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# A Shuttle and Depot Architecture for Reliable and Cost-Effective Refueling Operations in All Orbits

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**Abstract**

Commercial aircraft today are refueled up to 40,000 times throughout their life. Automobiles are refueled 750 times. Even launch vehicles are now being refueled 12 times or more, but spacecraft are never refueled. Spacecraft in operation today are frequently lifetime-limited by fuel capacity; even if the hardware is operating nominally, the spacecraft is discarded when it runs out of fuel. Additionally, the inability to refuel limits a spacecraft's ability to perform many maneuvers. Spacecraft refueling will drastically improve mobility and sustainability, critical components of a bustling in-space economy that must be addressed today in order for our in-space goals to be realized in the coming decades.

Orbit Fab is working to build a ubiquitous, rapidly available propellant supply chain in Earth orbit and beyond. This vision will end the single use paradigm for spacecraft and enable the next generation of missions based on extended lifetimes and unlimited flexibility for maneuvering. To make this vision a reality in an efficient and cost effective way, Orbit Fab has developed a refueling architecture based on Depots and Shuttles. This architecture is capable of refueling customers through several different levels of refueling service as best fits the use case of a particular mission. Fuel Shuttles are highly maneuverable vehicles capable of completing rendezvous, proximity operations, and docking (RPOD) with customer spacecraft and transferring fuel to them using Orbit Fab's GRIP and RAFTI. Depots are passive vehicles which can be used to refuel Orbit Fab's Shuttles or RPOD capable customer spacecraft. This paper details a 'levels of service' taxonomy that Orbit Fab has developed to classify the roles different vehicle designs can play in refueling operations. This taxonomy can accelerate initial feasibility analysis and early planning for refueling mission scenarios. These levels of service may also be applicable to other use cases within the on-orbit servicing, assembly, and manufacturing (OSAM) ecosystem. The paper presents a model of reliability and cost for the Depot-Shuttle architecture and compares it to other architecture options within the levels of service framework. This analysis demonstrates that the Depot-Shuttle architecture is able to provide high service reliability to refueling customers without being cost prohibitive. The paper then presents examples of considerations which drive the mission plans and architectures used for refueling in LEO and GEO. The paper concludes by discussing the next steps towards the deployment of Orbit Fab's Depot-Shuttle architecture.

**Keywords:** refueling, on-orbit servicing, architectures, constellations

**Acronyms/Abbreviations**

| | |
|---|---|
| 6DOF | 6 Degree of Freedom |
| CORE | Common Orbital Refueling Elements |
| ESPA | Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter |
| GEO | Geostationary Orbit |
| GRIP | Grappling and Resupply Interface for Products |
| LEO | Low Earth Orbit |
| OSAM | On-orbit Servicing, Assembly, and Manufacturing |
| RAAN | Right Ascension of the Ascending Node |
| RAFTI | Rapidly Attachable Fluid Transfer Interface |
| RPO | Rendezvous and Proximity Operations |
| RPOD | Rendezvous, Proximity Operations, and Docking |
| SPARK | Smart Prox-ops and Rendezvous Kit |
| UMPIRE | Universal Mission Planner to Investigate Refueling Effectiveness |

## 1. Introduction

Orbit Fab envisions a thriving, bustling in-space economy. Such an economy is not possible without a robust refueling network. Unlike cars, aircraft, and rockets, satellites are not currently designed for refueling and are normally thrown away after running out of propellant. Orbit Fab exists to change this single-use paradigm.

The U.S. Space Force reported in 2021 that $100B worth of satellites have been abandoned in the last 10 years. Many of these satellites would not have been abandoned had they been resupplied with propellant to continue their mission. For example, in mid-2021 the Measat-3 GEO broadcast and telecommunications satellite ran out of fuel prematurely. This resulted in a $45M insurance claim on the satellite, which at the time of writing is in dispute. After the anomaly was detected an attempt was made to move the satellite from GEO to a graveyard orbit, but the satellite was moved less than halfway to its graveyard orbit before becoming inoperable, resulting in increased risk to other satellites in the GEO belt [1]. More recently, in 2022, the Telesat Anik F2 satellite ran out of fuel and was forced to retire three years before its expected end of life. The satellite was not insured, and the fuel shortage will likely cost its operators $13M in lost revenue next year [2].

Not only will on-orbit refueling prevent expensive, premature, and hazardous failures like these, it will enable new mission concepts and help extend the operational lifetimes of space assets. Missions will no longer be constrained by the limitations imposed by the amount of propellant they carry at launch, driving new approaches to spacecraft design and operations. This results in significant cost and schedule savings. One spacecraft can complete repeated or extended missions, saving costs and schedule delays for asset replacement. Spacecraft can also be launched with less initial fuel supply and refuel later, saving on system size, complexity, and launch cost. Access to fuel on-orbit also offers enhanced flexibility; with refueling available, spacecraft operators can more easily elect to reposition assets based on changing operational circumstances. Additionally, refueling increases the efficiency and availability of other on-orbit servicing and manufacturing (OSAM) activities by enabling complex servicing vehicles to operate longer and serve more clients over a wider variety of orbits. Orbit Fab recently signed the first on-orbit satellite fuel sale agreement with Astroscale US to deliver up to 1,000 kg of Hydrazine and Xenon propellant in GEO [3]. This delivered propellant will result in increased servicing capability and lifetime for Astroscale's OSAM satellites. Refueling will decrease costs and increase revenues for satellite operators as shown in Figure 1.

