FINAL
REPORT

STARPORT 1

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Space Studies Program 2016

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The Starport 1 space station is depicted on the front cover orbiting Earth,
with the Moon and Mars in the background.

Front cover credit: Giulia Faglioli

Logo credit: Giulia Faglioli (text) and Erik Falk-Petersen (image)

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Dr. François Spiero	Co-Chair
Jarosław Jaworski	Teaching Associate
Merryl Azriel	Editor
Jaime Babb	Editor
John Connolly	SSP Program Director

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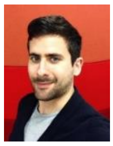
	**Mr. Enrique García**	***Project Manager***		**Mr. Cenan Al-Ekabi**	***Coordinator***		**Dr. Alex Brinkmeyer**	***Deputy Project Manager***
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ABSTRACT

For centuries, humans have imagined living in space and, since the beginning of the space age, this has become a reality for a few hundred fortunate people. Over the past 10 years, space has become more accessible to people all over the world through affordable tourist flights and research opportunities. We envision that within the next 20 years there will be a public and commercial demand for a commercial space station in low Earth orbit (LEO) capable of accommodating 200 people in an artificial gravity environment. We have designed such a facility, called Starport 1, to serve as both a destination hotel and a manufacturing and research facility. This design includes an engineering description and computer-aided design (CAD) model of the station, which addresses structure, interfaces, attitude and orbit control, power, and life support with a highly modular configuration. This modularity will allow use of the assembled sections of the station during the construction period from 2035 to 2040, and enable expansion as well. Modules are built on a rotating ring skeleton, which simulates 0.8 g, which is sufficient for humans to avoid many of the detrimental effects of life in space. The analysis also considers the business, legal, and policy aspects. A variety of stakeholders are expected to participate in Starport 1 activities, with funding from both government and commercial investment supplementing revenue streams from microgravity manufacturing and tourism. We also propose solutions for limiting and mitigating the risks to health associated with operating in space. Residents of Starport 1 will face psychological challenges that we mitigate through the envisioned organization of a space settlement society and community enhancements. These will include pleasing architecture and accommodations. Our goal is to make life in space as comfortable as life on Earth.

FACULTY PREFACE

Each year, ISU runs an intense Space Studies Program (SSP) at a different host site throughout the world. In 2016 the program was held at the prestigious Technion – Israel Institute of Technology in Haifa, Israel.

An important part of the summer program is the team project, in which participants work on solutions for challenging space-related problems. Developing ideas for future space activities requires the participants to work in an international, intercultural, and interdisciplinary group; essential skills for a career in the global space sector.

For the first time in ISU history, one of the team projects in SSP 2016 was commissioned by a commercial space company. In January 2016, executives of the space company Stinger Ghaffarian Technologies started Axiom Space LLC, a new endeavor to develop commercial activities in LEO. The first step in this commercialization is expected to be the addition of a module to the International Space Station (ISS).

Team Project Starport 1 focuses on one of the potential next big steps in LEO: microgravity research and manufacturing. A commercial manufacturing plant in space would require a significant scaling up of today's orbital capacity, as it would necessitate the use of much larger modules, in addition to requiring many more people to operate than the ISS.

The station that the sponsor commissioned ISU to work on will have the capacity to house up to 200 people. To maximize the health, comfort, and productivity of the inhabitants, the station will be equipped with an artificial gravity habitation module adjoining the microgravity manufacturing site.

The sponsor asked the team to primarily look at some of the engineering challenges of the station, such as the design to connect rotating to static modules, habitation requirements, orbital dynamics, assembly and disassembly aspects, and energy management. Because of the interdisciplinary nature of the Space Studies Program, we have also considered additional aspects, notably in legal, human performance, business, and scientific fields.

The 38 professionals assigned to this project did an outstanding job of organizing themselves into a highly effective and efficient team. The result of their efforts is this report, which addresses the sponsor's design requirements while incorporating the unique interdisciplinary ISU perspective to the challenges of living and working in space. We are convinced that the results of this project will provide an excellent basis for the sponsor to start realizing its vision of building the first commercial city in space.

We would like to extend our thanks to Michael Suffredini, president of Axiom Space, for putting his confidence in ISU. We would also like to thank Jarosław Jaworski, our teaching associate, who ensured this team project stayed on track to meet all sponsor and ISU requirements.

Remco Timmermans, BBA MA
François Spiero, Ph.D.

Team Project Starport 1 Co-Chairs,
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PARTICIPANT PREFACE

In the following report, we describe the design of a commercial artificial gravity space station, Starport 1. We designed Starport 1 for on-orbit assembly, to be completed by 2040. This station must house a population of 200 people and comprise two key sections: one with a microgravity environment for manufacturing, research, or other purposes, and another with artificial gravity to provide an Earth-like environment for guests and residents of the station to live in, reducing the deleterious physical effects of long term microgravity exposure.

We are an interdisciplinary team of students of the ISU, who carried out this project as part of ISU's SSP. SSP brings together students from a multitude of countries and with a diverse set of backgrounds, disciplines, and skills. This diversity posed several challenges for us, but also provided us with a great learning opportunity.

Project co-chairs François Spiero and Remco Timmermans supervised the project. Teaching Assistant Jarosław Jaworski supported us during the project. The co-chairs and teaching assistant helped initiate the project, after which we assumed the management of the project.

We completed this project over six weeks. We went through several phases: literature review, planning, design, integration, and report writing. Our efforts resulted in this report, an executive summary delivered on 28 August 2016, and a final presentation delivered on 31 August 2016.

This report provides a guide to the different aspects to be considered in the design, construction, and operation of a large artificial gravity station. We intend it to be used by engineers as a starting point towards the design of such a station, and by business professionals aiming to understand the business case and prepare a business plan for creating and operating such a station.

Figure 0-1: The Starport 1 team

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

Acronym/ Abbreviation	Meaning
ADM	Additive manufacturing (facility)
ADR	Active debris removal
AES	Advanced exploration systems
AG	Artificial gravity
AMF	Additive manufacturing facility
AOC	Attitude and orbit control
AOCS	Attitude and orbit control system
BEAM	Bigelow expandable activity module
BNNT	Boron nitride nanotubes
C_2H_2	Acetylene
CAD	Computer-aided design
CEO	Chief executive officer
CFRPEEK	Carbon fiber reinforced polyether-ether-ketone
CH_4	Methane
CO_2	Carbon dioxide
DOF	Degrees of freedom
e.g.	exempli gratia
ECLSS	Environmental control and life support system
EDRS	European Data Relay System
EMI	Electromagnetic interference
ESA	European Space Agency
ESAMM	Extended structures additive manufacturing machine
ESO	European Space Observatory
ESP	Electrostatic precipitator
EVA	Extravehicular activity
FAA	Federal Aviation Administration
FDM	Fused deposition modeling
FP	Framework program

Acronym/ Abbreviation	Meaning
g	9.81 m/s^2
GCR	Galactic cosmic ray
GNSS	Global navigation satellite system
H_2	Hydrogen
HEPA	High-efficiency particulate arrestance / High-efficiency particulate air
HMC	Heat melt compactor
HVAC	Heating, ventilation, and air conditioning
IADC	Inter-Agency Space Debris Coordination Committee
IBDM	International berthing and docking mechanism
IGA	Intergovernmental agreement
IMU	Inertial measurement unit
ISS	International Space Station
ISU	International Space University
LEO	Low Earth orbit
LRR	Logistics reduction and repurposing
MCT	Mars Colonial Transporter
MEO	Medium Earth orbit
MOI	Moment of inertia
n.d	No date given
NASA	National Aeronautics and Space Administration
NSF	National Science Foundation
OSHA	Occupational Safety and Health Administration
PPP	Public-private partnership
PR	Public relations
R&D	Research and development
RPM	Revolutions per minute
SAD	Seasonal affective disorder
SCWO	Supercritical water oxidation
SDBD	Surface dielectric barrier discharge
SFP	Spaceflight participants
SGAC	Space Generation Advisory Council
SLS	Space Launch System

Acronym/ Abbreviation	Meaning
SMAC	Spacecraft maximum allowable concentration
SPC	Special purpose company
SPE	Solar particle event
SSO	Sun synchronous orbit
SSP	Space Studies Program
STEM	Science, technology, engineering, and mathematics
STTR	Small business technology transfer
TT&C	Telemetry, tracking, and command
TtG	Trash to gas (technology)
UN	United Nations
US	United States
VASIMR	Variable specific impulse magnetoplasma rocket
VCs	Venture capitalists
ZBLAN	Zirconium Barium Lanthanum Aluminum Sodium

1. INTRODUCTION

Space stations have been part of the dream of space exploration for well over a century. Visionaries such as Konstantin Tsiolkovsky and Hermann Oberth first contemplated their potential (Angelo, 2003). Space stations offered the opportunity to establish a human presence in orbit, by creating an environment in which humans could live and work.

As the space age dawned, space stations were seen as a place in which astronauts could take advantage of microgravity conditions (NASA, 2008). The microgravity environment has traditionally been used for scientific research and technology demonstrations. These uses are reflected onboard ISS, which agencies primarily use for these purposes (ESA, 2013).

Microgravity may enable the production of new materials, products, and pharmaceuticals. We discuss manufacturing optical fibers and optical mirrors, as well as bio-printing tissue and organs for use on Earth. These new applications coincide with the rise of commercial space utilization, and may create new demand for space stations in the future.

1.1 Historical space stations

The first space station to be put in orbit was Salyut 1, launched in 1971 by the Soviet Union. This was the first of a series of Soviet Salyut stations, the last one being Salyut 7, which re-entered the atmosphere in 1991. These were monolithic stations, formed of only one module, to which a transfer craft could be docked.

Following the Apollo program, the United States of America used their last Saturn V rocket to put Skylab in orbit. This was the first American space station and, like Salyut, was monolithic. It was launched in 1973 and re-entered the atmosphere in 1979.

The Soviet Mir was the first space station to incorporate a number of different modules. This made it possible to build a station larger than a single launcher could accommodate. It also allowed the operators of Mir to extend its lifetime by repairing and replacing certain parts (NASA, 2014a).

ISS was Mir's successor. It resulted from the collaboration of a coalition of agencies, including those of the United States of America and the Russian Federation. ISS became the largest structure that humans have ever placed in orbit. It is expected to remain in operation until 2024 (ESA, 2016).

The Tiangong-1 space station, the product of China's space program, was launched in 2011. It is a monolithic station, but China has plans for a larger, modular station in the near future (Space News, 2016).

1.2 The need for artificial gravity

Space stations have provided a wealth of scientific data (Evans, et al., 2009). They have produced great advances in space technology, such as water purification and filtration systems, and improved eye surgery devices (ISS Program Science Forum, 2015). Long-term occupation of space stations has shown us the effects of microgravity on human physiology. Muscle loss, bone loss, and vision decay are some of the most severe effects, as they can have consequences for astronauts even after their return to Earth. A number of countermeasures have been developed, such as exercise machines simulating gravity by loading the user. However, these countermeasures do not eliminate the adverse effects of microgravity. Our inability to control the effects of microgravity imposes a time constraint on astronaut flights, which limits the useful time in which they can conduct their missions. (Buckey, 2006)

Artificial gravity creates an Earth-like environment in which humans could live while reaping the benefits of spaceflight. Access to such an environment could allow a permanent presence in orbit while avoiding the adverse effects of microgravity.

1.3 Project rationale

The Starport 1 team project was sponsored by Axiom Space LLC, and supported by its president, Michael Suffredini. The project aim was to design a space city of 200 inhabitants to be completed in orbit by 2040.

Axiom Space's vision is:

"To colonize Earth orbit as a means to sustain deep space exploration. To build an affordable, state-of-the-art city in Earth orbit by 2040 where any of us could live, visit, work, and play."

1.3.1 Mission statement

The Starport 1 team defined the following mission statement for this project:

"The aim of this project is to conduct a conceptual design study for a commercial space station on behalf of Axiom Space. This station will contain a section with artificial gravity and another with a microgravity environment, both of which shall be fully operational by 2040. The station will allow people to live in an Earth-like environment, while enabling in-orbit manufacturing, scientific research and space tourism. This study will focus primarily on the engineering challenges and will also take into consideration policy, legal, business, and societal aspects."

1.3.2 Project objectives

The team derived the following project objectives from the mission statement:

- Propose a name for the space station;
- Identify the key engineering and non-engineering areas for the artificial gravity station program;
- Propose an architecture, configuration and systems layout for the station;
- Perform an initial structural analysis of the station, including static and dynamic analyses;
- Recommend the locations of the launch bases and operations centers, and discuss the operation of the station;
- Propose a launch and assembly strategy including in-orbit assembly and spin-up of the station;
- Recommend optimized orbital parameters;
- Propose a disassembly and end-of-life strategy;
- Recommend a space debris avoidance strategy;
- Propose the internal layout of the station;
- Discuss the hazards posed by radiation on the health of space station residents;
- Propose a role distribution within the station, including crew, visitors, support staff and others, and discuss community-related issues;
- Propose a management and ownership model for the station;
- Recommend different revenue streams and funding sources; and

- Discuss the legal framework for a commercial LEO facility and recommend areas of further study.

1.4 The Starport 1 team

In the initial stages of the project, we decided to name the station. To choose the team and station name we had several word-association sessions, linking any words we each could think of to the concept of a space station. These words were compiled into a list of possible names, narrowed down into the top 50 choices, and then the top five choices. After a team vote on the final five choices, we agreed on the name Starport 1. Throughout this report, we refer to the station as Starport 1, and the team as the Starport 1 team.

1.5 Structure of this report

We designed this report as a manual to guide initial analysis of a Starport 1-like space station. We begin in Chapter 2 with the initial design requirements, as defined by the sponsor and Mr. Jarosław Jaworski. We then discuss the overall design of the Starport 1 station in Chapter 3. This includes the overall station configuration in Chapter 3.1, as well as the different subsystems in Chapter 3.2. Chapter 4 covers the series of procedures for building, launching, assembling, operating, maintaining, and finally de-orbiting Starport 1. The habitat and life support systems of Starport 1 are discussed in Chapter 5. The societal makeup of the inhabitants of the station, including such aspects as roles and governance, are studied in Chapter 6. The legal and policy aspects of the station, including such issues as ownership and government funding, are described in Chapter 7. The different income streams and business models for the station are explored in Chapter 8. Finally, in Chapter 9 we provide a comprehensive overview of our recommended mission architecture, including a timeline for its implementation.

2. SCOPE

Within this report we discuss the critical aspects to be considered for the design and operation of a space station. This includes technical, financial, organizational, political, social, scientific, and business. We propose an artificial gravity space station architecture, configuration, and systems layout. We recommend technical approaches for life support, guidance, navigation, and control, and power systems.

We indicate areas that need to be developed between now and 2040 to allow smooth station assembly and operation. We address the medical implications of artificial gravity and microgravity and their effects on the body and also assess the radiation hazards related to long term occupation of space and the potential long term health impact for space station residents.

We propose the optimum number of crew needed to operate the station, and the total number of occupants. This will include crew, support staff, infrastructure operators, security, and visitors. We define community-related issues associated with a station this size that should be considered.

We address the expected station response to external disturbances, such as atmospheric drag and mass redistribution due to visiting spacecraft.

We address what is outside the scope of the report in the relevant chapters. We propose areas of further analysis in these chapters where applicable.

3. STATION REQUIREMENTS

The team project sponsor defined requirements for the station, as detailed in Table 3-1. These formed the basis for our research and analysis, and were used to drive the design decisions. For each requirement, we have identified whether our work is compliant with the requirements, and in which chapter the result is included. The column labelled as "C?" indicates Starport 1's compliance with the relevant requirement (C - Compliant, PC - Partially Compliant, NC - Non Compliant).

Table 3-1: Requirements for artificial gravity space station (Suffredini and Jaworski, 2016)

No.	Requirement	C?	Chapter	Reason for NC/PC
1	Station shall be resilient to temporary loss of spin	C	4	
2	Station shall use nuclear power to power the station (or recommend another source)	C	4	
3	Station rotation rate shall be within the range of 1.9 and 2.5 rpm	NC	4	Station size reduced to accommodate mass considerations, thus rate of rotation increased to 2.9 rpm.
4	Station shall provide gravity in the non-industrial sections	C	4	
5	Station shall include a gravity environment for day to day living and a microgravity environment for the industrial area	C	4	
6	Station shall provide crew and logistics transfer capability from non-rotating to rotating section	C	4, 5	
7	Station shall allow pressurized and non-pressurized docking and berthing	C	4, 5	
8	Microgravity section shall be large and expandable, maintain a microgravity environment for manufacturing and research, technology testing, and exploration system design and development	C	4, 9	
9	Station shall be assembled using launchers available up to 2040	C	5	
10	Station shall allow safe disposal after retirement	C	5	
11	Station shall be located in LEO	C	5	
12	Station shall provide comfortable environment to work, live, and play	C	6	
13	Station shall be as self-sufficient as possible to limit cargo transportation	C	6	
14	Gravitational section shall contain residences, ~~a~~ hotel, shops, school, recreational areas, crew and family living areas, and docking facilities, and other key areas defined for this section	NC	6	Schools and family living areas are not considered, as too early to take children safely into space.
15	Station shall accommodate no fewer than 200 people, including long-term residents with families, and temporary residents	PC	6, 7	100 people accommodated due to assembly schedule; 200 people accommodated by 2045

4. STATION DESIGN

4.1 Requirements

We derived the concept and general configuration of the artificial gravity (AG) space station from the requirements in Section 3, and design and operational considerations. We distinguished between primary and secondary requirements, giving each requirement a weighted score to reflect its importance in the overall station design. Table 4-1 shows some of the main driving requirements and their respective scores.

Table 4-1: The main primary and secondary driving requirements

Importance	Requirement	Weighting (out of 10)
Primary	The station shall have a habitation zone where artificial gravity is in effect	10
Primary	The station shall have a microgravity section	10
Primary	The station shall have enough space to accommodate up to a minimum of 200 people when fully constructed	10
Primary	The station shall be available for habitation by 2040	9
Primary	The station shall be commercially operational from the initial assembly stage	9
Primary	The station shall be designed and constructed for LEO	8
Secondary	The station shall minimize the cross section to prevent debris collision and to minimize drag	6
Secondary	The station design shall support replaceable modules	5
Secondary	The station shall have large communal areas	3

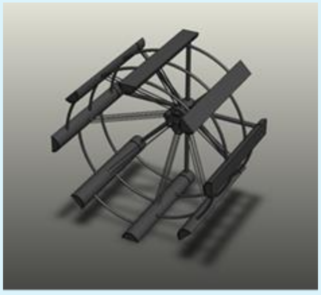
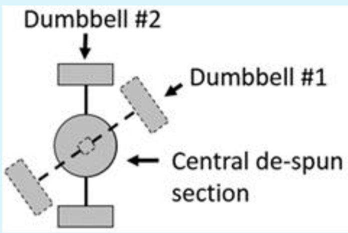
4.2 Concept selection

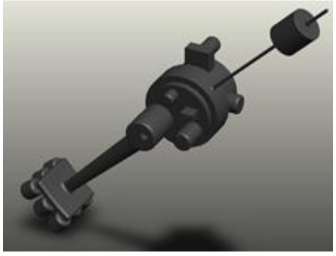
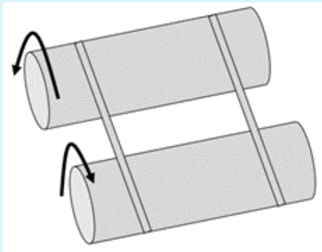
After compiling a comprehensive list of design requirements, we conducted research into different AG space station concepts and identified eight configurations (shown in Table 4-2).

