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Orbital Reef: Redefining Commercial Space Station Operations

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Abstract

Blue Origin and Sierra Space are jointly developing and deploying a commercially owned and operated space station in low Earth orbit (LEO) called Orbital Reef. The Orbital Reef baseline configuration will be operational later this decade prior to ISS transition. Orbital Reef provides all the necessary services and amenities required by researchers, manufacturers, service providers, and visitors alike, including space transportation and logistics, space habitation, equipment accommodations, and operations by an onboard crew. We are building on lessons learned from ISS operations by implementing new commercial processes, capacities, and product offerings, all aimed at lowering barriers to entry and expanding access to a global customer base. The Orbital Reef will be the common interface and operating system in space upon which hundreds of customers can pursue their applications, leveraging all or portions of the system's offerings. Orbital Reef's tenet of "space as a service" drives our approach to commercial operations with a customer-centric philosophy. Our Customer Experience (CX) office ensures the access, services, and capabilities that enable our customer's mission success in a safe, reliable, and cost-effective manner. The design and development of Orbital Reef products, services, and ecosystems are based upon our customer's requirements, needs, and desires. The Orbital Reef architecture is designed to optimize commercial station operations and diverse customer mission profiles. Example customer missions include ground-based principal investigators conducting research on Orbital Reef, civil space astronauts performing training missions, and private guests with experiential motivations. This paper describes how Orbital Reef will balance the unique operational considerations of these customer missions with station-critical operations in a commercial environment.

Keywords: Orbital Reef Commercial Space Station

Acronyms/Abbreviations

AWS	=	Amazon Web Services
CBM	=	Common Berthing Mechanism
CLD	=	Commercial LEO Destination
CX	=	Customer Experience
ECLSS	=	Environmental Control and Life Support System
EVA	=	Extravehicular Activity
EVR	=	Extravehicular Robotics
HSRB	=	Human System Risk Board (NASA)
IDSS	=	International Docking System Standard
ISS	=	International Space Station
LEO	=	Low Earth Orbit
LIFE	=	Large Integrated Flexible Environment
LCVG	=	Liquid Cooling Ventilation Garment
MLE	=	Middeck Locker Equivalents
MSFO	=	Mission Systems and Flight Operations
NASEM	=	National Academies of Science, Engineering, and Medicine
SAFER	=	Simplified Aid for Emergency Rescue
SANS	=	Spaceflight Associated Neuro-Ocular Syndrome
SMA	=	Safety and Mission Assurance
SPS	=	Single Person Spacecraft

1. Introduction

Orbital Reef is designed to be the first free-flying commercial destination in LEO. The space station reimagines the well-understood and successful terrestrial model of mixed-use business and research parks, applying the model to space. The undersea reef namesake evokes a stable home for life in a harsh environment with a diverse, growing, and self-reinforcing ecosystem. Orbital Reef lowers the barrier to entry and reduces the risk of doing business in space by providing shared infrastructure for a wide community of users. Orbital Reef removes the need for customers to manage infrastructure and creates the predictability needed for investment. A variety of customized spaces in this new mixed-use business park enables specialization in new business ventures across established and nascent markets, ranging from research and industry to entertainment and hospitality to port-of-call for exploration missions. Orbital Reef is a partnership between Blue Origin and Sierra Space, with teammates Boeing, Redwire Space, Amazon/AWS, Genesis Engineering, and Arizona State University.

Orbital Reef also continues to address the need to meet current scientific research and exploration technology goals not yet met. Research conducted onboard the International Space Station (ISS) has addressed many of the priorities designated within the 2011 National Academies of Science, Engineering, and Medicine (NASEM) Decadal Survey [1]. However, the development of research and technology will not be completed by the end of the ISS program in 2030, as concluded in the Academies' Midterm Assessment [2]: "a large amount of science remains to be done to best support the move to deep space." The report found "fundamental understanding of human health and behavior risks in microgravity, combined with fundamental microgravity physics and materials, in an integrated manner, is essential to extending the human neighborhood beyond LEO." It identified that "significant risks remain, particularly in understanding the radiation environment and its effects, environmental control and life support, human behavior, and protecting long-term crew health with integrated countermeasures." In this report, NASEM recommends increased coordinated use of the ISS along with privately developed facilities to accelerate the science needed to continue space exploration.