In order to enable on-orbit refueling, Orbit Fab has developed the RAFTI fueling port. RAFTI is a TRL 8 commercially available simplified docking and refueling interface designed for cooperative and prepared refueling in space. It is a drop-in replacement for a satellite fill-and-drain valve and enables autonomous ground and on-orbit fueling operations. When equipped with the RAFTI fueling port, satellites can refuel from a commercial network of disaggregated fueling spacecraft in Low Earth Orbit (LEO), geostationary orbit (GEO), and cislunar space. Orbit Fab is also developing the Grappling and Resupply Interface for Products (GRIP) which is the active docking interface capable of mating with RAFTI on-orbit and performing fuel transfer.

To date, Orbit Fab has flown two missions to build out its refueling network and capabilities. The first, Furphy, flew to the ISS in 2018 and became the first commercial mission to replenish the ISS water supply. It proved out critical path refueling technology including propellant transfer and fluid dynamics. The second, the Tanker-001 Tenzing satellite, flew in 2021 carrying

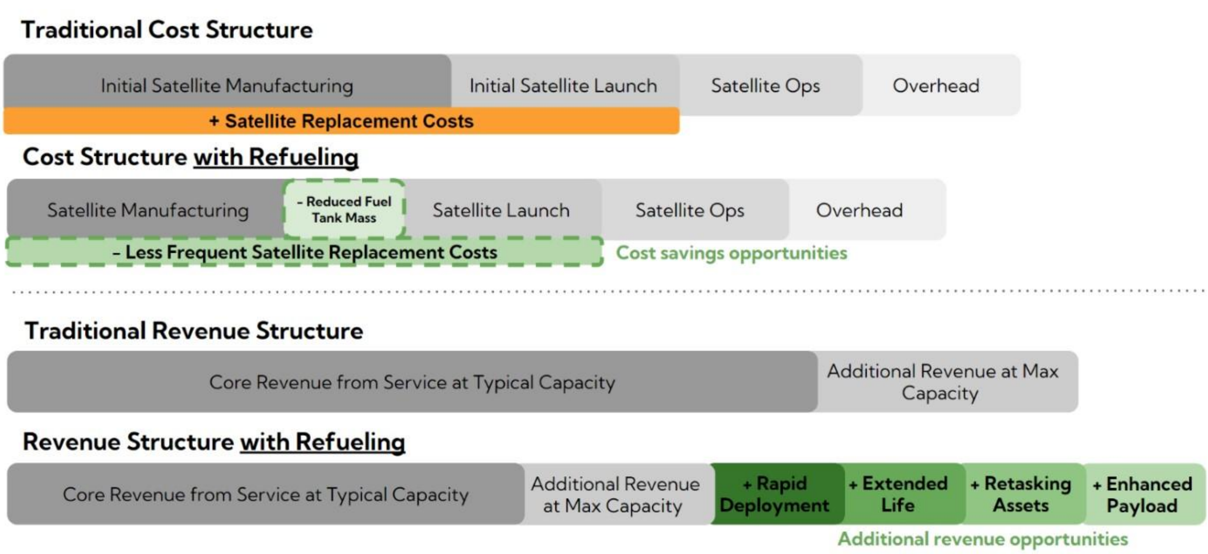


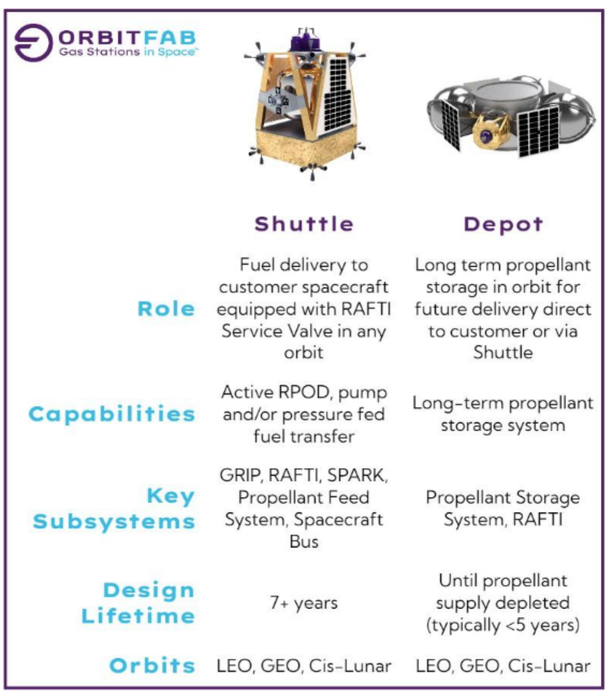

Fig. 1. Satellite refueling on orbit enables significant cost savings and increases the number of revenue opportunities for assets

high-test peroxide as Orbit Fab's first Fuel Depot in space. These missions serve as technology advancement milestones towards the Orbit Fab in-space refueling network.

This paper discusses the Orbit Fab refueling architecture, including how Shuttles and Depots relate to one another and support an effective refueling network, in Sections 2 and 4. The paper also covers Orbit Fab's expected levels of refueling service in Section 3. Section 5 details examples of considerations that must be taken into account when developing refueling architectures and mission plans in LEO and GEO. Last, Section 6 outlines Orbit Fab's plans for developing refueling technologies leading to the first commercial in-space refueling operation expected in 2024.

