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ADVANCED ELECTRIC PROPULSION SYSTEMS WITH XENON AS A PROPELLANT

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Abstract— *The objective of this paper is to assess different Electric Propulsion technologies for space applications with more ecologically sustainable gases utilized as propellants and evaluate the benefits. Xenon production is a highly extravagant process as it involves many stages of air refrigeration and expansion. The cost of Xenon additionally increases due to increment in its demand by automotive industry, healthcare industry and space applications. In fact, even if Xenon is to be availed as a waste of Argon production, its very low percentage in air composition makes the separation of the same amount of gas extremely difficult. Since the production efficiency is substantially low for current technologies, it is still possible to reduce Xenon demand by assessing different Electric Propulsion technologies using Argon and Krypton as propellant.*

Keywords- *Electric Propulsion; Hall Thruster; Ion Thruster; Helicon Injector; Variable Space Magneto plasma Rocket.*

I. INTRODUCTION

Electric propulsion (EP) was first proposed more than 100 years ago by Robert H. Goddard and Konstantin E. Tsiolkovsky and is being used for space applications since 1960s. Electrostatic thrusters like Hall and Ion thrusters are increasingly popular for use in the space applications. They are now used in about 20% of the commercial satellites for attitude and altitude control [1, 2]. Intensive development is going on with the focus on new concepts, addressing demands and challenges for long-term and high manoeuvre spacecraft operations which is difficult with the use of existing systems. These systems would focus on providing a suitable alternative for precise orbit control, orbit transfers, interplanetary EP-powered missions, small spacecraft control, etc. [3, 4]. Electric propulsion systems convert electrical energy into directed kinetic energy of a propellant, thus generating thrust in a given direction. Advantage of EP systems comparing to other propulsion systems is the generation of a direct, well-controlled acceleration of the propellant with higher velocities [4]. The development of the Variable Specific Impulse Magnetoplasma Rocket (VASIMR) was initiated in the late 1970s to address a critical requirement for fast, high-power interplanetary space transportation systems [5]. Utilizing ionized gases, accelerated by electric and magnetic fields, these devices expand the performance envelope of rocket propulsion far beyond the limits of the chemical rockets [6].

Propellants like Xenon (Xe) and other noble gases are widely used in space industry due to their ability to ionize at relatively low voltages [7]. Ionized Xe is used in a wide range of application such as fluorescent lightning, plasma displays, flash lamps, etc. Xenon and other rare gases are produced almost exclusively as a by-product of the separation of Nitrogen (N_2) and Oxygen (O_2) from air for industrial applications. From the environmental point of view, the production process of 1m^3 of Xe is expensive because processing 1m^3 of air requires 1kWh of electric power on an average. This is even more important considering that the demand of Xe for space propulsion application is foreseen to substantially increase in the future. Hence, finding a valid alternative is mandatory as the change from Xe to Krypton (Kr) or Argon (Ar) as a propellant does not impose major problems onto the existing propellant feeding systems. Although the dynamic pumping of N_2, O_2 or Hydrogen (H_2) in propellant feeding systems components at high vacuum levels poses a major problem [8].

Argon, Krypton and Xenon are traditionally used in EP because of their chemical inertness. Moreover, loss in power is often referred to as ionization costs. Higher the ionization costs, lower is the available power for thrust generation. Xenon has a higher ionization rate at lower energy levels. As a result, at a given temperature in the discharge plasma, a higher neutral flow will be ionized per unit time, which increases the mass utilization efficiency and thus the specific impulse [8]. This maximizes its storability and reduces the costs of the propellant storage system on-board the satellite. Due to the economical and procurement problems, some researchers have focused their attention to investigate the possibility to use other gases for space propulsion applications. The assessments often concern the comparison between Xe and Kr, with the latter one seen as the most promising low cost propellant for future missions [7, 8].