2. Overview of Expected Orbital Reef Capabilities

Orbital Reef is a large commercial space station slated to be built in the late 2020's in advance of the planned retirement of the ISS. It is designed for LEO operations and can support Orbital Reef Crew, Guest, and customer payload operations [3].

Orbital Reef's preliminary baseline configuration (Fig. 1) consists of four large, habitable modules. It includes pressurized payload accommodations for hundreds of Middeck Locker Equivalents (MLE); large volumes of passive and conditioned stowage; a modernized microgravity research laboratory equipped with exposed-payload interfaces, science airlock, and full suite of payload facilities; external robotics; and two methods for extravehicular activity (EVA) – traditional suited EVA and Single Person Spacecraft (SPS). Visiting vehicles and a SPS can support co-orbiting free-flyers for any customer, allowing for autonomous exploration experiments, isolated microgravity environments, and unique views of the Orbital Reef, the Earth, and deep space.

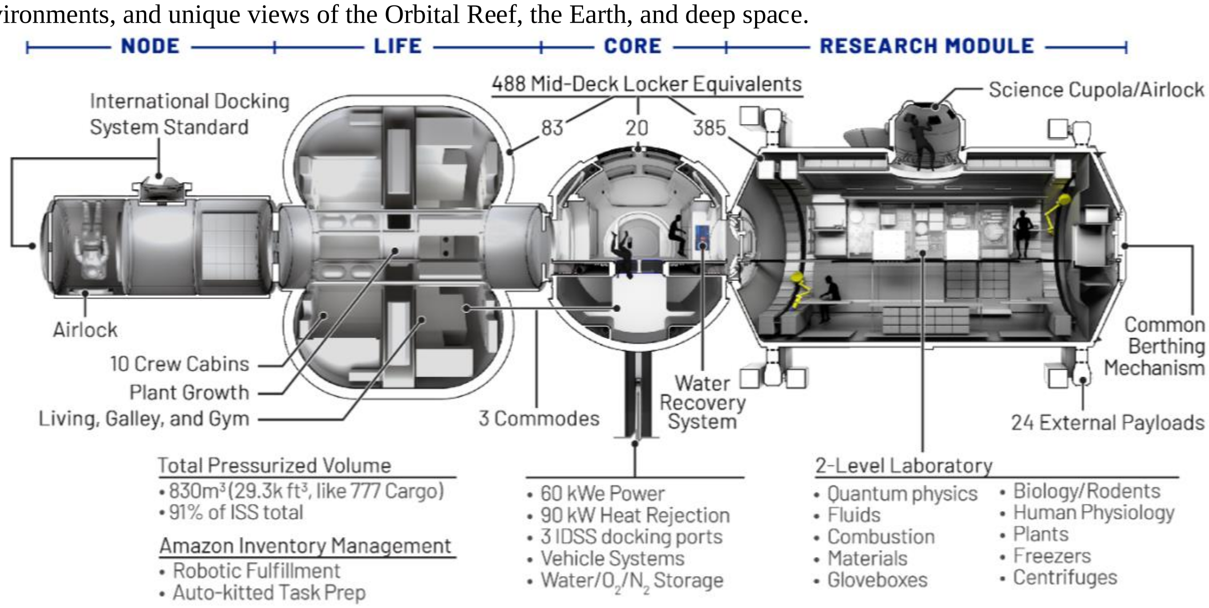

Fig. 1 Orbital Reef with four pressurized modules: Node, LIFE, Core, and Research

The station offers payload accommodations from lockers to large facility payloads to dedicated modules (small or large; rigid or inflatable). Attached modules can be simplified, since the Core provides utilities and life support services at the berthing interface. Adding identical core units increases the number of berth locations and ports in lockstep with the power and other technical capacity needed.

Orbital Reef will evolve over time to include destination elements and transportation elements, all through simply expanding on its basic set of modules. These common building block modules are described further in the following sections. The architecture is designed to be scalable from one to many, with attached modules serving individual customer needs (Fig. 2). The configuration of Core units with Masts and attached modules allows the complex to add power and other vehicle utilities: docking ports for visiting, operations, and lifeboat vehicles; and life-support capacity as the market grows.

Fig. 2 Future configuration of scalable Orbital Reef architecture

The Orbital Reef program has already passed its System Requirements Review (SRR), its System Design Review (SDR) and is on the road to Preliminary Design Review (PDR) in 2023. As the Orbital Reef team continues to refine the architecture, the more detailed design of the system will be shared in later publications.