## 2. Fuel Depots and Fuel Shuttles

The Orbit Fab refueling architecture consists of two types of vehicles: Fuel Depots and Fuel Shuttles. Fuel Shuttles are highly capable and maneuverable vehicles with active RPOD capabilities. Depots are focused on the long-term storage of propellant and used to refuel Orbit Fab Fuel Shuttles and RPOD capable customer spacecraft. Figure 2 describes the basic characteristics of Depots and Shuttles. Both vehicle types are built on the Orbit Fab Common Orbital Refueling Elements (CORE), which includes the components which are essential to all Orbit Fab refueling vehicles. These components include, at minimum, the RAFTI Service Valve, docking fiducials, fluid management, and a tank. GRIP and fluid pump are included if the spacecraft will be actively docking with RAFTI on a client or Depot. Figure 3 illustrates the way that CORE builds into Depot and Shuttle designs.




| | Shuttle | Depot |
|---|---|---|
| Role | Fuel delivery to customer spacecraft equipped with RAFTI Service Valve in any orbit | Long term propellant storage in orbit for future delivery direct to customer or via Shuttle |
| Capabilities | Active RPOD, pump and/or pressure fed fuel transfer | Long-term propellant storage system |
| Key Subsystems | GRIP, RAFTI, SPARK, Propellant Feed System, Spacecraft Bus | Propellant Storage System, RAFTI |
| Design Lifetime | 7+ years | Until propellant supply depleted (typically <5 years) |
| Orbits | LEO, GEO, Cis-Lunar | LEO, GEO, Cis-Lunar |

Fig. 2. Orbit Fab's Fuel Shuttles and Depots fill different roles in a refueling architecture, and therefore have different capabilities and design parameters

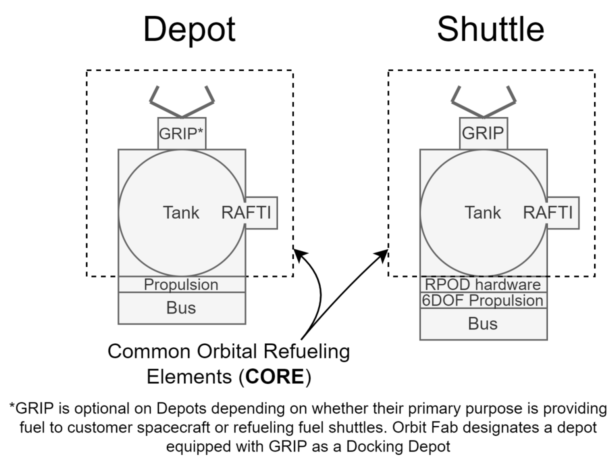



Fig. 3. Orbit Fab's Fuel Depots and Shuttles are based on Common Orbital Refueling Elements (CORE)

Fuel Depots are designed to transport fuel into space and store it as effectively and efficiently as possible. Depots are low cost, designed to contain a high mass-fraction of fuel and minimal electronics which provide ADCS and payload support functionality. Once in orbit they follow a simple concept of operations, maintaining and monitoring propellant storage and performing maneuvers only as needed for station keeping purposes while they await fuel transfer. Depots are built on CORE, which includes RAFTI for fuel transfer. When depleted, a Depot is safely decommissioned in accordance with standard procedures for its operational orbit.

Fuel Shuttles are also built on CORE, but also have RPO capabilities provided by a Smart Prox-ops and Rendezvous Kit (SPARK) and a highly maneuverable propulsion system. Shuttles are also equipped with GRIP to enable docking with the RAFTI interface. Because of their RPOD capability, Fuel Shuttles enable propellant to be transported from a Depot to a client equipped with RAFTI. Fuel Shuttles are higher value than Depots and will be reusable dozens of times, amortizing cost over their service life. Fuel Shuttles are designed with high individual reliability as they interface with customer spacecraft and are intended for long service life.

The CORE-based design of all Orbit Fab refueling vehicles, including both Shuttles and Depots, enables shared development cost across vehicle types, lowering overall architecture development costs. Most Fuel Shuttles will be equipped with a hydrazine propulsion system, whether they deliver hydrazine, xenon, or other propellants. This further decreases cost, and, even more importantly, decreases propulsion system risk. Rather than rely on several different types of thrusters designed for different types of propellant, with varying levels of flight heritage and RPOD performance, one reliable propulsion system is selected and used on all vehicles.

## 3. Levels of Refueling Service

In order to provide a common language for discussion of refueling operations and support analysis of architecture alternatives, Orbit Fab has designated four levels of service for refueling. These levels of service are outlined in Figure 4. These levels of service encompass the full range of approaches to refueling between two cooperative (i.e. controlled and participating in the refueling conops) and prepared (i.e. designed with refueling in mind) vehicles. The levels are defined based on the critical phases of the refueling operation. The Rendezvous phase consists of matching the orbits and phasing between the two participating vehicles to bring them to a range of around 1 km. At this point, the Proximity Operations phase begins in which one vehicle uses relative sensors and guidance, navigation, and control to close the distance between the two vehicles. At a range of around 10 meters, the final approach phase begins. In this phase the active vehicle uses closed loop control to align RAFTI and GRIP in the capture box for docking. Docking consists of the initial contact and GRIP actuation and is always performed by the Orbit Fab vehicle.