II.VARIABLE SPECIFIC IMPLUSE MAGNETO PLASMA ROCKET (VASIMR)

The VASIMR engine, as depicted in Figure 1, is a high power, electrothermal plasma rocket which is capable of exhaust modulation at constant power. It consists of three major magnetic cells: ‘forward’, ‘central’ and ‘aft’, where plasma is injected, heated and expanded in a magnetic nozzle, respectively. This magnetic configuration is known as asymmetric mirror. The main injection of propellant is handled by the forward cell and the ionization subsystem. To further heat the plasma to the desired magnetic nozzle input conditions, the central cell acts as an amplifier. The aft cell is a hybrid two-

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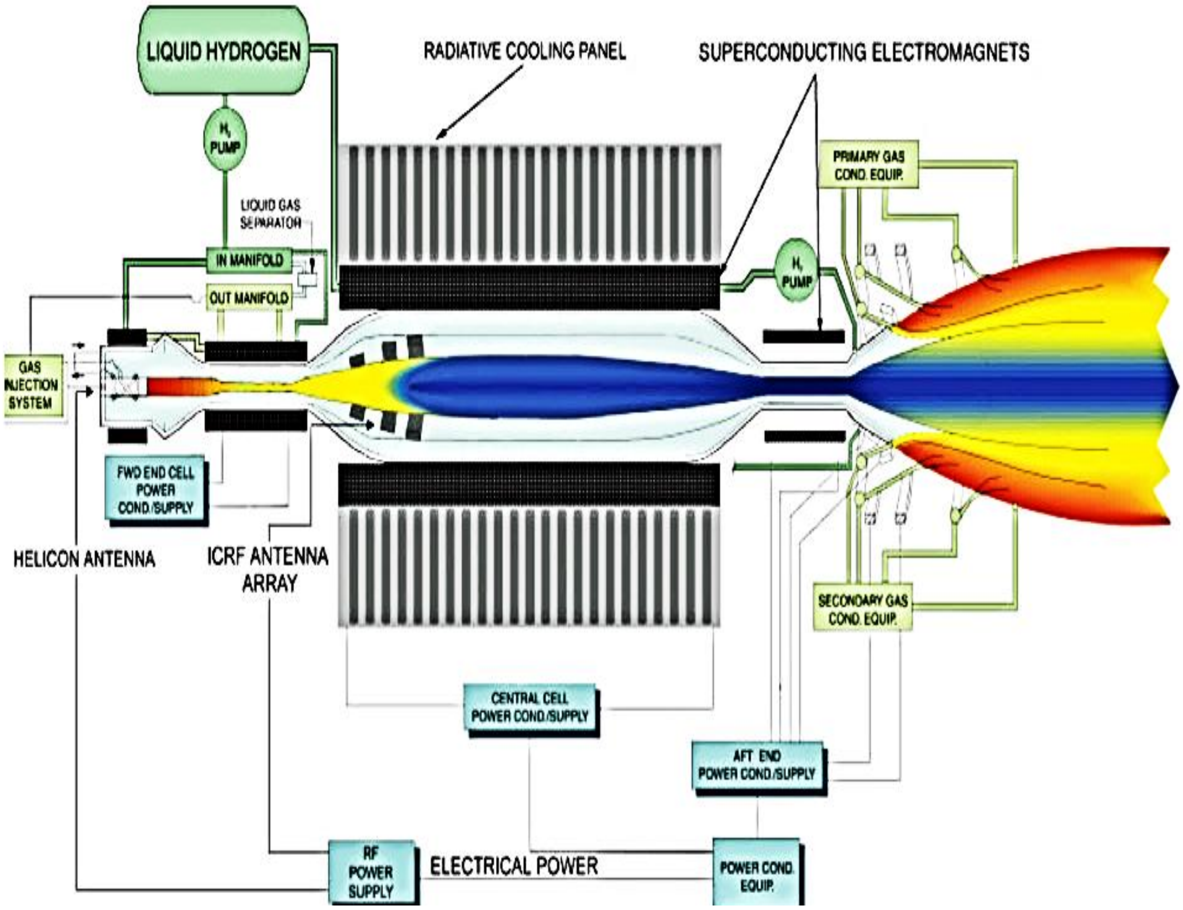
stage magnetic nozzle, which converts the thermal energy of the fluid into directed flow. It also protects the nozzle walls, insuring efficient plasma detachment from the magnetic fields. Important system characteristics include an electrodeless design in a multi-stage architecture, optimizing overall system function. A hybrid magnetic nozzle with a 'plasma afterburner' provides high thrust capabilities. While the present VASIMR system is driven by an external power source, it can serve as a precursor to an eventual fusion rocket, paving the way for future technologies. Such development is going to revolutionize space travel, as we know it today.