1.1 A Continuously Customizable Space Station: Orbital Reef System Elements

1.1.1 Core Module

The Core module is the central thoroughfare for connected modules and visiting vehicles to Orbital Reef (Fig. 4). Core is a rigid metal pressure vessel with approximately 250 m^3 of usable habitable volume, approximately one-third of the entire ISS. It acts as a primary hub for docking or berthing other modules with additional Cores to provide a linear backbone for expansion of the station. The Core provides open space for liveability and congregation, modular equipment locations, stowage, and large Earth-facing windows for on-station guests and crew (Fig. 3). It contains one commode and minimal accommodations for the first human-tended visits, as well as an environmental control and life support system (ECLSS) sized to support up to ten astronauts as more modules are attached. The Core also provides human support functions, central command and control and data processing, high data rate communications infrastructure with the ground, and on-board broadband Wi-Fi for multimedia devices. It also houses payloads with both internal and external payload interfaces. A Core can be transformed into anything from a warehouse to a studio, to a hotel. It is a multipurpose space that can grow the space station as needs evolve and markets expand.

Fig. 4 Core module

Fig. 3 View inside the Core module

1.1.2 LIFE™ Module

The Large Integrated Flexible Environment (LIFE) is where guests and crew will rest and recharge during their stay aboard Orbital Reef. LIFE is an inflatable, soft-good habitat that is approximately 290 m^3 of usable habitable volume (Fig. 6). It contains up to ten sleeping quarters, two commodes, a hygiene compartment, and ECLSS for up to ten crew. The module provides the primary support for station habitation, including galley, exercise equipment, plant growth hardware, storage, and support for human health and hygiene. LIFE also provides lab space to host payloads and research facilities to perform science. The LIFE Module is robotically berthed with the Core following launch.

Fig. 6 Large Integrated Flexible Environment (LIFE) Module

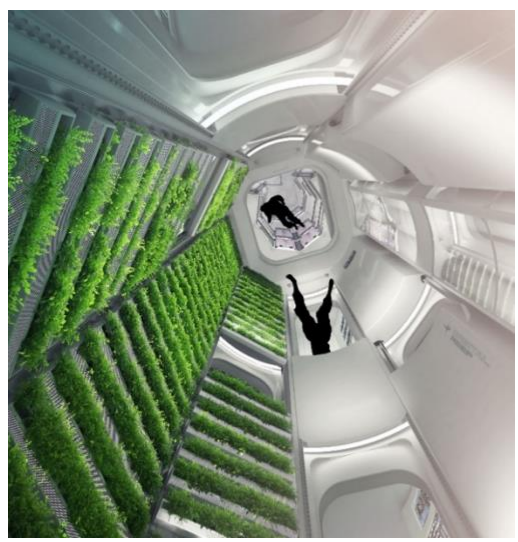

Fig. 5 View inside central core of LIFE Module

1.1.3 Node Module

Fig. 8 Node Module

Fig. 7 View Inside the Node Module

The Node Module is a complementary hub for vehicular and extravehicular transit. Node is constructed of a rigid metal pressure vessel with approximately 40 m^3 of usable habitable volume. It is capable of hosting external payloads, supports visiting vehicles with two International Docking System Standard (IDSS)-compatible visiting vehicle ports, and has an airlock for suited extravehicular activity (EVA). The module also provides basic vehicle functions, including independent maneuvering capability for mating itself with the Orbital Reef and supporting overall station-keeping requirements.

1.1.4 Research Module

The Research Module (Fig. 9) is a multi-disciplinary science and multi-use laboratory, customizable to customer requirements. This space is a rigid pressure vessel outfitted with research facilities, payload airlock/cupola(s), and both internal and external payload interfaces. The module, which is similar in size to the Core, provides extensive workspace and payload support services for customer payloads and contains essential multi-user facilities (e.g., gloveboxes,

Fig. 9 View inside the Research Module

freezers, incubators, etc.), as well as additional stowage volume. The Research Module is berthed after LIFE and Node to augment the full onboard research capabilities.

1.1.5 Mast

The Mast element (Fig. 10) provides for the Space Station Segment's overall energy generation and storage, thermal collection and rejection, communications, and other critical systems. The Mast features 100kWe deployable solar arrays. These masts increase onboard power generation and provide an external robotic arm and docking and berthing nodes to enable resilient configuration changes during assembly and growth of Orbital Reef.