4.2.1 Description of concepts

Table 4-2: Preliminary concepts for Starport 1

Concept Name	Visualization	Descriptions
Load bearing modular tube		▪ Wheel configuration with a circular cross section ▪ Toroid is divided into modules that can be assembled into a complete structure

Concept Name	Visualization	Descriptions
Hollowed out asteroid (NASA, 2016)		▪ Consists of a suitably sized asteroid with its interior hollowed to a cylinder ▪ The asteroid is spun on its axis to establish AG
Load bearing skeleton with modules		▪ Consists of a central de-spun section connected to a circular outer ring ▪ On the outer ring inflatable modules are attached in pairs (for balance)
Banded Cylinder		▪ Similar to the load bearing skeleton with modules, except the modules extend out along the axis of rotation
Out-of-plane Cylinders		▪ Similar to the load bearing skeleton with modules, except the modules extend out along the axis of rotation
Dumbbell		▪ Modular concept that is composed of pairs of modules geometrically opposite one another and linked by a truss ▪ Station can be expanded by adding subsequent dumbbells until finally, a full torus forms

Concept Name	Visualization	Descriptions
Counterweighted single section		▪ An expandable rotating section, counterweighted by a large, moveable mass (e.g. a water reservoir, a waste deposit, an asteroid, etc.) to which it connects through a central module
O'Neill Cylinder		▪ Cylindrical structure that rotates to provide artificial gravity ▪ Usually O'Neill concepts consists of a pair of parallel cylinders that rotate in opposite directions to cancel out gyroscopic effects

4.2.2. Concept selection process

We were able to immediately discard options that we deemed would not be able to comply with any of the primary requirements. Using this process, we reduced our potential concepts down to four, which are laid out in Table 4-3.

Table 4-3: Reasons for eliminating initial concepts

Concept	Reason for Elimination
Hollowed out asteroid	Not feasible for 2040 timeframe (and uncertainty in finding suitable asteroid).
Banded Cylinder	The station structure is out of plane of the wheel and hence the mass and volume of modules would be very large, resulting in a large, complex structure that would be unfeasible for 2040.
Dumbbell	Each module pair would need to be connected by a spoke that can withstand the centripetal force of rotation. This would result in a complex structure with a high mass. This would require more launches to assemble - not feasible for 2040 timeframe.
O'Neill Cylinder	Cylinders would need to have an excessive pressurized volume - not feasible by 2040 due to size.

To identify the final concept out of the remaining choices, we assigned scores for each concept based on how well each option would be able to meet each requirement (effectiveness score). The requirement weighting was multiplied by the effectiveness score, and scores were summed for each concept to find the best ranked concept. An example of this method is presented in Table 4-4.

Table 4-4: Example of weighted scoring method for concepts

	Final Concepts				
Requirement	**Weighting (Out of 10)**	**Load Bearing Modular Tube**	**Load Bearing Skeleton with Modules**	**Out-of-plane cylinders**	**Counterweighted Single Section**
The station shall be available for habitation by 2040	9	6	7	3	6
The station shall have large communal areas	3	7	6	7	6
TOTAL:		75	81	48	72

The load bearing skeleton with modules concept was the clear winner based on our ranking system. However, we were aware of the subjectivity of our method, especially in its sensitivity toward weighting variations, so we further discussed the advantages and disadvantages, concerns, and design challenges of the remaining concepts. We determined that the load bearing skeleton with modules was indeed the most feasible design for our station.

4.3. Overview of chosen concept

Figure 4-1 presents our design of Starport 1. We identify two main parts: the stationary microgravity area at the center (Section 4.5), and the outer ring, which rotates to create an AG environment (Section 4.6). This section provides a general overview of Starport 1, including its dimensions and angular velocity, its components, and the interface between the microgravity and AG sections. Table 4-5 gives the general specifications of Starport 1. Throughout this chapter, each of these specifications will be discussed.

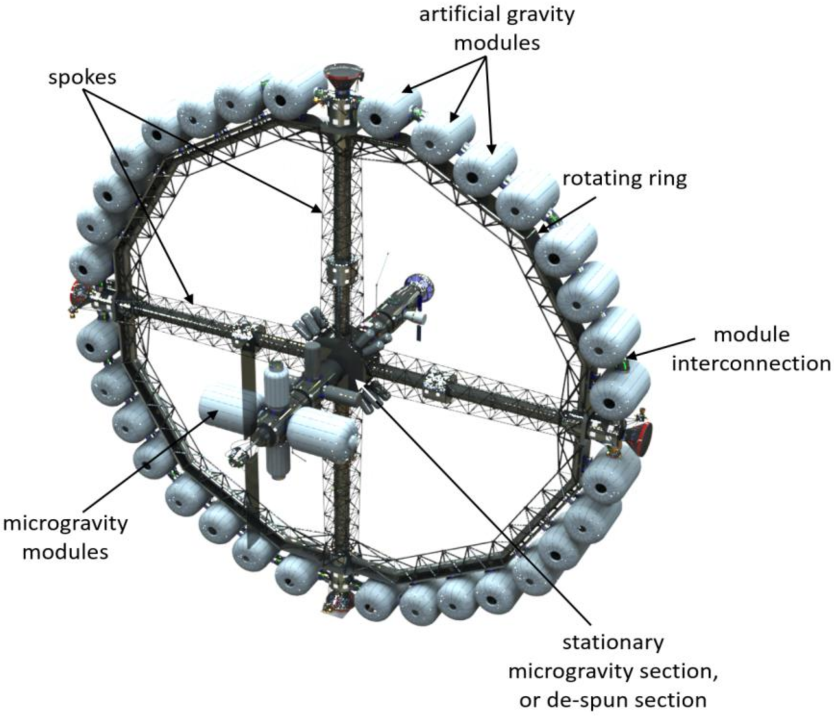


Figure 4-1: General design of Starport 1

Table 4-5: General specifications of Starport 1

Starport 1 specifications	
Diameter (not including modules)	150 m
Diameter of the central section	20 m
Angular velocity	2.9 rpm
Artificial gravity in modules	0.7 - 0.8 g (depending on the floor in the module)
Mass estimate	10,000,000 kg
Maximum number of AG modules	32

4.4. Dimensions and angular velocity

The modules on the rotating ring experience a centrifugal force. This force points radially outwards as shown by Figure 4-2. Combining Newton's second law with his expression for gravitational force, we find an expression for the proportionality of the centrifugal force F to the gravitational force on Earth F_G, as shown in Equation 1:

$$\frac{F}{F_G} = \frac{R\Omega^2}{g}; \qquad (1)$$

where R is the radius of the station, g the gravitational acceleration and Ω the angular velocity. As explained in Section 6.2.3, the maximum magnitude of artificial gravity that will be created on the station is 0.8 g. This is a compromise between the negative effects of reduced gravity on the human physiology, such as reduced bone mass, and the needed radius and angular velocity of the station. Our client suggests an angular velocity of $\Omega = 2\ rpm$ in order to minimize Coriolis effects. This means that the radius R needs to be 179 m. Reducing this radius, would reduce the mass and size of the station, but would increase the angular velocity needed to simulate 0.8 g, as plotted in Figure 4-3. A high angular velocity causes a high Coriolis force, as shown by Equation 2.

$$\vec{F}_c = -2m\vec{\Omega} \times \vec{v}; \qquad (2)$$

where $\vec{v}$ is the velocity vector of the object upon which the Coriolis force acts. This Coriolis force should be limited because it decreases the comfort of people living on the station.

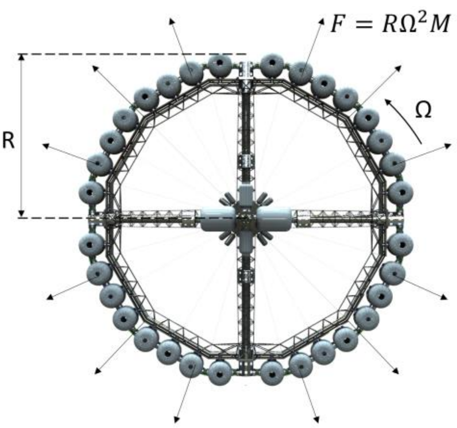


Figure 4-2: Centrifugal force acting on the station due to its rotation

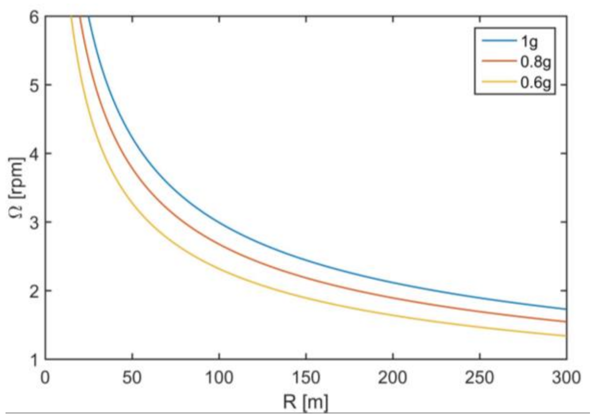


Figure 4-3: Angular velocity versus radius of the station

As explained in Section 6.2 of this document, Ω should be limited to 4 rpm for human comfort. We chose 75 m for the radius of the ring excluding modules, which corresponds to an angular velocity of 2.9 rpm to create 0.8 g of centrifugal force on the floor in a module that is farthest away from the center of the station. On the structural ring, there will be artificial gravity of 0.7 g as illustrated by Figure 4-4. This allows for a margin between Ω and the maximum allowed value of 4 rpm.

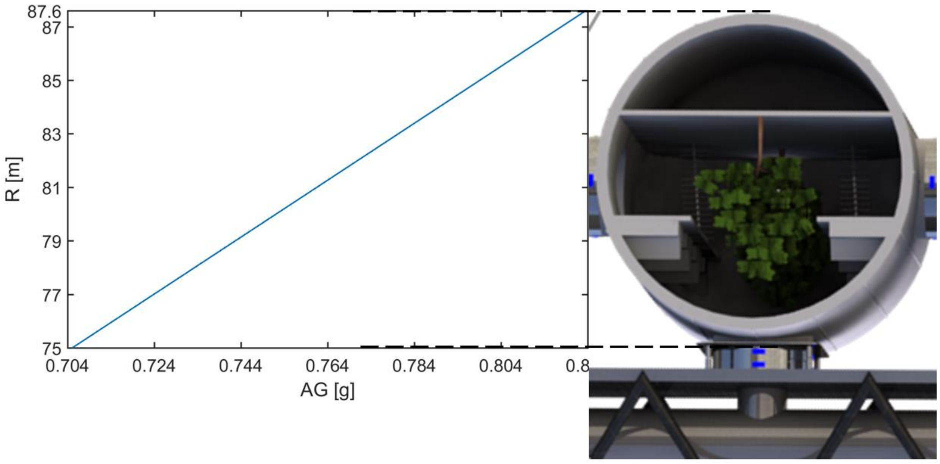


Figure 4-4: Artificial gravity within a module, with representation of module for comparision

4.5. Microgravity section

The main design drivers for the microgravity section of Starport 1 are either applicable to the whole station (e.g. structural integrity and ease of assembly) or specific to this area of the station. The latter includes:

- Commercial flexibility: facilities for research and production, with possibility to expand accessible workspace and customize modules (see Section 0 for details);
- Need for a robotic service arm: docking of vehicles, shifting and servicing the modules of the central section;
- Docking access for various vehicles (see Section 4.5.3 for details); and
- Tourism: the cupola, separation from manufacturing area.

4.5.1. The central hub

Figure 4-5 and Figure 4-6 show the central hub of Starport 1. The hub supports the bearing, to which the four spokes that support the rotating ring attach. Elevators connect to the hub to allow access to the rotating ring. The hub has a cupola that provides a 180-degree field of view.

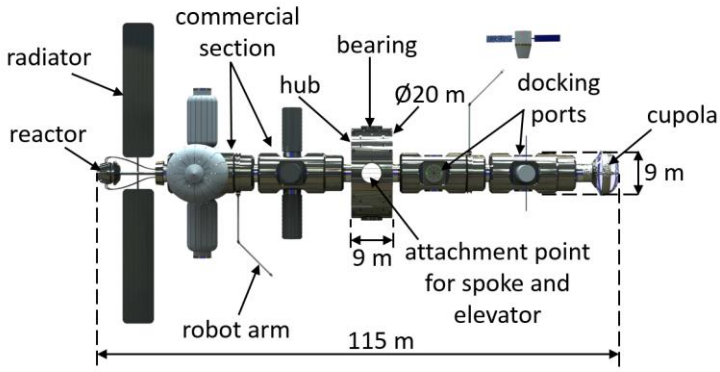


Figure 4-5: Horizontal view of the central hub

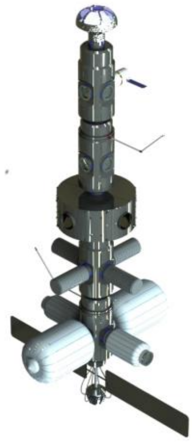


Figure 4-6: Vertical view of the central hub

4.5.2. Commercial section with manufacturing and research modules

We expect that customers will be interested in using microgravity modules to pursue their own projects. The commercial section provides an interface to attach standard or customized modules in a microgravity environment. Since the commercial section consists of modules, it can be expanded in the future. The research facility in the microgravity section of Starport 1 will use an inflatable module, like the current Bigelow B330 module (see

Table 10-1 in Appendix A for its dimensions), because of their high volume to mass ratio (Bigelow Aerospace, 2016; NASA, 2016). For experiments that require low interference due to vibrations, the module will temporarily disconnect from the station. It will reattach using robotic arms or stand-alone propulsion (Spaceref.com, 2011). To support disconnection of the research facility it will have full stand-alone capabilities including environmental control and life support system (ECLSS), a power system, and a propulsion module to avoid drifting away from the station during re-boosts.

4.5.3. Docking

To ensure the safety of the crew and the station, we suggest locating the docking section at the end of the microgravity section. This keeps the docking port stationary, avoiding the additional complexity and risk of docking a vehicle to a rotating spacecraft. Once the orbit of a spacecraft that will dock with the station matches its orbit, the relative velocity between the spacecraft and a docking port located on the microgravity section would be zero. However, the relative velocity of the modules on the rotating ring would be about 23 m/s, given that the ring's radius is 75 m and the rotation is Ω=2.9 rpm, equivalent to 0.3 rad/s (given in Table 3). Since these modules are rotating, it would be difficult for a spacecraft to match this velocity.

ISS supports a maximum of seven vehicles docked at the same time (NASA, 2010). For a larger complex like Starport 1, more docking ports will be necessary to handle traffic in optimal conditions, since more launches for supplies and for visitors to the station will be needed compared to ISS. In addition, there will always be at least one spacecraft docked to Starport 1 that can transport people back to Earth at any time, in case of for example, a medical emergency that cannot be dealt with on the station. If necessary, the station must be able to accommodate new expandable docking modules.

4.6. Artificial gravity section

The primary considerations for choosing modules on the AG part of Starport 1 are high volume to mass ratio, protection against radiation and debris, and ease of movement between compartments. Modules are also expected to be easily replaceable in case of damage. We chose to use inflatable modules due to their great volume to mass ratio as opposed to rigid modules. This results in higher achievable volumes using available launchers and lower launching costs (NASA, 2016). These types of modules are also space proven (Pearlman, 2016). The outer sections of the station will use the inflatable Bigelow BA 2100 module concept. Section 4.8 elaborates on the structure to which these modules are attached.

Table 10-1 in Appendix A contains the dimensions of this module. A tunnel with a diameter of 3 m connects a module to its neighboring module. This way, two people can comfortably pass through this interconnection. The module interconnections are shown in Figure 4-8. These tunnels connect to the side of a module. We chose this orientation to maximize the amount of modules that can be fitted on the ring. However, the inflatable modules will have to be adapted to allow for airlocks on its sides. We recommend additional research in cooperation with the module manufacturer in order to make this feasible. Because the tunnels connect the hearts of the modules, the crew will feel less isolated and will be required to pass through the heart of different modules when moving through the AG section of Starport 1. This aspect is discussed further in Section 7.4.1. For more information on the docking ports used on the modules see Section 4.5.3. The large interconnection to the heart of a module also creates the possibility for a large open space spanning over multiple modules. However, the layout of the interior of each module must be adapted to avoid disturbing the operations of a module when people pass through it. The ceiling height within a module is 2.4 m (as discussed in Section 6.1.1), and the corridor connecting each module is 3 m high.

To withstand the centrifugal force, vertical support will have to be added inside the modules in order to be able to bear its own centrifugal load and to support the floors inside the module. Bigelow modules are designed for microgravity; as a consequence, structural support will have to be developed to withstand 0.8 g.

4.6.1. Coriolis effect considerations

A major consideration in the AG part of Starport 1 is the Coriolis effect, which is the sideways force that an object experiences when it moves in a rotating frame in the radial direction. The magnitude of this force depends on the square of the rotational velocity multiplied by the velocity in the direction perpendicular to the axis of rotation (Bailey, et al., 1989). Humans must adapt to the Coriolis effect and shifting from the stationary to the rotating part of the station might further introduce difficulty to the learning process required to adapt to the Coriolis effect (Rabe, et al., 2009). The forces and accelerations on the human body are considered in detail in Section 6.2 of this document.

4.7. Microgravity and artificial gravity interface

The spinning ring and spokes are connected to the microgravity section using a bearing that also contains a seal and drive-system. Section 4.12 describes this system in detail. An elevator moves through these spokes. As it moves, the artificial gravity force decreases linearly with the distance to the axis of rotation of the ring: $g = l\,\Omega^2/9.81$ where g is the fraction of Earth gravity experienced and

l the distance to the axis of rotation. This section will discuss three different elevator concepts to move to and from the microgravity section.

4.7.1. Unpressurized elevator shaft

The elevator shaft running through a spoke is unpressurized. When an elevator approaches the central de-spun section, it will latch and connect to an airlock at the circumference of the microgravity part. To stay latched and static, it will simultaneously detach from the rail above it. Since rotational velocity in this area will be relatively low due to the small radius of rotation (~6 m/s for a central station radius of 20 m), the latching will be smooth. An alternative to this approach is to have the airlocks on the rotating part of the bearing: the elevator shaft will be attached to an airlock that will rotate over a bearing. When the elevator attaches to the airlock, it will keep rotating at low speed and remain available for access from the central section. The main disadvantage of this approach is the need to dock twice to an airlock every time the elevator is used, which will be time consuming.

4.7.2. Manual movement through a shaft

Manual motion across the station would require a pressurized shaft. If the air moves freely between the microgravity section and the AG ring, a pressure gradient will be created due to the increasing centrifugal force towards the ring. A complex pumping system is needed to maintain a pressure of 1 bar in the central section. In addition, the Coriolis effect will cause an uncomfortable sideways force acting on people moving through the shaft. We do not recommend this solution because of these two reasons.

