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Small Body Ascent Enabled by In Space Resource Derived and Produced Hydrogen Peroxide

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Abstract

Current research trends in In Situ Resource Utilization (ISRU) and In Space Manufacturing of propellant are heavily focused on the production of cryogenic propellants such as liquid hydrogen and oxygen. The authors have been studying an alternative approach: the manufacture of a storable monopropellant, High Test Peroxide (HTP).

Previous work by John S. Lewis [NIAC Phase I Final Report for NNX15AL85G (2016)] explored the feasibility of In Space Production of Storable Propellants from resources available on asteroids, Mars and the Moon. Dimethyl ether (DME) and HTP were identified as the preferred storable bipropellant combination for deep-space missions and retrieval of space-derived resources to Earth orbit. However, difficulties producing DME indicated a need to first develop systems that extract water for production of storable hydrogen/oxygen-based propellants.

A simplified architecture, which was not explored, involves the extraction of water and production of HTP for use as a monopropellant for multi-target missions. While monopropellant HTP specific impulse is lower, system complexity is significantly reduced.

As such, the authors have begun to study an innovative "Grand Landed Tour" multi-target exploration mission taking advantage of ISRU HTP production to explore and land on asteroids in the outer belt. This concept could similarly enable multiple-landing tours of the icy moons of any of the outer planets, of the Jupiter Trojan asteroids, or of other water-rich objects, such as Earth's Moon. Such an architecture could enable a low cost sample return mission from the lunar surface with significantly smaller landed mass on the moon and increased cost effectiveness.

The mission study assumes delivery to a Ceres rendezvous trajectory, which is not the emphasis of the work being undertaken, although efforts will be made to minimize initial system mass. At Ceres, as at all destinations, we will make science measurements and generate enough propellant to launch and proceed to the next target. The outer belt offers a series of intriguing objects, including the Hilda asteroids in a 3:2 orbital resonance with Jupiter.

This paper discusses the initial mission objectives and requirements of this study, the major trades undertaken and details the technical path forward in the industrial chemistry work needed to understand the size, weight, power and cost of a conversion system capable of taking in water and producing propellant grade HTP. It concludes with a discussion of the future work being undertaken by the interdisciplinary team across industry and academia.

Keywords: in-situ resource utilization, asteroid mining, high-test peroxide

Acronyms/Abbreviations

DME	Dimethyl ether
HPS	HTP Production System
HTP	High-test peroxide
ISS	International Space Station
NASA	National Aeronautics and Space Administration
NEA	Near-Earth asteroid
NIAC	NASA Innovative Advanced Concepts
OGA	Oxygen Generation Assembly
PEM	Proton exchange membrane
TRL	Technology Readiness Level
WHS	Water Harvesting System
CO_2	Carbon dioxide
H_2O	Water
H_2S	Hydrogen sulfide

Nomenclature

Delta-*v*	Change in velocity
I_{sp}	Specific impulse

1. Introduction

The asteroids constitute a very diverse group of objects, ranging from dwarf planets like 1 Ceres to meter-sized fragments in Earth-approaching orbits. These bodies provide clues to processes that have been occurring throughout Solar System history, including processes whose effects have long since been erased on planets and their moons [1]. For this reason, they have become increasingly important targets for scientific exploration. In addition, many of them contain volatiles and other potentially useful resources [2].

In-situ high-test peroxide (HTP) production can enable a fundamentally different type of mission, such as a “Grand Landed Tour” landing on four or more small bodies. These missions can provide data of a type that has never been obtained before for an important class of objects. This type of mission, and others enabled by the innovation of in-situ HTP production, can open completely new avenues of exploration.

HTP, which is non-cryogenic, can be used as a monopropellant to launch from the surface of even the largest asteroid, as well as to achieve the delta-v necessary to transit between asteroids or dwarf planets, and to provide the propellant needed for a soft landing. For example, given a Ceres escape velocity of 0.638 km/s, and a demonstrated I_{sp} of a HTP monopropellant of 192 s [3] (where 198 s is the theoretical maximum I_{sp} [4]), the mass ratio for launching to Ceres escape velocity is 1.4, meaning a 1-tonne vehicle requires 0.4 tonnes of HTP propellant, which can be manufactured from ~0.45 tonnes of water.

In this paper we evaluate a Grand Landed Tour mission to the outer asteroid belt, landing at each asteroid visited. The outer asteroid belt is a region that has only been explored via telescope and the occasional spacecraft flyby, but this mission would make landings possible on a number of these important objects. Furthermore, this concept could similarly be applied to enable multiple-landing tours of the icy moons of any of the outer planets, of the Jupiter Trojan asteroids, or of other H_2O-rich objects.

