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A review of research in low earth orbit propellant collection

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ABSTRACT

This comprehensive review examines the efforts of previous researchers to develop concepts for propellant-collecting spacecraft, estimate the performance of these systems, and understand the physics involved. Rocket propulsion requires the spacecraft to expend two fundamental quantities: energy and propellant mass. A growing number of spacecraft collect the energy they need to execute propulsive maneuvers in-situ with solar panels. In contrast, every spacecraft using rocket propulsion has carried all of the propellant mass needed for the mission from the ground, which limits the range and mission capabilities. Numerous researchers have explored the concept of collecting propellant mass while in space. These concepts have varied in scale and complexity from chemical ramjets to fusion-driven interstellar vessels. Research into propellant-collecting concepts occurred in distinct eras. During the Cold War, concepts tended to be large, complex, and nuclear powered. After the Cold War, concepts transitioned to solar power sources and more effort has been devoted to detailed analysis of specific components of the propellant-collecting architecture. By detailing the major contributions and limitations of previous work, this review concisely presents the state-of-the-art and outlines five areas for continued research. These areas include air-compatible cathode technology, techniques to improve propellant utilization on atmospheric species, in-space compressor and liquefaction technology, improved hypersonic and hyperthermal free molecular flow inlet designs, and improved understanding of how design parameters affect system performance.

Contents

1. Introduction

Many spacecraft today rely on rocket propulsion to conduct maneuvers while in space. While other mechanisms exist to propel spacecraft, rocket propulsion remains the most common and

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technically mature option. Successful rocket propulsion requires the expenditure of both energy and propellant mass. For chemical propulsion options, the necessary energy and mass are stored together in the form of chemical propellant. While chemical propulsion remains a critical component of any space mission, many spacecraft are transitioning to electric propulsion to realize savings in propellant mass and improved specific impulse (I_{sp}). Electric propulsion options typically make use of an inert propellant such as xenon and inject electrical energy which is stored separately to generate thrust. Because propellant mass and energy are no longer coupled chemically, electric propulsion architectures can make use of in-situ power collection via solar photovoltaics rather than carry the energy from mission start. While spacecraft can now collect the energy they need for propulsion on-orbit, they still must carry all of the necessary propellant mass from the ground. No capability exists today for collecting propellant in-situ.

Propellant limitations have long hindered our exploration and exploitation of space by driving up costs and limiting spacecraft capabilities. These costs and limitations can potentially be mitigated by collecting propellant mass in space rather than carrying the full mission requirement at launch. The closest potential source of propellant mass is Earth's upper atmosphere, and is available to spacecraft in low Earth orbit (LEO). Developing the capability to collect ambient upper atmospheric gas and use it for propulsion may allow spacecraft to sustained access lower altitudes and enable the construction of an on-orbit refueling infrastructure.

This work reviews the efforts of previous researchers to study and develop technology to collect propellant in LEO. The first efforts to develop this capability occurred in the late 1950s and 1960s, when it was seen as a potential approach to reducing the cost of lunar missions. These early efforts largely focused on nuclear powered architectures which potentially offered significant advantages over nuclear rocket technology. The wind-down of the Apollo program in the late 1960s and early 1970s led to the first era of concepts being largely obscured in literature until after the end of the Cold War. Renewed focus in recent years has led to international efforts to develop components necessary for a propellant collection architecture.

Declines and uncertainty in funding in the aerospace industry today motivate researchers to identify and develop alternative approaches to spaceflight which may present economic benefits [1,2]. This motivation, along with the recent success of the low-orbiting Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission, has driven increased interest in propellant collection technology. New efforts have begun to address specific challenges of accomplishing sustainable propellant collection on-orbit. This comprehensive review presents the current state-of-the-art of propellant collection and air-breathing technologies, and reveals avenues for continued research.

The manuscript is organized into five distinct sections. The following section introduces the fundamentals of sustainable propellant collection and details some basic design requirements and approaches to acheive them. Section 3 reviews the seminal work of Demetriades and others during the Cold War from a historical perspective. More recent studies are presented in Section 4, which demonstrates the renewed interest in propellant collection technology with a particular focus on the design of thrusters to attain high performance on ambient propellants. The final section proposes avenues for continued research given the results of the research conducted thus far.

2. Propellant collection fundamentals

In this section we introduce the general concept of propellant collection in LEO. A successful and sustainable propellant-collecting design must meet two basic system requirements. It must have sufficient thrust performance to counteract aerodynamic drag, and it must generate sufficient power to operate the propellant-collecting system. Numerous parameters contribute to determining the drag and power requirements of a propellant-collecting design. Eq. (1) details the relationship of the basic parameters in determining the drag:

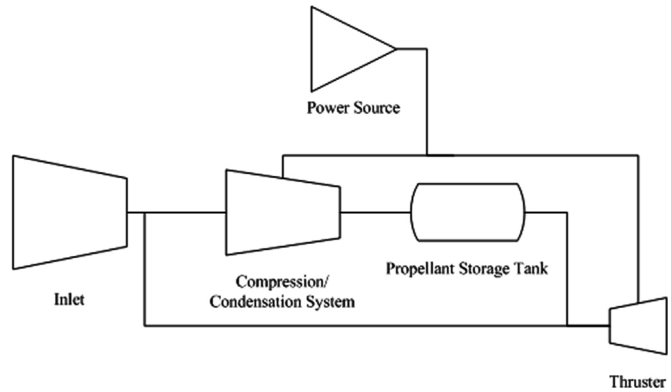

Fig. 1. Propellant collection system diagram.

$$D = \frac{1}{2} C_D \rho A_{s/c} v^2 \tag{1}$$

where C_D is the drag coefficient, ρ is the ambient density, $A_{s/c}$ is the frontal area of the spacecraft, and v is the spacecraft velocity. The drag coefficient and spacecraft frontal area are functions of the spacecraft size and geometry. The drag coefficient, density, and velocity are all functions of the orbit parameters. Altitude is especially important for its significant effect on the magnitude of the density and drag coefficient.

Fig. 1 is a system diagram of for a generic propellant collection system. An inlet accepts the oncoming flow into the vehicle and into the propellant-collecting device. The design of the inlet contributes to the drag coefficient and determines to amount of the oncoming flow which is actually accepted into the system. Concepts diverge with respect to the handling of the flow inside the device. In general, three distinct approaches are found in proposed designs. One option is to allow all of the flow to simply pass through to a thruster for acceleration, similar to a ramjet. Another option is to divert a portion of the flow and capture it for storage while minimizing the interference with the remainder of the flow. A final option is to stop all of the flow within the vehicle, although not all of these designs store propellant. Clearly, a number of options exist for handling the collected atmospheric gases. Regardless of this, all designs converge again at the thruster.

To counteract the drag force experienced as a result of collection, all designs must include a thruster which accelerates at least a portion of the collected flow and exhausts it from the vehicle. Nearly all designs select an electric thruster for its superior I_{sp} which is necessary to sustainably overcome the drag force with the available collected flow. The power requirement to deliver the necessary thrust performance is often times very large, on the order of kilowatts per square meter of frontal area or more depending on altitude. Thus, the efficiency of the thruster plays a major role in any propellant-collecting design by amplifying the ideal power requirement which the power source must meet.