4.7.3. Pressurized elevator shaft concept

Figure 4-7 shows this concept. Since there may be a pressure difference between the spinning and de-spun sections of Starport 1, we suggest using an elevator with seals at its top and bottom, riding in an airtight tube between the two sections. There will be a sliding door to enter and exit the elevator, and a pressure valve to equalize the pressure during the ride. In this scenario, the ring, spokes, elevator tube, and outer part of the bearing will rotate together. When the elevator is partially (about 2 m) in the microgravity section of the station, it rotates at only 4 m/s and people can simply float out of the elevator into the central section of the station. If the elevator stops working, this mechanism will still allow for the transport of people and equipment through the pressurized shaft.

We have chosen this elevator concept because of its simplicity and because it allows to easily keep both the rotating and stationary section of the station at a pressure of 1 bar.

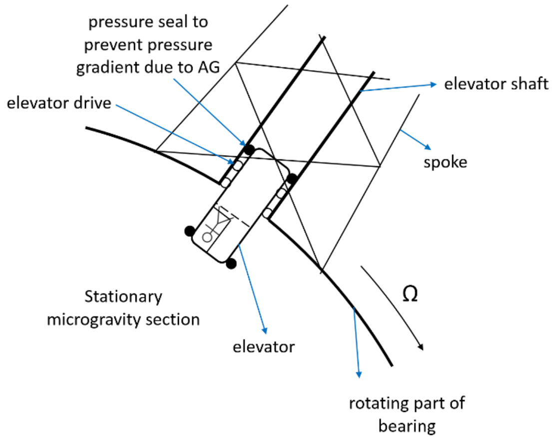


Figure 4-7: Pressurized elevator shaft concept

4.8. Structural components

4.8.1. Main layout of the bus

The structural framework of Starport 1, or the "bus," will mainly consist of trusses. These structures can withstand large forces with a limited mass. They are space proven and form the main structural element of the ISS (NASA, 2010). Figure 4-8 shows the main layout of the bus.

The bus of Starport 1 will be designed to withstand the load caused by rotation. All operational structures such as elevators and modules will be attached to this framework using struts. We chose this approach because it reduces the structural requirements of the operational system, as they only need to be able to support their own centrifugal force. Additionally, the ability to add modules to and remove them from a framework increases the modularity of the design.

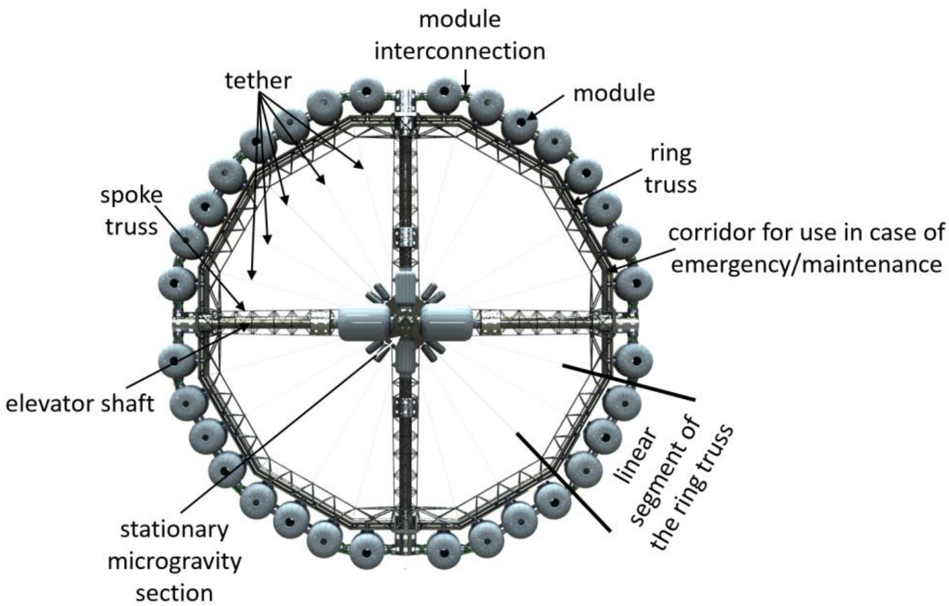


Figure 4-8: Structural components of Starport 1

As shown in Figure 4-8, the central section is connected to the ring by four spokes, with an elevator shaft running through each one. Two spokes will each contain a cargo elevator, while the other two will each have an elevator for transporting people. We chose to have four elevators to limit the mean distance to an elevator on the platform of the rotating ring and to enable combination of the elevator shafts with the spoke trusses. The circumference of the ring with modules is 2π· 87.6=550 m (the radius of the ring is 75 m and the diameter of a BA 2100 is 12.6 m) (Spaceref.com, 2011). When a person is at the farthest point from an elevator, i.e. near a cargo elevator, the distance to the nearest elevator is one fourth of the circumference: 138 m. Between two spokes, there will be five tethers connecting the central bearing to the linear truss segments. As a result, the tethers will redirect part of the load due to bending on the main truss. Flexural loading is caused by the tendency of the structure to bend.

The ring is a truss consisting of linear sections with a triangular cross-section (Figure 4-9). Because these sections are linear, as opposed to curved, it is easier to fit multiples in a single fairing of a launch vehicle. These linear segments are connected to each other using a flange and bolt system. Section 0 further discusses the assembly sequence of the ring and of the station in general. Pipelines with water, waste, etc. will be placed on top of this structure. These supply lines are discussed in detail in Section 4.8.3. A pressurized cylindrical corridor will run through the interior of the triangular truss, allowing crew members to move between modules in a case where the connection between two modules has to be sealed due to maintenance requirements or an emergency. The main way to move through the module interconnections, as discussed in Section 4.6. This way, the radiation shielding and diameter of the corridor in the ring do not have to be adapted for regular use, which conserves mass.

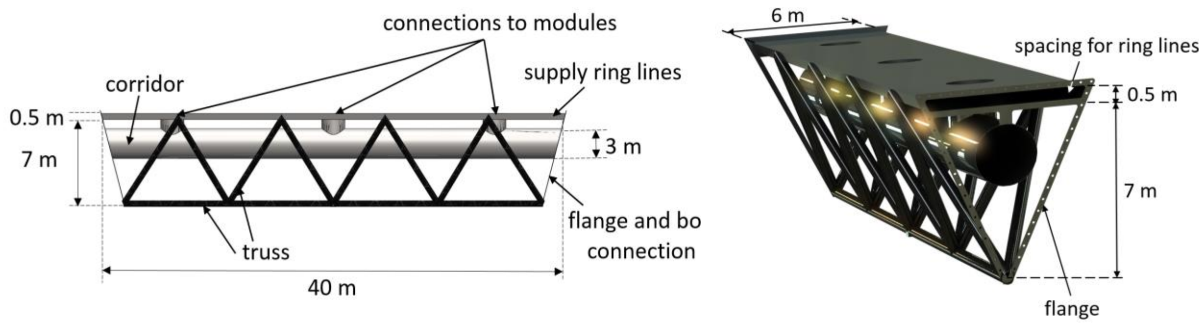


Figure 4-9: Linear segments of the rotating ring

Figure 4-10 displays the connection between the elevator shaft and the rotating ring. The spoke truss will be connected to the linear segment of the ring and the elevator shaft will be attached to a cylindrical module.

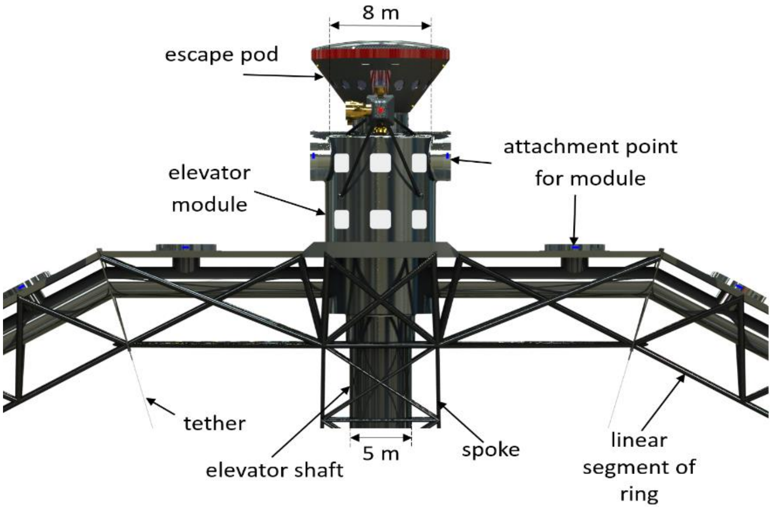


Figure 4-10: Connection between an elevator shaft and the rotating ring

Struts will connect the load bearing truss structure with the elevator shaft and module. We chose to add extra structural support to the ring using tethers. Section 4.9 further elaborates on the internal loading of the structure.

4.8.2. Materials

To minimize the cost of manufacture and increase the ease of assembly and maintenance, we should use modular structural elements as much as possible. The struts must have low mass to limit the number of launches, which is proportional to the mass of Starport 1. The stiffness of the structure must be high to limit the displacement of the station under dynamic loading. Finally, the materials must be strong enough to withstand the centrifugal force.

We chose to use carbon fiber hollow tubes for the outer ring and the truss structure of the spokes. This material is light, stiff, and strong (with a density of 1,800 kg/m^3, a Young's modulus of 100 GPa and a yield strength of 600 MPa; (American Chemical Society, 2003). It is also widely used in satellites, so it is space proven. The cables between the spokes will be made of Twaron, an extremely strong and stiff material that is similar to Kevlar, with a density of 1,400 kg/m^3, a Young's modulus of 100 GPa and a yield strength of 2,700 MPa (NauticExpo, 2016). Using these materials, we make a mass estimate of the station excluding AG modules. This results in approximately 6,800,000 kg. The total mass of the station, including 32 BA2100 modules of 100,000 kg each (see

Table 10-1 in Appendix A), then amounts to about 10,000,000 kg. However, this is a rough estimate and we recommend a more detailed analysis of the station's mass in future work.

4.8.3. Supply systems

All modules on the rotating ring are connected to a ring line on top of the ring trusses. This ring line supplies the following materials to the module: water for everyday use (e.g. water consumption and hygiene by the crew, agriculture and farming); water for cooling the modules, shielding, fire safety; waste; air in case of decompression of a module; propellant for the attitude control system; data and communication lines; and power lines.

The pipeline providing water will also be used to compensate for changes to the center of gravity of Starport 1 by pumping it to different locations in the ring line. This counteracts the effects of people moving around and other disturbances to the station. Consider a case where 100 people will move to one location on the ring. This means that this system must be able to compensate for about $100 \cdot 70 =$ 7,000 kg, which corresponds to 7 m^3 of water. This amount of water must ideally be stored in only one linear segment of the 40 m long ring truss with space for supply lines that are 0.5 m tall, as seen in Figure 4-9. As a result, a reservoir with a cross-section of about 0.5x0.35 m needs to be located on the ring. For each supply, we chose to use a double redundancy system in the ring line by embedding two separate pipelines into the ring structure. Figure 4-11 shows the connection points for modules and supply lines.

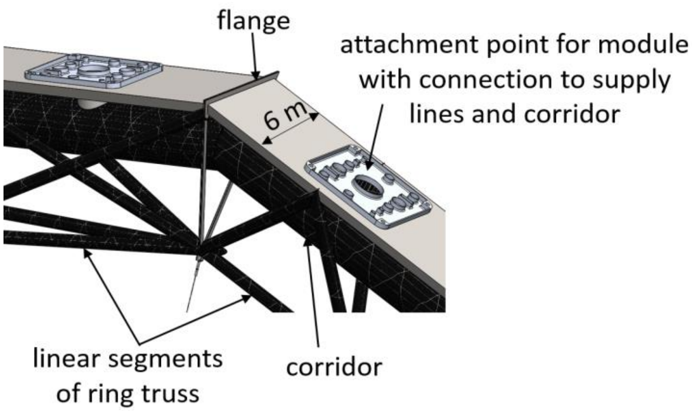


Figure 4-11: Connection points for modules and the supply system

If the pipe failed somewhere along the ring, the damaged part could be sealed off with valves, allowing the ring line to remain operational.

4.9. Structural analysis

We conducted a structural analysis of the final conceptual design and determined the dimensions of the trusses and tethers. We also confirmed that Starport 1 will keep its structural integrity for 2 loading cases: when a BA2100 is attached to each attachment point on the ring and when the ring is not yet assembled and only the spokes are rotating.

For our structural analysis, we considered the trusses and the tethers as one-dimensional elements. This is a good assumption since their length is significantly greater than their width and height: the ring has a circumference of 471 m and a cross section of 6x7 m; the spokes have a length of 60 m and an average cross-section of 12x12 m. Given that this is a simple approximation and that the structural integrity of Starport 1 must be guaranteed in a variety of load cases, we used a safety factor of three in our calculations, as compared, for example, to the standard factor of 1.5 used in aircraft components (Engineeringtoolbox.com, 2016). We recommend a more detailed analysis as future work that takes into account the thermal stress in the structure and that considers additional load cases such as the failure of a spoke or tether. We chose to design Starport 1 to be able to hold a mass of 7,500 kg per meter on its ring: one linear segment of 40 m holds three modules of approximately 100,000 kg (see Table 10-1 in Appendix A). Additionally, a spoke must be able to support three modules when the ring is not yet built; this means that one spoke must be able to support three modules on its own.

4.9.1. First load case: completed ring with 32 modules

The goal of this calculation is to determine the internal stress in the ring and spokes and choose the dimensions of the trusses. Figure 4-12 and Figure 4-13 show the models used in the calculations. All equations used in this analysis are based on general structural mechanics (Smith, 2001).

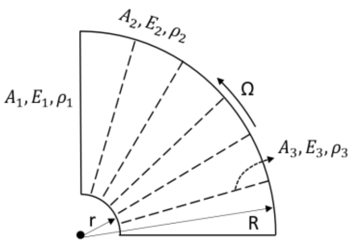


Figure 4-12: One quarter of the structure

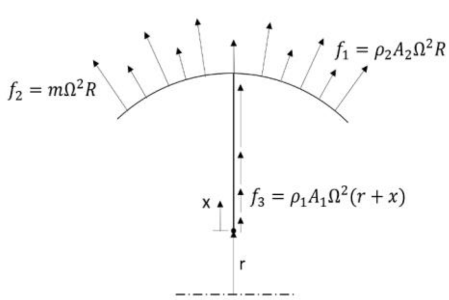


Figure 4-13: External forces acting on the structure

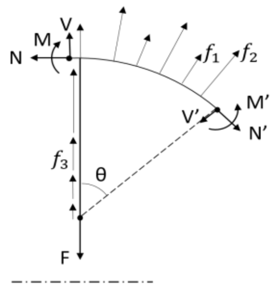


Figure 4-14: Free-body diagram of a spoke/tether and part of the ring

In Figure 4-12 and Figure 4-13, E is the Young's modulus, representing the stiffness of the material, A is the surface area of the cross section, ρ the density, and Ω the angular velocity. The rotating structure is equivalent to a stationary structure with a distributed centrifugal force acting on it. This load can be written as follows:

$$f = a \cdot \rho A = l\Omega^2 \rho A; \quad (3)$$

where a is acceleration and l the distance from the center of rotation. We use this method to determine all forces acting on the station, as shown in Figure 4-13. In Figure 4-13, m is the mass of the modules attached to the station, which is expressed in kg per m and equals 7,500 kg/m. Due to the symmetry of the structure, it is sufficient to only consider one eighth of the station. We draw a free body diagram of part of the ring shown in Figure 4-14. F is the reaction force exerted by the central bearing on the spoke or tether and N, V, M are the internal forces: tension, shear force, and bending moment, respectively.

We solve a system of static equilibrium equations (horizontal, vertical, and torque equilibrium), resulting in expressions for N', V', and M':

$$N' = (V - F + \rho_1 A_1 \Omega^2 \tfrac{R^2 - r^2}{2}) \sin\theta + N\cos\theta + (\rho_2 A_2 + m)\Omega^2 R^2 (\cos\theta - \cos 2\theta); \quad (4)$$

$$V' = 2(\rho_2 A_2 + m)\Omega^2 R^2 (\sin^2 \tfrac{\theta}{2} + \tfrac{\cos\theta - \cos 2\theta}{2}) - N\sin\theta + (V - F + \rho_1 A_1 \Omega^2 \tfrac{R^2 - r^2}{2}); \quad (5)$$

$$M' = M + \left(V - F + \rho_1 A_1 \Omega^2 \tfrac{R^2 - r^2}{2}\right) R\sin\theta + NR(\cos\theta - 1) + 2(\rho_2 A_2 + m)\Omega^2 R^3 \sin^2 \tfrac{\theta}{2}; \quad (6)$$

There are a total of seven unknowns: the F terms in the spoke and the three tethers, as well as N, V, and M in the spoke connection. A free body diagram of a quarter of the structure shows that V = 0. We can calculate M using the symmetry of the station; the angular displacement θ due to bending of the ring in the connection with the spokes and 45° from the spokes has to be zero, as shown in Equation 7.

$$\Delta\theta = \frac{1}{EA}\int_0^{\pi/4} M'Rd\theta = 0; \qquad (7)$$

$$\Rightarrow M = \frac{4-2\sqrt{2}}{\pi}\left(\left(V - F + \rho_1 A_1 \Omega^2 \frac{R^2-r^2}{2}\right) R - NR\right) + \frac{\pi-2\sqrt{2}}{\pi}(\rho_2 A_2 + m)\Omega^2 R^3; \qquad (8)$$

This leaves five unknowns. To calculate F for each spoke/tether, the elasticity of the structure needs to be taken into account. The elongation due to internal forces of the spokes/tethers, Δl, should equal the radial displacement of the ring, ΔR, on the attachment point of the corresponding spoke/tether. First, we calculate Δl:

$$\Delta l = \int_r^R \varepsilon dl = \int_r^R \frac{N}{EA} dl = \int_r^R \frac{1}{EA}\left(F - \rho A \Omega^2 \frac{l^2-r^2}{2}\right) dl = \frac{F(R-r)}{EA} + \frac{\rho\Omega^2 r^2 (R-r)}{E} - \frac{\rho\Omega^2 (R^3-r^3)}{6E}; \qquad (9)$$

ε is strain and E is the Young's modulus. ΔR consists of a displacement due to tension, ΔR_t, and a displacement due to bending, ΔR_b:

$$\Delta R_t = \frac{\Delta l'}{\theta} = \frac{1}{\theta}\int_0^\theta \frac{N}{EA} R d\theta$$

$$= \frac{R}{\theta EA}\left(\left(V - F + \rho A \Omega^2 \frac{l^2-r^2}{2}\right)(1 - \cos\theta) + N \sin\theta + (\rho_2 A_2 + m)\Omega^2 R^2 \sin\theta\,(1-\cos\theta)\right); \qquad (10)$$

$$\Delta R_b = \frac{1}{EI}\iint_0^\theta M' R^2 d\theta$$

$$= \frac{R^2}{EI}\left(M\frac{\theta^2}{2} - \left(V - F + \rho A \Omega^2 \frac{l^2-r^2}{2}\right) R \sin\theta + NR\left(\frac{\theta^2}{2} - \cos\theta\right) + (\rho_2 A_2 + m)\Omega^2 R^3\left(\frac{\theta^2}{2} + \cos\theta\right)\right); \qquad (11)$$

By imposing $\Delta l = \Delta R$ for the spoke and tethers, we can calculate F. The only remaining unknown is N. We calculate this force from the free body diagram of one quarter of the station. Every parameter in the equations for N', V', and M' is known. As a consequence, the internal forces in the structure can be determined. The internal stress from tension equals

$$\sigma_{tension} = \frac{N'}{A}; \qquad (12)$$

The internal stress from bending equals

$$\sigma_{bending} = \frac{M'y}{I}; \qquad (13)$$

where y is the distance to the neutral fiber in the ring and I the second moment of inertia.