At the highest level of service, Delivery, a Fuel Shuttle transports propellant from a Fuel Depot to the customer. The customer remains in their operational orbit, and the Fuel Shuttle performs rendezvous, proximity operations, final approach, and grappling with GRIP. The next level, Full Service, has the customer maneuver for the rendezvous, matching orbit and phasing with a Fuel Shuttle; the Shuttle then completes RPOD and transfers propellant to the customer. At the Partial Service level, a rendezvous-and-proximity operations-capable customer performs maneuvers up to approximately 10 meters from the Fuel Shuttle. The Fuel Shuttle then performs a final approach and grapples with the customer using GRIP. In most cases this level of service is not preferred as it requires RPO capabilities on both systems but it may be useful in the case of in-space inspection missions which expect to participate in proximity operations without closing to within 10 meters. The lowest level of service, Self Service, rather than involving a Fuel Shuttle and Depot, relies on a Docking Depot. The Docking Depot is a Fuel Depot equipped with GRIP which is not capable of RPOD like a Shuttle, but is capable of detecting a customer and grappling using GRIP. At this level of service, the customer is responsible for performing RPO to place RAFTI within the GRIP capture volume.

At all levels of service, the Orbit Fab spacecraft is responsible for the active transfer of propellant into the customer spacecraft. Fuel Shuttles are equipped with fluid pumping hardware to draw propellant out of a Fuel Depot and transfer propellant into a customer spacecraft. Docking Depots also contain fluid pumping hardware for propellant transfer to customer spacecraft.

The Shuttle-Depot architecture enables levels of service 2-4 in order to offer customers propellant at a price point and concept of operations that imposes minimal, if any, additional capabilities onto their spacecraft. It is expected that the Delivery level of service will be the most common for refueling operations as it removes the need for RPO capabilities on the customer spacecraft. Docking Depots enable the Self Service level of refueling, allowing RPOD-capable customer spacecraft to travel to the propellant source for refueling.

| *Levels of refueling service offered determined by which party conducts each phase of RPOD operations.* | Phases of Rendezvous Proximity Operations and Docking (RPOD) | | | |
|---|---|---|---|---|
| | Rendezvous (Diff Orbit to 1km) | Prox Ops (1km to 10m) | Final Approach (10m to 1mm) | Docking (contact / grappling / docking) |
| **1. Self Service** | | | | |
| Orbit Fab Vehicle | | | | X |
| Client Vehicle | X | X | X | |
| **2. Partial Service** | | | | |
| Orbit Fab Vehicle | | | X | X |
| Client Vehicle | X | X | | |
| **3. Full Service** | | | | |
| Orbit Fab Vehicle | | X | X | X |
| Client Vehicle | X | | | |
| **4. Delivery** | | | | |
| Orbit Fab Vehicle | X | X | X | X |
| Client Vehicle | | | | |

Fig. 4. The roles of Orbit Fab and client vehicles vary depending on the selected level of refueling service

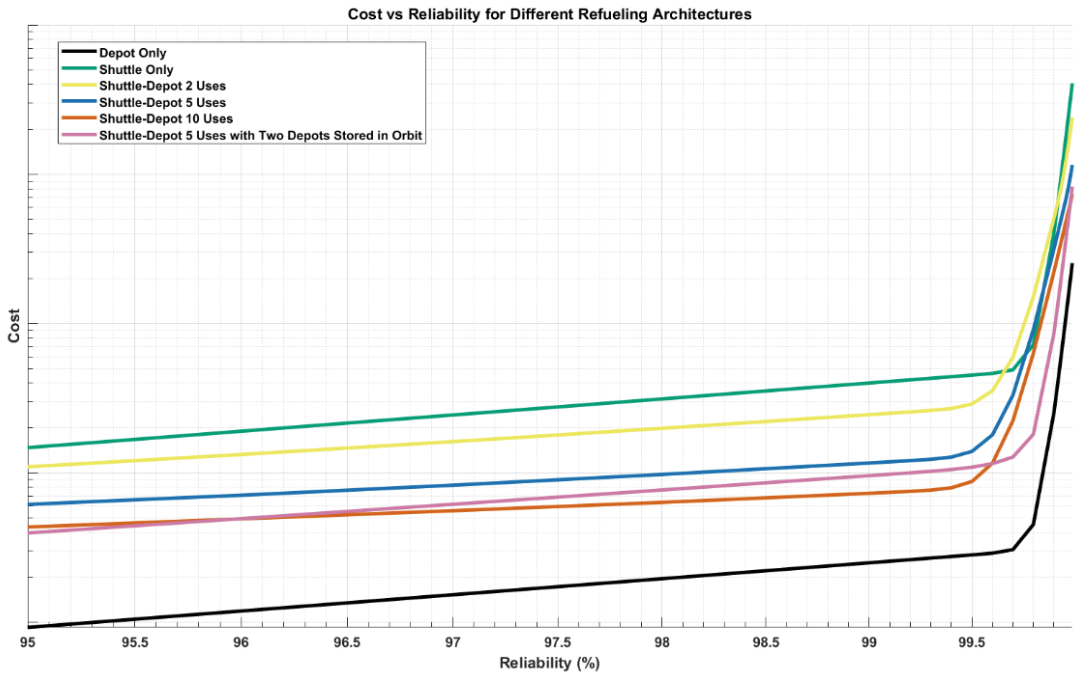



Fig. 5. Cost vs. reliability for refueling architectures considered

## 4. Architecture Selection Based on Cost and Reliability

To develop the Depot and Shuttle refueling architecture discussed in the previous sections, Orbit Fab has conducted extensive analysis of possible refueling architectures. This analysis has included using the Universal Mission Planner to Investigate Refueling Effectiveness (UMPIRE) tool to examine how different architecture options can service various customer scenarios and analysis of the cost and reliability of different architecture options. The former analysis has been published previously [4] while this paper will focus on the latter. The results of the cost and reliability analysis conducted demonstrate that the Depot-Shuttle architecture is the optimal solution for the majority of refueling scenarios and levels of service.