3. Cold War era efforts

This section details the seminal work in propellant collection from the initial publication in 1959 to the final Cold War era publication in 1985. The proposals in this era represent many of the most extreme architectures in propellant collection literature. This section is organized chronologically.

3.1. Seminal work

Sterge Demetriades was the first researcher to propose collection of air by an orbiting spacecraft in his seminal 1959 paper [3]. He proposed a Propulsive Fluid Accumulator (PROFAC) device that would collect, liquefy, and store incident air for use as propellant. PROFAC would collect air on-orbit rather than carrying its required propellant from the ground. In this way, the PROFAC system would dramatically reduce launch mass needed for a mission. Demetriades envisioned this device as a direct competitor to the chemical and nuclear propulsion options which were being explored by others at the time for an eventual moon mission.

In PROFAC's original envisioning, an 11-ton vehicle would collect approximately 400 kg of air each day from a 10 m^2 collector at an orbital altitude of 100 km. To counteract drag, Demetriades proposed a magnetohydrodynamic (MHD) thruster powered via a nuclear reactor with a total electrical output of 6 MW. His 1959 work briefly mentions solar power. It asserts, without proof, that solar power is viable at altitudes above 150 km while the PROFAC concept is only economically feasible below 135 km. Without any details, it is not possible to determine how Demetriades arrived at this conclusion.

Demetriades cites earlier work he presented with Kretschmer in 1958 as the origination for the PROFAC concept [4]. The 1958 work involved utilizing the energy stored in the form of dissociated oxygen in the upper atmosphere as a power source for propulsion of exospheric aircraft. As an aircraft, this work was intended to power vehicles operating at sub-orbital velocities.

A final paper by Demetriades in 1962 lays out some concepts of operations (CONOPS), but does not discuss them in detail [5]. Demetriades performs the first analysis of the thermodynamics of cryopumping in a modified Brayton cycle to collect propellant in this work. However, Demetriades does not suggest a mechanism to move cryopumped air from the cryopumping surface into storage. He also attempts to optimize the PROFAC concept for minimum energy expended per unit mass of stored air. He finds that the minimum rests at roughly the design point where half of the collected air is used for propulsion while the other half is stored.

3.2. Growth of the community and alternative approaches

In 1960, only a year after Demetriades' seminal work; Bussard proposed scooping hydrogen from the interstellar medium [6]. The vehicle would release energy from the collected hydrogen via fusion and accelerate the reaction products to generate thrust. This concept has been made famous in Science Fiction works as the Bussard Ramjet [7] and remains the most extreme “air” breathing concept in scientific literature. While nearly all documented air-breathing concepts developed in the Cold War era considered nuclear power sources [3,5,6,8–14], no other concept proposed performing nuclear reactions directly with the collected matter.

Berner and Camac worked concurrently with Demetriades to develop a detailed analysis of an air-breathing concept for collecting propellant for other vehicles [14]. Their work was published to the broader scientific community in 1961 [8]. Their work includes a basic analysis of all of the major components of a propellant-collecting spacecraft and makes a number of notable contributions. This is the first work to seriously consider and analyze solar power in addition to nuclear power. It is also the first work to propose and analyze a chemical absorption process for collecting incoming air as opposed to a compressing inlet. The first detailed analysis of the incident heat flux on the spacecraft as a result of accelerating the oncoming flow is also included in this work.

Perhaps most importantly, Berner and Camac establish the “weight-doubling time” parameter. This is the amount of time required for the spacecraft to store a surplus of propellant equal to its dry mass. They go on to use this parameter along with the launch vehicle and spacecraft costs to estimate the vehicle lifetime necessary to recover these investments (economic breakeven time) for a propellant-collecting concept. Using this methodology along with data available to the community in 1961, Berner and Camac determine that the economic breakeven time for a propellant-collecting vehicle is less than a year for both nuclear powered and solar powered craft. By establishing the weight-doubling time and using it to arrive at the economic breakeven time, they show that elliptical orbits will take longer to break even economically.

Berner and Camac's work relies on primitive atmospheric data which limits its accuracy. Additionally, they fail to factor eclipsing of the sun by the Earth into their analysis for solar powered options. Berner and Camac also fail to consider variation in atmospheric density as a result of solar and geomagnetic activity. These limitations to the Berner and Camac work cast doubt on the validity of their findings. Berner and Camac themselves conclude that limitations in propulsion technology at the time of publishing are the primary obstacle to feasibility. With 50 years of development in electric propulsion technology since then, this may no longer be the case.

In 1961, Zukerman and Kretshmer considered utilizing energy released from atomic oxygen recombination during compression of incoming air to provide all of the input energy into the flow for acceleration as part of a ramjet system [15]. This work determined that there is insufficient energy from atomic oxygen recombination to enable sufficient thrust to counteract the drag force. However, Zukerman and Kretshmer note that the addition of a fuel into the flow can supply enough energy to overcome drag. This work allows us to exclude chemical propulsion as a sustainable option for propellant-collecting space vehicles.

Reichel et al. expanded on Berner and Camac's work with a paper in 1962 studying the possibility of a nuclear-powered, air-scooping electric propulsion system [9]. Their proposed concept would operate just on the edge of space at 110 km with a 5-MW nuclear power source. At this altitude their vehicle would be able to collect nearly 60 kg of air per hour. Reichel conducted an analysis of the compression and liquefaction power requirements for his design, and in 1978 Reichel resurrected his proposed concept under the name AIRScoop as a means to deliver the components needed for a 475-GW space solar power plant [10].

3.3. International and post-apollo efforts

Researchers in the Soviet Union also looked at air-breathing concepts in the 1960s. Most of this work is in Russian, but a summary publication by Dolgich in 1969 was translated for researchers in the West. The summary publication details 10 other papers published in the Soviet Union with a specific focus on the power requirements for sustainable air-breathing propulsion. Most notably, this work asserts that propellant collection can enable a spacecraft to accommodate as much as 2.5 times the payload as a spacecraft that does not use propellant collection [13]. However, the referenced paper which presumably supports this assertion is not available in English.

In 1975 Cann proposed the Space Electric Ramjet (SERJ) as a form of air-breathing space propulsion [16]. SERJ is effectively an electromagnetic engine with an inlet similar to Demetriades' MHD thruster which ionizes and accelerates the flow through the engine. In a notable shift from previous efforts, Cann studies using a solar power source rather than a nuclear reactor. While he is not the first to mention solar power as an option, he is the first to consider it exclusively. As part of his analysis of the concept, he determines the minimum altitude at which solar power can supply sufficient power to overcome drag. His calculations indicate a minimum altitude of approximately 160 km when the solar panels are parallel to the flow. Unfortunately, Cann's analysis suffers from two deficiencies. First, Cann does not seem to consider the effect of eclipse on his power estimate. In order to maintain orbit the ramjet would have to counteract drag for the entire orbit, not solely when in direct sunlight. Second, his assumptions of solar cell efficiency are outdated when compared with presently available technology. Both of these deficiencies limit the applicability of the findings of the SERJ study when viewed from a modern context.