(Fig 1: The VASIMR concept; Source: AIAA 2000-3756 The Physics and Engineering of the VASIMR Engine)

2.1. Basic Physics & Working Principle

The Lorentz force on the ions in a magnetized plasma forces them to follow circular paths defined by a quantity known as the Larmor radius i.e. radius of the circular motion of a charged particle in the presence of a uniform magnetic field. Associated with this radius, the frequency of particle rotation about the lines of induction is known as the cyclotron frequency [9]. The frequency of the Radio Frequency (RF) power matches that of the gyrating motion of the ions. It deposits the wave energy in motion perpendicular to the magnetic field. This motion must be redirected into axial momentum in order to generate thrust. [9, 10]. As long as the expansion is small over scale lengths comparable to the ion's Larmor radius, the ions convert their perpendicular motion into axial motion through the adiabatic conservation of the magnetic moment. The total energy increases due to the RF power added to the ions, but the division of energy between the perpendicular and axial directions changes as the ions move down the magnetic gradient [11].

The topology of magnetic fields dictates that the lines of force must close onto themselves. If the ions were to cling tightly to them, no thrust would be possible. Fortunately, the ions can only follow the field lines as long as these do not curve sharply, a principle known as adiabaticity [12]. Moreover, as they move away from the magnets, the strength of the field decreases rapidly and so does its force. The detachment of the plume from the field takes place mainly due to the loss of adiabaticity and the rapid increase of the local pressure β, which is defined as the local ratio of the plasma pressure to the magnetic pressure [11, 12].

The motion of the plasma electrons should be similar to that of the ions. The ions carry the bulk of the momentum; however, the electrons tend to cling more tightly to the magnetic field and their detachment may affect the dynamics of the plume or even induce a local distortion of the magnetic field [13]. Recent theoretical calculations have considered the detachment problem by looking at the transition from sub-alfvenic to super-alfvenic flow where alfvenic is a type of magneto-hydrodynamic wave in which ions oscillate in response to a restoring force provided by an effective tension on the magnetic field lines. This perspective is akin to the subsonic to supersonic transition in a C-D nozzle. Laboratory experiments and further theoretical studies are underway to further refine VASIMR's physics models.

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Under certain operational conditions involving low exhaust velocity, a hypersonic neutral gas blanket is being considered downstream of the nozzle to enhance plasma detachment while producing an afterburner effect [14]. The implementation of Common Protocol Template (CPT) in the VASIMR engine is done through a number of mechanisms. The most important of these is the selective partitioning of the RF power for plasma production (in the helicon injector) *vs* ion heating (in the central cell). Helicon plasma devices are capable of producing high density plasma close to fully ionised species. For high thrust operation, a greater fraction of the total RF power is vectored to the helicon injector, making a rich denser plasma. For high I_{sp} operation, bulk RF power is routed to the ion heating central cell. This creates a higher I_{sp} flow, with associated reductions in thrust. In either case, it is important to achieve a high level of ionization and to minimize the power losses at the helicon source. The total RF input is constant and is kept maximum for efficient utilization of the electrical power source.
Another important area of engineering involves the miniaturization of the RF power generation and delivery system (amplifiers, transmission lines and antennas.) Presently, solid-state technology is being used to produce voltage generation systems capable of generating up to 50kW. The transition to a high power VASIMR will require the use of vacuum tube technology. Laboratory tetrode tubes at power levels of 100-200kW have been available for many years. However, these devices have not been manufactured to operate in space. Considerable engineering research remains to be done to explore the application of tetrode tubes for utilization in generation of plasma.