1.1.6 Single Person Spacecraft

The Single Person Spacecraft (SPS) element is a small free-flying spacecraft designed by Genesis Engineering that provides a shirt sleeve environment for one person to perform untethered extravehicular activities for maintenance, inspection, assembly, or tourism operations (Fig. 11). It eliminates pre-breathing and other traditional operational constraints while offering a practical option for professional and adventure travel excursions outside the space station. Traditional suited extravehicular activities will also be available onboard Orbital Reef.

Fig. 10 Mast installed on Core Module

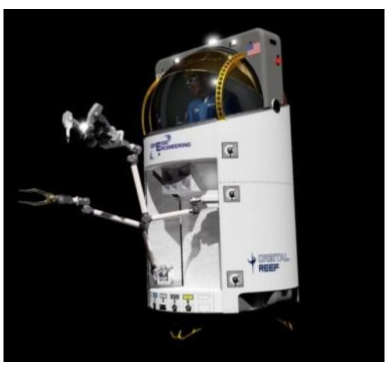

Fig. 11 Single Person Spacecraft enables suit-free Orbital Reef

Fig. 12 New Glenn Reusable Launch Vehicle

1.2 Increasing Flexibility: Supporting Vehicle Systems

Orbital Reef has the flexibility of hosting a variety of vehicles to support end-to-end operations and provide alternative modes of transport to humans and cargo. Orbital Reef vehicle elements include Blue Origin's New Glenn, Sierra Space's Dream Chaser, and Boeing's Starliner.

1.2.1 New Glenn Launch System

New Glenn is a heavy-lift, two-stage launch vehicle developed and designed by Blue Origin to launch up to 45,000 kg to LEO (Fig. 12). The first stage booster is designed to be fully reusable, performing a powered vertical landing downrange on a landing platform vessel at sea and returning to flight within a month up to 12 times per year, lowering cost for recurring resupply and crew missions. New Glenn's 7 m (23 ft) diameter payload fairing has more than two times the payload volume of existing 5 m (16 ft) fairings and enables the wide diameter of Orbital Reef Modules.

1.2.2 Dream Chaser Visiting Vehicle

Dream Chaser is a reusable 6-ton cargo spaceplane developed by Sierra Space and planned to service ISS resupply beginning in 2023 (Fig. 13). Dream Chaser comes in cargo and crew variants capable of safely transporting payloads and people to Orbital Reef and back safely to most typical runways on Earth. This capability enables low-g landing for returning sensitive payloads and people, and immediate offloading of returned samples.

1.2.3 Starliner Visiting Vehicle

Starliner (Fig. 14) is a reusable capsule developed by Boeing and planned to service ISS crew transportation beginning in 2023. The vehicle is designed to transport up to five people to Orbital Reef. Starliner completed its Orbital Flight Test 2 (OFT-2) uncrewed flight test to the ISS in May 2022.

Fig. 11 Dream Chaser Reusable Spaceplane

Fig. 14 Starliner Reusable Spacecraft

3. Orbital Reef Commercial Space Station Operations

In 2020 the ISS entered its third decade of operation. The first decade of the station was the decade of construction. The second decade was moving from initial scientific research to full utilization. The third and final decade will be focused on delivering results. During its first two decades of operation, the space station evolved from "an outpost on the edge of space into a highly capable microgravity laboratory [4]." This orbiting laboratory enables researchers from around the world to take advantage of microgravity, exposure to space, and a unique perspective on Earth to conduct research in this space station environment. Although the ISS is a partnership among many nations, each with distinct goals, every partner shares a unified goal to use this laboratory for the betterment of humanity [4].

When new Commercial LEO destinations are put into orbit to replace the ISS at the end of the decade, they are challenged to operate as both multi-government laboratories and as a successful business. The Orbital Reef mixed-use business park approach provides a modular, flexible architecture designed to grow with market needs [5]. This approach is different from over 60 years of human spaceflight. The commercial paradigm provides all essentials, including logistics and launch, orbital operations, outfitted habitat and research modules, secure data services, and end-to-end customer experience. This new type of business approach to space enables a space station where science, exploration, commercial, and adventure travel happen together. A focus on commercial efficiency and reimagined logistics reduces capital and operating expenses to enable the long-term vision of millions of humans living and working in space.

This new era of commercial space station assembly and operations is going to have some new challenges not faced by the ISS. We will highlight a few of those: assembly without a space shuttle, reducing EVA for assembly and maintenance, and developing markets beyond the current ISS community.