Focusing on in-situ HTP production has reduced the complexity of the technical innovation, but unknowns remain. The Grand Landed Tour of the asteroid belt, with landings on multiple bodies, has not previously been detailed. Engineering trade studies and modelling of the most prospective system solution(s) must be performed in a mission context. Requirements such as mass and power are ill-defined at this stage and this paper aims to answer these questions in more detail.

Previous work has made progress on an HTP production system, and future publications will further develop the system architecture. This work focuses on detailing the Grand Landed Tour and the mass and power required for a system capable of executing the mission.

2. Previous work

A NIAC Phase I proposal written by John S. Lewis explored the feasibility of In-Space Production of Storable Propellants [4] from resources available on asteroids, Mars and the Moon. It identified the storable propellant/oxidizer combination of dimethyl ether (DME) and HTP for deep-space missions and retrieval of space-derived resources to high Earth orbit.

Phase I work showed that the extraction of CO_2 for DME production introduced excessive complications to the mission, and recommended that early missions retrieve only water for production of hydrogen and oxygen based propellants. This led to the realization of a simplified architecture that was not explored in depth in the NIAC proposal: extraction of water and production of HTP for use as a monopropellant for multi-target exploration missions. Monopropellant HTP can be used for ascent from any asteroid, while requiring a system with much lower complexity than bipropellant HTP or cryogens. Figure 1 shows the overall process for generating propellant from asteroid materials as investigated in the Phase I NIAC.

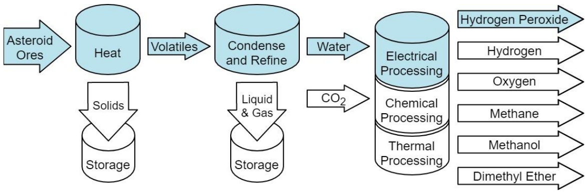

Figure 1. Process flow for manufacturing propellants from asteroid ores. Blue indicates a path to produce HTP to fuel a multi-target Grand Landed Tour of the asteroid belt.

Recent Orbit Fab publications have considered the advantages and limitations of various propellants for in-situ use. A trade study of in-situ propulsion options, reproduced in Table 1 from Geiman et al. 2021 [5], showed that HTP is a compelling option for in-situ use. The ability of HTP to be produced in situ, stored during multi-year transfers, and provide ascent thrust all contribute to its usefulness as a propellant for the Grand Landed Tour. A further presentation presented a laboratory-proven method for producing hydrogen peroxide in situ using only water and energy as inputs [6]. These publications support the conclusions in the NIAC Phase I proposal regarding the promise of HTP as an achievable in-situ propellant. This paper builds on these works to study an innovative Grand Landed Tour multi-target exploration mission taking advantage of in-situ HTP production.

The NIAC Phase I concluded that on-asteroid processing, including heating, condensation, electrolysis, concentration, and freezing, is a feasible route and involves both low- and high-TRL technologies. More recent work by Orbit Fab and

Table 1. Trade study in Geiman et al. 2021 [5] compared propulsion systems and found HTP monopropellant ideal for in-situ use.

Characteristic	Solar Electric	Direct Solar Thermal	Chemical	Water Solar Thermal	Cryo ISRU	Biprop HTP/ Hydrocarbon ISRU	Monoprop HTP ISRU
Complexity	low	med	low	med-high	high	med- high	low-med
Ascent Thrust	no	no	yes	no	yes	yes	yes
Solar Array / Collecting Area	high	high	low	high	high	medium	medium
ISRU	no	yes	no	yes	yes	yes	yes
Storable	yes	yes	yes	yes	no	yes	yes

others in areas such as HTP production [5,6], refueling [7], and regolith processing [8,9] has since raised the TRL of many of the technologies that will enable a Grand Landed Tour.

These conclusions point to several unexplored, exciting, and valuable aspects where further investigation is warranted. It was seen that in-situ HTP production offers a significant advantage to the previously studied work and can enable new missions. If successful, the lower equipment complexity will aid TRL advancement and infusion into future NASA missions for the 2020s and beyond. Extracting and processing water into HTP could be the key steppingstone to later missions producing and working with important cryogens such as hydrogen, oxygen, and methane.

