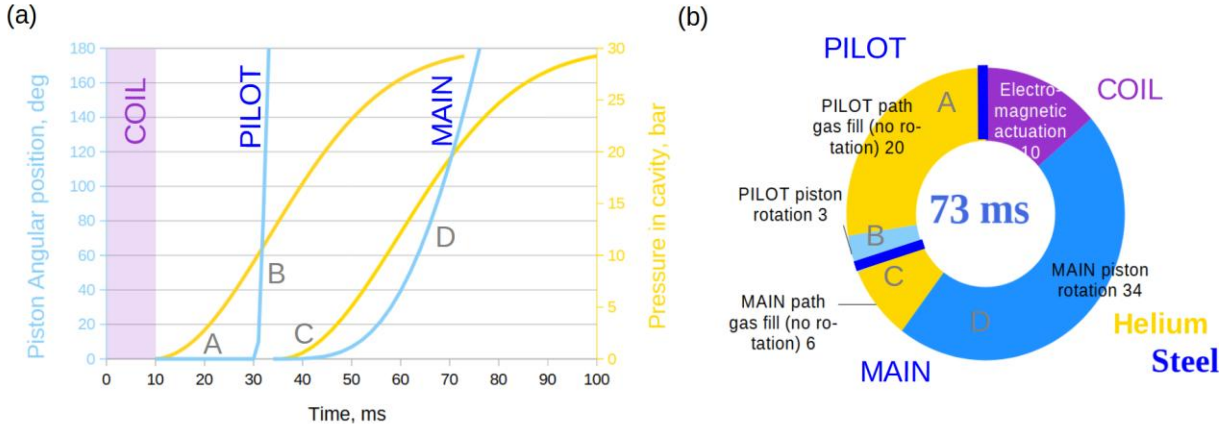

Figure 6. Time for valve to open: (a) pressurization with helium and rotation with a steel piston, and (b) partitioning

Reducing piston's cavity volume, whist maintaining contact surface for pressure to act, might be another way to achieve a faster pneumatic cavity pressurization (and thus rotation). When replacing the material property of the pistons from stainless steel to aluminium, the time to full rotation of the pilot piston reduces to 2ms (i.e., -1ms), that of the main piston reduces to 24ms (i.e., -10ms) [Figure 7a], resulting in a total time taken for the valve to open reduction to 62ms (i.e., -11ms) [Figure 7b].

Often pressurizing inert gases used on the pneumatic systems are the same as those used in tank ullage pressure, where a popular choice for cryogenic tanks is either helium (Hedayat et al, 2007) or nitrogen (Turner 2005, Cannon 2010, Barbosa et al 2018). These gases are also safe to mix with most fuels and oxidizers, where nitrogen is cheaper than helium, but slower to respond pneumatically. This is because an important difference in gas characteristics between the two is the speed of sound, being for helium 1365m/s (at 0◦C and atmospheric pressures) [Wedler & Trusler, 2023] while for nitrogen being not too dissimilar from air with 330 m/s [since this is 78% nitrogen] (also at 0◦C and atmospheric pressures) (Zuckerwar, 2002).