Minovitch took another look at air-breathing spacecraft concepts in the 1970s and 1980s, culminating in two conference papers in 1983 and 1985. His work refers to such technology as “self-refueling rockets” rather than “air-breathing spacecraft”, which effectively communicates the difference in his approach to the concept. In his 1983 paper, Minovitch proposed a system in which solar power generated at a single ground station is transmitted via microwave to orbiting collector vehicles at a total radiated power exceeding 10 GW [11]. For continuous operation, he proposed orbiting an additional “power relay spacecraft” which would effectively act as a reflector for the ground station. This is a completely original approach to addressing the power requirements of an air-breathing spacecraft. It is also the most complex approach, relying on multiple ground and space assets for operation. In his 1983 paper, he proposed a collector craft with a dry mass of 600,000 kg. This is notable because it is roughly five times the payload capacity of a Saturn V, and 150,000 kg more than the International Space Station [17].

The 1985 paper replaces the microwave power system with a nuclear reactor, but is similarly astronomical in its scale to the 1983 concept [12]. Minovitch proposes a 700,000 kg dry mass craft with a 105,000 kg nuclear reactor generating 3500 MW of power. He justifies this by making the argument that because the propellant is free the spacecraft mass no longer matters. The flaw in this argument is that such a craft still needs to be manufactured, assembled, and launched. This would require an extremely high up-front investment. Despite the flaws in the economics of the concept, Minovitch succeeds in having vision for the potential of the technology. Minovitch proposes using such a vehicle as an interplanetary transport whereby the vehicle would expend propellant when departing a planet and collect new propellant or “refuel” during an aerocapture maneuver upon arrival. This is the first direct mention of utilizing this technology around other planets. Minovitch would be the final researcher to consider air-breathing concepts for a decade.

Demetriades' proposal to collect ambient gas on-orbit for use as propellant dates back the late 1950s at a time when the United States was unquestionably behind the Soviet Union in space technology. Both superpowers actively sought the high ground space, and later the moon presented from a strategic perspective. Still in its infancy, the American space community developed some of the most extreme, extravagant, and extraordinary concepts based on the most optimistic view of the future the community has ever had. Among these ideas was propellant collection, which was proposed as a means to provide access to propellant while in space as an option to reduce the cost of transporting payload to the moon. More future-oriented researchers considered the applicability of propellant collection for developing orbital power systems and even interstellar travel. Soviet researchers also saw the potential advantages of propellant collection and studied the topic independently. Ultimately however, massive reductions in funding at the end of the Apollo era as a result of the United States “winning” the space race as well as a perceived inevitability of nuclear rocketry led to the abandonment of propellant collection until after the Cold War. Table 1 summarizes the efforts presented from this exciting era.

4. Contemporary efforts

The conclusion of the Cold War largely marked the end of concepts which rely on massive nuclear-powered vehicles and a break in research of air-breathing concepts. The idea was slowly and quietly revived in a series of Master's theses from the Massachusetts Institute of Technology spanning nearly a decade [18–20]. Renewed interest also brought new focus. Much of the work performed since the 1990s concentrates on a single component of propellant-collection system rather than a full system study. This focus has led to developments in air-breathing electric propulsion and inlet analysis which invalidates the simplistic assumptions made by researchers in the Cold War era. Current efforts are proceeding across the globe with diverse objectives.

While the previous section was organized chronologically, this section is organized on a component-by-component basis. Section 4.1 details the efforts of American, Japanese, and European researchers to develop and adapt gridded ion thruster technology for operation on ambient gases. Section 4.2 focuses on the use of Hall effect thrusters to generate thrust from the ambient gases. Section 4.3 reviews the efforts to develop propellant collection concepts for use around other planets for a variety of unique objectives. The final section presents the efforts of various researchers to develop and quantify the performance of inlet designs for capturing of ambient gas, which are crucial to the operation of a propellant collection system.

4.1. Gridded thrusters

The first documented analysis of an air-breathing spacecraft concept after Minovitch is the 1995 Master's thesis of Conley [18]. Conley's thesis work is the first practical study of utilizing a gridded ion engine in an air-breathing form to counteract atmospheric drag experienced by a spacecraft. This study is unique in that it does not attempt to make use of the gas which is directly

Table 1
Summary of Cold War era propellant collection concepts.

Researcher	Concept	Mission	Power source	Thruster	Inlet	Propellant stored
Demetriades [3]	PROFAC	Lunar transport	Nuclear	MHD	Aerodynamic	Yes
Bussard [6]	Bussard ramjet	Interstellar travel	Fusion	Fusion- theoretical	Electrodynamic	No
Berner and Camac [8]	Air scooping vehicle	Resource collection	Nuclear/Solar	MHD	Chemisorption	Yes
Zukerman and Kretschmer [15]	Atomic oxygen ramjet	Satellite operations	Chemical	Chemical	Aerodynamic	No
Reichel [9]	AIRScoop	Orbital construction	Nuclear	Electric thruster	Aerodynamic	Yes
Cann [16]	SERJ	Satellite operations	Solar	MHD	Aerodynamic	No
Minovitch [11]	Self-refueling space vehicle	Interplanetary transport	Nuclear/Microwave	Various	Aerodynamic	Yes

impinging with the leading edge of the main vehicle, but rather entrains the wake of the main vehicle in a large gridded ion engine downstream. While this work gives a detailed treatment of the plasma physics inside the device, it makes several assumptions which negatively impact the quality of the results. Most important among these is the neglect of drag on the ion engine component even though it accounts for over 99.8% of the frontal area of the spacecraft.

Dressler took a slightly different approach to Conley's LEO ion thruster concept with the Ambient Atmosphere Ion Thruster (AAIT) in 2006 [21]. This device is among the simplest air-breathing thrusters ever proposed. In his original conference paper the AAIT is simply two grids electrically biased relative to one another and placed perpendicular to the flow. The AAIT concept proposed exploiting the ambient ion populations present in LEO as propellant by electrostatically accelerating those ions which pass through the AAIT to produce thrust. The original concept has no method of producing its own ions. Dressler's analysis indicates an AAIT would have to be several times the size of the spacecraft in order to counteract aerodynamic drag in circular orbit altitudes ranging from 300–500 km. This is in agreement with Conley's analysis however it is based on two major simplifying assumptions which limit its accuracy:

- Dressler assumes a constant drag coefficient of 2 with the justification that “this is a free molecular flow regime”. Numerous sources dating back to 1959 show that the drag coefficient exceeds 2 and in fact varies with orbital altitude [22–26].
- Dressler's approach cannot be realized given his original design. The incoming ion population has a potential equal to the local space potential, as does the spacecraft itself. Biasing the two grids relative to one another does not provide a net acceleration because the plasma environment around the grids is at the space potential and no neutralization occurs. Instead, King states that the incoming ion population must be raised in potential by some means in order to lead to net acceleration [27].