3. Prospective mission enabled by in-situ refueling

3.1 Research objectives and concept of operations

We propose a Grand Landed Tour of the outer Main Asteroid Belt, landing on several asteroids

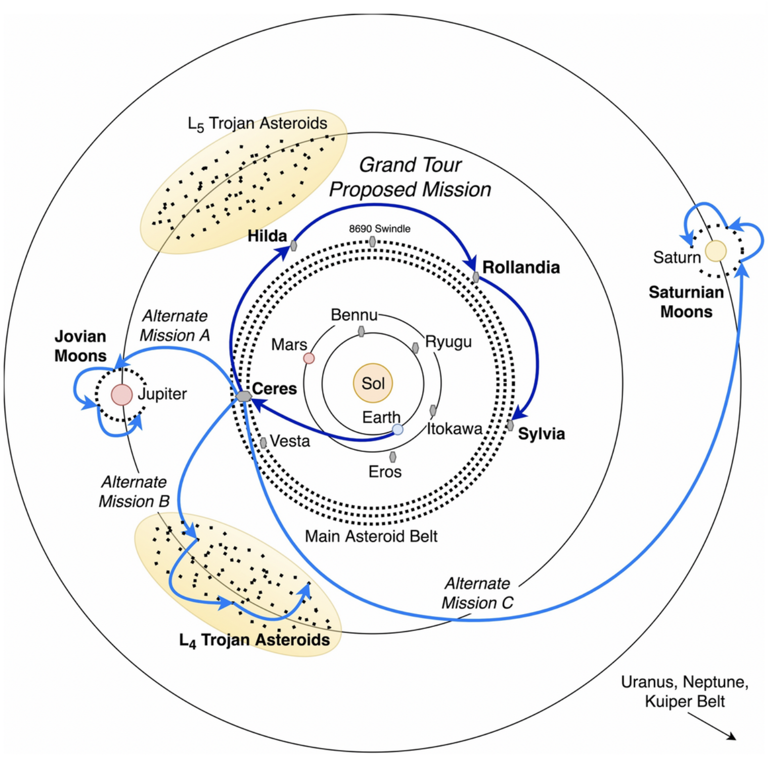

Figure 2. The proposed Grand Landed Tour mission (dark blue) lands on multiple small bodies. The innovative approach of ISRU HTP production provides the capability to land, refuel, ascend, and repeat the process on a new science target, offering expansion of potential locations and capabilities. Alternative missions A, B, and C (light blue) provide examples of enabled missions to outer body moons and asteroids.

along the way. The proposed mission trajectory is shown in Figure 2, in dark blue. Three alternative missions are shown in light blue, illustrating the versatility of the mission architecture. Delivery to a Ceres rendezvous trajectory by a launch vehicle or carrier spacecraft is assumed, and is not analyzed in this paper although an emphasis is placed on minimizing the initial mass. At Ceres, as at all destinations, scientific measurements are made and enough propellant is generated to launch and proceed to the next target. The outer belt offers a series of intriguing objects. This technology could enable a tour that would ultimately include landings on asteroids in groups such as the Trojans and the Hildas. One intriguing object is 153 Hilda, the largest and namesake of the Hilda asteroids. Like Jupiter's Trojan asteroids (in a 1:1 orbital resonance with Jupiter, some of which are flyby targets by the Lucy mission), the Hildas (in a 3:2 orbital resonance with Jupiter) may provide clues to the early dynamical evolution of the Solar System, and may be related to the Trojans [10,11]. The orbital resonance is scientifically important for dynamical reasons, but our interest is in asteroid origin and evolution. Wong et al. [12] showed two basic spectral types of Hilda asteroids, with the difference possibly due to the presence or absence of H_2S, a hypothesis easily tested by in-situ measurements. Hence, another target would be a Hilda asteroid from the other spectral group, such as 1269 Rollandia, which is spectrally a D-type (Hilda is a C-type). Another intriguing outer belt asteroid to investigate would be 87 Sylvia, the 8th largest asteroid, which is an X-type. 87 Sylvia is not a Hilda asteroid, but is another dark, presumably carbon-rich, outer Main Belt asteroid, and is unusual in that it has two known satellites [13]. The trade study considers several outer Main Belt destinations similar to Hilda, Rollandia, and Silvia. The Concept of Operations is shown in Figure 3.

HTP was closely examined in the NIAC Phase I, but not for ascent. In this paper, a key objective is to determine what might be achieved by focusing on HTP production on the surface of dwarf planets or massive asteroids. The ongoing development of a system to produce HTP from H_2O is a key step, which we evaluate in the context of this ground-breaking mission architecture.

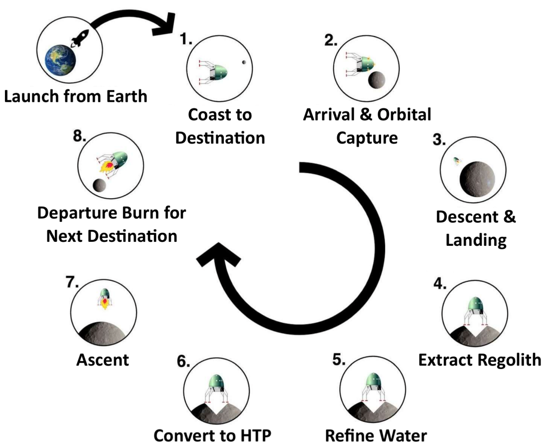

Figure 3. Major mission phases for the Grand Landed Tour. The cycle may continue as long as the spacecraft can operate. Steps 2 and 4 will include scientific investigations of the target.