3.1 Assembly Without a Space Shuttle

As the first Apollo Moon landing approached in 1969, NASA planners were laying out a broad and ambitious space plan for the next two decades. These plans included space stations, more trips to the Moon, including permanent lunar bases, and then the ultimate objective, the first human mission to Mars [6]. In these original plans the Space Shuttle's primary mission was merely to serve as a logistics vehicle for supporting a space station. It was just one of many pieces required to meet the human Mars landing.

These space plans were derailed by a changing US emphasis on space. With the race to the Moon won and a wane in public interest, NASA was forced to face the fact that the era of unlimited support for space programs had passed, and it would face the prospect of reduced funding. Thus, plans for human travel to the Moon and Mars had to be abandoned and the emphasis shifted to a combination space shuttle/space station architecture. A space station became NASA's central goal and one that it felt was essential to any other human space efforts, such as a lunar base or mission to Mars. However, it became apparent that building a space station without a low-cost logistics system would not be economically or politically feasible. A space station required a space shuttle to make it happen. As the political process continued, it became evident that economic pressures would make it difficult to simultaneously develop both a space shuttle and a space station. With focus from the White House and Congress being placed on a space shuttle alone by deferring space station schedules, the Space Shuttle began emerging as an independent program [7].

After a lengthy development, the Space Shuttle began to reach a regular launch cadence in the early 1980's after 24 shuttle flights were flown in five years. The Space Station Freedom program was started that depended on the Space Shuttle increasing its launch rate to support both flights for its assembly and operation, as well as the other missions it flew since it had become virtually the only method the United States had to get to space. During its development the Space Shuttle's need for economic justification and building coalition support (through a vehicle that could launch it all) fed each other [8].

Sadly, the early Space Shuttle success many had taken for granted for changed on January 28, 1986, with the *Challenger* accident. According to the Presidential Commission that reviewed the Space Shuttle failure, the nation's reliance on the Space Shuttle system as its principal space launch capability created a relentless pressure on NASA to increase the flight rate. The Space Shuttle program was then limited to missions that were Space Shuttle unique or had national security or foreign policy implications. Various studies showed this limitation in scope, was not restrictive enough. An inability to safely increase the Space Shuttle flight rate, and its inherent reliability, showed that focusing on just supporting space station assembly operations would be all that it could realistically do [8]. When another failure was realized with the *Columbia* accident, this theory was sadly validated, and the Space Shuttle was primarily focused on space station flights until the retirement of its fleet (Fig. 15). It returned to its original mission of delivering crew and cargo for space station assembly and operation, while also providing other valued services like water transfer from its fuel cells and reboost. Its unique combined crew and cargo capabilities in a single flight are missed as the next space station assembly and operation are planned.

Fig. 125 The Space Shuttle Endeavor docked to the International Space Station on May 23, 2011

The fleet of vehicles discussed in Section 1.2 represent a substantial reduction in launch costs, which is a major cost of supporting a space station program. This is true even when considering that it takes two separate crew and cargo launches to serve the combined functions of a single Space Shuttle flight. However, there are complications with coordinating these crew and cargo flights during assembly. The significant capability of the New Glenn launch vehicle does allow for larger modules than the ISS, but supporting flights are needed to complete outfitting. This has resulted in a greater reliance on autonomy when the Orbital Reef modules are launched. The fact that the Chinese and Russians have demonstrated building and operating space stations without an equivalent Space Shuttle capability gives confidence it can be done.

3.2 Reducing EVA for Assembly and Maintenance

With a commercial space station needing to focus on economics, reducing EVA is a clear opportunity for improving costs and safety. EVA is considered a high-risk operation requiring many hours of ground training and additional on-orbit preparation. EVA activities on the ISS currently require on-orbit space suits with various additional parts to accommodate the entire range of users (106 resizing parts). They also require the Simplified Aid for Emergency Rescue (SAFER) which is a mini jetpack that allows astronauts to fly back if they were to become disconnected from the ISS.

In addition, Liquid Cooling Ventilation Garments (LCVG) are worn by the users to maintain thermal control. Also, because space suits operate with low-pressure pure Oxygen, pre-breathing equipment is required to prevent Decompression Sickness. Tools designed to be operated with a pressurized glove in the space environment are also needed. Translation handrails are required to traverse the station exterior as well as foot restraints at a work location so both hands are left free. Extensive training is required, most of which is performed in a neutral buoyancy facility. When accounting for all the development costs as well as operations costs of conventional EVA, it is a substantial impact to the viability of a commercial space station [9].