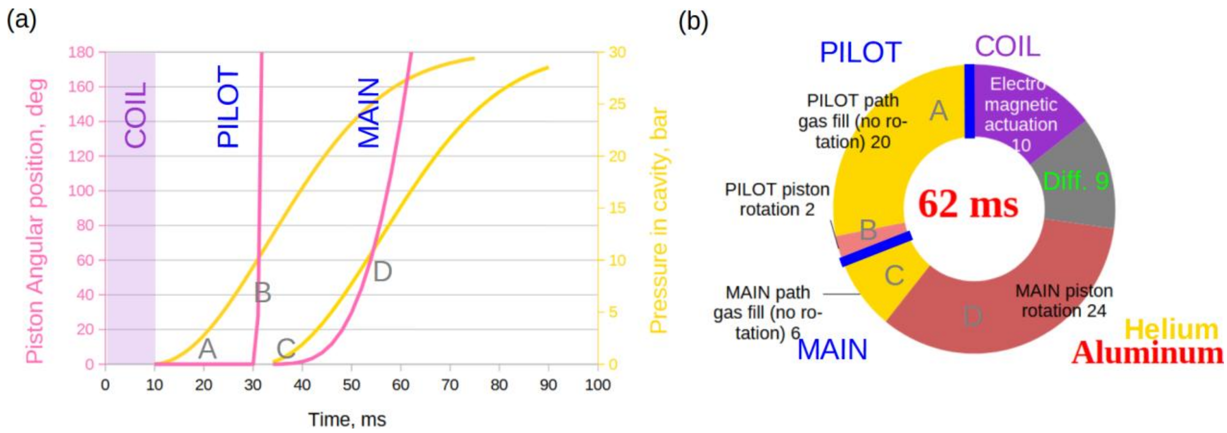

Figure 7. Time for valve to open: (a) pressurization with helium and rotation with an aluminum piston, and (b) partitioning

Essentially, this means that a pressure wave traveling through a path conduit (like, a tube) will propagate much faster using Helium (as the pneumatic driving agent). This is seen in Figure 8a, where the time take for a helium pressure wave to sweep the path plus cavity in the pilot valve is around 6 times faster than a nitrogen pressure wave. These, however, are still a couple of orders of magnitude smaller than the considered computational time step for the computation of the gradual pressurization of the path plus cavity in the pilot valve (set to 1ms).

Substituting the pressurization gas from Helium to Nitrogen has a small increase (i.e., +4ms) in response time of the nitrogen fluidic pressurization processes (Figure 8b) is observed. This rise is small because of the very small volume inside the path plus cavity in the pilot valve. For actuators involving larger pressurizing volumes (i.e., larger valves), the faster response of helium over nitrogen becomes much more noticeable (Barbosa et al,2018), thus making helium a preferred pneumatic agent (specially for rocket tank pressing systems). As an overall conclusion, different choices of piston material properties and pressurization gases can have a significant impact on the reaction speed of the ROVA valve combo to open. While in some cases, a fast reaction time might be desired (like during an extremely fast actuation), in others cases one may advert this (like in cyclic operations, where a less violent opening is desired to enable less maintenance, and thus a longer valve life).

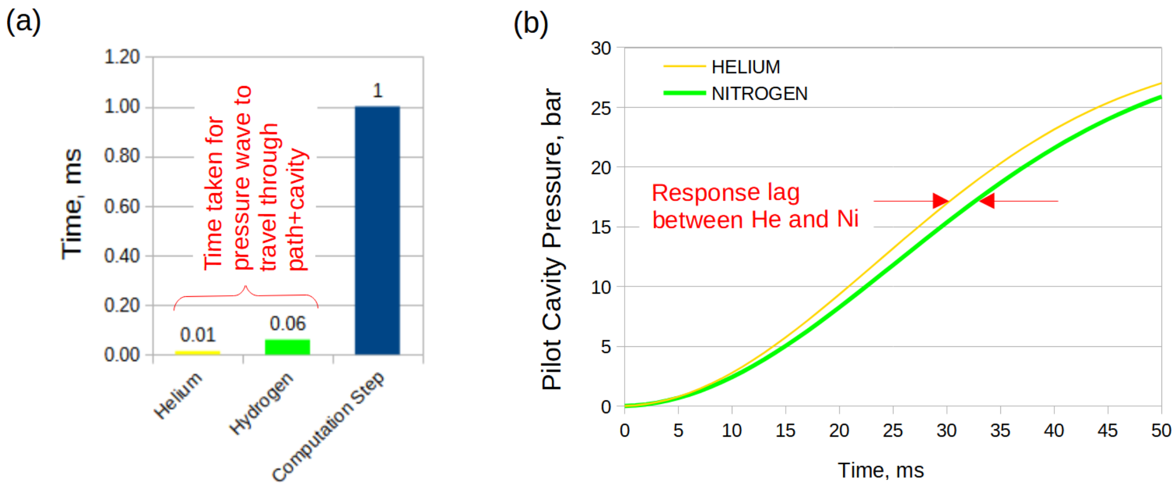

Figure 8. Response time: (a) wave propagation vs computational step, and (b) time lag between helium and nitrogen