3.2 HTP handling storability and stability

HTP is currently undergoing renewed interest within entrepreneurial companies and government organizations. However, challenges and misconceptions about working with HTP persist [14,15]. Many prior complexities have discoverable and actionable causes, which can be safely managed. Early production of HTP retained significant contaminants which led to anomalies, but today's peroxide is very pure and decomposes extremely slowly, with a model indicating that stannate stabilizers limit the decomposition rates to 10^{-4}–10^{-5} % per year [4]. Monopropellant HTP has flight heritage on several spacecraft, including the Orbit Fab Tanker-001 Tenzing fuel depot, launched in mid-2021 [7]. Operational lifetimes of 3–6 years were demonstrated on the Syncom 2, Syncom 3, Intelsat I, Intelsat 2-2, Intelsat 2-3, and Intelsat 2-4 satellites without any HTP anomalies [16]. In addition to the earlier quantitative model demonstrating long-term peroxide storability, laboratory research performed at Rice University has found that HTP production in the proposed scheme is free of sources of contaminants that could catalytically destroy HTP.

4. Major innovations of this approach

There have been asteroid tours proposed before (most notably Lucy, the tour of the Jupiter Trojans scheduled to launch in 2021) [17], but these are predominantly flyby missions. Past and funded missions are shown in Figure 4. Dawn orbited two different asteroids, Vesta and Ceres, the only example of a single mission including more than one rendezvous. Only four missions have touched the surface of an asteroid: NEAR-Shoemaker, Hayabusa, and Hayabusa2, and OSIRIS-REx. Those were either touch-and-go (the sampling phase of the Hayabusas and OSIRIS-REx), an impromptu end-of-mission landing (NEAR-Shoemaker), or a short-lived small rover (the MASCOT rovers associated with Hayabusa2). None have been full spacecraft optimized for extended surface operations. Besides getting more detailed surface compositions, an actual lander could probe the interior of an asteroid with radar, perform some of the measurements that can only be done by a landed mission or a sample return (isotopic analyses of rocks, microscopic imaging), and better measure the geotechnical properties that would be necessary for future surface operations ranging from rovers to in-situ resource applications. The rovers deployed on Mars over the past decades have demonstrated the value of extended surface operations for scientific discovery. For example, in-situ observations by the Curiosity rover revealed that water persisted for an extended period of time on the Martian surface, using evidence such as rounded pebbles which were only possible to observe by visiting the surface [18].

Furthermore, the objects on which we have landed have all been small near-Earth asteroids (NEAs). While the two most recent NEAs visited, Ryugu and Bennu, are carbon-rich asteroids believed to have originated much farther out in the Main Belt, they have been changed by their time at 1 AU from the Sun or less. Outer Main Belt asteroids observed in their native environment would be more likely to preserve the materials available at the beginning of the Solar System, most notably organic materials and volatiles like water.

The most volatile-rich asteroids, attractive for in-situ HTP production, are also those most important to understand the origin and evolution of critical compounds such as water and organics, and are located in the outer portion of the Main Belt. This part of the Main Belt is most difficult to observe or reach from Earth and receives the least sunlight, making solar thermal propulsion least efficient. Our approach, generating storable propellant as we go, would make it possible to progressively move farther out in the Belt, ultimately getting to fascinating but poorly-known asteroids such as the Hildas as shown in Figure 2.

The leg to Ceres is simplified in Figure 4, as a Mars slingshot may be necessary due to the ~10 degrees inclination with respect to the Earth. Ceres is the logical first step, both because it is known to be volatile rich and because it is such a scientifically-interesting body to study [19]. However, it is also the