The material choices presented in Table 4-6 result in the internal stress distributions in the spokes and tethers shown in Figure 4-15.

Table 4-6: Dimensions of structural elements analyzed

Carbon tubes in the spokes		Carbon tubes in the ring		Twaron tethers	
Outer radius	250 mm	Outer radius	500 mm	Radius	30 mm
Thickness	5 mm	Thickness	14 mm		

In Figure 4-15, x = 0 m is the top of the spoke (to which the ring is attached) and x = 60 m corresponds to its base. This figure shows the stress in the tethers in one quarter of the station. Due to symmetry, this force is the same in the other quarters. We chose to make the spokes wider near the base because the internal stress is largest where the spoke and the de-spun section meet.

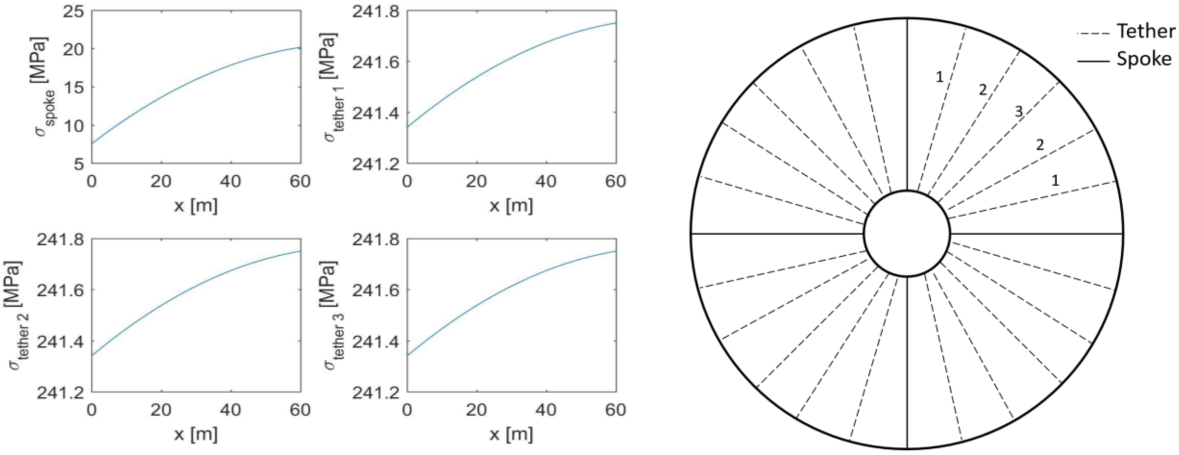


Figure 4-15: Internal stress distributions in spokes and tethers

Figure 4-16 shows the internal stress in one quarter of the rotating ring. The top left shows the tensile stress, while the top right shows the stress due to bending, also called flexure, on the inside of the ring. These plots show that the forces due to the bending of the ring are much higher than pure tension.

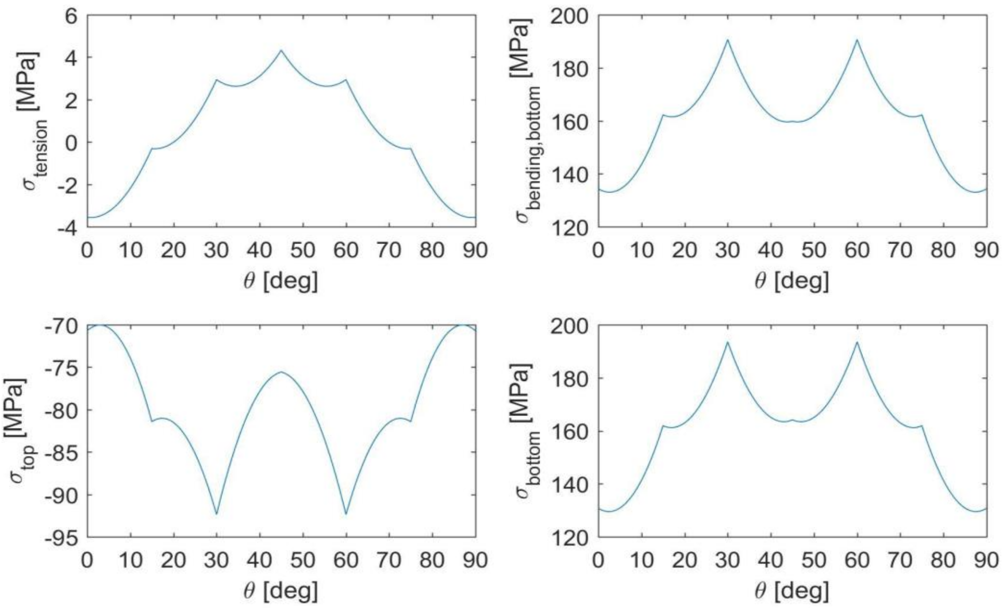


Figure 4-16: Internal stress distribution in the ring

The triangular cross-section of the ring is well suited to resisting flexure. However, we also considered a rectangular cross-section since it is more resistant to bending. We ultimately chose the triangular cross-section because it offers a good compromise between mass and bending resistance.

The bottom left and right of Figure 4-16 show the total internal stress in the outer and inner parts of the ring, respectively. We conclude that the maximum stress is reached at the inner part of the ring structure, 30 degrees from a spoke. As a consequence, the maximum module mass that can be attached to Starport 1 near this point is 7,500 kg per meter. Near the spokes, the allowed mass is higher. A more detailed analysis is necessary to determine the exact value.

4.9.2. Second load case: 3 modules attached to a spoke

We verify that the chosen dimensions of structural elements are sufficient to maintain structural integrity in the second load case. In this case, three modules of 100,000 kg each are attached to a spoke while the ring is not present (of which one is the elevator module). Figure 4-17 shows the free body diagram of the spoke.

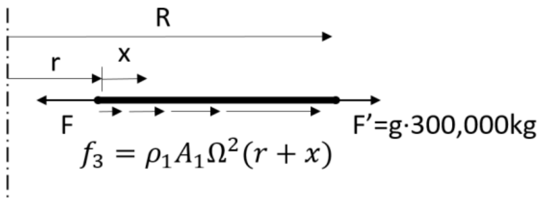


Figure 4-17: Free body diagram of a spoke

The internal stress is shown in Equation 14. The maximum internal stress, that is reached for x=0 m is shown in equation 15. Since this value is less than one third of the yield strength of carbon tubes (600 MPa), we conclude that structural integrity is maintained.

$$\sigma = \frac{N\prime}{A_1} = \frac{2F - \rho_1 A_1 \Omega^2 ((r+x)^2 - r^2)}{2A_1}; \quad (14)$$

$$\sigma_{max} = \frac{F\prime}{A_1} + \frac{1}{2}\rho_1 \Omega^2 (R^2 - r^2) = 88\ MPa \qquad (15)$$

4.10. Adding and removing modules

We recommend that modules are added and removed when the ring is de-spun, avoiding a complex system to add or remove them during spin. We considered three possible methods for adding and removing modules to and from the rotating ring, in case the lifetime of a module or the need of customers to swap out modules would necessitate such a system: a crane that can rotate independently of the rest of the station, a separate spacecraft to dock a module to the ring, and a rail system on the structure of Starport 1. We explore these methods in the following section.

4.10.1. Crane

The crane is a truss structure that will be attached to the central section of Starport 1 by means of a bearing. It will extend out beyond the rim modules and will be balanced by a moveable counterweight. To add a module to the ring, it will dock with the crane while the latter is stationary. The crane will spin up to match the rotational velocity of the ring modules, allowing the module to attach safely to the ring. On the opposing side of the ring, water is pumped to an empty module that the crane has already placed there. This keeps the center of gravity of the ring on the axis of rotation. The advantage of the crane is that it offers a very simple procedure for adding or removing a module. However, the crane is a complex structure that will add mass to the station. It will also necessitate a second bearing and drive system to spin it up.

4.10.2. Small shuttle

A small shuttle, that can move independently of Starport 1, will attach to the module and transport it to the ring. The shuttle will perform the docking maneuver. This will require very complex maneuvers requiring highly precise and fuel-consuming attitude control and propulsion to match the rotation of the ring while carrying a module. This will increase the traffic around the station. The use of a small shuttle for servicing purposes, rather than for replacing modules, would be much more feasible. An alternative to the separate craft is to include propulsion systems in the modules themselves, as is possible for Bigelow modules (Spaceref.com, 2011).

4.10.3. Rail system

A rail system on the spokes and the ring will transport a module from the central de-spun section of Starport 1 to the rotating ring. The module will dock with a stationary section in the center of the station. It will spin up to match the rotation of the spokes inside the stationary center section to allow the rails on the spokes and ring to transport it. This method is promising, but requires a sturdy truss structure for the spokes since it must withstand the centrifugal and Coriolis effects caused by the module.

We chose the rail system for Starport 1 since it is the most feasible and least massive option. However, if the use of a separate spacecraft or the onboard propulsion systems of a module to dock to the rotating ring should become feasible by 2040, we recommend this approach.

4.11. Attitude and orbit control systems

The primary objective of the attitude and orbit control system (AOCS) is to ensure that Starport 1 can maintain a stable orientation and orbit. We placed particular importance on the roll control of the station because it provides the rotation necessary to achieve AG. The AOCS requires control over all six rotational and translational degrees of freedom (DOF).

One of the major differences between the attitude control of Starport 1 and other existing space stations is the fact that the station is spinning and is a gyroscope. Due to the orbital angular momentum and spin angular momentum of the station, gyroscopic precession needs to be taken into account when designing the attitude control system. It is essential that future analysis of the station control system delves into gyroscopic effects and what must be done to ensure a stable and desired orbit.

The majority of the research for the preliminary attitude and orbit control (AOC) design consists of consideration of types of sensors and actuators. Future detailed design of the AOCS should investigate control system design and stability, as well as how to counteract precession and utilize gyroscopic forces due to the rotation of the station.

4.11.1. Major design drivers

Table 4-7: Major AOCS design drivers

Parameter	Impact
Station mass and moment of inertia	Impacts angular momentum and required thrust
Station structure, diameter, and configuration	Impacts thruster forces and placement (it cannot be placed where its plume will interfere with living modules)

Parameter	Impact
Orbital parameters	Impacts choice of thrusters from drag values and thrust requirements for re-boosting
Anticipated drag force	Thrusters to provide compensating force to retard drag forces
Mission requirements/required pointing accuracy	Mission requirements determine pointing accuracy – direct impact on thruster choice.
Available power	Electric propulsion directly affected by power limit. A nuclear reactor makes electric propulsion more attractive due to availability of electrical power.
Assembly requirements	Because AG has to be provided during construction, it will influence thruster choices

4.11.2. Thrust and propellant requirements

Assuming an attitude system based on reaction control, it is necessary to determine the thrust requirements for spin-up, stationkeeping, attitude control and debris avoidance, since these will drive the selection of the station actuators and propulsion system. In addition to this, we wanted to maximize the self-sustainability of the station and minimize dependency on re-supplying missions, so we also considered the efficiency, or specific impulse, I_{SP} of thrusters to reduce the need for propellant re-supplies.

We have focused on the requirements for roll and spin-up of the station. Although out-of-plane attitude changes are immensely costly in terms of propellant, thrusters could be placed on the outer regions of the de-spun section to provide yaw and pitch rotation for full 6-DOF attitude control. However, this could also provide loading on the bearing system, which future studies should investigate. The extent to which out-of-plane attitude correction is needed depends on the pointing accuracy requirements of Starport 1, which will likely be driven by commercial and business aspects of the station that are not yet known.

4.11.3. Artificial gravity/roll control

One of the major challenges associated with the AOCS for Starport 1 is how to spin the station to the rotational velocity necessary to achieve AG. It would be possible to do this either on the entire station after it has been assembled, or progressively adding components to the station while it is already spinning.

There are various spin-up techniques, including conventional thrusters or the use of gravity gradients. If we choose thrusters, the type, number, and placement of thrusters required to achieve spin will need to be considered. Several constraining factors also need to be taken into account when deciding on the method: these include the bearing friction and resistive/drag forces that act to oppose the rotation of the station; the maximum allowable angular acceleration for the onboard crew; the power restrictions (for the case of electric propulsion); the technology and types of engines available at the time of final design and procurement; the time requirements to spin-up station; and the maximum loading of the primary structural elements.

4.11.4. Choice of thrusters

Knowing the desired radius, rotational velocity, and mass distribution of the station, the spin angular momentum, L, can be computed based on the parameters shown in Table 4-8.

Table 4-8: Parameters used for preliminary spin calculations

Parameter	Symbol	Value	Unit	Notes
Station radius (Distance to outer ring excl. modules)	r	75	m	Assuming that the station radius and radial distance of thrusters are the same
Rotational velocity	Ω	0.30	rad s^{-1}	2.9 Revolutions per minute (rpm)
Station mass estimate	m	7.5×10^6	kg	Overall station mass estimate (1×10^7 kg) - hub mass estimate (2.5×10^6)
Moment of inertia	I	4.22×10^{10}	kg m^2	Assuming the entire mass of station is distributed around the edges, $I = mR^2$

$$L = I \cdot \Omega; \quad (16)$$

$$L = 1.28 \times 10^{10} \text{ kg m}^2 \text{ s}^{-1}$$

The value for L is the desired change in momentum, or impulse, J:

$$J = Tt = rFT; \quad (17)$$

With Equations 16 and 17, we can determine the time needed for thrust values to impart the necessary momentum to the station to achieve 2.9 rpm.

The time requirements to spin-up the station will affect the choice of thrusters; the continuous thrust required to achieve a particular spin-up time depends largely on the type of thruster. In general, it is important that the thrusters have a high I_{SP} and medium to high thrust. High I_{SP} is important for minimizing operating costs and avoiding the need for resupplying propellant. The thrusters must also provide enough thrust to spin-up the station quickly and maintain the spin in the presence of retarding forces that oppose the rotational motion of the station.

In a detailed design scenario, it would be important to investigate the precise effects of solar radiation pressure, orbital precession, gravity gradients, bearing friction, and other forces that could potentially slow down or inhibit the station's spin. Initial calculations suggest that the space station will be subject to a retarding drag force of 0.012 N/day. This amount does not include bearing friction.

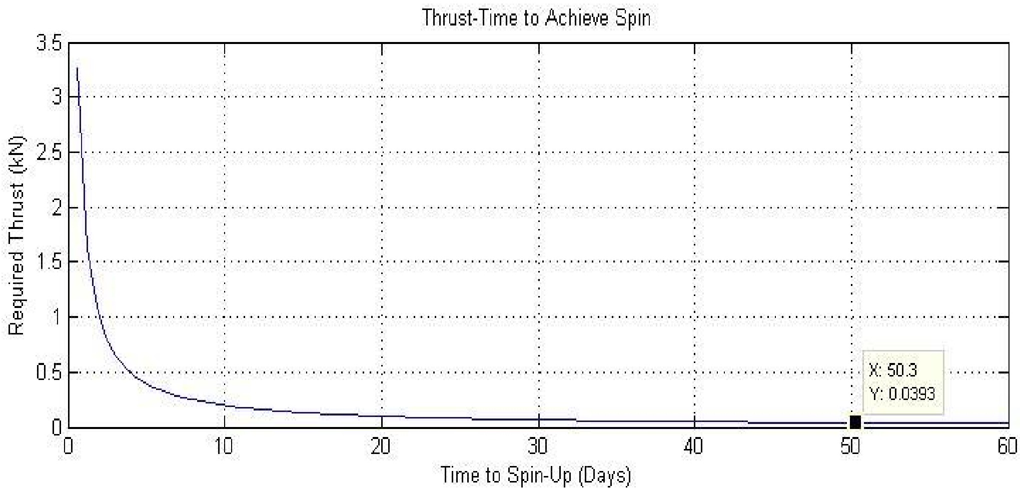


Figure 4-18: Time required to spin up Starport 1

After carrying out a trade-off study of various types of chemical and electrical propulsion systems, we decided to opt for electric thrusters for several reasons. Firstly, one of the limiting factors of electric propulsion systems today are the significant power requirements that are often hard to meet due to the limited power available from sources such as solar arrays. However, since we propose to use a nuclear reactor to generate power, this constraint is not pressing. In addition, electric propulsion systems have high I_{SP}, which means that propellant re-supplies will be kept to a minimum. Finally, although we assume the use of engines that are currently under development, the thrust output of electric propulsion engines can be assumed to be scalable with power input; hence, it is likely that by 2040, higher thrust electric engines will be available – for example, magnetoplasmadynamic thrusters that can provide up to 25 N of thrust (Choueiri, 2009).

One of the highest thrust electric engines currently under development is the VX-200 variable specific impulse magnetoplasma rocket (VASIMR), which is said to deliver 5 N thrust and an I_{SP} ranging from 3,000-12,000 s (Squire, et al., 2008). The minimum number of these thrusters required depends on the thrust required for stationkeeping, as well as the desired spin-up time of the station, which has yet to be defined. Given the geometry of the station, it would be preferable to have pairs of engines, since we propose to mount them on booms out of the plane of the center of gravity (which is discussed later); thus, having pairs would counteract induced torques from asymmetry. The elevator shafts are ideal structures on which to mount thrusters due to structural reinforcement at these points.

We chose to use eight VASIMR thrusters that, when operated simultaneously and continuously, could spin the station from 0 to 2.9 rpm within 50 days, as shown in Figure 4-18. With each thruster requiring 210 kW each, the power requirements would be 1.68 MW. Once the thrusters achieve the desired spin rates, there would be ample thrust available to offset the predicted drag forces. The required number of thrusters is likely to change when the engines and the spin-up time are defined.

4.11.5. Propellant

We can calculate the propellant mass required to spin-up the station using the rocket equation. The effective exhaust velocity, v_e, is 47,088 m/s. This was derived from the specific impulse of the VASIMR, which is approximately 4,800 s. The dry mass of the station, m_f, is assumed to be around 7,500 metric tons. Assuming an angular velocity of 2.9 rpm, $\Omega = 0.3\ rad/s$. The radius, r, is taken to be the distance from the center of the station to the outer ring (75 m). The tangential velocity of the station is the Δv

required to spin the station. The propellant for the VASIMR is assumed to be Argon (Squire, et al., 2008).

$$\Delta v = v_e ln\frac{m_o}{m_f}; \qquad (18)$$

$$\Delta v = \Omega r = 22.5\, rad/s; \qquad (19)$$

$$Station\ Wet\ Mass = m_o = m_f e^{\frac{\Delta v}{v_e}} = 7503585\ kg; \qquad (20)$$

$$Propellant\ Mass = (m_o - m_f) \approx 3600\ kg; \quad (21)$$

4.11.6. Thrust, moment, and placement considerations

For attitude control, we propose for thrusters to be placed as far as possible from the center of gravity to maximize the torques. Factors constraining the placement of thrusters are related to the interaction between exhaust plumes and the station structure. In terms of roll, it is preferable to have thrusters mounted on the outer ring. However, this would put the exhaust plume close to the habitat modules. Possible solutions include mounting thrusters on booms extended either radially outwards from the station or parallel to the spin axis, as shown in Figure 4-19.