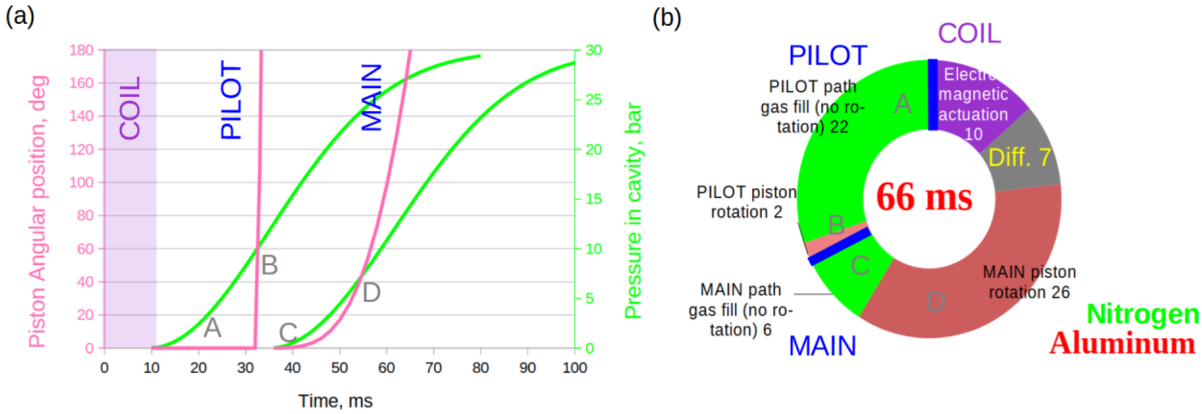

Figure 9. Time for valve to open: (a) pressurization with nitrogen and rotation with an aluminum piston, and (b) partitioning

5. Conclusion

Rockets that deliver satellites into space — like the RFA ONE — have complex internal pneumatic networks governing their internal operations — like for example the tank pressurization system — for which, they require the usage of regulators, actuators and electro-pneumatic valves. Commercially-available (for ground applications) electro-pneumatic-operated directional control valves have limitations, namely a translating piston that often gets jammed (by scratches and dents developed during operation), and a restrictive pilot operational pressure ranging from 1.5 - 10bar (due to the design limitation of a spring-loaded seal). Rocket applications present much harsher operational conditions, requiring tolerance to much higher pilot operational pressure ranges (potentially in excess of 30bar). The new ROVA (pilot+main) valve combo [presented in this article] employs rotational-type pistons to alleviate surface damage (and thus jamming problems), and its pilot valve is designed such that it operates virtually independent of the range of the governing piloting pressure. At a rocket level, these advantages enhance operational robustness of the valves (and of the overall pneumatic system as a whole), removing the need to have a lower and higher pneumatic network feeding pressure — thus allowing a single high pressure supply to drive both small electro-pneumatic-operated valves, and large purely-pneumatic main valves and regulators—resulting in lesser pneumatic supportive hardware, and thus a lighter and less complex rocket. Moreover, the ROVA main valve design is practically insensitive to main gas/liquid pressures (as the inherent torque applied to the ROVA main rotational piston is small, and easily overcome by the pilot-induced torque), and thus practically non-impactful to the ROVA valve's reaction time and overall operability. The end-result of this study is an alternative higher-end (electropneumatic pilot + pneumatic main) valve combo solution comprising of the novel ROVA design that despite showing arguably more complexity than commercial alternatives, it will enable a system-level benefit that ultimately yields a significant net positive impact on the RFA ONE rocket architecture, lean operation and performance.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Canadian Center of Science and Education.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and peer review

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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