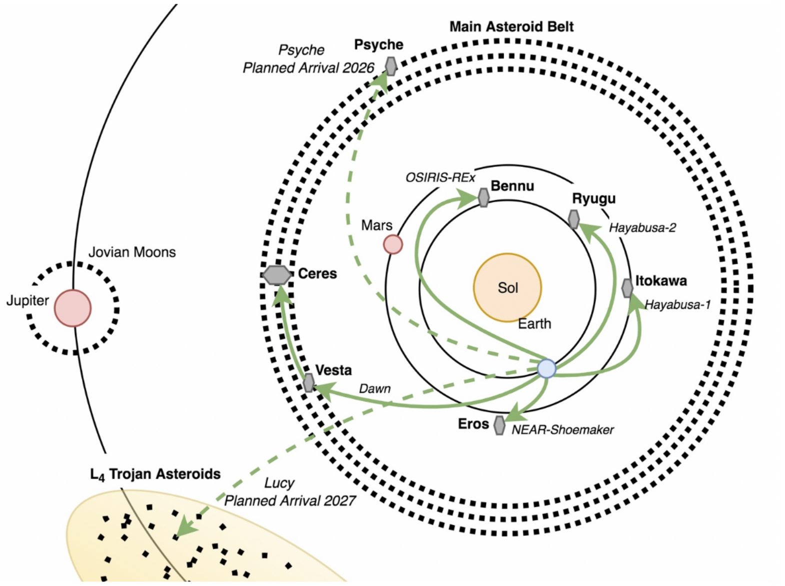

Figure 4. Of all the dedicated asteroid missions completed, ongoing, and planned, only a single mission, Dawn, has successfully rendezvoused with more than one asteroid. This is largely due to limitations from a finite on-board fuel supply. Production of HTP from in-situ water enables asteroid tours with multiple rendezvous and landings.

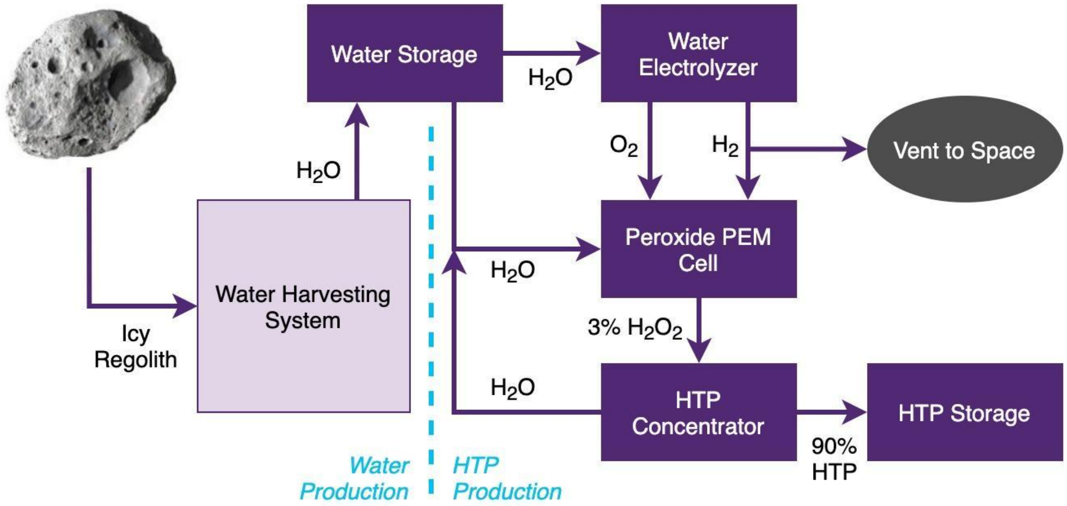

Figure 5. System architecture for Grand Landed Tour propellant production, which enables complete transformation of icy regolith into propellant-grade HTP. The WHS block is shown in light purple, with the HPS blocks in dark purple.

largest gravity well of any body in the Main Asteroid Belt (with an escape velocity of ~640 m/s, compared to ~50–100 m/s for the other objects we have discussed).

An alternative is to start not with Ceres, but with a small, volatile-rich NEA for which less propellant is needed to escape its gravity, but which could provide fuel for the ride to the Belt.

5. System architecture

The system responsible for the conversion of asteroidal ice into propellant grade HTP can be broken down into two subsystems. The first, the Water Harvesting System (WHS) collects regolith ice and processes it into water. The second, the HTP Production System (HPS), converts this water into 90–98% HTP, storing the HTP for use in reaching the next destination. The HPS is in development by Orbit Fab, and this paper focuses on this subsystem as a key enabling technology for the Grand Landed Tour. Several systems which are capable of handling part or all of the conversion from icy regolith into liquid water are in development by organizations including Masten Space Systems, Lunar Outpost, Honeybee Robotics, TransAstra, and NASA [8,9,20,21].

The combined system is shown in Figure 5 and will be capable of processing icy regolith into rocket-grade propellant.

5.1 HTP Production System

The HPS which enables the Grand Landed Tour takes advantage of the fact that both water and hydrogen peroxide are composed solely of hydrogen and oxygen. All that is required is to rearrange the atoms, resulting in hydrogen peroxide and excess hydrogen, which can be used for another process or discarded, depending on the system architecture use case.