The analysis of cost and reliability conducted considered many possible refueling architectures, four of which are presented here. The Depot only option includes only Depots which do not have active RPO capabilities and may or may not be capable of docking. Similarly, the Shuttle only option includes only Shuttles which are capable of active RPOD. Two different Depot-Shuttle architecture options were considered, one which involves having one Depot on orbit at a time to refuel Shuttles for reuse and one which involves having additional Depots available as back-ups. Each type of vehicle was assigned a base cost estimate for implementation with 95% reliability. This base cost is lower for Depots than for Shuttles as they require less complex busses, less capable propulsion systems, and do not need active RPO capabilities. Generally costs grow exponentially as reliability approaches 100%, so an exponential function was used to model the increase in the base cost as reliability increases [5].

Figure 5 shows the relationship between cost and reliability for the different architecture options considered over a range from 95-100%. Figure 6 shows the same data zoomed in to highlight the 99% to 100% region. For purposes of this analysis, reliability is defined as the percentage of success for the end-to-end refueling operation. The cost as a function of reliability for the Depot only and Shuttle only options was generated by applying the exponential scaling relationship to the base costs for the Depots and Shuttles. For the Depot and Shuttle cases, the cost assumes that the Shuttle is reused across a given number of refueling operations while a new single-use Depot is used to refuel the Shuttle for each refueling after the first. It is possible costs may be further reduced for a given reliability by using larger Depots that can refuel a Shuttle for multiple operations; this will be examined in future work. The reliability was calculated based on both the Shuttle and the Depots needing to be successful to achieve end-to-end success. An interior-point optimization approach was used to find the balance of reliability between the Shuttles and the Depots which would minimize costs. In general, this resulted in higher reliability for the Shuttles as their cost is spread across multiple uses which matches the expectation of Shuttles being the more complex and capable vehicles. The cost is presented without values because the precise costs

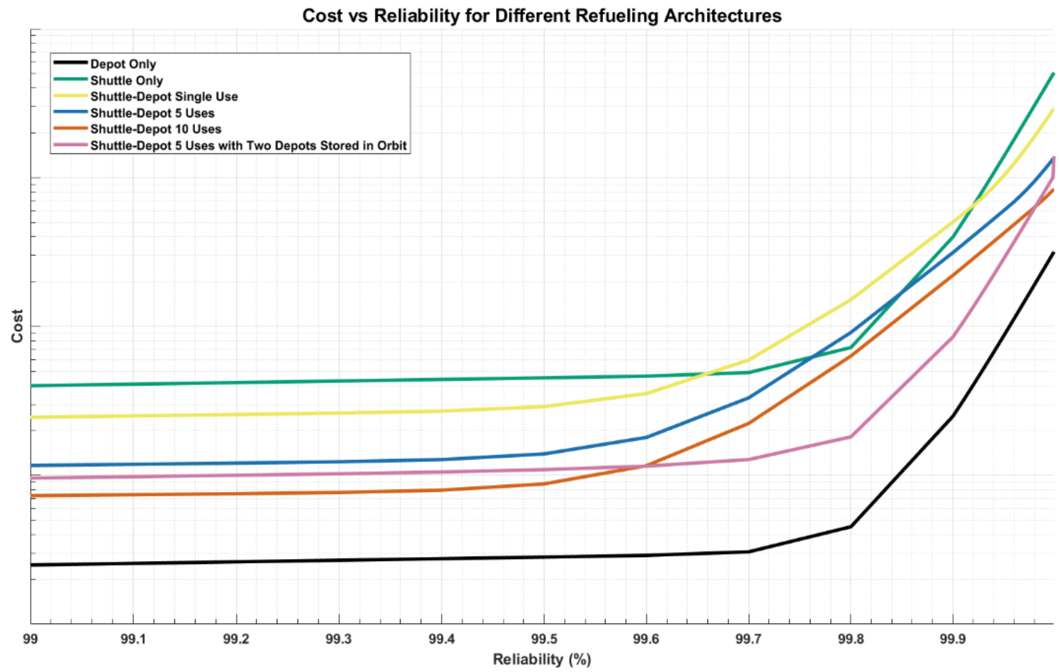



Fig. 6. Cost vs. reliability for refueling architectures considered (99-100% detailed view)

will be mission scenario dependent however the general trend holds the same across scenarios.

The results show that the Depot only option is the cheapest for a given reliability level which matches expectations given the generally lower cost of Depots. As the number of uses increases, the cost for the Depot-Shuttle architecture decreases due to the cost of a reliable Shuttle being split across multiple refuelings. At very high reliability levels (>99.5%) the advantage of the Depot-Shuttle architecture over a Shuttle only approach is somewhat reduced because both the Depots and Shuttles need to be very high reliability. This is mitigated in the case where multiple Depots are available to refuel the Shuttle because the necessary reliability per Depot is reduced.