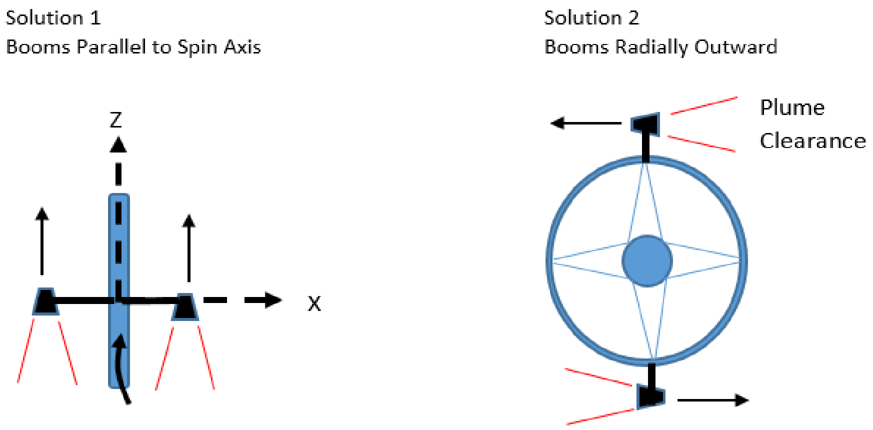


Figure 4-19: Mounting and boom positions for the thrusters

To provide motion along the other degrees of freedom, we will utilize thrust gimballing to reduce the need for additional thrusters aligned with a particular axis. Given the mass of Starport 1, it would be impractical to use reaction wheels or magnetorquers for attitude control of the station; thus, we have proposed the use of thrusters. The high fuel requirements for out-of-plane attitude corrections could be offset by using high I_{SP} thrusters.

Thrusters attached to the rotating outer ring could be actively gimbaled to provide rotation in roll or translational motion in the X, Y, and Z directions. Using the same thrusters to provide pitch and yaw rotation is harder because the rotating ring causes the position of the thrusters relative to the station center to change with time. This is not a problem for translational motion, since all thrusters can be fired simultaneously in the same direction; however, pitching and yawing the station means that asymmetric thrust firing is necessary. Since the station is rotating, asymmetric thrust firing will induce unwanted torques, unless thrusters are fired at specific times when they are perpendicularly aligned with the rotation axis. Compensating for these torques will require a complex active control system that will require more propellant. To simplify this problem, gimbaled thrusters for providing pitch and yaw (as well as X, Y, Z translation) could be mounted on the central, de-spun section.

4.11.7. Attitude determination and control

The station design requires orientation of the station such that the rotating ring is in the orbital plane, with the minimum cross section being exposed to minimize drag. Since this means that the axis of rotation stays perpendicular to the orbital plane during orbit, the axis of rotation does not have to change direction during orbit which means that attitude control will be minimal. In order to ensure that attitude is maintained, the attitude and orbit determination system will be autonomous, and this will require robust onboard computer systems. In addition, we propose the use of a continuous active feedback control system to provide autonomous thrust actuation and attitude correction. Spin stabilization will also be achieved since the station is itself rotating in the orbital plane.

The choice of sensors for attitude determination depends largely on the pointing accuracy requirements for the station, which are currently unknown. However, we assume that the station will use a combination of relative and absolute attitude determination sensors. Rate gyros and inertial measurement units (IMUs) will be used to obtain instantaneous angular rates with global navigation satellite system (GNSS) to compensate for drift errors, while star-trackers can be used for instantaneous attitude determination. Sensors should be placed on booms extended from the de-spun section to avoid interference from the rotational elements of the station.

4.12. Bearing, sealing, and drive

4.12.1. The bearing system

The main bearing of the station is of the hydrostatic type, that is, it relies on pressurized fluid for separation of the spinning and de-spun parts. Since the loads can vary in our application, we need a type of bearing that can handle various types of loads, in addition to being able to operate in a situation where the bearing fluid is depressurized. The loads from the two areas of the station can be divided into axial and radial forces. These sections have two different “pads” that are fed with pressurized fluid that is non-flammable, resistant to water absorption, low levels of outgassing, and resistant to air bubble formation. The lubricant flow, in combination with the load on the bearing, gives rise to a pressure, which is a direct measure of the applied force. Monitoring these forces will allow us to balance misalignments between the station sections by varying the lubricant flow and the maximum pressure. This will be the case for loads in the axial and radial directions. Moreover, since there are several bearing pads on the circumference of the bearing, it will be possible to balance the two bodies at all angles. There will also be a complete backup bearing system for service and redundancy.

The radial bearings are made of metal with a bearing grade plastic surface, and the whole body of the bearing pad sits on a spherical bearing of its own. The radial pad compensates for geometric machining tolerances (i.e., wobble) of the bearing face by continuously changing its angle. This is a system that will function without electronic controls or any kind of operator action as the plastic bearing face can “run dry” for extended periods of time. The axial bearing works in much the same way but, as there are severe spatial constraints on the area of the bearing, this pad might not have a spherical alignment feature, but rather a two-way self-compensating function along the axis of the station. We propose to mount both types of pads in the spun section of the bearing, enclosed in individual chambers to prevent lubricant contamination of the station’s insides. Figure 4-20 shows a typical arrangement of the bearing and seals.

One side of the bearing has a moveable axial pad, while the other side has a “held” pad to enable thermal expansion of the hub itself. We can also mount the different bearing pads on hydraulic cylinders, allowing the bearing system itself to compensate for the off-center weight distribution of the station. However, this compensation can only happen within acceptable limits of the main seals and the possible girth gear drive.

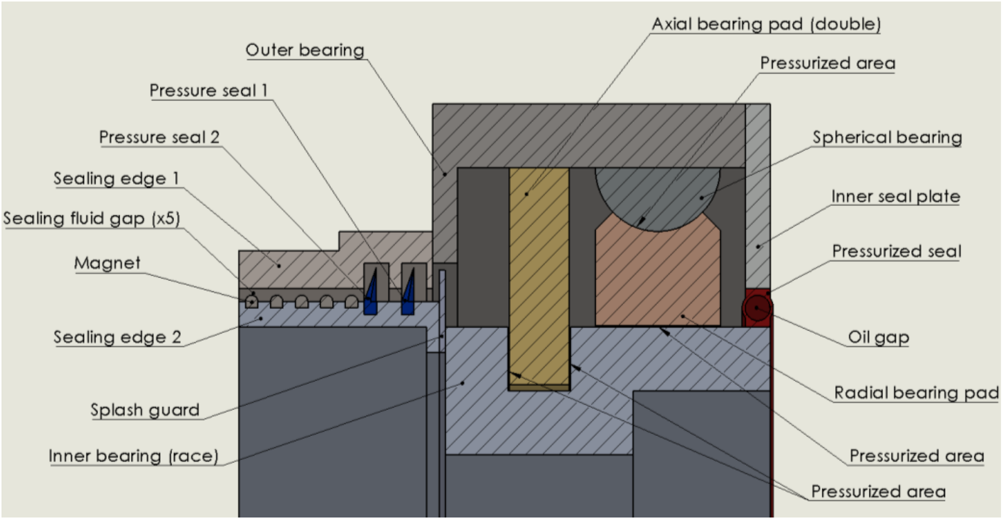


Figure 4-20: Typical arrangement of the bearing and seals

4.12.2. Sealing

Sealing the bearing is a challenge due to the pressure difference between the vacuum and the pressurized areas. This is typically done with a fluid seal, which in the case of Starport 1, will consist of five separate magnetic fluid rings combined with magnets. The five different rings of the seal will serve to lower the pressure successively by 0.2 bar with every ring. The pressure in the area between each of the seals will be monitored continuously and kept stable. The magnetic fluid will be cycled, conditioned, and refilled on a regular basis.

There will also be double redundant pressure seals inside the bearings that activate on air flow. If the magnetic fluid seal fails the interior atmospheric pressure of the station would compress the flexible seal rings, providing an airtight barrier. Since there are two seals, there is triple redundancy, excluding the internally pressurized seal on the inside of the station. This interior seal would be able to keep the inside of the station free from lubricant spillage, as it actively compensates the degree and area of sealing by internal pressurization.

4.12.3. Drive

The drive system maintains the angular velocity difference between the microgravity section and the ring. Thrusters on the ring counteract atmospheric drag that would gradually reduce its angular velocity. The drive system keeps the central section stationary, i.e. counteracts the friction in the bearing and seal that would cause the center section to start spinning. There are two main options for the drive system: electric motors located in the bearing or thrusters located on the bearing or elsewhere on the microgravity section. We recommend the electric motor system, if this could be designed to provide enough torque to overcome the friction of the sealing system. Although the gears and motors of such a system can be heavy and expensive to use, there will be significant power-saving possibilities over using thrusters. This option needs further investigation; the friction caused by the bearing and seal described in the previous section needs to be determined accurately before a drive system can be designed.

If the drive or bearing system seizes, the microgravity section would spin up and the angular velocity of the ring would decrease by a negligible amount, because of the large moment of inertia of the AG section (see Section 4.11). This means that sudden loss of AG is not possible even in the case of failure of the bearing, seal, drive, or propulsion systems.

4.13. Power systems design

We made a rough estimate of the station's power requirement: 1.68 MW will be necessary for spin-up using thrusters, maintaining rotation using electric drive or thrusters, and stationkeeping (Section 4.11). We estimate about 3 MW for operations, habitat, and ECLSS. This value is based on the ISS power requirement of 110 kW (NASA, 2010). The mass of the fully assembled ISS is about 420,000 kg (NASA, 2010), which is about 24 times smaller than the estimated mass of Starport 1. This gives an estimate of $24 \cdot 0.11 = 2.64 \simeq 3$ MW rounding up to add an uncertainty margin. Finally, we introduce a 25% margin to the power estimate to account for manufacturing. This amounts to a rough estimate of about 6 MW. The production of electrical power will occur in the microgravity section and will be transferred to the AG sections through a slip ring (COSMAU, 2016).

4.14. Power subsystem design

Table 4-9 shows different methods for generating power for space vehicles, along with advantages and disadvantages of each type. We do not consider nuclear fusion, since we do not envision it to be a reliable power source by 2040.

Table 4-9: Types of space power generation (Choi, 2016; World-nuclear.org, 2016; Young, 1993)

Power Generation Method	Description	Advantages	Disadvantages
Chemical	Conversion of chemical energy into electricity using a battery	High reliability	Short life cycle (days)
Photovoltaic cells	Converting solar energy into electricity using a photovoltaic solar array	High reliability Long Lifetime of ~10 years	Low efficiency: current max. 25%
Solar dynamic power module	Concentration of solar energy to heat a working fluid that in turn drives an electricity-producing mechanism	More efficient than photovoltaic arrays (up to 40%) 60% less drag than photovoltaic arrays	No space heritage
Radioisotope thermoelectric generator	Radioisotope heat source (typically plutonium-238) and a thermoelectric converter	Independent of solar flux Long lifetime (plutonium-238, with a half-life of 86 years) Can be used for heating	Radiation heavy (200-300 kg/kW) Expensive ($7-20M per kW) Electrical output is time dependent
Nuclear fission reactor	Fission reactors use heat from nuclear fission to generate electricity (makes them independent of solar flux)	One reactor's output power is approximately 10-100 kW, but could be more in the near future (MW range)	Harmful radiation output Legal issues Not space proven

A comparison of the main requirements of different power generation methods is shown in Figure 4-21.

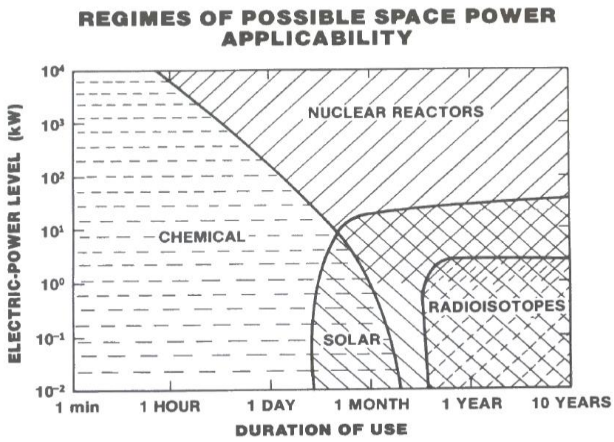


Figure 4-21: Regimes of space power (Angelo and Buden, 1983)

4.14.1. Chemical generator

For short durations of up to a few hours, chemical fuels can provide up to 60,000 kW of power, but for durations of a month, use is limited to 1 kW or less, as Figure 4-21 shows. As a consequence, it is not suited for the power supply of Starport 1.

4.14.2. Solar energy generator

The life cycles of solar energy generators meet the lifetime requirements of the station but they need a large area to meet the station's energy needs (up to 6 MW) and they have a low energy conversion efficiency. The efficiency of the photovoltaic system is only 25%, so the area of the solar array will have to be very large. Analysis shows that in LEO (380 Km), an output of 10 KW would need an area of 35,200 m^2. This is too large for the station as it will make orbital maintenance difficult and be resource intensive. For the solar dynamic power system, although the conversion efficiency can be increased to 40%, the solar array area needed is still very large (~25,000 m^2), making it unsuitable for the station as well.

4.14.3. Nuclear generator

A radioisotope thermoelectric generator with a large size and low output (<10kW) is not suitable for use in a large space station. Research into existing Space applications for nuclear fission reactors shows that the largest output is the SAFE 400 with a 100-KW power output. Advanced reactors are being developed for Mars missions by Rosatom State Nuclear Energy Corporation. Their reactor has a thermal power generation of 4 MW and electrical power generation will be 1 MW: its efficiency will reach 25%. They intend to finish testing by 2018 (International Atomic Energy Agency, 2005).

Sources suggest that, in the future, much more powerful reactors will be available for use in Space power generation; for example, experts expect the development of a reactor using a Helium-Xenon Brayton cycle with a turbine input temperature of 1,300 K. With this technology, we estimate that the whole system can provide 3 MW energy and will weigh approximately 30 metric tons, with a radiator area of 1,800 m^2 (Cliquet, 2012; NASA, 2015b).

The above reactors are suitable for use on Starport 1. We would need three reactors for the station mounted in a triangular configuration on the ring, with two of the reactors providing long term power, and one to provide redundancy. The reactors must be placed away from inhabited areas and a shadow shield shielding the modules from the reactor, will need to be placed if that is not sufficient to mitigate the radiation. The use of a nuclear reactor will require innovative design for the housing of the reactor to prevent the release of radioactive material in the event of a station failure. There will also need to be international agreement on the policy and legality of launching radioactive payloads. Section 9.2.1 further discusses the legal issues related to the use of a nuclear reactor in Starport 1.

4.15. Recommendations for future work

Further analysis of some subsystems of Starport 1 is required to come to a more detailed and complete design. Additional calculations for different load cases are required to design the structure of the station in detail; this should be done through a finite element analysis. This also allows analysis of the structural behavior of the station under dynamic loads. This is important for docking for example.

Furthermore, we recommend:

- detailed analysis on the interaction between the AOCS and the gyroscopic forces that will occur when a force is applied to the rotating ring and how this affects the control and attitude of Starport 1;
- research on the use of a nuclear reactor on the space station, both from an engineering perspective (what radiation shielding is required, fail-safe mechanisms that have to be implemented), as from a legal perspective;
- cooperation with Bigelow to adapt their modules to be able to support 0.8 g through the use of internal structural support, as well as to allow for airlocks on the sides of the modules; and
- detailed analysis of the bearing and seal system to determine the friction caused by this system. This will allow to design the drive system in detail.

5. Assembly, Operations, and De-orbiting

5.1. Introduction

In this chapter we discuss mission requirements such as the orbit selection, stationkeeping, and inclination of Starport 1. Such considerations as radiation shielding, maximum size of the modular structural and habitat elements, propulsion system required for attitude control, and debris avoidance maneuvering requirements represent the driving parameters behind station design (Johnson and Holbrow, 1977). Based on the selected orbit and station configuration design, we discuss the launcher selection and the assembly sequence of Starport 1. Other requirements of the station, such as the docking ports, space debris detection and avoidance, and station operations, are also included. Finally, we address the procedures for emergency situations in Starport 1 and explain the de-orbiting of the station.

5.2. Orbit selection

In choosing the orbit of Starport 1, we considered several trade-offs. The requirements specify the LEO regime; this is commonly defined as less than 1000 km altitude. We examined several possible orbit options, focusing on autonomous operations, stationkeeping, debris avoidance, launch and assembly, and de-orbiting, before finalizing the orbit selection.

We consider the current and in-development launch vehicles that would be required, including the number of launches to each orbit, the payload mass each launcher can lift, and the fairing size achievable with each launch system (this relates to the maximum external dimensions of the payload). Given the main requirement of minimizing the number of launches only two launchers were shown to be feasible. LEO is the closest orbital regime to Earth. This proximity reduces the required number of launches needed for assembly and operations, as the launchers can lift a more massive payload.

We performed an analysis of three orbits in the LEO regime, one near the altitude currently occupied by ISS and Tiangong 1, one at the edge of the inner Van Allen belt, and one halfway between these two. The orbits were compared based on three central criteria: atmospheric drag, which causes the station to lose altitude requiring it to be re-boosted; the debris environment, which can cause damage to and depressurization of the station; and, the radiation environment which damages electronics and causes short and long term health problems for the crew.

Orbits with altitudes of around 400 km are used for current and past generations of crewed space facilities (ISS - 400 km, Mir - 385 km, Tiangong 1 - 365-385 km) (Peat, 2016; Zak, 2001; Blau, 2016). These orbits have the best radiation environment, as they are deep inside the Earth's magnetic field. Another advantage of this lower altitude is a more benign debris environment, as LEO satellites tend to be placed in higher orbits (Figure 5-1 and Figure 5-2). However, the drag on the station from the residual atmosphere is significant. For example, ISS needs approximately 8.6 metric tons of fuel per year to maintain its altitude (NASA, 2011).

Conversely, orbits on the edge of the inner Van Allen belt, at around 800 km altitude, have a much higher debris risk. This is because 800 km is within the range of altitudes required to support a Sun synchronous orbit (SSO) used by imaging satellites, as it allows them to revisit the same point on Earth at the same time of day. The frequent use of this altitude band means that there is a lot of debris (old spacecraft and spent rocket bodies) at this altitude. This altitude also has a very harsh radiation environment, due to its proximity to the inner edge of the Van Allen belt where the proton fluxes increase rapidly. The main advantage of this altitude is that re-boost maneuvers are not required as there is almost no residual atmosphere and the momentum of the station will maintain its orbit.