The HPS requires only water and power as inputs, and produces propellant-grade HTP, which can be up to 98% concentration. This paper analyzes a system which produces 90% HTP. The HPS is composed of three major subsystems: the electrolyzer, the proton-exchange membrane (PEM) cell, and the concentrator.

Water is separated into hydrogen and oxygen in an electrolysis cell. Electrolysis cells exist which have space heritage and are high-TRL, so the development of this system will not primarily rely on electrolysis cell development. Approximately 2–4% of the water used by the HPS must first be electrolyzed and is then introduced to the PEM cell.

The PEM cell rejoins the hydrogen and oxygen into hydrogen peroxide. On the cathode side of the cell, the following oxygen reduction reaction is caused by a catalyst-coated membrane: $O_2 + H_2O + 2e^- \rightarrow HO_2^- + OH^-$. On the anode side, the following hydrogen oxidation reaction is caused by a second catalyst-coated membrane: $H_2 \rightarrow 2H^+ + 2e^-$. The products of these two reactions are combined via a porous solid electrolyte in the central flowing water stream to produce 3% hydrogen peroxide. This process is summarized in Figure 6. This PEM cell is in development at Rice University.

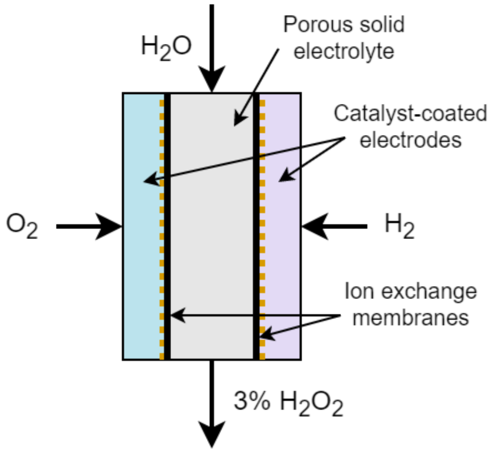

Figure 6. PEM cell which produces a continuous pure stream of low-concentration hydrogen peroxide from inputs of water, oxygen, hydrogen, and power.

The resulting low concentration stream of hydrogen peroxide passes through a concentration system, consisting of a series of concentration steps which successively remove water, transforming 3% peroxide into 90% HTP. This concentration system is produced by X-L Space Systems, which has commercially deployed similar HTP systems. As a final step, the output stream of HTP is stabilized and stored.

The ability to produce propellant on site at an asteroid or other celestial body means that missions that would have previously been limited to one or two stops, due to fuel tank capacity, can now be extended semi-indefinitely. Furthermore, the HPS is not limited to one configuration and can be adjusted to the desired architecture to include inputs of oxygen, hydrogen, and air, which reduce system energy requirements.

6. Trade study

We performed a trade study to determine the mass and power required for each system in order to execute the Grand Landed Tour. We compare the mass and power requirements given various refueling rates at the destination asteroids.

We created rough estimates of the delta-*v* required to travel between asteroids similar to Sylvia, Rollandia, and Hilda, including ascent and descent, as well as the approximate transfer time. These data are summarized in Table 2. This enables us to calculate propellant mass required to make each stop using the Tsiolkovsky rocket equation. The propellant mass informs the corresponding dry mass of equipment necessary to harvest water and produce the HTP propellant, based on how rapidly we wish to refuel the spacecraft.

Table 2. Approximate delta-*v* and time required to travel between the surfaces of several Main Belt asteroids.

	Ceres to Silvia	Silvia to Rollandia	Rollandia to Hilda
delta-*v* (km/s)	2.1	2.1	0.7
time (yr)	2.8	3.6	3.9

The refueling time at each asteroid can be calculated using the estimated relationship between HTP production rate and system mass and power. Thus, by scaling the WHS and HPS up or down, we scale the rate of HTP production up or down. The optimal system size may be selected based on desired spacecraft mass or power, in conjunction with preferred mission duration. A larger system enables more rapid refueling. The maximum refueling duration may be selected to coincide with optimal timing for the next small-body transfer. As each small-body transfer requires a different amount of propellant, the system may be designed around the transfer that requires the most propellant. We will describe the results of the trade study in terms of the longest refueling stop.

The results of the trade study are summarized in Figures 7 and 8. Figure 7 shows a plot of the maximum spacecraft wet mass in units of kilograms. Figure 8 shows a plot of the spacecraft power consumption during HTP production in units of kilowatts. Both figures are plotted against the maximum refueling time in units of months.