A similar trend is seen in Figure 7 which shows the relative costs for the different architecture options to achieve 99.7% reliability which corresponds to a 3-sigma confidence level in mission success. At this reliability level, the Depot-Shuttle architecture outperforms the Shuttle only option as long as the Shuttle can be reused at least three times. Significant benefits are also seen with two Depots available to the Shuttle compared to only one because of the lessened reliability required per Depot. Having three Depots available to the Shuttle shows comparatively less benefit over two, indicating diminishing returns.

In all cases considered, the Depot only architecture shows lower costs for a given reliability. However, for most mission scenarios this architecture does not represent a viable option for several reasons. Most importantly, the Depot only option can only provide refueling at a Level of Service of 1 (Self-Service) and the customer vehicle needs to include RPO capabilities which are costly to implement and would in most cases make the actual total cost of refueling to the customer higher. Additionally, because the customer spacecraft would be performing RPO the customer would assume all associated risks, making it a less attractive option. Table 1 summarizes the benefits and drawbacks of the architecture options considered in this analysis. Based on a consideration of all relevant factors, the Depot-Shuttle architecture options present the most attractive balance of cost, reliability, and level of refueling service.

## 5. Refueling Service for Various Orbits

Orbit Fab's Depot and Shuttle refueling architecture is designed to service customer spacecraft in various orbits, including LEO (particularly sun-synchronous orbits (SSO)), and GEO. Refueling solutions are also under development to service various other locations, including cislunar space. Each orbital regime has unique mission and architecture planning considerations to take into account. This section highlights two such considerations, Right Ascension of Ascending Node (RAAN) drift for LEO and phasing alignment in super-GEO orbits to support GEO refueling. Orbit Fab conducts analyses of these and other mission planning considerations for customers using UMPIRE.

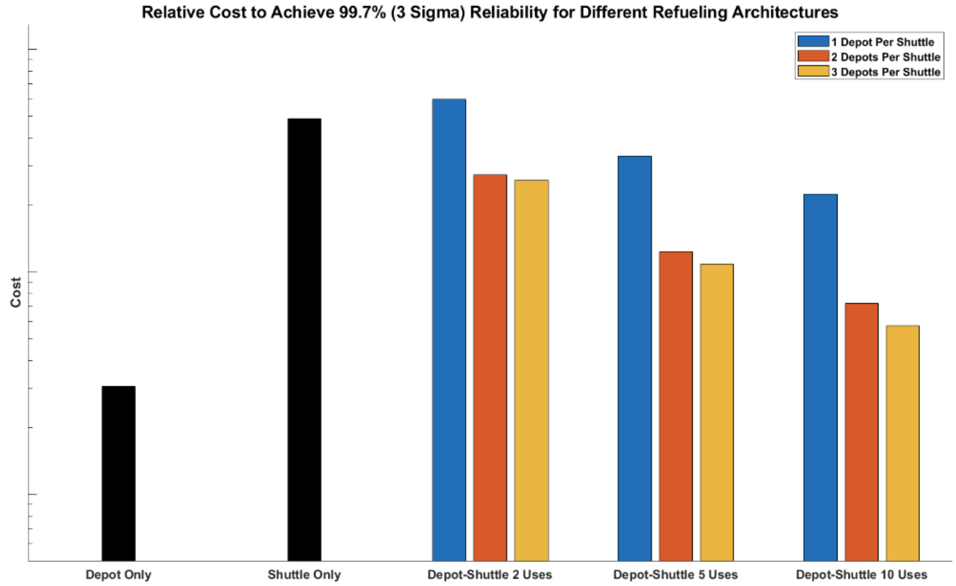



Fig. 7. Cost to achieve 3-sigma reliability for each architecture considered

Table 1. Summary of advantages and disadvantages of each refueling architecture highlights benefits of an architecture which involves both depots and shuttles

| Architecture Option | Cost to Achieve Reliable Refueling | Constraints | Risks to Customer | Levels of Service Enabled |
|---|---|---|---|---|
| **Depots Only** | Low - Multiple depots in orbit provides redundancy against failures | Very High - Customer needs to have RPOD system to refuel. Depots have limited maneuverability for servicing different orbits. | High - Customer bears risks of RPOD system failures | 1 |
| **Shuttles Only** | Very High - Additional hardware of shuttles drives costs for high reliability without reusability from depots | Low - Capable of refueling any spacecraft equipped with RAFTI with the correct fuel type in an appropriate orbit | Low - Orbit Fab RPOD system assumes risks associated with successful RPOD assuming customer compliance with RPOD conops | 1-4 |
| **Depot + Shuttle** | Moderate - Depots enable reusability for shuttles enabling fuel delivery at lower cost | Low - Capable of refueling any spacecraft equipped with RAFTI with the correct fuel type in an appropriate orbit | Low - Orbit Fab RPOD system assumes risks associated with successful RPOD assuming customer compliance with RPOD conops | 1-4 |
| **Multiple Depots + Shuttle** | Low-Moderate - Availability of additional depots in orbit enables cheaper manufacturing of depots with the same total architecture reliability | Moderate - Constrained by launch availability for placing multiple depots in orbits of interest | Low - Orbit Fab RPOD system assumes risks associated with successful RPOD assuming customer compliance with RPOD conops | 1-4 |