King's analysis improves upon Dressler's original design analysis with the help of the Atmospheric Electric Propulsion Mission Performance Tool (AEPMPT) [27]. The AEPMPT allowed King to parametrically search for orbit and AAIT design configurations which produce a thrust-to-drag (T/D) ratio equal to or greater than one. He assumed a constant drag coefficient of 2.4, which lies within the results of previous analyses in contrast to Dressler's assumed drag coefficient [25,26]. King also accounted for additional ionization of the incoming flow required to raise the ion potential above the space potential, though he does not propose a mechanism for accomplishing this. King's high-fidelity analysis finds numerous configurations which provide T/D ratios greater than one for circular orbits at altitudes of 500 km and greater. This work proves that drag compensation using atmospheric propellants is possible and in some configurations does not require a compressing inlet, although King himself points out that satellites orbiting at 500 km already have substantial orbit lifetimes.

Japanese researchers have made significant progress with more traditional ion engine designs which include an ionization stage. The air-breathing ion engine (ABIE) first proposed by Nishiyama in 2003 integrates a novel inlet design with an ECR ion engine [28]. Fig. 2 shows a conceptual schematic of the ABIE. Air enters the ABIE inlet from the left side of the page. The inlet provides high transmission probability for the incoming air, but low transmission probability for air attempting to escape. It accomplishes this by collimating the incoming flow with a grid of long and narrow tubes [28]. Incoming air is assumed to be hyperthermal: the bulk velocity of the flow is much greater than the thermal velocity of the flow [22]. The incoming flow is also assumed to be free molecular: the mean free path of the incoming air is much larger than the characteristic length of the device. When the inlet is pointed along the velocity vector of the spacecraft, most of the air passes through the inlet without interacting with the tube walls. Once through the inlet, the air is decelerated out of a hyperthermal free molecular flow regime with a solid diffuser located aft of the inlet. The much slower and random thermal velocity flow which tries to escape the engine via backflow through the inlet is hindered from doing so by the long and narrow tubes. They have low transmission probability as can be deduced from Clausing's work in conductance of free molecular flow through tubes [29].

Once thermalized by the diffuser, the collected air must be ionized and accelerated to produce thrust. Ionization is accomplished via a microwave electron cyclotron resonance (ECR) ionization source. The ionized air is then accelerated via a series of

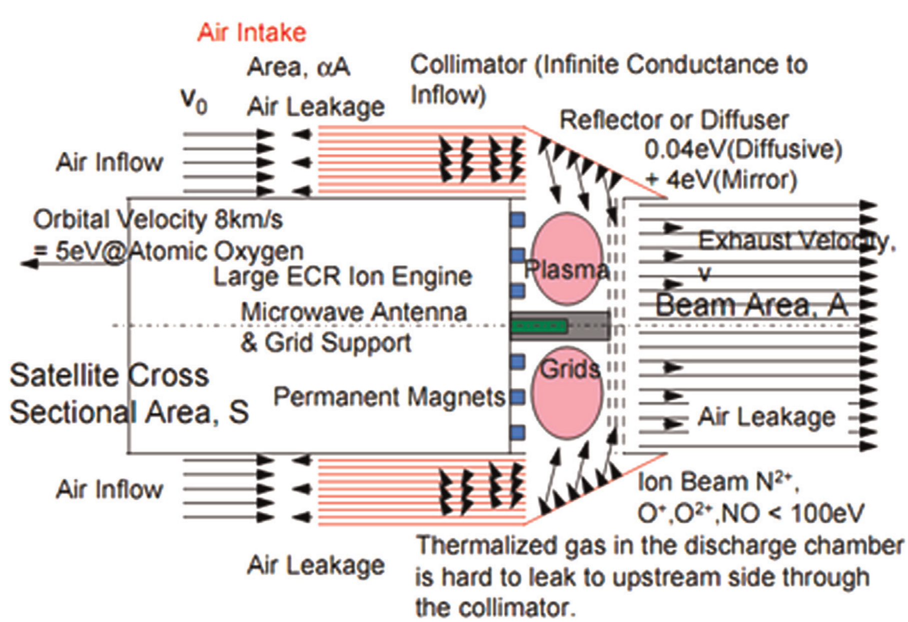

Fig. 2. Air breathing ion engine conceptual schematic [28].

biased grids as in a typical ion engine. The ABIE is currently the most developed air-breathing concept to have a fully designed, built, and integrated engine and inlet combination. Development of this concept has reached the experimental stage with an integrated design [30]. Researchers simulate the incoming hyperthermal free molecular flow with a pulsed laser detonation beam source operating on either pure nitrogen or pure oxygen. Peak pressure in the thruster ionization stage has reached as high as 3.6 m Torr, with only ~0.1 m Torr required for thruster operation [30]. These tests have demonstrated the effectiveness of the inlet at preventing captured air from escaping and have successfully demonstrated thrust. However, the ABIE has only been tested in a pulsed mode and without a neutralizer cathode present in the system.

In addition to the Japanese ABIE effort, European researchers have also made progress testing gridded ion engines on atmospheric propellants. Cifali et al. tested the radiofrequency ion thruster (RIT) RIT-10-EBB on pure N_2 and pure O_2 propellants in 2011 [31]. The RIT-10 is a thruster with successful flight heritage on the ARTEMIS spacecraft. Cifali's RIT-10 was modified to operate on atmospheric propellants instead of xenon. Cifali reports using argon to ignite the engine, citing difficulty experienced when trying to ignite using the atmospheric propellants. The cathode used in this work also ran on xenon. Cifali ran the cathode on xenon because traditional thermionic emission sources such as lanthanum hexaboride (LaB_6) are readily oxidized at the temperatures required for electron emission. These difficulties highlight remaining technical issues with operating electric thrusters on atmospheric gases.

Despite these setbacks, Cifali was able to demonstrate thrust levels of 5.25 mN on nitrogen and 6 mN on oxygen at 450 W. This corresponds to a T/P of 11.6 mN/kW for nitrogen and 13.3 mN/kW for oxygen. More recent tests of the RIT-10 with a mixture of nitrogen and oxygen demonstrated similar results [32]. Modeling and experimental results produced by Feili et al. demonstrate a lower propellant utilization efficiency and power efficiency for nitrogen and oxygen propellants over commonly used xenon propellant. Feili predicts a propellant utilization efficiency (η_u) on nitrogen of 35.1% for a given set of conditions in comparison to 65.2% for xenon. Similarly, he predicts a RIT-10 operating on nitrogen will have a power efficiency of only 63% for a given set of conditions in comparison to 76.5% if operating on xenon at the same conditions. The difference in these values highlights the trade in performance made when selecting atmospheric propellants over xenon for electric propulsion.