2.2. Components

The main building blocks of the VASIMR concept are as follows:

- The helicon plasma source
- The ion cyclotron-resonance heating (ICRH) section
- The magnetic nozzle

2.2.1. Helicon Plasma

Helicon plasma source includes three major components which are Radio Frequency (RF)-field structure, power balance, and particle balance. The source operation requires excitation of plasma for power deposition. Therefore, the RF-field structure is determined by the excited plasma. Due to the RF antenna frequency, the excited plasma stems from electron response without involvement of the ions. Through the elastic electron-neutral and electron-ion collisions, the RF-power supplied by the antenna is absorbed by the electrons. By exciting the background gas in inelastic collisions, the electrons lose their energy. This energy being lost from the plasma is via radiation. The fast electrons with energies above the ionization threshold produces plasma. The plasma production does not aff ect the power balance because the excitation rate is much faster than the ionization rate. The recombination rate is negligible when compared to the ionization rate because the degree of ionization is small.

2.2.2. Ion Cyclotron Resonance Heating (Icrh) Section

The Ion Cyclotron Resonance Heating (ICRH) has two distinct features in VASIMR. First, each ion passes the resonance only once, therefore gaining an energy that is much greater than its initial energy. Second, the ion motion is collisionless, i.e. the energy gain is limited not by collisions but by the time the ion spends at the resonance while moving along the field lines. Hence the ion’s final energy, as well as the RF-power absorption efficiency, depends on the incident-flow velocity.

2.2.3. Magnetic Nozzle

In order to shape the outgoing plasma flow which in turn creates thrust to propel the rocket, VASIMR uses a magnetic nozzle. The ions pushing against the vacuum magnetic field on their way out of the nozzle generate thrust. When the energy density of ions exceeds the energy density of the guiding magnetic field, the plasma flow detaches from the nozzle. At this instant the magnetic field is no longer strong enough to control the flow. There are two stages in producing the thrust i.e. accelerating the incoming plasma flow and detaching the flow from the rocket.

III. GRID ION THRUSTERS

Richard Welle performed a theoretical assessment of the performance of an ion engine fed with Xe, Kr, and Ar. Investigations showed that with lighter gases, ionization cost went up while utilization efficiencies went down which was lesser than 10%. This meant that for an orbital transfer mission from LEO to GEO (ΔV = 6000 m/s) with I_{sp} = 2000s, a Kr propelled mission will take 16% longer duration than a Xe propelled mission and an Ar propelled mission will coparatively require 63% more time. For a commercial satellite, this delay could result in substantial non-operational losses but at the same time cheaper propellant cost would provide a considerable costs savings. A trade-off is obviously required but from the viewpoint of scientific mission, the low cost and the high I_{sp} can really let Kr Ion propulsion be an affordable solution for long range missions. NASA’s interest in this topic has been clear since before 2000, ranging from the interest in developing a high I_{sp} (>10000 s), 10-30kW Kr Ion engine in support to the Interstellar Probe project to subsequent studies about EP concept for space explorations [15, 16]. The work of *Gilland et al.* provided an interesting comparison between the efficiencies of a representative ion thruster fed with different propellants. Figure 2 represents the

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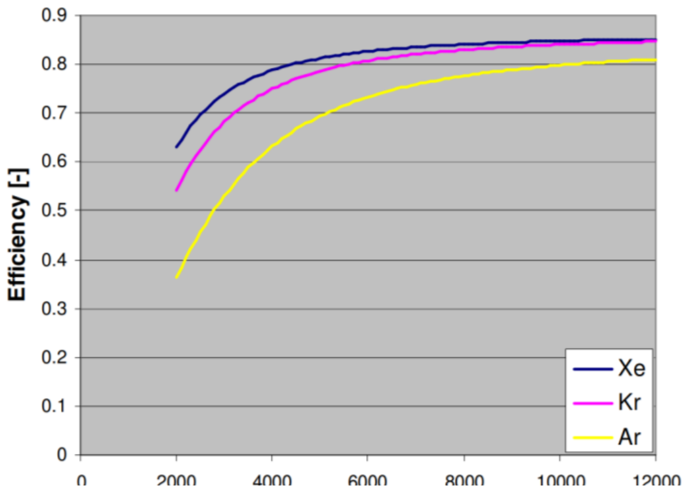
observed data for an application like previously mentioned interstellar ion engine and for the required I_{sp}, the difference in efficiency between Xe and Kr can be considered negligible.