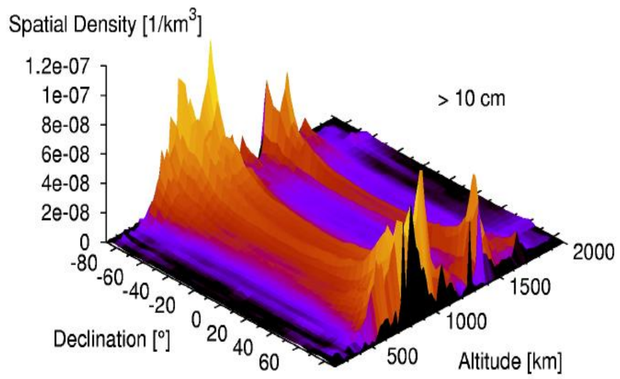


Figure 5-1: Spatial density of space debris >10 cm in LEO (Jehn, 2016; used with permission)

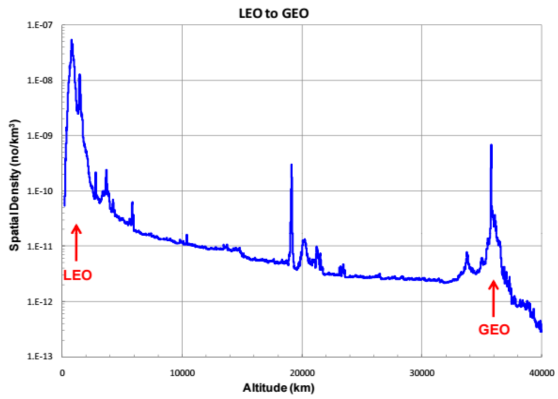


Figure 5-2: Debris density in LEO, MEO, and GEO orbits (Liou, 2012; used with permission)

We believe that the selected orbit with an altitude of 600 km is the best compromise between these two extremes. Our SPENVIS simulations show that at this altitude the radiation environment is a factor of ten times more benign than at 800 km, and that the orbit is high enough to avoid the worst effects of the residual atmosphere, as the station will be in the exosphere, rather than the thermosphere (NASA, 2016). This leaves debris as the main problem facing the station's orbit. There is a significant amount of debris at this altitude (Jehn, 2016), but we proposed to keep the station below the worst of the peak, in the 550-600 km region. The radiation environment and the debris hazard will also be affected by the selected inclination discussed below.

5.3. Inclination

As well as considerations of debris and radiation, the selection of inclination is significantly influenced by the choice of launch sites, and hence launch vehicles, as discussed in Section 5.4.1. The selected launch vehicles are the NASA Space Launch System (SLS) Block 2B and the Falcon Heavy. To avoid protracted negotiations to move the launch sites, it is assumed that these rockets will launch from their home launch site at Cape Canaveral. We propose to launch into a 33 degree orbit, which is accessible from both Cape Canaveral and Spaceport America in Mohave, launching due East from Mohave gives us the largest velocity advantage from the Earth's rotation allowing the maximum payload mass to be launched using the less powerful Falcon Heavy rocket. Being in a 33 degree orbit means that Starport 1 avoids the increased radiation dose associated with travel through the polar regions. It also avoids a large proportion of the South Atlantic Anomaly, so not only is the received ionizing dose lower, but extravehicular activities (EVA)s are less time constrained and can be conducted for a higher percentage of each orbit.

A 33 degree inclination also allows for access to the Solar System if Starport 1 were to be used as a base for launching interplanetary missions. Most of the planets are within 10 degrees of the ecliptic plane (Strobel, 2013) which is at an inclination of 23.5 degrees relative to the rotation of the Earth.

This means none of the missions will need to change inclination more than two or three degrees to get them to Mars or Venus and then the gravity assist maneuvers used to get to other planets can be used to change the inclination further if necessary.

While better than the Earth's surface, LEO is not gravitationally the best place to launch interplanetary missions from. The recommended uses for interplanetary travel would be to refuel second stage boosters to allow them to be used again for interplanetary transfer, and also as a final stop at the end of a crewed mission. Docking to Starport 1 one would mean that the spacecraft would not need to take an Earth atmosphere reentry module with it and so would save a significant amount of mass.

The downside of placing Starport 1 in a low inclination orbit is that it cannot be accessed from all launch sites without inclination changing maneuvers. This mostly affects resupply missions, which have a lower payload mass. So, they should not be considered too much of a problem, compared to the losses associated with launches during construction attempting to achieve a higher inclination.

5.3.1. LEO stationkeeping

The most significant orbital perturbation in LEO is drag. The drag in proportion to the orbital density and the ballistic coefficient K_D. The coefficient K_D is directly related to the area-to-mass ratio, as shown in Equation (22):

$$K_D = \frac{cross\text{−}section\ area}{mass} \cdot C_D; \qquad (22)$$

Due to the proposed attitude of the station, the rotational axis remains constant in the inertial direction, Starport 1's main cross-sectional area in the velocity direction is between 7,000 to 20,000 m^2. Table 5-1 shows some initial stationkeeping calculations. We looked for an orbit that requires small amount of fuel per day. We chose 600 km, which meets these criteria. The mass of the station is such that $K_D < 0.01$, and at orbital altitude of 600 km stationkeeping requires little fuel (Mishne, 2000). Due to the cross-section area, solar radiation pressure should be considered. However, at 600 km mean altitude it does not have a significant influence. The required velocity increment needed is 0.0121 m/s, applied constantly with electric propulsion or once a day with conventional thrusters.

Table 5-1: Altitude loss in one day as function of mean orbit altitude and ballistic coefficient

Orbital altitude (km)	(C_D=3) Altitude loss (meters) where ballistic coefficient, K_D, is:					Air density in solar max conditions (kg/m³)
	K_D=0.1	K_D=0.075	K_D=0.05	K_D=0.03	K_D=0.01	
400	-3390.66	-2543.00	-1695.33	-1017.20	-339.07	7.55E-12
450	-1627.20	-1220.40	-813.60	-488.16	-162.72	3.61E-12
500	-814.31	-610.73	-407.16	-244.29	-81.43	1.8E-12
550	-419.98	-314.99	-209.99	-126.00	-42.00	9.25E-13
600	-222.82	-167.12	-111.41	-66.85	-22.28	4.89E-13
650	-120.73	-90.55	-60.36	-36.22	-12.07	2.64E-13
700	-67.46	-50.60	-33.73	-20.24	-6.75	1.47E-13
750	-38.55	-28.91	-19.27	-11.56	-3.85	8.37E-14
800	-20.29	-15.22	-10.14	-6.09	-2.03	4.39E-14

5.4. Launch and assembly of Starport 1

Based on ISS experience (Nixon, 2016), the assembly of Starport 1 must begin no later than 2030. This requirement is also based on possible launchers and manufacturing technologies.

5.4.1. Launcher selection

We performed a survey of the available launchers. Isakowitz, Hopkins, and Hopkins (2004) provide a list of launch vehicles that can carry more than 10 metric tons to LEO. Hill and Creech (2014) give details about SLS and the SpaceX Falcon User's Guide (2015) gives the payload volume details for the Falcon 9 launch vehicle. As per Spaceflight 101.com (2016), Falcon Heavy is similar to Falcon 9. For Starport 1, the expected mass is 10,000 metric tons, and the payload capability of the launcher should be around 100 metric tons to LEO. The size of the payload volume should have a diameter of 10 m and a length of 25 m.

SpaceX's Mars Colonial Transporter (MCT) (Spaceflight Insider, 2015) is a launch vehicle with a capability to transport 100 metric ton to Mars. MCT's capabilities have not yet been released, but unofficial numbers show payload volume which is 15 m in diameter and 50 m in length. As the timeline of MCT development is not clear, we have not included MCT launches in the baseline roadmap. We recommend reexamining MCT for future launch purposes beyond 2035.

Based on the above considerations, this leaves the only suitable launcher as SLS Block 2B (Boen, 2015), which has a payload volume with 9.7 m diameter and 25 m usable length that can lift 130 metric tons to LEO. As of 2016, SLS is still under development; we assume that it will be flight-proven by the year 2030.

If for any reason SLS program is cancelled, an alternative launch vehicle has to be chosen. As of now there are no promising vehicles equivalent to SLS Block 2B capabilities. Like MCT the details of Chinese Long March 9 program are not clearly available except for the payload mass capacity of 125 metric tons. Usage of Falcon Heavy type of vehicles as the prime vehicle calls for a design change for all the station components. This also results in smaller size of the modules which increases the number launches enormously leading to less economically viable option with increased uncertainty in the assembly delays. This has to be studied further in detail so that dependency of one launch vehicle can be avoided.

SLS will launch the major sections of the station including the microgravity section and the main structure. These launches will be supported by several launches of the SpaceX Dragon Heavy that can launch 4.6 m diameter and 12 m usable length of payload with a payload mass of 50 metric tons. Compared to other launch vehicles of this capacity, Falcon Heavy is cheapest in launch cost per kilogram of payload mass. The detail of the launch schedule is discussed in Section 0.

5.4.2. Sizing of modules

The sizing of the modules is based on business, research, and life sciences requirements as well as the launcher's capability to transport modules to the needed orbit. SLS is primarily considered for the transport of station modules. The SpaceX Falcon Heavy launch vehicle will be used for construction of smaller modules and for supplying the station. Table 5-2 shows the different Starport 1 payload capacities.

Table 5-2: Different payload capacities and launchers

No.	Selected Sizes	Vehicle
1.	15 m (diameter) x 50 m (long)	MCT
2.	10 m (diameter) x 25 m (long)	SLS
3.	5 m (diameter) x 13 m (long)	Falcon Heavy

5.4.3. Assembly sequence

The assembly of Starport 1 will begin with the microgravity section. The microgravity segment will be the central hub of the station and will connect with the artificial gravity segment. Table 5-3 lists the assembly sequence with a timeline for manufacturing, testing and assembly. By 2037, two of the four girder structures, or spokes, will be built with four modules on it which will be tested for six months. After in-orbit testing and qualification, the section is de-spun and the full artificial gravity section is built with eight more modules on it. Starport 1 will be fully operational from then on and another 20 artificial gravity modules will be added onto the ring without de-spinning the artificial gravity section. We recommend that no de-spinning of the artificial gravity modules will be required to add other modules. Assembly will be done with a mobile robotic arm with rails fixed to the bottom of the girder. This robotic arm can be removed and stored after operations are completed. Additionally, a servicing satellite will bring the modules from launch and dock them to the station. Table 5-4 details the overall number of launches required.

Table 5-3: Assembly timeline and sequence

SQ	Part Name	Size (m) (Diameter x Length) or (Length x Breadth x Height)	Mass (metric tons)	Launcher	No. Launches	Manufacturing & testing	Launch date	Time of completion
				Microgravity Section				
1.	Self-Sustaining Module-I & II and Reactor	9 x 18 (each)	100	SLS	2	Jan 2025 – Oct 2029	Jan 2030	Feb 2030
2.	Centre Hub	9 x 9	80	SLS	1	Jan 2025 – Nov 2029	Mar 2030	Mar 2030
3.	Self-Sustaining Module-III & IV (to which modules from earth can dock)	9 x 18 (each)	100	SLS	2	Jan 2025 – Jan 2030	Apr 2030	May 2030
4.	Docking Module	9 x 18	100	SLS	1	Jan 2025 – Jan 2030	Apr 2030	May 2030
5.	Robot Arm with Circular rail -I	25	20	Falcon Heavy	1	Jan 2025 – Mar 2030	Jun 2030	Jul 2030
6.	Manufacturing Module-I to IV	4.5 x 18 (each)	20 (each) (4 Nos)	Falcon Heavy	4	Jan 2025 – Nov 2030	Aug 2030	Aug 2031
7.	Robot Arm with Circular rail -II	25 long	20	Falcon Heavy	1	Jan 2025 – Dec 2030	Sep 2031	Nov 2031
8.	Research & Additional Module- I to II	4.5 x 18 (each)	20 (each) (4 Nos)	Falcon Heavy	4	Jan 2027 – Aug 2031	Dec 2031	Nov 2032
9.	Tourist Cupola	9 x 10 (long)	50	SLS	1	Jan 2028 – Aug 2031	Dec 2032	Feb 2033
	Manufacturing and Research Activities	Raw material supplies	Max. of 130 ton Cargo to be sent to Earth	Falcon Heavy / SLS	Multiple Missions		Apr 2033	Dec 2034
10.	Centre Hub – Bearing Holder Arm -1 to 8	23 x 9 (each)	40 (each) (8 Nos.)	SLS	8	Jan 2030 – Aug 2034	Jan 2035	Feb 2035
11.	Centre Hub – Bearing Holder -1 to 8	10 (Chord Length) x 9	40 (each) (8 Nos.)	SLS	8	Jan 2030 – Aug 2034	Mar 2035	Apr 2035
				Artificial gravity section				
12.	Bearing Assembly (8 missions)		40 (each) (8 Nos.)	SLS	8	Jan 2031 – Jan 2035	Apr 2035	Aug 2035
13.	Girder – 1 (2nos.) and Elevator Shaft 1&2 (2 Nos.)	14 x 12 x 20 and 5 x 11	3.3 (each) (2 Nos.) and 3 each	SLS	2	Jul 2031 – Apr 2035	Sep 2035	Oct 2035
14.	Girder Module (2 nos.)	10 x 7	25	SLS	1	Jul 2031 – Apr 2035	Oct 2035	Oct 2035
15.	Girder – 2 (2nos.) and Elevator Shaft 3 (2 Nos.)	12 x 12 x 21 and 5 x 11	3.3 (each) (2Nos.) and 3 (each)	SLS	1	Jul 2031 – Apr 2035	Nov 2035	Dec 2035

SQ	Part Name	Size (m) (Diameter x Length) or (Length x Breadth x Height)	Mass (metric tons)	Launcher	No. Launches	Manufacturing & testing	Launch date	Time of completion
16.	Girder – 3 (2 nos.)	10 x 12 x 21	3.3 (each) (2 Nos.)	SLS	1	Sep 2031 – Sep 2035	Jan 2036	Feb 2036
17.	Ring Girder -1 with elevator module (2 Nos.) and Wire ropes (4 Nos.)	40 x 6.5 x 7 Wire rope - 55 (long)	57 (each) + 20 (each)(elevator module) = 77 (each)	SLS	2	Dec 2031 – Dec 2035	Mar 2036	Apr 2036
18.	Propellant storage Modules (8 Nos.)	5 x 11	10 (each)	Falcon Heavy	2	Jul 2032 – Jan 2036	May 2036	Jul 2036
19.	AG Module – Bigelow BA2100 type (4 Modules)	8 x 12 (uninflated)	70	SLS	4	Sep 2032 – Mar 2036	Aug 2036	Nov 2036
20.	Propellant Filling Operations	-	50 (each) (Total for 8 cylinders 400 metric tons)	Falcon Heavy / SLS– Choice based on Pricing	8/4	Jan 2033 – Aug 2036	Dec 2036	Jan 2037
21.	Testing of Station by spinning up and Despinning	-	-	-		-	Jan 2037	Oct 2037
22.	Girder – 1 (2nos.) and Elevator Shaft 1&2 (2 Nos.)	14 x 12 x 20 and 5 x 11	3.3 (each) (2 Nos.) and 3 each	SLS	2	Jan 2033 – Jun 2037	Oct 2037	Nov 2037
23.	Girder Module (2 nos.)	Ø10 x 7	25	SLS	1	Jan 2033 – Jun 2037	Nov 2035	Nov 2035
24.	Girder – 2 (2nos.) and Elevator Shaft 3 (2 Nos.)	12 x 12 x 21 and 5 x 11	3.3 (each) (2Nos.) and 3 (each)	SLS	1	Apr 2033 – Aug 2037	Dec 2037	Jan 2038
25.	Girder – 3 (2 nos.)	10 x 12 x 21	3.3 (each) (2 Nos.)	SLS	1	Sep 2033 – Nov 2037	Feb 2038	Mar 2038
26.	Ring Girder -1 with elevator module (2 Nos.) and Wire ropes (4 Nos.)	40 x 6.5 x 7 Wire rope - 55 (long)	57 (each) + 20 (each) (elevator module) = 77 (each)	SLS	2	Dec 2033– Dec 2037	Apr 2038	May 2038
27.	Ring Girder -2 with docking adaptor (8 Nos.) and Wire ropes (16 Nos.)	40 x 6.5 x 7 Wire rope - 55 (long)	38 (each) + 2 (each)(elevator module) = 40 (each)	SLS - 4 wire ropes in each mission	4	Mar 2033 – Jan 2038	Jun 2038	Jan 2039
28.	Mobile Robot Arm -1 with rail unit (2 Nos.)	25	20	Falcon Heavy	1	Jul 2033 – Jul 2038	Feb 2039	Mar 2039
29.	AG Module – Bigelow BA2100 type (12 Modules)	8 x 12 (uninflated)	70	SLS	12	Jan 2034 – Aug 2038	Apr 2039	Mar 2040
30.	Propellant Filling Operations	-	50 (each) (Total for 8 cylinders 400 metric tons)	Falcon Heavy / SLS– Choice based on Pricing	8/4	Jan 2035 – Jan 2039	Apr 2040	May 2040
31.	Start of Operation	-	-	-		-	May 2040 onwards	
32.	AG Module – Bigelow BA2100 type (20 Modules)	8 x 12 (uninflated)	70	SLS	20	Jan 2036 – Jun 2040	Sep 2041	Dec 2045

Table 5-4: Overall number of launches

1	Total mass of station	Approx. 10000 metric tons
2	Total no. of launches	94
3	Total no. of launches by SLS	82
4	Total no. of launches by Falcon Heavy	12

5.5. Docking ports

Our aim for the new station is to produce a new, standardized docking port to allow the crew modules to dock to each other, the station structure, and any inbound ships. By using a standard, we can ensure compatibility with future third party hardware, as well as avoiding having to undock modules, e.g. a specialized docking port module during assembly. The proposed docking port has an internal diameter of 3 m, allowing two people to walk through the port side by side and providing plenty of space for moving machinery. Maximum outer diameter of 10 m for the rigid modules maximizes usable space while retaining the structural rigidity of the module. The main module infrastructure (electrical cables, water, etc.) will run through the main truss of the artificial gravity ring. However, to provide secondary cabling routes between modules and primary connections between microgravity sections, the docking port will contain several different sizes of trucking in the main contacting face. These trucking sections will automatically connect and seal when the docking port is attached and will be inside the main vacuum seal. This means they will be accessible by crew from within the pressurized environment, allowing connections to be made between modules without needing an EVA.

5.6. Station management and operations

The Starport 1 space station is designed to house up to 200 people when fully operational. When considering the concept of operations, we will use the heritage of three previously flown space stations: ISS, Mir, and Tiangong 1. Current ISS operations require continuous and constant ground personnel support and monitoring. Additionally, the ISS requires constant support from payload ground control stations.

In Starport 1, we will have autonomous and robotic operations for many of the nominal maintenance procedures. To reduce the workload of the crew and reduce ground station involvement we aim to increase autonomy. Some examples of the required systems are autonomous orbit determination and stationkeeping, nominal autonomous housekeeping routines, and autonomous life support routines such as a filter-less particulate and trace gas control system. Monitoring and automatic change detection should be included and alerts to station crew as well as remote ground systems when necessary. We recommend reviewing International space station operation procedures and migrating many to autonomous control (Spaceref, n.d).

We propose that communications with the station will be achieved using the European Data Relay System (EDRS) (ESA, n.d). Instead of communicating directly with the ground, Starport 1 will communicate with one of two geostationary spacecraft which relay data continuously by direct laser link. This means only one ground station will be needed at one time to process all the communication to and from Starport 1.