Cifali's test campaigns with the RIT-10 were performed in support of Di Cara's RAM-EP effort in Europe which first appears in the literature in 2007 [33]. The RAM-EP concept “seeks to enable low altitude missions” below 250 km by developing an air-breathing electric propulsion system. Di Cara's study focused on a hypothetical vehicle with 1 m^2 drag area and a drag coefficient of 2.0. The RAM-EP concept was the first to consider non-continuous thruster strategies by only generating thrust when not in eclipse. In particular, the study looked at two sun synchronous orbits (SSO) with operation during 2/3 and 5/6 of the orbital period. Di Cara's study determines that air-breathing options are not competitive above 250 km because annual propellant requirements to maintain orbit decrease rapidly above this altitude. Most importantly, the RAM-EP concept study identifies power as the primary limiting factor for the concept.

4.2. Hall effect thrusters and alternative thrusters

In addition to his gridded ion engine tests with the RIT-10, Cifali also tested a Hall effect thruster (HET) in support of the RAM-EP effort [31]. A Snecma PPS 1350-TSD was tested with pure nitrogen and a nitrogen/oxygen mixture. The thruster was ignited with xenon and the cathode operated on xenon. Results from HET operation on atmospheric propellants indicate lower propellant utilization efficiency in concordance with the RIT-10 results. As expected from a HET, the T/P ratio is significantly higher than for the RIT-10. Cifali reports 21 mN/kW on pure nitrogen and 24 mN/kW on the mixture. However, Cifali also reports significant rusting on the anode after operation with the nitrogen/oxygen mixture. The limitations Cifali discovered regarding ignition and corrosion highlight the technical challenges of running an electric propulsion device on oxygen.

The first researchers to propose a HET which utilizes ambient gas were Pigeon and Whitaker in 2004 [34]. They proposed a concept whereby ambient gas is ingested via random thermal motion and accelerated to produce thrust. Xenon was used as the ambient gas in their initial experiments, in which they indirectly measured μN levels of thrust. However, later work demonstrates that the performance of such a device is insufficient to compensate for drag on-orbit [35].

Pekker and Keidar proposed a concept similar to Dressler's AAIT concept whereby oncoming flow is fed directly into accelerating grids, but with a Hall acceleration mechanism instead of the aforementioned grids [36]. Like the AAIT, Pekker and Keidar's concept fed oncoming flow directly into the device without any compression mechanism. Most of the work focuses on the design and scaling of the thruster components using a detailed first order analysis. Their analysis indicates effective operation for drag compensation using this concept at altitudes in the range of 90–95 km with 9.1–22 N of thrust for a drag area of 0.1 m^2, although they point out the power requirements for this level of performance are 1.6–2 MW. Power levels of this magnitude are not currently realizable on-orbit. Pekker and Keidar's work confirms that an air-breathing HET should have a mechanism to raise the pressure of the flow prior to injection into the HET to allow for operation at higher altitudes.

Diamant proposed a 2-stage HET called the air-breathing cylindrical Hall thruster (ABCHT) for drag compensation [37]. The two stages consist of an ECR ionization stage similar to that on the ABIE with a traditional HET for acceleration. Diamant built a prototype of this thruster and operated it on xenon. The results of the test indicate the possibility of a lower thrust efficiency as a result of the inclusion of the ECR ionization stage. Like many researchers, Diamant also points out the limitations of thermionic cathode technology for neutralization with atmospheric gases [31]. To address this, he has proposed and conducted tests on a microwave cathode for air-breathing propulsion [38]. The results of testing on argon and xenon indicate current-to-power ratios as high as 90 mA/W on xenon and 50 mA/W on argon. While promising, Diamant notes a significant technical challenge may lie in delivering number densities on the order of 10^{20} m^{-3} of atmospheric gas to the cathode.

Shabshelowitz conducted a more detailed study than Diamant in his dissertation looking at rf thruster systems for air-breathing electric propulsion [39]. Shabshelowitz's 2013 dissertation gathered performance data for two thrusters with helicon technology. The first thruster is called the radiofrequency plasma thruster (RPT). It is a simple helicon plasma device. Similar devices have produced ion acceleration approaching 30 V on argon [40]. Test results from the RPT indicate low I_{sp} on the order of 330 s and low rf thrust efficiency on the order of 0.7% on argon. Shabshelowitz ran the RPT on pure nitrogen and air, but was unable to measure any additional thrust from rf power deposition over the cold gas thrust.

The second thruster tested by Shabshelowitz is the Helicon Hall Thruster (HHT) [41,42]. The HHT is a 2-stage thruster with a helicon ionization stage and a Hall acceleration stage. Like Diamant's

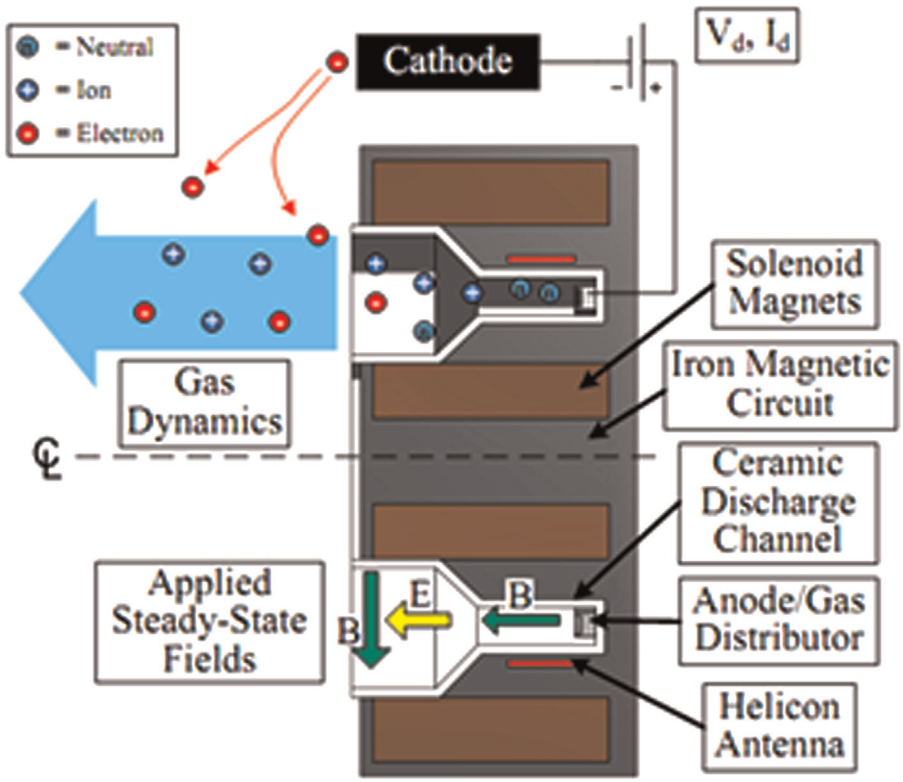

Fig. 3. A notional schematic of the HHT from Shabshelowitz's dissertation [39].