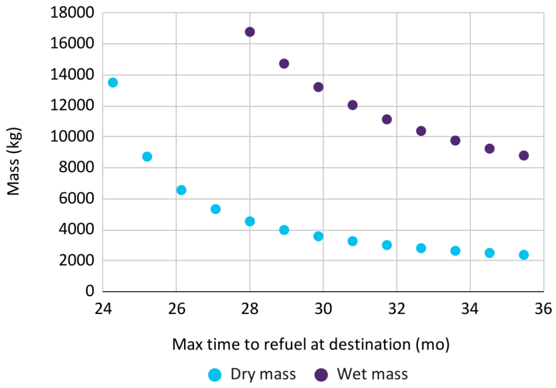

Figure 7. Total spacecraft dry and wet mass, including WHS and HPS, for various refueling durations.

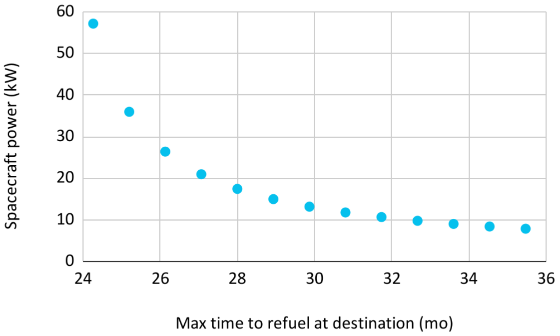

Figure 8. Total spacecraft power during refueling, including WHS and HPS, for various refueling durations.

Both spacecraft mass and power experience a steep incline as the allowed refueling time is decreased. This is due to the fact that, as WHS and HPS become more massive in order to generate fuel more rapidly, the amount of fuel that must be generated to launch those systems also increases. Between 26 and 28 months the curves become less steep. If the maximum refueling rate for a low spacecraft mass and power is desired, selecting a refueling time within that range may be a good choice. If, on the other hand, mission duration does not matter and we wish for spacecraft mass and power to be minimized, we might design a system with a maximum refueling time greater than 28 months, farther to the right.

6.1 A specific mission scenario

A landed mission to the four specified bodies requires three refuelings. Suppose we desire a maximum refueling time at any of the three refueling destinations of no more than 32 months. Then, according to trade study calculations of mass and power presented in Figures 7 and 8, the spacecraft dry and wet masses will be, respectively, 2800 and 10500 kg, with a maximum power of 9.8 kW during refueling. Given the fuel required based on delta-*v* estimates in Table 2, the minimum refueling time will be approximately 8 months, and the total time spent across all three refuelings will be 6 years. Including transfer times, the entire mission will take 18 years. Thus, on average, a new asteroid surface is visited every 4.5 years throughout the duration of the mission.

Note that while the refueling portions of the mission require up to 9.8 kW, more than two thirds of the mission is spent transferring between small bodies and requires much less power, likely around 1 kW.

A comparison of this mission to past asteroid missions is provided in Table 3.

Table 3. Mass and power of previous missions and proposed Grand Landed Tour

Mission	Dry mass	Max power at final destination
Hayabusa2 [22]	500 kg	1.46 kW
OSIRIS-REx [23]	880 kg	1.3 kW
Dawn [24]	748 kg	1.3 kW
Grand Landed Tour	2800 kg	9.8 kW

Because the Grand Landed Tour mission contains the WHS and HPS, which convert icy regolith into propellant, spacecraft mass and power requirements are higher than previous asteroid missions.

Due to the high power requirements during refueling, radioisotope power may be the best power option for this mission. Many notable missions have used radioisotope power systems, including Cassini and the Mars rovers Curiosity and Perseverance [25–27]. Use of radioisotope power could avoid the problem of solar panel contamination by regolith stirred up during repeated takeoffs and landings, and could provide heat needed to melt regolith ice. The trade study mass presented in this paper assumes use of a radioisotope power system. Future work should include a trade study of various power options for the Grand Landed Tour.

6.2 Mass and power calculation background

The mass and power of the electrolysis unit are based on the International Space Station (ISS) Oxygen Generation Assembly (OGA), which uses electrolysis to produce breathable oxygen from water [28]. Although the Grand Landed Tour does not require a human-rated electrolysis system, and electrolysis technology has improved since the OGA began operating in 2000, the numbers reported after 14 months of operation are used in this trade study as a worst case scenario.

The mass and power of the PEM cell are estimated based on measurements from ongoing work with a laboratory PEM cell unit at Rice University.

The mass and power of the HTP concentrator are estimated based on commercially deployed terrestrial systems from X-L Space Systems, with margin added for development as a microgravity system.

The mass of the WHS was estimated based on data reported by TransAstra on the Honey Bee system, which is an optical mining system [29]. This type of system was chosen as a baseline instead of a drilling system because of its ability to scale to suit a variety of mission sizes.

To account for expected improvements in performance throughout development, the mass and power of the WHS, electrolyzer, and PEM cell are multiplied by a scaling factor of 0.7.