5.7. Space debris detection and avoidance

Space debris (Inter-Agency Space Debris Coordination Committee, 2007) are both artificial and natural objects. Artificial debris include non-operating satellites and remaining parts from rocket launches. Natural debris includes meteorites and interstellar particles. Space debris can cause major damage to the station. Protection and mitigation will differ depending on the debris size (Lockheed Martin, 2014). Three main categories are identified: small debris with a diameter of less than 1 cm, medium debris, ranging in size from 1 cm to 10 cm, and large debris, which may be bigger than 10 cm in size.

We base Starport 1 debris mitigation on recommendations from Adriaensen et al. (2012). The station will be protected from small debris by specific shielding. Medium sized debris will be tracked on the ground (Phipps, 2012) as well as in orbit with an onboard debris detection and tracking telescope. New technology suggests de-orbiting the debris by combining a telescope and a laser performing ablation. This solution is feasible for debris from 5 mm up to 10 cm. In 2017, Raken, a Japanese company will test such a sensor on the ISS (the JEM-EUSO telescope), which is expected to detect debris from a distance of 100 km. After detection, the CAN laser, mounted next to the JEM-EUSO, will ablate the debris and change their orbit (Ebisuzaki, 2015; JEM-EUSO Program, 2016). Additionally, 1 mm debris can be detected with a space based telescope, like ESA and Airbus Defence and Space are developing for microsatellites (Ebisuzaki, 2015; Ultzmann, 2014). If required, special EVAs will be performed to fix any debris damage.

From 2020, active debris removal (ADR) is expected to become a reality, so we can safely assume that in 2040 the number of large debris will be reduced or maintained, as well as many technologies developed in the ESA e. de-orbit program (ESA, 2016). We suggest using one of the ADR satellites as a companion for Starport 1, to orbit in front of Starport 1. The ADR satellite will remove threatening debris larger than 10 cm. Another option is to use the natural drag and big cross section of the station to change the station orbit and avoid the debris.

5.8. Emergency procedures

An important advantage of having a space station in LEO is that the crew can be able to return to Earth quickly. We aspire to have the station operate autonomously and allow an option for entire crew evacuation without total loss of the station. If evacuation is required, we envision escape pod technology based on the spacecraft crew escape systems under development for ISS (Clark, 2015).

5.8.1. Evacuation due to fire

In the event of a fire alarm, relevant procedures will be activated to evacuate nonessential personnel while attempting to extinguish the fire. Evacuation can proceed using the pressurized maintenance corridor (see Figure 5-3) in the structure ring connecting all modules, as mentioned in Section 5.8. The affected module will be isolated, and the ventilation system will be shutdown to avoid spreading toxic gas products to other modules. Starport 1 will be equipped with a variety of monitoring sensors. In the extreme case, evacuation will be considered but if it is a survivable fire, there are specific post-fire cleanup protocols. Gas sensors to detect poisonous gases such as CO, HCN and HCl. If it is considered safe and the smoke is not too concentrated, a crew member can don a fire mask and investigate the module, and begin making the module habitable and safe for use again. A “smoke eater” will cycle the air through a filter and CO absorbent (see Section 6.3.5). Once the gas and particle concentrations are at safe levels, the Starport 1 ventilation system can be turned on again.

5.8.2. Uncrewed station

Stationkeeping and orbit determination should be autonomous, so that in case of an evacuation procedure, the Starport 1 infrastructure is not lost entirely. If such an evacuation occurs, station managers in mission/ground station control will be able to command the vehicle from the ground and operate, allowing it to remain in orbit indefinitely. Most of the equipment of Starport 1 can be operated remotely from the ground, transition to ground control after evacuation should be smooth. Starport 1 can operate unattended on minimal functions, until station operators can launch another crew.

5.8.3. General evacuation procedure

A single evacuation ship should separate from the space station within minutes. In the unlikely event of an emergency such as a rapid depressurization, the crew will evacuate. Starport 1 will have four major docking points for spacecraft that can handle up to 25 people each. 100 people can be evacuated at the same time. Evacuation routes will use the maintenance corridor as well as traveling through the modules. As the population grows, additional spacecraft will be added. For medical emergencies that cannot be handled by the station health care, a small ship (like the Soyuz capsule) will be used to send the patient, a doctor, and one family member if necessary back to Earth. Figure 5-3 shows the location of emergency evacuation ships.

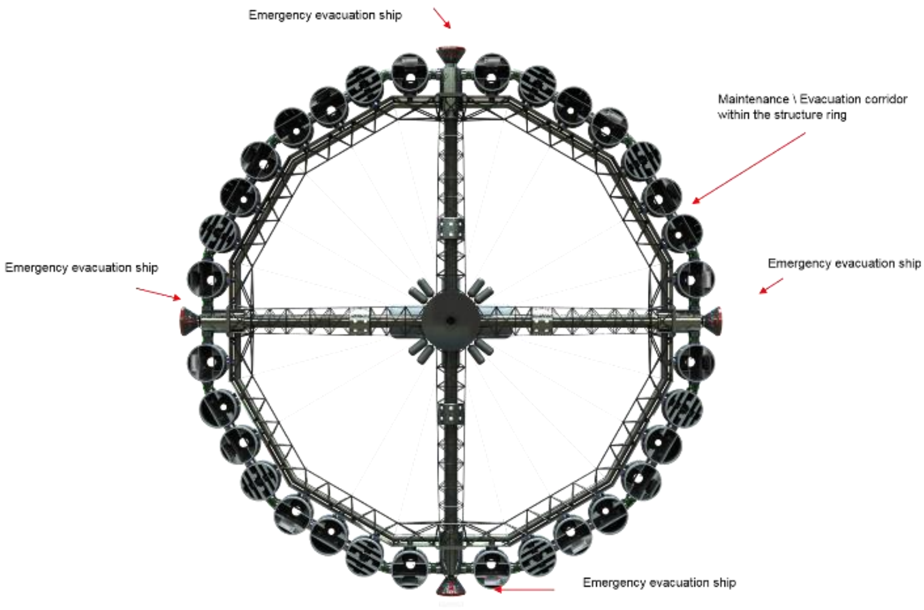


Figure 5-3: Location of evacuation modules

5.8.4. Evacuation training

Crew will periodically simulate emergencies at the space station to remain familiar with escape routes, safety hardware, and communication protocols. Crew members and space tourists will be required to spend an hour every month conducting emergency drill procedures to practice communication, familiarize themselves with safety gear and procedures, and memorize evacuation routes. The crew bears full responsibility for any actions performed in departure from the crew procedures. Crew members will be put in charge of each station segment and will be responsible for performance of all the emergency procedures in his or her respective area.

5.9. De-orbiting

The United Nations Debris mitigation guidelines require that at the end of operational life LEO satellites be de-orbited in less than 25 years after end of operations. Starport 1 is a large space station, with an extensive cross-sectional area. Depending on the ratio, the station may require active maneuvers or orientation to perform de-orbiting. For K_D of about 0.01, the station can de-orbit in less than nine years, and all that is required is to stop stationkeeping. Some fuel must be kept for active maneuvers to ensure that the station is targeting the southern Pacific Ocean.

However, using STK software for lifetime analysis, which was based on the cross-section area and ballistic coefficient, if K_D is smaller than 0.004, an active de-orbiting maneuver is required. There is an option to disassemble the station, much like a reverse assembly procedure, separating the microgravity center from the artificial ring or the shafts. After separation, each main part will extend a drag sail to increase the drag effects and improve the de-orbit maneuvers. Before disassembly the nuclear RTG generator will be disassembled onboard and packaged in specialized containers to be send back to Earth in specialized cargo ship.

6. HABITAT

An artificial gravity station presents many unique habitability, healthcare, environmental control system, and sustainability challenges. We describe and discuss them in this section. The main difference between Starport 1 and previous stations is the AG section, which has been added as a countermeasure against deleterious effects of microgravity on the human body, so this will be the focus of our analysis this section. Architecture and habitat design of the microgravity section will be modeled after previous microgravity designs used in the ISS.

6.1. Facilities and accommodation

We have designed Starport 1's habitation facilities to promote flexibility and modularity while incorporating natural design elements. Starport 1 is likely to accommodate a wide variety of human inhabitants, including operating crews, research scientists, manufacturing workers, and tourists.

6.1.1. Allocation, architecture, and layout of the AG modules

We recommend using Bigelow BA 2100 modules due to their low mass-to-volume ratio. These modules will be parallel to the rotation axis to minimize Coriolis effects (discussed below in Section 6.2.3). Figure 4-2 shows this configuration. We have assumed a ceiling height of 2.4 m since this is the standard comfortable height for buildings on Earth (Rybczynski, 2012). This height will also allow up to four floors to be included in a BA 2100 module, with additional space for utility routing and pipework. There is a 3 m high corridor, connecting the middle floors of each module through which inhabitants can move from one module to the next. Section 0 discusses the number of modules and the order of assembly. In 2040 the majority of modules will be a mix of accommodation and communal areas, although there will be one entire accommodation module designed expressly for tourists. Figure 6-1 shows a preliminary study of the modules' interior. Since the Bigelow modules are empty inflatable units, they can easily be purposed and adapted to fulfill the station's changing needs. As Starport 1 grows, future modules will be designed to accommodate increasing commercial demand, such as storefronts, theaters, and sports fields. Figure 6-2 shows the 2060 configuration of Starport 1 with all the amenities expected at destination hotels, and configured to promote community and prevent isolation.

Figure 6-1: Layout of two proposed modules; garden (left), and living quarters (right)

Roughly half of the modules will be for agriculture, manufacturing support and storage space. On either side of this segment, crew quarters will be split by shifts, with opposing diurnal cycles for synchronization of schedule and activity. Medical facilities and mission control will be on the periphery of the hotel room segments, which surround the social hub of the station. Six modules will serve as the center of activity for guests, containing restaurants, bars, shops, a cinema, fitness center and spa, as well as luxury tourist suites. Additional community-promoting facilities in the hub consist of a large community gathering space, meeting rooms and a park. One of the four elevators will lead straight to the social hub for hotel guests, and the remaining three will serve the crew and transport supplies.

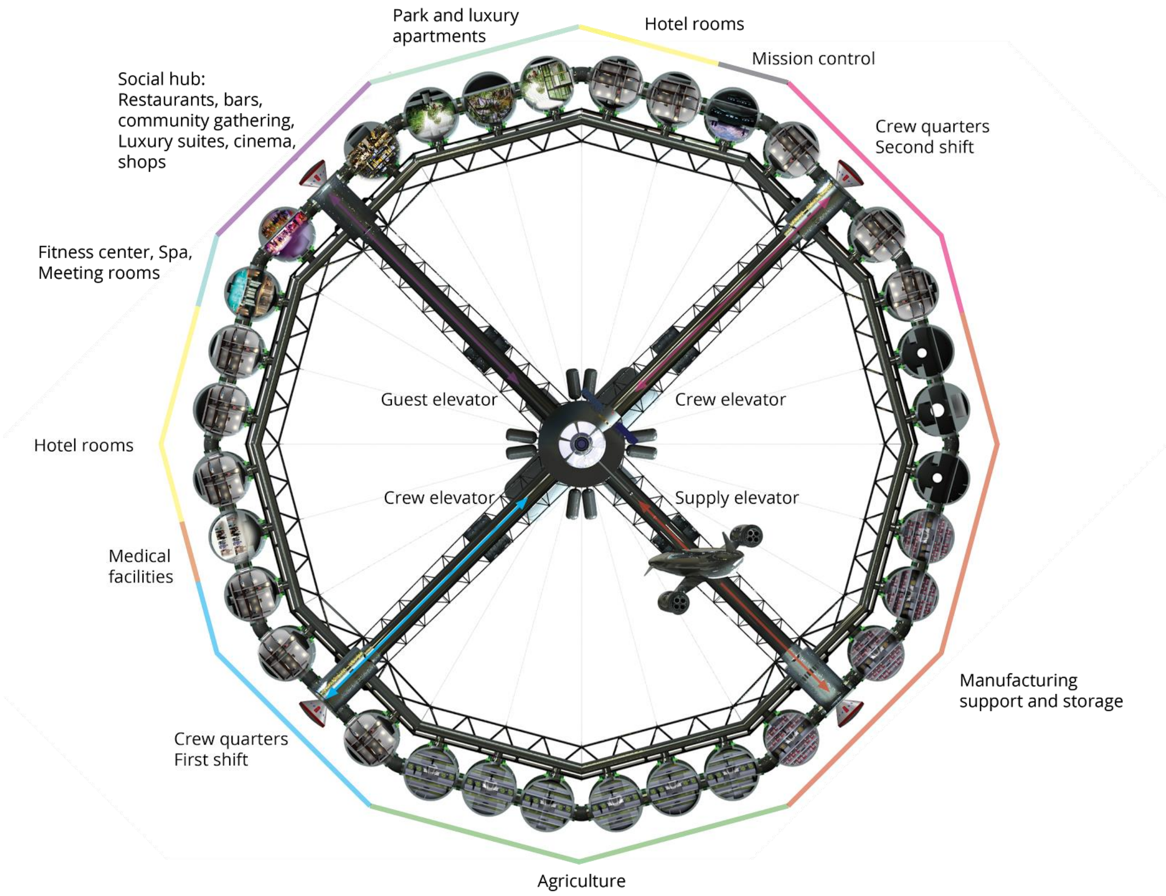


Figure 6-2: Allocation of modules to promote community in Starport 1

6.1.2. Accommodation

The area required for one sleeping room is 10 m^2 per person (Liberia Maritime Authority, 2006). At minimum, there will be a bed, a table, a chair, and power and data connections in each room. When the modules arrive in 2040 the crew will move from microgravity quarters to suites within the AG section. There will be one suite for every five people, with each module containing two to three suites. Sanitary facilities for each suite will include a toilet, a washbasin, and showers, which will be designed taking into account the Coriolis effects. Each person will have a private room inside the suite, in order to provide privacy. There will also be a common shared space within each suite. For information on windows and lighting, see Section 6.2.1.

6.1.3. Gardens

There will be several gardens throughout the station, each with a different configuration. The garden area will have a layout and appearance similar to parks on Earth, as shown in Figure 6-3. Mirrors and screens will surround the area and be used to increase the perception of open space, as well as create the feeling of different weather and seasonal patterns. There will be a small water fountain designed to celebrate the uniqueness of the AG environment, particularly the interesting effects that Coriolis will have on such a feature. There will also be kinetic art and sculptures to highlight the unique features of the environment.

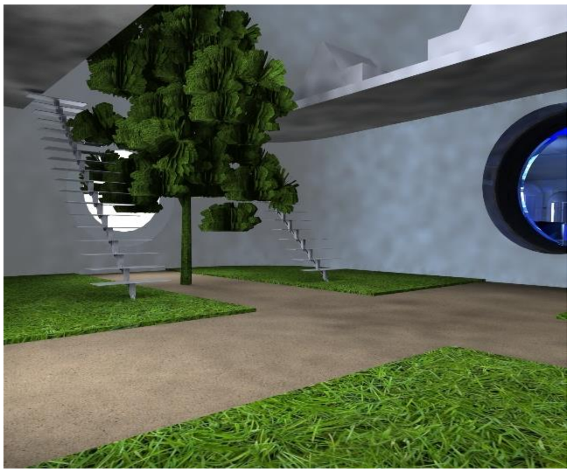



Figure 6-3: Garden module in the station

6.1.4. Dining

To promote a sense of community, dining on Starport 1 will be a communal, cafeteria-style experience. There will be several dining halls available throughout the artificial gravity section; in the 12-module phase there will be a dining hall in each of the separate sections so that one does not need to cross the microgravity section to get food. For one dining hall seating thirty, we need 450m^2 (Liberia Maritime Authority, 2006).

6.1.5. Recreational facilities

Recreational facilities will include communal areas designed to promote relaxation and comfort. These can be places for reading and writing, as well as playing games. (Liberia Maritime Authority, 2006). There will also be a fitness center for exercise and gym equipment. Virtual reality will be an integral part of entertainment on Starport 1, with rooms dedicated to this activity and adaptable to holographic technology once it becomes available. There will be recreational areas in the microgravity unit near the cupola. In all of these common areas activities will be organized and promoted, helping to foster and maintain a sense of community.

6.1.6. Place of worship

A virtual faith room will allow guests and residents to practice their faith onboard. The use of screens and moveable furniture will allow this room to take on the appearance of the place of worship of many denominations and faiths, while minimizing the number of rooms and people involved.

6.2. Healthcare and well-being

In this section we will focus on areas that represent significant differences or challenges of the artificial gravity environment from previously encountered space environments.

6.2.1. Windows and lighting

Starport 1 will complete an orbit of Earth every 96.5 minutes. We will provide an Earth-like lighting and day-night environment and avoid disruptive effects from perceived rotational motion by limiting the external windows in the artificial gravity segment to maintain the uniform outer structure of radiation shielding (Diaz Artiles, 2016). We suggest fitting the artificial gravity section with e-windows (screens), which, in accommodation sections, can be individually adapted to display preferred images. This solution will contribute towards a need of individualization of personal space, and provide the ability to vary the visual appearance of the room. The possibility to observe the outside world will be provided in a cupola in the microgravity section and in select locations in the garden area.

Lack of sunlight can disrupt the body's natural circadian cycle. Disturbances to this cycle contribute to the development of physical and neuropsychiatric diseases (Urs, 2012). To maximize human performance, health, and well-being in space, we propose an artificially regulated circadian cycle on Starport 1 with 12 hours of daylight and 12 hours of night (Flynn-Evans, 2016). This will be regulated with the use of artificial lighting that will vary in tone and intensity throughout the day, mimicking Earthly conditions. Monitoring the brightness of lighting conditions through the use of seasonal affective disorder (SAD) lighting will promote optimal well-being (Buckey, 2006).

To increase operational productivity and the effective amount of usable area on the station we suggest splitting the inhabitants into two separate day-night cycles, each offset by twelve hours. These two time zones would allow continuous use of work and production areas, without the detrimental effects of shift work on humans. Such a solution will increase productivity and support the business model of manufacturing.

6.2.2. Use of color and sound

Microgravity and rotational motion is disorienting. We will use visual cues to indicate orientation and direction, particularly in the microgravity section (Harris and Jenkin, 2002). Bright lights will indicate orientation toward the artificial gravity section. Following Russian methodology on ISS, which is perceived by astronauts as having greater habitability than U.S. sections, the microgravity section will have brown floors, white ceilings, and green walls (Schlacht and Birke, 2010). The artificial gravity section will use color to identify different modules and to create a variable environment in line with the philosophy of natural design. Earthly stimulus mimicry will be used to create surfaces, and structures that bear visual resemblance to those encountered on Earth (Schlacht, 2011).

When designing the station, it is important to minimize noise pollution from ECLSS infrastructure and to control sound levels in habitable modules. However, we will not discuss the details of this topic in this document.

6.2.3. Forces and accelerations

The main forces Starport 1 inhabitants will experience are the centripetal force and the Coriolis forces. Centripetal force provides the artificial gravity and this depends on the radius of the station as well as the rotation speed. To generate the 0.8 g of Starport 1's outer AG section the gravity gradient, measured by the difference in gravity from an inhabitant's feet to their head, will be 2.5%; this will be imperceptible to an inhabitant. The gravity gradient from the top floor, with a height difference of 10 m, is also acceptable as it is only 12% (Clément, 2015).