As a result, Orbital Reef is planning to rely on Extravehicular Robotics (EVR) as its primary assembly and limiting conventional EVAs to only contingencies and training missions. Substantial improvements in robotic technologies, as well as designing for robotic assembly and maintenance will support this economical and safety driven approach.

3.3 Developing markets beyond the current ISS community

Orbital Reef will have the capabilities to serve the current ISS community from NASA to the many international and few commercial partners that have participated in its twenty plus years of operations. But with NASA stating that it wants to be "one of many customers" and that it plans to provide funding to two CLD providers, serving the current ISS market demand will be insufficient. Also, there are many emerging markets which the ISS has not supported or is unable to support from nations that have not yet had the opportunity to participate to emerging commercial interests. Orbital Reef is taking two innovative approaches to growing the market now so that it will be ready for Orbital Reef operations later in the decade.

The Reef Starter program is designed to reduce barriers of entry for start-ups becoming users of Orbital Reef. The Orbital Reef team is increasing awareness of the benefits of in-space operations for commercial business, providing expertise to advance the next generation of solutions and sparking investment in innovative ideas. On September 22, 2022, Reef Starter announced its Innovation Challenge as an initial step in building this community. The global challenge, in partnership with TechConnect, selected four early-stage companies on December 8, 2022, to receive awards of up to $100,000 and customized workshops with the Orbital Reef team to accelerate their access to space. Reef Starter received hundreds of applications from a variety of markets, including life sciences, material sciences, atmospheric monitoring, entertainment, and computing technologies. The top 20 applicants participated in a pitch day with judges from Orbital Reef partners and teammates, who selected the winners based on commercialization plans, technical maturity and roadmap, and overall presentation quality.

Soon after its award at the end of 2021, Orbital Reef organized a University Advisory Council to advance planning for research on Orbital Reef. Led by Arizona State University the 15 members also include Colorado School of Mines, International Space University, Massachusetts Institute of Technology, Oxford University, Purdue University, Southwest Research Institute, Stanford University, University of Central Florida, University of Colorado at Boulder, University of Florida, University of Michigan, University of Texas at El Paso, University of Texas Medical Branch, and Vanderbilt University. Not only are they providing an important voice of the customer to influence the design of Orbital Reef, the University Advisory Council members are also helping imagine ways the market can be expanded.

These are only two of the public methods that the Orbital Reef team is implementing to grow the LEO economy to make Orbital Reef economically viable. The CX team every day is bringing a customer focus to engineering efforts while working closely with Business and Sales organizations to identify new opportunities and ensure needed capabilities are included in the design.

4. Customer Experience Role in Orbital Reef

The purpose of the Orbital Reef CX team is to discover customer needs, engage customers to implement those needs, and deliver amazing customer experiences. This includes providing the physical hardware, services, and processes in support of customer payloads, guest hosting, and other unique customer services. Partnering with Business Development, the CX team helps convert leads into sales by understanding customers objectives and translating them into requirements, concept of operations, design, and processes for engineering implementation. From inception to experience completion, the CX team walks with the customers on their journey making sure they are delighted at every step. By directly reporting to the Orbital Reef Program Manager, the CX team ensures the voice of the customer is heard.

As systems engineers, the CX team performs a systems integrator role as the voice of the customer. The CX team includes scientists, user experience designers, architects, industrial designers, and engineers bringing a diverse set of perspectives to customer needs. The CX team supports Orbital Reef Guests, customer payloads, and service users during all stages of the mission from inception to conclusion, as well as re-engagement activities. Orbital Reef Guests includes everyone flying to Orbital Reef that is not employed by Orbital Reef to outfit, operate and maintain the space station, known as Orbital Reef Crew. Orbital Reef Guests could include individuals from Government agencies

(NASA, international civil astronauts, and other government personnel) and commercial industry (industry professionals doing work in space such as research and manufacturing). Orbital Reef Guests also includes occupation-driven personnel (such as entertainment and media), and tourists. The CX team will support payloads that come in both standardized sizes and bespoke configurations. Customer payloads may be hosted internally (pressurized) or externally (unpressurized). They may or may not require crew interaction while onboard Orbital Reef. On-orbit customer services may include science experiments using in situ instruments and materials, live interaction with Orbital Reef crew, or remote control of Orbital Reef space station assets like external cameras.