3.1. COMPONENTS

Grid Ion thrusters consist of five units:

- Power processing unit (PPU)
- Power source
- Propellant management system (PMS)
- Control computer
- Ion thruster



(*Fig 2: Representative ion thruster efficiency, η, for Xenon (Xe), Krypton (Kr), and Argon (Ar).*; *Source; Xe Ion Propulsion for Orbit Transfer by V. K. Rawlins, M. J. Patterson, and R. P. Gruber*)

Any source of electrical power such as solar or nuclear power is the power source. A solar electric propulsion system (SEP) uses solar cells in order to generate power. PPU converts generated electric power by the power source by supplying the power required for each component of the ion thruster, such as the positive and negative grids, discharge chamber and the hollow cathodes. Propellant flow from the propellant tank is controlled by the PMS. The design of PMS is highly sophisticated hence it does not require moving parts. Xenon propellant enters from the propellant tank. A hollow cathode starts emitting electrons which impact the Xe atoms, thus losing an electron and creating positive Xe ions. Through the holes in positive grid, positive ions are pushed due to gas pressure. Due to the electric field between the positive and negative grid, it starts accelerating the ions such that the ion beam is exhausted out through the nozzle. Ion thrusters are capable of propelling spacecraft up to 90km/s. They can be compared to the conventional propulsion system which are used in Space Shuttle which are capable of a top speed of only about 8km/s. The trade-off for high speed is due to the low thrust applied to the spacecraft. The drawback is that the ion thruster must be operated for a long time in order for the spacecraft to reach its top speeds.

IV. HALL EFFECT THRUSTERS

Linnell et al. focused his attention on Hall thrusters following the interest of the EP community. Krypton has relatively large I_{sp} as compared to Xenon. Linnell studied and addressed the reasons for the Kr efficiency gap separating the Hall thruster anode efficiency into four separate terms: charge utilization, propellant utilization, current utilization and voltage utilization.

Anode efficiency is a measurement of the effectiveness of axially directed ion kinetic energy in electron volts as compared to the thruster discharge voltage [17]. Results showed that the propellant utilization and beam divergence appear to be the dominant factors responsible for the efficiency gap. With respect to Kr, Xe propellant utilization is about 5 to 10% better and beam divergence efficiency is 8% higher. This leads to a total anode efficiency of 5 to 15% higher than Xenon. At the same time, Linnell showed that this gap can be reduced by increasing the anode flow rate as it produces many positive effect such as the improvement of Kr's anode efficiency by almost 8%. The increment in the ionization rate lead to increase in the propellant utilization which increased current utilization efficiency and beam divergence, allowing ions to start accelerating earlier in the acceleration zone, thus reducing the divergence. A successive paper from *Linnell et al.* demonstrated that Kr acceleration zone is actually longer than that of Xenon [18]. As a confirmation of these conclusions, study of *Garrigues et al.* showed an analogue 15% difference between experimental efficiency with an SPT-100 (*Stationary Plasma Thruster*) fed with Xenon and Krypton. Another important aspect is covered by *Kieckhafer et al.*, demonstrating that erosion rate due to sputtering is lower for Kr than other propellants at very high energy levels. Other than confirming that, SPT-100 provided highest I_{sp} for a given acceleration voltage and it also minimized the ionization costs at high exhaust energy level [19, 20].