2-stage thruster, the helicon ionization stage is intended to increase ionization and propellant utilization efficiencies. Fig. 3 is a notional schematic of the HHT from Shabshelowitz's dissertation. The helicon ionization stage can be seen closest to the anode while the Hall section is near the thruster exit. Similar to Cifali, Shabshelowitz operated his thrusters with a cathode operating on xenon rather than atmospheric gases. This limitation in his research further highlights the present deficiency of knowledge in the cathode segment of electric thruster system design for atmospheric constituents.

Shabshelowitz ran the HHT in 2-stage and Hall-only modes on xenon, argon, and nitrogen propellants. His results show decreasing T/P with increasing RF power when running in 2-stage mode. The data demonstrates improved propellant utilization efficiency for all propellant species when using the helicon stage, but the observed improvement is not sufficient for the added power input. In Hall-only mode Shabshelowitz's data demonstrates propellant utilization efficiency on nitrogen of approximately 10%. Unfortunately Shabshelowitz only ran the HHT at 200 V discharge voltage and 4.8 mg/s for nitrogen propellant, so there is only one data point. T/P and propellant utilization efficiency increase with increasing mass flow rate for xenon according to Shabshelowitz's data, and Shabshelowitz's only flow point on nitrogen is half of the lowest flow rate of xenon.

Where Shabshelowitz used an experimental approach to studying the use of atmospheric propellants in a HET, Garrigues used a computational approach [43]. Garrigues selected a notional vehicle with drag coefficient of 2, frontal area of 1 m^2, continuous 1 kW available power, and a circular orbit at 250 km altitude. From that notional design, Di Cara's work indicates a maximum thrust of 20 mN is required to counteract aerodynamic drag [33]. Garrigues employs a hybrid axisymmetric model with 2 different thruster channel lengths and a discharge voltage of 300 V to search for configurations which meet that thrust performance target. He also varies magnetic field strength off of the nominal field required for xenon and the mass flow rate.

Garrigues' model indicates a mass flow rate greater than the oncoming mass flow rate is required by a HET to provide the required thrust to counteract drag for his notional vehicle. This result occurs because of low propellant utilization efficiency (~10%) and low thrust efficiency (~5%) at the desired thrust performance. However, Garrigues' results also show increasing propellant utilization efficiency and thrust efficiency with increasing mass flow rate, peaking at ~22% and ~7% respectively on molecular nitrogen. While Garrigues correctly concludes that a HET in his design space cannot deliver the necessary performance for a notional vehicle, he fails to consider the possibilities of a larger vehicle, varied discharge voltage, or a sufficient range of magnetic field strengths and channel lengths. Garrigues does succeed in providing some valuable data which roughly agrees with Shabshelowitz's results.

One final thruster concept which warrants mention is the field reversed configuration (FRC) electrodeless Lorentz force (ELF) thruster being developed by Kirtley et al. since 2011 [44]. Kirtley makes the argument that thruster efficiency is fundamentally a function of the molecular weight of the propellant, where lower molecular weight propellants lead to lower thruster efficiency. The ELF thruster concept mitigates the poor efficiency of low molecular weight propellants by injecting neutrals into the plasma downstream of the ionization stage in a process called neutral entrainment. Rather than trying to ionize all propellant, the ELF thruster uses accelerated ions to ionize the injected neutrals via charge exchange interactions. Kirtley asserts that with the neutral entrainment scheme the charge exchange interaction is effectively free in terms of energy, so the newly ionized particle's ionization cost is effectively zero. By reducing the average ionization cost, the thruster efficiency at low I_{sp} can be increased. To date, Kirtley has demonstrated operation on neon, but has yet to do so with nitrogen.

As can be discerned from the preceding sections, numerous

Table 2
Summary of thruster studies for operation with air constituents.

Investigator	Thruster	Study type	Propellant	Cathode type	Max I_{sp} (s)	Max thrust efficiency (%)
Conley [18]	LEO ion thruster	Theoretical	N/A	N/A	N/A	N/A
Dressler [21]	AAIT	Theoretical	N/A	N/A	N/A	N/A
Nishiyama [28]	ABIE	Experimental	N_2 and O_2	N/A	~3,800	~4.2
Cifali et al. [31]	RIT-10-EBB	Experimental	N_2 and O_2	Hollow (Xe)	~5,000	~28
Cifali et al. [31]	PPS1350-TSD	Experimental	N_2 and N/O mix	Hollow (Xe)	~900	~10
Pigeon and Whitaker [34]	Near-vacuum HET	Experimental	Xe	N/A	~8,743	N/A
Pekker and Keidar [36]	Air-breathing HET	Theoretical	N/A	N/A	N/A	N/A
Diamant [38]	Microwave cathode	Experimental	Xe	ECR	N/A	N/A
Diamant [37]	ABCHT	Experimental	Xe	Filament	N/A	N/A
Garrigues [43]	HET model	Theoretical	N/A	N/A	N/A	~7
Kirtley [44]	ELF	Theoretical	N/A	N/A	N/A	N/A
Shabshelowitz [39]	HHT	Experimental	Nitrogen	Hollow (Xe)	~800	~7

contemporary researchers have taken their own unique approach to accomplishing propulsion with atmospheric propellants. Table 2 summarizes the approaches present in literature, revealing a wide spectrum of technical maturity and demonstrated performance. Of particular note are the experimental efforts, which have demonstrated a wide range of I_{sp} and thrust efficiency.

4.3. Propellant collection applications around other planets

HET technology has also recently been considered for “air-breathing” applications around other planets. Lamamy's 2004 Master's thesis was the first work in the literature after Minovitch to propose air-breathing concepts around Mars [20]. Lamamy's thesis proposed the propellant production in Mars orbit (PPIMO) concept as a compromise between chemical and electric propulsion options for interplanetary transfer. PPIMO would collect carbon dioxide from the Martian atmosphere and react it with hydrogen carried from Earth to synthesize methane, hydrogen, and oxygen. These propellants would be reacted in a chemical engine to produce the necessary impulse to transfer back to Earth from Mars. While Lamamy made a number of simplifying assumptions in his analysis, he shows the PPIMO concept can accomplish the same mission as an all chemical option with 30% less mass.

Hohman proposed the Martian atmosphere breathing HET (MABHET) concept to reduce propellant delivery requirements to Mars in 2012 [45]. Like the ABIE, the MABHET concept makes use of the same collimated inlet design to improve collection efficiency. Hohman performed experiments and analysis using a 1.5-kW HET on a simulated Mars atmospheric mixture. Unlike other experimental thruster tests, Hohman's setup included an ECR cathode operating on the same atmospheric mixture as the MABHET. Regrettably, Martian atmospheric make up is composed mostly of CO_2 in contrast to Earth's atmosphere of nitrogen and oxygen, thus data gathered from these experiments is of little use to researchers developing air-breathing HET or cathode technology for Earth's atmosphere.. However, Hohman's work demonstrates encouraging results for the feasibility of such a concept around Mars which further emphasizes the potential of air-breathing spacecraft technologies.