*5.1 LEO RAAN Drift*

In LEO, potential refuelable satellites tend to inhabit distinct serviceable clusters differentiated by orbital planes defined by RAAN and inclination. By strategically placing Depots and Shuttles near these serviceable clusters, refueling is made more efficient and customer costs are reduced. Using the Depot-Shuttle architecture, the vast majority of SSO customers are serviceable within 170 m/s roundtrip delta-v expenditure from Depots in a cluster optimized location. In addition, Fuel Shuttles/Depots can take advantage of differential RAAN drift in order to transfer between orbital planes in LEO. Fueling spacecraft which use this method effectively trade time for delta-v. A direct transfer between planes which costs a certain amount of delta-v can be accomplished with far less delta-v expenditure by simply waiting for RAAN drift to bring the spacecraft into the desired plane. Figure 8 illustrates the tradeoff between delta-v expenditure and time allowed for RAAN drift for the extreme case of a 180 degree plane change. For example, a Depot in a 70 degree orbit inclination would require approximately 350 m/s of delta-v to accomplish a 180 degree plane change in 10 months, But, if customer refueling needs are anticipated farther ahead of time and more time is allowed for RAAN drift to occur, the same plane change can be accomplished with significantly less delta-v. In an operational scenario, RAAN drift will occur in far less time, due to the fact that operational Depots will make single- or double-digit degree transfers, not 180 degree transfers.

*5.2 Super-GEO Orbits*

Of the operational satellites in geosynchronous orbit, nearly all are positioned in a geostationary orbit. Therefore, in order to optimize distance from the vast majority of serviceable satellites, Fuel Shuttles and Depots which service the GEO market are deployed to a super-GEO 'service lane' orbit 300 kilometers above the GEO belt. This causes Depots and Shuttles to precess around GEO every few months, enabling timely delivery to all GEO customers while only expending delta-v on the roundtrip from super-GEO to GEO. Figure 9 shows the precession time around the GEO belt for various super-GEO orbits as well as the necessary delta-v for transfer between that orbit and the GEO belt. Orbit Fab's GEO + 300 km 'service lane' orbit has been selected based on balancing delta-v needs with transit time. The first generation of refueling operations in GEO is expected to occur in this orbit as a risk mitigation of potential disruptions to spacecraft operating in GEO but it is expected that deliveries directly to the GEO belt will be available in the future.

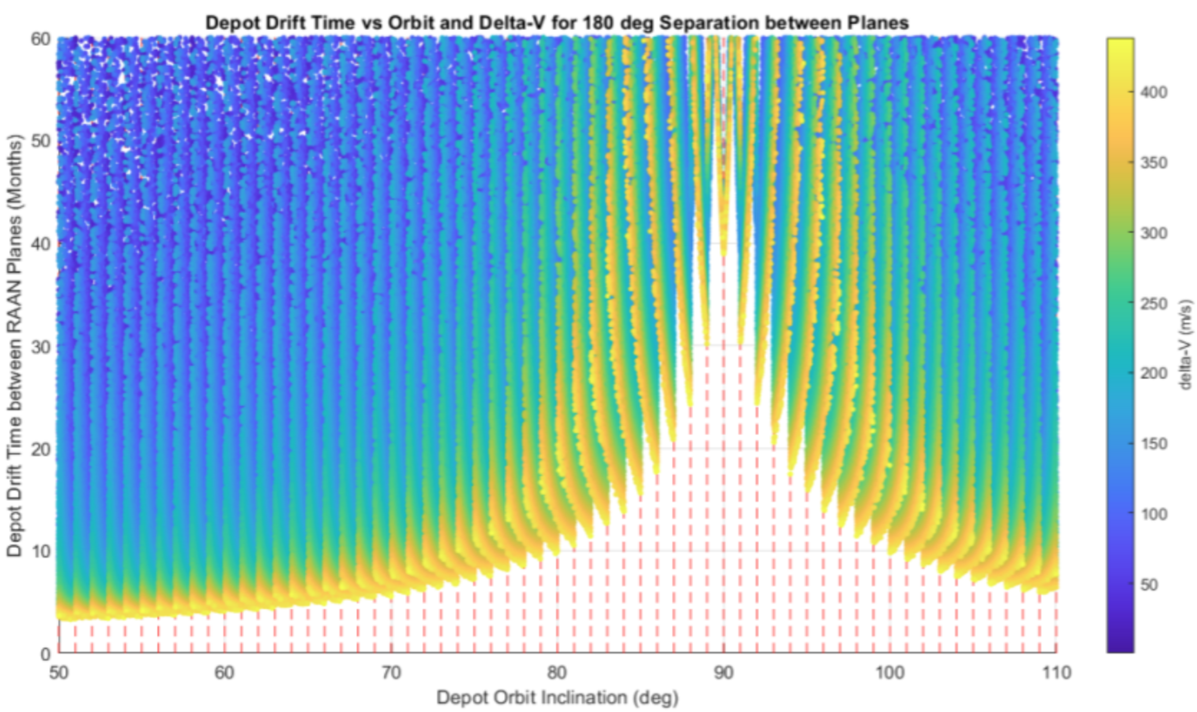


Fig. 8. For a Depot in a given orbital inclination, less delta-v is required to accomplish an extreme plane change if time is given for RAAN drift to occur [4]