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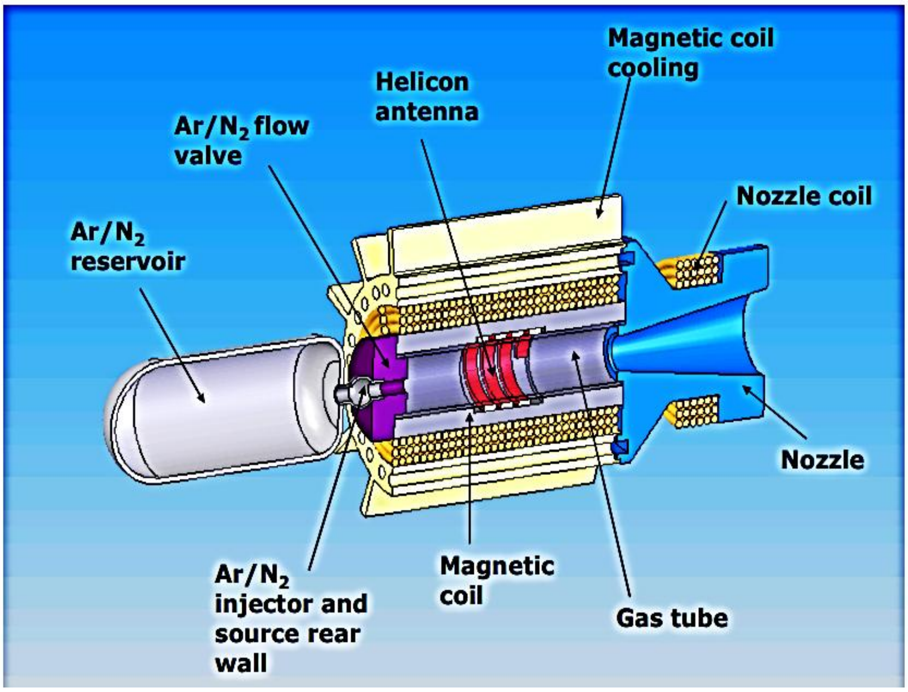
V. HELICON THRUSTER

A helicon plasma thruster is based on a helicon plasma source specifically designed to provide high plasma exhaust velocity. A helicon thruster is composed by few physical elements [21, 22]:

- A feeding system, able to provide the required neutral gas flow
- A glass tube, where the plasma is generated
- An antenna, having helix shape wrapping the glass tube
- A system of coils or permanent magnets, placed coaxial with the glass tube to yield a magnetic field able to confine the plasma and to increase power deposition of the antenna
- An additional system of coils, for the magnetic nozzle

The thrust is obtained by exhausting the plasma into vacuum and driving it through a suitable magnetic field whose gradient is optimized to increase plasma velocity. Plasma acceleration appears to be due to two main mechanisms [23, 24]:

(i) plasma expansion into a magnetic nozzle
(ii) plasma acceleration through a potential drop which, under some circumstances, builds up on the exhaust zone.



(*Fig3: Scheme of HPH.COM helicon thruster; Source: D.J. Santeler et al., Vacuum Technology and Space Simulation, NASA SP-105*)

HPH.COM is a double mode helicon based plasma thruster. Its first mode is a high efficiency low thrust mode in which the thruster operates in pure plasma, the second mode (COMBI) is a high-thrust, low-efficiency mode on which plasma is used to heat or decompose a secondary propellant.

The combined system allows to obtain a flexible system that can achieve several propulsion tasks, permitting a low thrust at high I_{sp} and a high thrust at low I_{sp}. [25] In most of the experiments, under many different conditions, the plasma exhaust velocity has been in the promising range of 10-20km/s. However, a simple prediction of the I_{sp} is still difficult since it is influenced by different factors, such as;

(i) Amount of wave deposited energy that is converted into available internal energy
(ii) Details of the electron distribution function
(iii) Supersonic expansion of plasma in the magnetic nozzle
(iv) Ion magnetization
(v) Magnetic detachment mechanism

Thus, both the development of theoretical models and simulation codes, beyond the state of the art, is considered fundamental to design and build a competitive helicon plasma thruster [26, 27].

In consequence of the large use of Xe as propellant for EP thrusters, the pumping systems of the existing vacuum test facilities are mainly designed to pump down this noble gas. Cryopump, which is a vacuum pump that traps gases and vapours by condensing them on a cold surface is usually employed in order to guarantee a clean and high vacuum level [28]. Commercial cryopumps operates on the principle of the condensation of the working gases. The vapour pressure-temperature relationship of the different gases determines the surface temperature of the cryopanels required to maintain a suitable low pressure in the vacuum chamber. Light gases like H_2 and Helium (He), as well as Neon (Ne) are