Palaszewski looked to the outer planets in his proposal to mine the atmospheres of gas giants for helium-3 [46]. Fig. 4 demonstrates a “scooper” architecture proposed by Palaszewski for use around Uranus. Helium-3 has long held interest in the space and fusion communities for its potential use as nuclear fuel in fusion reactors and relative abundance at extra-planetary destinations. Palaszewski's documentation of his effort is highly theoretical as one would expect for a concept which relies on so many advanced technologies. While most concepts involving the collection of atmospheric matter are air-breathing types, Palaszewski's is one of the few concepts which considers the storage and separation of the collected gas. Palaszewski's main interest in “atmospheric mining” is the potential to gather nuclear fuel for terrestrial reactors. This is entirely unique and original in that it is the only concept in the literature which proposes the return of a portion of the collected gas to Earth.

4.4. Inlet studies

While Cifali and many others studied the thruster component of propellant collection technology, other researchers studied the

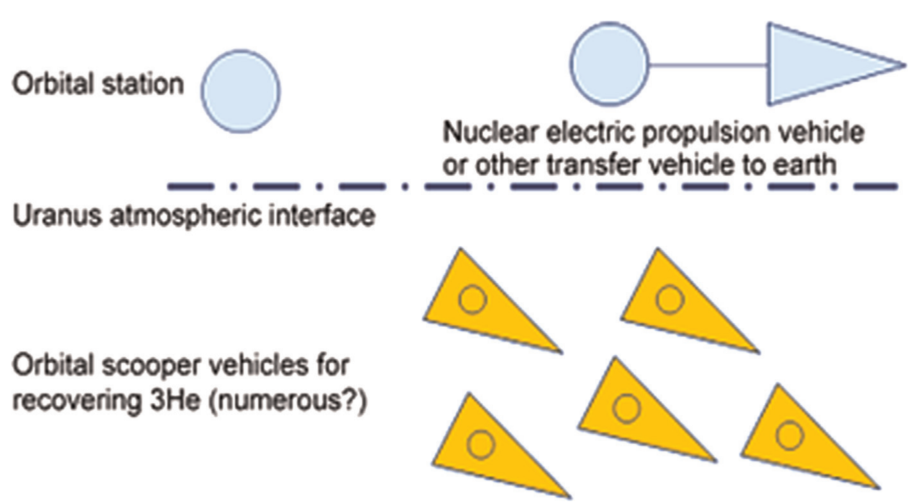

Fig. 4. Illustration adapted from Palaszewski demonstrating his system architecture for collecting He-3 around Uranus [46].

inlet component. Prior to Japanese [28,47,48] and European [33] studies of air-breathing inlet designs, McGuire performed direct simulation Monte Carlo (DSMC) analysis of a simple conical inlet design as part of his Master's thesis [19]. McGuire proposed a concept called the Aero-Assisted Orbital Transfer Vehicle (AAOTV) which would serve as a space tug system to transfer payloads from LEO to GEO. The DSMC results show a variation in drag coefficient and capture percentage with the angle of the conical inlet and its outer radius. Notably, none of his designs have a capture percentage greater than 50 percent. His analysis also indicates that smaller inlets will have better capture percentages. This is in agreement with the results of the Japanese with their collimated inlet design, which is effectively an array of small inlets and attains high performance when compared with most simple conical inlet designs. However, this result only holds for hyperthermal free molecular flow. As altitude approaches the Karman line and the flow compresses in the inlet, the flow can undergo a transition to hypersonic continuum flow.

Although generally not perceived as politically realistic in the community today, some researchers are taking a second look at the nuclear-powered concepts of the Cold War era. Jones et al. resurrected the original PROFAC concept in 2010 as a potential option to gather atmospheric propellant for manned exploration of Mars [49]. He performed DSMC analysis of a novel conical inlet design with a diffuser insert to increase the pressure at the back of the inlet. His results confirm an increase in pressure but he does not report on the effect of the diffuser on the percentage of oncoming air that reaches the back of the inlet. In fact, Jones assumes the capture percentage is one hundred percent. This is in contradiction to McGuire's results, which indicates that an aerodynamic collector cannot collect all of the oncoming flow [19]. Additionally, he does not make any estimates of power requirements which are critical in determining the feasibility of the concept.

The conical inlet designs studied by Jones and McGuire are one class of inlet proposed for propellant collection architectures. The other major design type is the collimated inlet design initially proposed by Nishiyama and adapted for use with Hohman's MABHET system. Each of these inlet design classes are demonstrated in Fig. 5. These two classes of inlet designs represent fundamentally different ideas about the state of the oncoming flow. Simple consideration of the roughly exponential behavior of atmospheric density with altitude reveals that the selection of the optimal type of inlet design depends strongly on the design altitude and flow regime of the propellant collecting craft. At altitudes where the flow is transitional, neither inlet may be ideal.

5. Avenues for continued research

The limitations of previous research identified in the preceding sections present opportunities for continued research. Despite 55 years of development, gaps remain in capabilities necessary to realize a sustainable propellant-collecting system. Some of the most important areas for continued research include:

Air-compatible cathode technology: Traditional thermionic cathode emission sources cannot operate in the presence of oxygen-containing species because the emission sources are readily oxidized at temperatures necessary for emission. This limitation poses a challenge for operating electric thrusters on atmospheric gases of which oxygen is a major constituent. Unfortunately, despite widespread acknowledgment of the need to develop this technology, efforts in this area are modest in comparison to cathodes that operate on noble gas [38,39,43]. The efforts of Hohman and Diamant are notable, albeit limited exceptions. Diamant has proposed and protoyped one possible solution with a microwave or ECR cathode design which does not use a thermionic emission source [38]. Hohman operated the MABHET thruster with his own ECR cathode design, but his experiments were conducted with simulated Martian atmospheric constituents rather than Earth constituents. There have been no reported results detailing the operation of a microwave or radiofrequency cathode on atmospheric gases for a propulsion application, although both have operated on xenon [38,50]. Other possible approaches to addressing this issue may be identifying a thermionic source which is not susceptible to oxidation while operating or simply filtering out oxygen-containing species from the cathode flow. Finally, it may be possible to avoid this issue by selecting a thruster design which does not require a cathode to operate such as an electromagnetic thruster. Demonstration of operation of any of these technologies will be necessary for continued development of propellant-collecting systems as a crucial component in many of the most technically mature air-compatible thruster technologies.