Mass and power of standard spacecraft systems, such as the spacecraft bus, were estimated based on an average of those on previous asteroid missions. 15% of mission dry mass excluding WHS, HPS, and power systems is allocated to the scientific payload, such as instruments, sensors, and other hardware for in-situ data collection.

It was assumed that the mass and power of the WHS and HPS subsystems scale linearly with HTP production rate. Electrolysis and PEM cell subsystems are expected to exhibit close-to-linear scaling, as flow output is proportional to cell area. WHS and concentrator subsystems are expected to scale sufficiently linearly for the estimates of system mass and power provided in this paper, but will exhibit some nonlinearity due to their complexity, particularly at very low and high flow rates. Future experiments should improve the estimation of subsystem scaling.

The mission trajectory defined in this paper was calculated as a hypothetical approximation. As the mission development progresses, the precise destinations and delta-*v* required for each can be calculated. Similarly, the mass and power requirements were estimated for each subsystem based on the best available source, including prior missions, laboratory experiments, and commercial experience. Later mission development should produce more precise estimates of mass and power.

Improvements in mass and power efficiency of the WHS and HPS will shift the mass and power curves to the left, resulting in great improvements in feasibility for shorter-duration missions.

7. Technical path forward

A number of risks must be addressed in the technical development of the Grand Landed Tour architecture, such as low water purity, regolith contamination and associated equipment wear, and asteroid regolith composition. Mitigation strategies could include extensive testing with regolith simulant and careful selection of asteroid destinations prior to launch, as well as maintenance of a fuel reserve and multiple or cyclical internal purification steps during the mission. Future work should conduct a detailed assessment of risks and suggested mitigation strategies.

Because refueling duration is sensitive to spacecraft mass and power consumption, priority should be placed on optimizing for energy efficiency and mass reduction. Future work should focus on raising the TRL of the key enabling technologies for the Grand Landed Tour. Table 4 highlights the status and TRL of the WHS, HPS subsystems, and spacecraft systems.

Table 4 TRLs of subsystems involved in producing propellant-grade HTP from icy regolith.

Subsystem	Status	TRL
WHS	Testing in laboratory space-analog environment [21,30].	2-4
Electrolysis	Operating in space environment [28].	9
PEM cell	Operating in lab environment [31].	3
Peroxide concentration	Operating in terrestrial commercial environment [32].	4
Spacecraft systems	Tanker-001 Tenzing carrying HTP flown by Orbit Fab in 2021 [7].	8–9

The WHS is the lowest-TRL system involved in the Grand Landed Tour spacecraft. While continuing in development, the WHS should be designed for the expected regolith composition and water content of the asteroids to be visited. Future publications and scientific efforts should explore this system's readiness for autonomous in-situ use. The mass and power of the complete WHS should be estimated and reported.

The PEM cell is currently at TRL 3 and has been continuously operated in a laboratory environment for over 100 hours [31]. In order to make the system ready for use in space, it must be scaled up and the construction materials should be optimized. Optimizations could include peroxide stability, cell longevity, autonomy, and tolerance to wide ranges of input water purity. Both the catalysts and the construction materials will play a role in these optimizations.

The concentrator is in operation in commercial settings on Earth, and is at TRL 4. For use on the Grand Landed Tour it should be modified to function in low-gravity or microgravity environments. These modifications will include the use of lighter materials, such as aluminum instead of stainless steel, and the addition of a radiative heatsink. At the same time, the concentration system should be optimized for completely autonomous operation and reduced power consumption, as it is the highest power subsystem in the proposed architecture.

8. Conclusions

Asteroid missions, particularly surface missions, are extremely valuable for scientific and economic sustainability. Landing on multiple small bodies in the Main Belt could shed light on the formation of the Solar System and provide valuable data for future prospectors of asteroid resources.

Past asteroid missions have been limited in scope and duration by their limited fuel supplies. Refueling propellant on-asteroid will improve the reach of future missions, and enable mission architectures that have previously been out of the question.

In-situ HTP production is enabled by the Orbit Fab HTP Production System in development with a cross-disciplinary group of collaborators. Prior to the development of the Orbit Fab HPS architecture, an HTP-fueled asteroid mission with in-situ refueling was infeasible due to the resources and complexity required to produce HTP. When combining the Orbit Fab HPS with other proposed technologies for asteroidal water harvesting, the Grand Landed Tour becomes possible.

The trade study presented in this paper paints a picture of the expected scale of an HTP-fueled ISRU mission, and sheds light on the priorities and next steps to develop the enabling technologies. A Grand Landed Tour mission could be one of the most effective ways to gain the mission expertise, scientific insight, and technology development necessary to reduce the cost of Solar System exploration and catalyze the Bustling In-Space Economy.

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