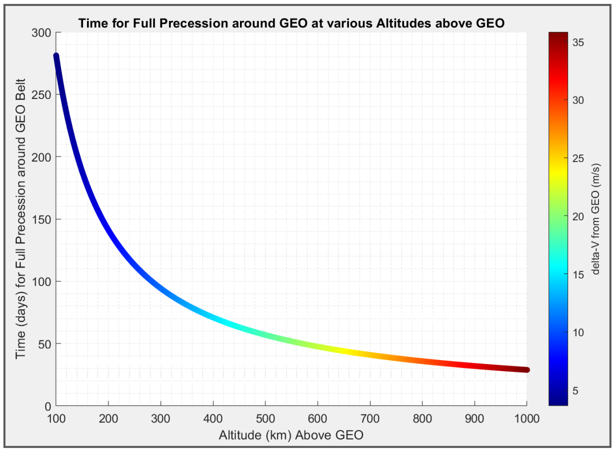



Fig. 9. Precession time around GEO belt and transfer delta-v for various super-GEO orbits

## 6. Roadmap to the First Commercial Satellite Refueling Mission

As the space industry grows, the number of missions and conops have expanded greatly, with greater demand for fuel across orbits. Geostationary Orbit (GEO), which traditionally has been an orbit that is very difficult to access and operate within compared to Low Earth Orbit (LEO), is quickly becoming one of these regions. With the recent announcement of the fuel sale agreement for Orbit Fab to deliver fuel to Astroscale in GEO in the late 2020s [3], the recent announcement of pricing for hydrazine refueling services in GEO [6], and many other refueling discussions and agreements in negotiation, Orbit Fab has committed to developing the required infrastructure to make this GEO refueling vision possible. One of the major steps in this is the Orbit Fab Rancor payload, which is a Docking Depot hydrazine ESPA port refueling module designed for GEO. This payload contains a number of different pieces of hardware, avionics, and software building off of the Tenzing mission which launched in 2021 intended to mature Orbit Fab's manufacturing, on-orbit experience, operations, and flight legacy. Orbit Fab's Rancor payload will include critical subsystems for operational testing in the GEO environment. The flight avionics will validate motor control and fluid systems control built on a 'careful COTS' radiation-hardened architecture. Rancor will include GRIP, Orbit Fab's active docking and fluid coupling mechanism, which will enable refueling of a client vehicle equipped with RAFTI. Additionally, the fluid storage and transfer system architecture will be validated through mission operations and provide a test bed for transfer operations and performance until the propellant is delivered to a client.

Orbit Fab is similarly developing the infrastructure necessary to create a robust refueling network in LEO and SSO, which will build on the Tenzing Depot. Orbit Fab is building towards the first commercial on orbit satellite refueling, the Trailblazer mission. Trailblazer will comprise two monopropellant hydrazine Fuel Shuttles built on the CORE module, launched to SSO. These Shuttles will be the first of many in Orbit Fab's low Earth orbit refueling network, and will complement the Tanker-001 Tenzing Fuel Depot and Rancor refueling module. The Trailblazer mission will first demonstrate a refueling between Orbit Fab vehicles prior to being commissioned for client refueling. Trailblazer will build on the technology advancements accomplished through Rancor, and will similarly be equipped with GRIP and RAFTI. Unlike Rancor, the Trailblazer satellites will also be equipped with the SPARK RPOD system which enables active rendezvous, proximity operations, and docking to provide all four levels of refueling service. Orbit Fab is also pursuing several opportunities to derisk key Fuel Shuttle technologies such as RPOD systems and fuel transfer through unit testing of individual system elements on the ground and in flight. These steps will enable implementation of Orbit Fab's refueling architecture and lead to ubiquitous access to propellant in orbit, which will reduce the cost of operating spacecraft and enable classes of missions which were previously infeasible due to delta-v requirements.

## 7. Conclusion

Recent high-profile satellite failures resulting from running out of propellant have highlighted the need for an available, reliable, and cost effective refueling network in orbit. Orbit Fab is working to build out a refueling network in Earth orbit and cislunar space. An effective refueling architecture will change cost structures and revenue structures for refueling customers and create new market opportunities. Cost-effective, reliable refueling will reduce the cost of operating in space, reduce waste and debris in orbit, and enable many concepts of operations which are not currently feasible.

Orbit Fab has selected a Depot and Shuttle architecture for refueling. This architecture is able to provide higher reliability at lower cost compared to a Shuttle only architecture while maintaining the ability to service a wider range of customer spacecraft than a Depot only architecture could provide. Orbit Fab's levels of refueling service connect this architecture with customer needs and capabilities to provide effective refueling for all customers. Depots and Shuttles are strategically positioned to take advantage of features of the orbit to create order-of-magnitude reductions in delta-v expended to reach the customer, reducing the cost of refueling. The CORE architecture enables Depots and Shuttles to share common features, reducing development and production costs. All of these design features add up to result in an affordable and reliable refueling network. The RAFTI fueling port is the first step towards this in-space refueling network. The Orbit Fab Tanker-001 Tenzing Fuel Depot is the first spacecraft in the fueling network to be deployed on orbit. This mission and related technology developments will pave the way for future Shuttles and Depots in LEO, GEO, and beyond, ultimately building a bustling in-space economy.

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