Techniques to improve propellant utilization on atmospheric species: The thruster experiments detailed in this review universally

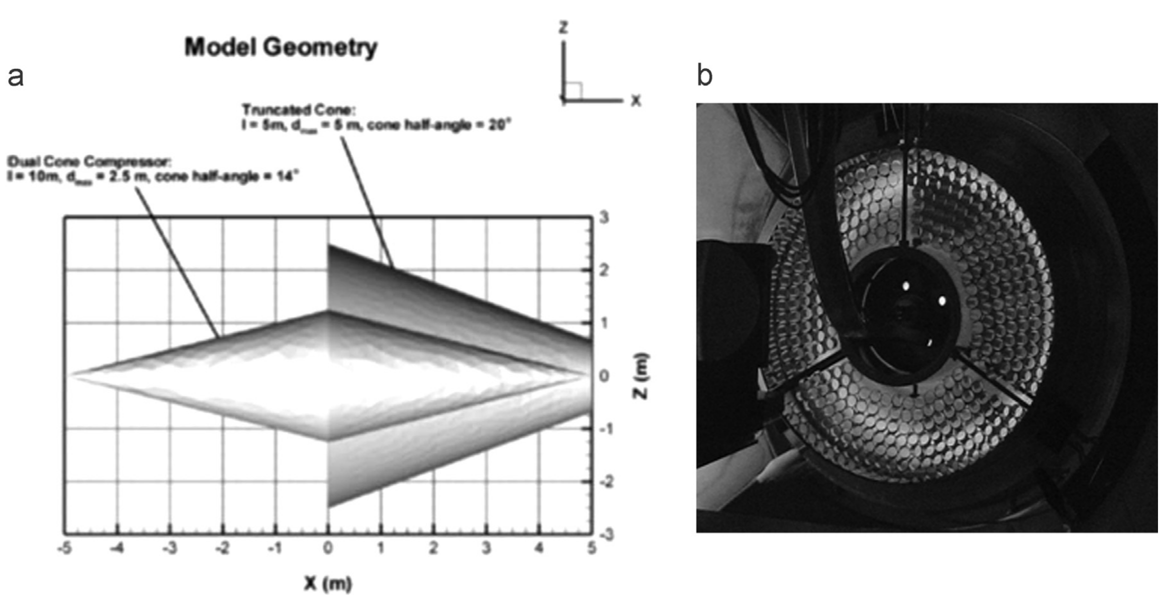

Fig. 5. Left: Jones' truncated cone with dual-cone compressor inlet [49]. Right: Tagawa's collimated inlet prototype [30].

encounter reduced propellant utilization efficiency for atmospheric gases when compared to equivalent operation on xenon [32]. This is to be expected; the diatomic species present additional energy modes for energy meant for ionization to fill, the major atmospheric constituents have lower ionization cross sections, and they have slightly higher ionization energies. While present ionization techniques and designs are sufficient to attain high propellant utilization on xenon, they are not well-suited for the efficient ionization of atmospheric propellant. Propellant utilization efficiency is a major contribution to overall thruster efficiency which itself is a major factor in determining the thruster power requirement. Potential approaches to improving propellant utilization may include identifying new ionization techniques and optimizing existing techniques such as the radiofrequency excitation studied by Shabshelowitz for atmospheric species [39].

In-space compressor and liquefaction technology: Compression and storage of collected propellant is a major function necessary for architectures like PROFAC and PHARO which intend to deliver propellant to other vehicles, and yet this sub-system remains the least addressed in the literature. Contemporary research efforts in particular have almost completely neglected the compression component of propellant collection. One potential reason for this deficiency in the literature is that the necessary technology is technically mature on the ground, where it in-principle operates under space-like conditions as pumping systems for vacuum chambers. Ultimately, maturity on the ground is not equivalent to maturity in space. Ground and space-based compression systems possess different design constraints. Ground-based pumping systems have ample access to electrical power and ambient external conditions for cooling. In contrast, a compression system for a propellant collecting spacecraft must operate exclusively in a much harsher space environment with restricted access to electrical power. While they may have to be tolerant against some vibration, ground-based pumping systems do not have survive launch into orbit.

Similar components to those one might imagine in an integrated compression and liquefaction system regularly operate in space. Components for cryogenic fluids are regularly integrated onto satellites as part of cryocooler systems for use with imaging instruments. Turbopumps are major components of liquid rocket engines and have similar design features to turbomolecular pumps. However, an integrated compression and liquefaction system which can reliably and efficiently operate completely in space-like conditions, survive launch loads, and provide the necessary level of compression remains to be demonstrated.

Improved hypersonic and hyperthermal free molecular flow inlet designs: The flow into the vehicle is a major contribution to the aerodynamic drag experienced by the vehicle, and determines the mass available for counteracting the drag and for storage. The available mass in turn determines the thruster performance required to overcome the drag which ultimately drives the power requirements for the system. As a result, the performance of the inlet drives the design requirements for all of the other components of a propellant collection system. By improving and optimizing inlet designs in these flow regimes, propellant-collecting designs can see improvements in their ability to collect and compress the oncoming flow while potentially reducing drag. The consequence of improvements to inlet performance is reduced performance requirements for the other components of the system. In this way, investments made to further inlet design are indirectly investments made to the other components as well.

As alluded to above, aerodynamic inlets presented in the literature thus far for propellant collection fall into two categories: inlets designed under the assumptions of hypersonic flow and inlets designed under the assumption of hyperthermal free molecular flow. At altitudes on the order of 100–120 km the flow is not adequately described by either set of assumptions, instead it is more appropriately described as transitional. A design which accepts the transitional behavior of the flow up front may lead to the aforementioned desirable improvements in performance over previous designs.

Improved understanding of how design parameters affect system performance: Demetriades, Berner and Camac, and others have performed robust treatments of the physics behind their proposed architectures. However, their models are all based on their own specific conceptions of a propellant-collecting design. These specialized models provide valuable information relative to their particular design concept, but fail to provide applicable insight into propellant collection as a technology in general. Each model in the literature relies on a number of assumptions which are justified on the basis of considering a single design or narrow range of designs. As such, they do not fully capture the physics of propellant collection as a technology. A physics-based model of propellant collection as a general concept which is free from the assumptions possible when considering only a subset of propellant collecting concepts is not present in the literature. Such a model might estimate the performance of the overall system by considering the performance of each of the major components and should have sufficient versatility to be applicable to all propellant collection designs. Development of this model will provide the community with a standard basis upon which to compare designs and concepts. A sufficiently detailed model will also provide valuable insight into which design parameters are most important and define requirements for them, thus improving our understanding of how the performance of each component in the system affects the overall design.

6. Concluding remarks

This review has presented the efforts of previous researchers to develop propellant collection technology, starting with the seminal work of Demetriades who proposed the first propellant collection concept for reducing the cost of lunar voyages. His work provided the foundation for subsequent efforts during the Cold War era. Development during this era was rapid as was most space-related research due to the space race. Ultimately, interest in propellant collection waned as funding declined in the post-Apollo years and focus shifted to other endeavors. Contemporary researchers, noting the growth in the size and maturity of the space industry, have refocused on propellant collection as a means to reduce the costs of operating space systems and access lower orbits. These efforts have led to developments in electric propulsion and inlet design which are critical to propellant collector design and have even led to the first experimental tests of an integrated design.

The concept of collecting atmospheric gas for use as propellant remains promising and recent efforts have advanced the field tremendously, however further development is required before we can begin to exploit this capability. By undertaking each of the efforts proposed in this work, the community can continue to develop propellant collection technology into a fieldable technology.

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