The CX team is responsible for translating customer and market requirements into the technical design solution. This is accomplished via:

- Developing of Design Reference Scenarios and Functional Use Cases from the customer and market perspective
- Identifying functions, capabilities, and services that meet customer and market needs, and implementing those capabilities and services
- Working with program system engineering and Integration team and engineering integrated product teams to identify system-level requirements and design drivers that impact the Orbital Reef design to fulfill those capabilities and services. An example is developing overall CX driven allocations and interfaces for power, heat rejection, and communications to meet market demand. These allocations may drive relevant system sizing.
- Developing the interfaces, hardware, services, and processes unique to CX to support customer needs.
- Supporting for the customer experience throughout the entire lifecycle
    - This can include customers who will physically fly as Orbital Reef Guests, as well as customers flying payloads or using other Orbital Reef services from Earth
    - Provide insight and be the voice of the customer across system design (complementary to Human Integration team role advocating for human needs and safety)
    - Define roadmaps for achieving human-centric capabilities and experiential visions
- Supporting payloads throughout the entire lifecycle
    - From first contact to test and certification, pre-launch, launch, on-orbit operations, return, recovery, follow-up, and re-flights

The CX team has initially focused on partnering with business development to discover Orbital Reef customers and determine their needs. Because the engineering team quickly needed customer requirements to drive the Orbital Reef design, CX engaged preliminary customers and experts in emerging markets to define the driving requirements for Orbital Reef. The role of a CX team is a new, but important one, for a space program. Already in the first year of the Orbital Reef program, the CX team has demonstrated its successful impact on the Orbital Reef program by bringing customer focus and requirements to the foreground. As the program continues, validating a commercial approach to space program execution driven by meeting customer needs will determine if the LEO economy will be realized.

5. Conclusions

Orbital Reef will open the next chapter of human exploration and development by facilitating the growth of a commercial LEO ecosystem and business model for the future. A summary of how Orbital Reef may serve the commercial LEO market is shown in Figure 16.

By reimagining how space stations can serve a LEO economy, Orbital Reef will help us take the first step to a bold vision of millions of people living and working in space for the benefit of Earth.

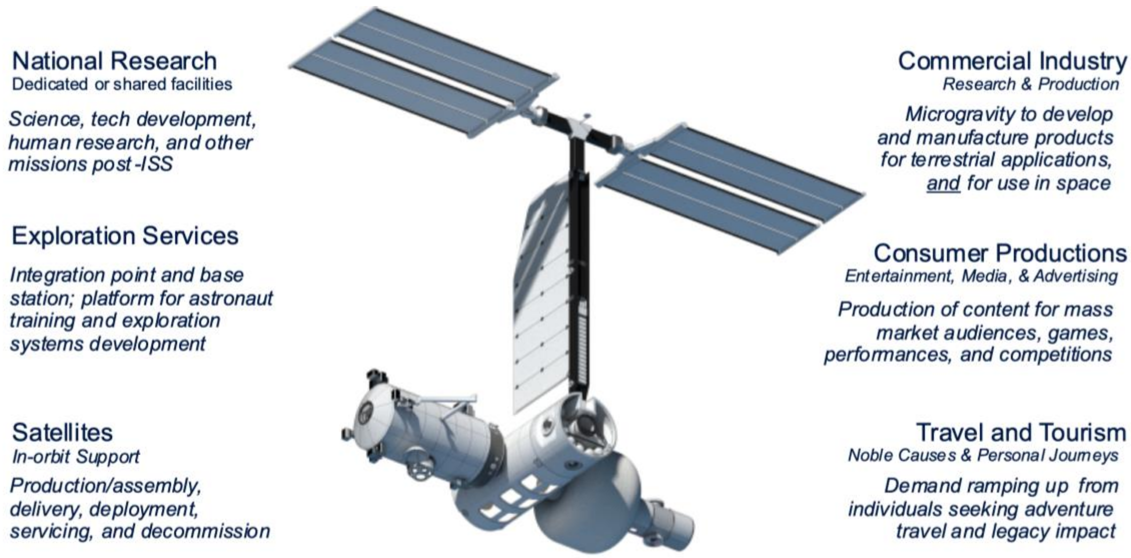

Fig. 16 Orbital Reef as a Hub for a Vibrant Emerging Space Economy

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