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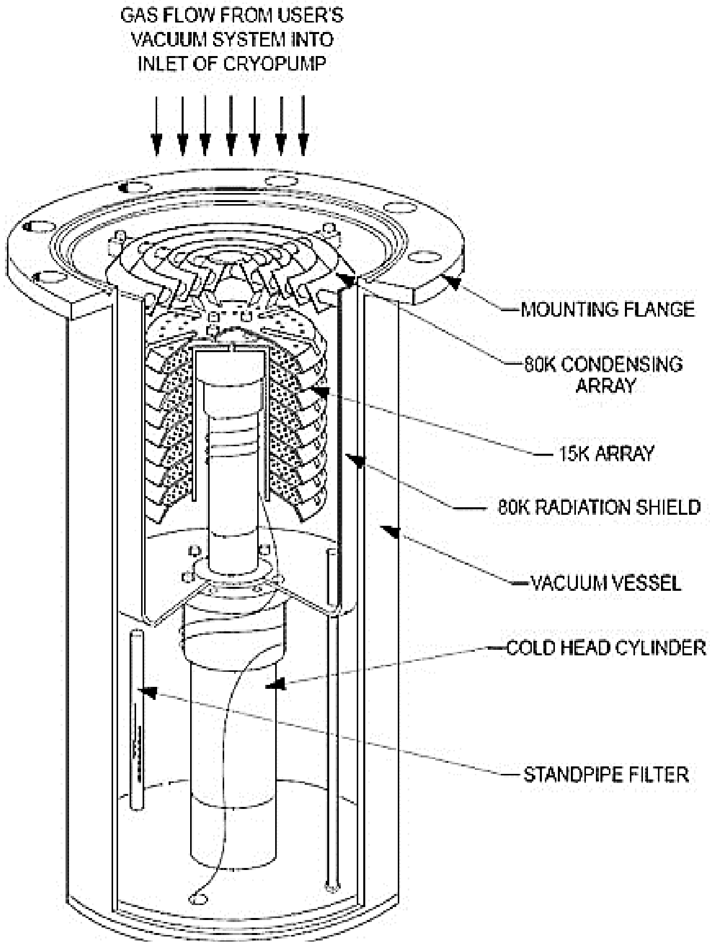
practically impossible to keep in a cryocondensate status. This is the reason why special activated charcoals are employed in commercial cryopumps in order to cryoabsorb those components and guarantee an adequate pumping capability over the full spectrum of the environment gases [29]. The EP test facilities presently engaged in industrial development activities usually operate special cryopumping systems that are efficiently designed to pump Xe at ultimate pressures to $1x10^{-7}$ mbar. For this purpose, cryopanels temperature is set in a range of 45-50K so as the Xe vapour pressure is better than $1x10^{-8}$ mbar. At that level of cryopanel temperature, the vapour pressure of Kr stays in a range of 10^{-4} to10^{-7} mbar. That value is obviously inadequate to guarantee a realistic vacuum environment. Therefore, working with gases different from Xe will require a redesign and upgrade of the existing cryopumping systems. Smaller cryopanels cooled by single-stage cryo refrigerators will provide the lower temperature required to pump efficiently the alternative propellants. However, this reduction in size of the cryopanels will have an impact on the overall pumping speed of the facility and therefore on the dynamic vacuum performance [30].



(*Fig 4: Cutaway view of a typical Cryo-T0rr cryogenic pump*; *Source: Cryo-Torr High Vacuum Pump Installation, Operation and Maintenance Instructions, 8040613, Rev. (4/2001)*)

VI. CONCLUSIONS

In order to evaluate the possibility of reduction in the dependency of Xe, its high cost and its non-predictable fluctuations in ion generation, an assessment is made using existing consolidated EP technologies with other noble gases. Ion thrusters demonstrated an increase in I_{sp} and an increment in transfer time for standard commercial missions. For scientific space exploration missions, the advantage of the higher I_{sp} as well as the possibility to reduce the efficiency gap to less than 1% will allow Kr propulsion to be considered as a valuable candidate for a trade-off. Regarding commercial missions, which typically require lower I_{sp} levels between 1500s and 3000s, Hall thrusters demonstrated an efficiency gap of about 15% that may be reduced with better understanding of the Kr ion dynamics inside the thruster while increasing the anode flow rate. Helicon thruster (VASIMR), although still under development, looks very suitable to operate with different propellant and their mixture thanks to their intrinsic low sensitivity to erosion and high versatility to many different operational conditions. Therefore, as a next step, future scope of research is to perform a study on spacecraft and mission levels to investigate the trade-off between cost reductions on the propellant, reductions in thrust and/or increase in power demand of the EP systems.

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