Linear motions perpendicular to the axis of rotation induce a Coriolis force. This is a major design driver and needs to be considered with every design element of the artificial gravity units. For example, with a station rotating counterclockwise and an inhabitant climbing a ladder will experience a sideways force to his or her left; an inhabitant descending would experience a side force to his or her right. We estimate the side forces to be 50 N for a person moving at a typical pace of 1 m/s. If we have stairs with a plane that is not parallel to the axis, the person would experience variation in gravity as well as the side forces from the Coriolis effect. As such we would carefully consider the effects of Coriolis on our placement of ladders and other transfer modes within the module.

For manufacturing simplicity, we have initially chosen a flat floor design. This will create an issue of apparent slope, which the inhabitants might find uncomfortable. This slope can be evaluated with the inclinations individuals experience in terrestrial conditions to see if it is disruptive. The choice between curved and flat floors could then be revisited with a more informed tradeoff of cost and acceptable comfort levels when the Bigelow modules are being manufactured (Hall, 2016).

When a person rotates his or her head in a different plane from the axis of rotation, this will cause an illusion of rotation different from reality. This experience is different from Coriolis, which results from linear movements; instead it results from an angular rotation (Clément, 2015). Therefore, it is important to design work stations screens and signs that encourage workers to move their heads up and down (vertically) as opposed to side to side (horizontally) (Hall, 2016).

6.2.4. Neurovestibular effects

The deleterious effects of microgravity on the human body, in particular the neurovestibular, musculoskeletal, and cardiovascular systems are well documented. Artificial gravity represents an integrated countermeasure against many of the physiological effects associated with prolonged exposure to weightlessness (Clément, 2007). However, the nature of the relationship (linear, exponential, etc.) between varying G forces (0-1.0) and the effect on each human system remains unknown. Also unknown is how much time each day would need to be spent in a given artificial gravity environment to achieve the full benefits of the countermeasure. A primary design driver of our station is to have a functioning module with artificial gravity available for use in 2035 to provide six months of research into these effects before operation. We chose 0.8 g as the force of gravity for our station because we believe that it will provide enough gravitation force to act as a sufficient countermeasure, while at the same time providing increased flexibility for station design by allowing for a slower spin rate for a given station diameter, which decreases other force and acceleration stresses on inhabitants (Diaz Artiles, 2016). Future research done on the station might show that less gravity is acceptable, or that more gravity is needed for countermeasures; however, at this point we simply do not have any more data on this subject. We do not expect that transitioning between 0.8 g and microgravity environments to have a serious effect on the musculoskeletal system. The effects of these transitions on other systems are beyond the scope of this report and we will focus here on the neurovestibular system exclusively.

The brain uses information from a variety of sources, namely otolith organs, eyes, semicircular canals, and position sense to synthesize a sense of body orientation and movement. When the brain receives conflicting signals it results in what is known as motion sickness (Buckey, 2006). Space motion sickness results from active head movements, particularly pitch and roll, and is due to otolith response to head tilt being different in the microgravity environment. Half of all astronauts require one to three days to adapt to microgravity (Clément, 2007). It is unknown whether this adaptation is done in parallel, or whether this represents a recalibration of the brain that must be done every time the body is exposed to a new gravitational environment (Meirhaeghe, 2016).

Future research could include investigating adaptation between a hyper-gravity environment and 1g gravity to determine the pattern and possibly predict if the body would require less time to adapt with each exposure (Meirhaeghe, 2016). This is critical to understanding the challenges, such as spatial disorientation and motion sickness, that may be experienced as many people will be spending several hours each day in the microgravity environment with possible multiple daily transitions between the microgravity and 0.8 g environment. Future research may also be directed at finding effective, non-sedating drugs against the motion sickness experienced in space. An added challenge comes from the lack of a good analog or model here on Earth to accurately predict and represent the forces of the microgravity environment in space (Jones, 2016).

Regarding rotation of the station, studies have suggested that humans can readily adapt to 3-4 rpm (Buckey, 2006).

6.2.5. Radiation protection and monitoring

For a space station in LEO the two main sources of radiation exposure are galactic cosmic rays and the Van Allen Belts (Jones, in press) (NASA, n.d.). This radiation represents a threat as it passes through station inhabitants and from more hazardous secondary particles — particularly neutrons — that it creates from passing through materials before reaching humans (NASA, 2007b).

Radiation represents both an acute and chronic threat to human health. Knowledge of the exact biological effects, particularly of long-term low-dose radiation, is limited and consists mainly of data derived from accidental and therapeutic radiation exposures. Radiation exposure is viewed to be cumulative, with particular cell-types, such as bone marrow, thyroid, eye, and gonads being more sensitive to radiation than others. A person's radiation exposure is influenced by the dynamics of the orbit and the solar environment (Jones, in press), and since these variables change with time, a person's radiation exposure on Starport 1 will be strictly monitored with dosimeters. Radiation has been known to have several delayed effects, such as cataract development and central nervous system effects. It is also linked with an increase in various forms of cancer, but this often appears only one to two decades after exposure (Jones, in press). Therefore, we will not be allowing people under 21 years old onboard and we will be following current NASA guidelines for monthly, annual, and career exposure (see Table 6-1). Notably, NASA standards include an annual exposure of 0.5 Sv, which is ten times the annual dose-equivalent of 0.05 Sv allowable to terrestrial radiation workers as dictated by U.S. Nuclear Regulatory Commission. These exposure limits represent educated guesses and can easily be revised downward or upward as new data becomes available. Future research should explore "adaptive response" or the concept that radiation exposure can induce an increase in DNA repair capability and thereby improve human radiation tolerance. The extent of this response and possible genetic link remains largely unknown (Buckey, 2006).

Table 6-1: Age and gender dependent career effective dose limits in Sv (Durante, 2011)

Space agency	Gender	Age at first exposure, (yr) 30	35	45	55
NASA (USA)	Female	0.47	0.55	0.75	1.1
	Male	0.62	0.72	0.95	1.5
JAXA (Japan)	Female	0.6	0.8	0.9	1.1
	Male	0.6	0.9	1.0	1.2
ESA		1.0	1.0	1.0	1.0
FSA (Russia)		1.0	1.0	1.0	1.0
CSA (Canada)		1.0	1.0	1.0	1.0

In addition to shielding, all people on Starport 1 will be given daily antioxidant pills because studies have shown that antioxidants may help the body combat damage done to cells by ionizing radiation (Brown et al 2010). We recommend further studies specifically aimed for radiation protection looking at compounds detailed on pages 70-71 of Buckey (2006). Windows will be limited to specific areas in the station and will not be present in residential quarters to further maximize radiation shielding.

There will be two levels of radiation shielding in the structure of Starport 1. The microgravity modules will be constructed from triple skinned aluminum sections with liquid water filling the void between the hulls as shown in Figure 6-4. A triple skinned design was chosen as it allows the incorporation of the pressure vessel, radiation shielding and debris impact shielding into one neat package.

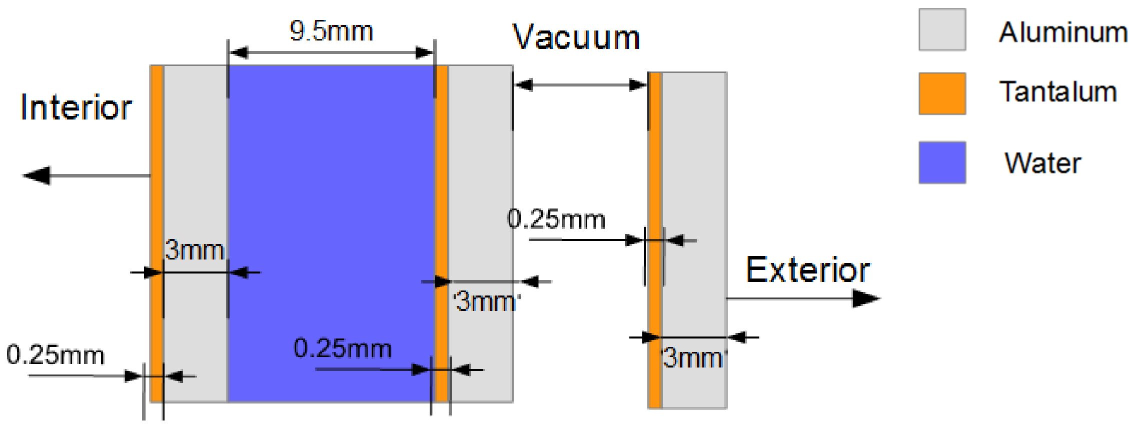


Figure 6-4: Cross-section of the hull radiation shielding

Figure 6-4 shows a cross section of the hull indicating each aluminum section and the water storage volume. The aluminum sections are lined on the inside with a thin layer of tantalum to absorb the environmental and bremsstrahlung x-rays. The gap between the central and outer plates can be filled with Kevlar laminate to provide additional debris shielding.

The inner layer of aluminum forms the pressure hull of the module and the inner radiation shield. The water and the middle layer of aluminum form the bulk of the radiation shield and the outer layer forms Whipple shield with the middle layer to protect from micrometeoroids. The outer shield vaporizes the impactor removing most of the energy allowing the middle aluminum layer to protect the station. Should the middle aluminum layer be breached, the water will freeze around the hole to block it until the panel can be repaired. Finally, the outer layer of aluminum will be coated with a layer of tantalum to allow it to function as an effective radiation shield as well as forming part of the debris protection. This allows the maximum bulk shielding volume to protect the crew.

For the inflatable sections, and as optional additional shielding for the rigid modules, boron nitride nanotubes (BNNT) (Tibeault et al., 2012) will be used as they may be woven into the ballistic protection fabric of the expandable modules or wrapped around them once they are expanded in the form of a woven sheet. To protect the rigid modules, the boron nitride sheet would be fixed between the debris shield and the outer hull.

Finally, once the station is fully assembled and the power systems finalized, superconducting wires will be used to enclose the torus and provide magnetic shielding which would allow long-term habitation in the artificial gravity environment (Battison et al, 2012). This would provide excellent active shielding although the power requirement would be in the order of 100 MW with current technology. Magnetic shielding was selected as the final goal as it is the only shielding that can entirely block radiation. Bulk shielding such as the aluminum and BNNT can only reduce the energy of the incident radiation, they also have additional interactions such as causing spallation from cosmic ray impacts and releasing x-rays from high energy electrons. The magnetic shielding can remove all of these effects as it changes the direction of the incoming particles, deflecting them rather than stopping them. This means there are no secondary interactions apart from with the highest energy cosmic rays which have a much lower flux than radiation at lower energies. We believe that this is one of the critical pieces of technology that will make it possible for children to come onboard Starport 1 by 2060.

6.2.6. Medical care

For the 2040 station, which will start with 100 people, we will have two licensed physicians as well as two other crew members who have separate full-time positions, but have also successfully completed either paramedic or nursing training. These personnel will all receive additional training to become proficient in common aerospace medical issues and basic dental skills. As the station inhabitants grow in number, additional medical personnel may be added if it is found necessary. There will be at least one medically trained person available in the microgravity and artificial gravity section at all times.

Due to space and mass constraints, medical facilities on Starport 1 in 2040 will be minimal. Basic medical equipment will include several defibrillators throughout the microgravity and artificial gravity units and one medical bay in the artificial gravity unit, which will include an ultrasound machine and other supplies similar to the current ISS complement. One room will have dual use as a seclusion room in case of a mental instability, or infectious containment. The station will rely heavily on telemedicine and developing technologies, such as improvements in quantified health technology and diagnostics. The focus of the medical care for life-threatening issues will be stabilization and evacuation. As the station grows in 2060 and beyond, we plan to expand the medical facilities to include an operating bay equipped for laparoscopic and robotic surgeries.

We anticipate that infectious diseases will be a challenge on Starport 1 as this is a commonly encountered issue in confined quarters. To decrease infection vectors, anyone going to the station will be subjected to a quarantine period before departure. In the case of tourists, this period can also be used for training for the unique environment. In addition, non-alcoholic hand sanitizer will be available at the entrance to every room in the station and use will be monitored. To minimize the risk of medical incidents in general, all crew, workers, and tourists will be subjected to selection criteria.

6.2.7. *Crew selection and training*

While Starport 1 is designed to be a space city by 2060, allowing people of all ages onboard, in 2040, stringent crew selection will be needed to minimize medical complications. This is because of the limited data available on a broader population's reaction to spaceflight and the potential for complications arising from the unique environment. The amount of time on the station will directly correlate with the stringency of standards; tourists will have the most relaxed standards, with increasing requirements the longer the anticipated length of stay. The 2040 model excludes anyone who is less than 21 years old, pregnant, or any premenopausal biological female who has not been on birth control for more than 2 weeks. As medical technology continues to improve and we learn more about the effects of radiation and the microgravity environment, specifically on youth and fetal development, we will adjust the standards accordingly. The exact medical standards for both short and long term population are beyond the scope of this publication.

Psychology is another important consideration and will also be a key component of selection, particularly for long-duration personnel. We will utilize evaluations and screening methods similar to NASA guidelines and guidelines for space passengers (Rayman et al., 2002). As Starport 1 will be populated by an international crew, training in communication, sensitivity, conflict resolution, and personal strengths recognition will be required. Such an approach will enhance crew cohesion, peaceful cooperation onboard, and will build internal resources for times of distress. For further discussion of this topic see Section 7.4.

6.2.8. *Well-being*

Creating a thriving society of space dwellers will be supported by careful crew selection and close attention to availability of meaningful activities on the station.

Close social bonds promote physical health and are one of the main contributors towards psychological well-being (House, 2001; Thoits, 2011). The station design supports communal activities, which counteracts isolation and social withdrawal. Hallways between modules are 3 meters wide allowing for easy passage from one section to another. Figure 6-2 shows the proposed 2060 layout with main dining, entertainment and recreational activities strategically located in one area to promote intermingling and community development.

We recommend the provision of regularly supervised sessions and meetings with trained personnel for inhabitants. These individual or group meetings will offer ongoing support in individual development and achieving optimum well-being, recognizing the unique stresses of the station, which include: separation from family and friends; isolation; close confinement; and fear of potential risks such as mission failure, technical failure, space debris collisions, and radiation effects. These meetings would serve as a platform for maintaining commitment, communication, cooperation and command which are dimensions identified by military and aviation psychology as building team cohesion (Grice & Katz, 2005).

Art and music will be encouraged among inhabitants as it can enhance quality of life by enabling personal expression of feelings and experiences, and offer psychological support during a prolonged time in space (Ono & Schlacht, 2011). Art can also contribute towards the decorative and aesthetic appearance of the station; music as a shared experience can help promote a sense of community.

Garden spaces will serve both as a plant growing space and as green recreational areas supporting well-being. Crew and tourists will be encouraged to participate in agricultural activities. Small green plants will be provided in the accommodation in line with evidence of plant's contribution to better performance, health, and well-being (Hall, n.d.). The color green specifically has been recognized to support accurate perception of time (Ono & Schlacht, 2011).

Station inhabitants will also have the opportunity to participate in an informal education regarding operation and maintenance of the station, societal work, and will have regular opportunities to communicate with Earth.

6.3. Environmental control and life support systems

The difference between uncrewed and crewed spaceflight is that crewed missions have an ECLSS which consists of the equipment necessary to keep humans alive and comfortable. Air and water quality for Starport 1 are addressed in this section, as well as waste disposal, microbial control and fire safety. Technologies recommended in subsequent paragraphs may be surpassed by future enhancements. Disruptive technologies could emerge in the time period before the assembly begins, taking life support closer to a closed loop.

6.3.1. Air revitalization

In the spacecraft cabin, there is no source of fresh air readily available. It must be revitalized by the removal of CO_2 and replenishment of oxygen. Trace contaminant gases and aerosol particles such as dust and lint from human inhabitants must be captured and removed.

CO2 capture/separation

On ISS, elevated carbon dioxide (CO_2) levels are the main challenge facing the air revitalization subsystem and technology improvements are necessary. For Starport 1 we propose a swing adsorption system, which uses an adsorbent material to selectively capture CO_2 from an airstream. The most common swing adsorption systems rely on high pressure to adsorb the gas, and then the pressure changes to a lower value, causing the gas to desorb from the material surface, which is known as regeneration. Other types of swing adsorption systems rely on thermal cycling or application of a vacuum environment to desorb the selected gas, all of which require a significant amount of energy and substantial construction of pressure vessels to pressurize the entire gas stream. These more energy-intensive swing adsorption systems are common in industrial plants for CO_2 scrubbing of flue gases, a scale much larger than necessary for Starport 1 (Lee, et al., 2016).

A novel improvement on the previously mentioned systems is the electric swing adsorption system, which does not require a pressurized system and has much lower energy usage. This technique has potential use in residences in the form of an electrical appliance, which indicates that it would be of reasonable size with a low level of complexity for use in a distributed ECLSS. The concept uses a solid monolithic adsorbent which is conductive; when an electric current is applied, the adsorbent acts as a heating element, triggering regeneration (Lee, et al., 2016). Activated carbon is recommended for this application: it has large surface area and internal volume of micropores and, when formed into a monolith block, it has uniform electrical resistance. Other advantageous material properties include mechanical hardness and thermal shock resistance. A study conducted by Lee et al. (2015) tested a dual monolith electric swing adsorption device sized for a residential home. It drew in air with 3000 ppm CO_2, splitting the inlet airstream into a waste airstream with higher CO_2 concentration and a recirculating stream with lower CO_2 concentration. For safety, the demonstration used a temperature difference of 20°C, resulting in less efficient CO_2 capture. The study successfully demonstrated CO_2 removal by electric swing adsorption, although at lower efficiencies than industrial applications. Additional engineering and optimization of the monolith size and configuration can achieve significant improvements on this new adsorption concept. Other ways to improve this concept are integration into heating, cooling, ventilation, and air conditioning (HVAC) infrastructure to use heated or cooled airstreams to reduce energy consumption (Lee, et al., 2015).

In Starport 1, the electric swing adsorption CO_2 removal will take place downstream of air intakes and particulate control systems or filters, with an optimized air exchange rate to accommodate the removal of both aerosols and gaseous species. We will capture the waste stream of CO_2, compress it and store it as a liquid in a pressure vessel for further processing.

CO2 processing

Removing CO_2 is the most basic step in air revitalization. The Sabatier reaction is optimal for converting CO_2 into useful products, and is currently used on the International Space Station (Greenwood, et al., 2015). The CO_2 combines with hydrogen (H_2), and the resulting products are methane and water, as the Equation 23 shows:

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O + \text{energy}; \qquad (23)$$

ISS uses this process but does not take full advantage of the products, as methane is vented into space. However, plasma pyrolysis is a technique which can convert the methane (CH_4) into other hydrocarbons, thereby recovering more hydrogen from the vented gas to feed back into the Sabatier reactor (Greenwood, et al., 2015, Herdrich, et al., 2014). We recommend this process for use on Starport 1, and rather than venting, the resulting gas products could be used as fuel for stationkeeping or debris avoidance maneuvers.

Trace contaminant and particulate control

On ISS, a dedicated system controls contaminant trace gases (Macatangay, et al., 2009), and high-efficiency particulate air (HEPA)-level filtration controls airborne particles (Meyer, 2014). A new air-cleaning device can replace both of these systems, resulting in mass and energy savings. In place of conventional air filtration, an electrostatic precipitator (ESP) can be used to remove smoke and dust particles from gas streams. The ESP imparts a charge on the particles and sends them through an electric field where they move towards, and adhere to, a grounded electrode. This removes the particles from the air flow at high efficiency rates, dependent on the particle size distribution and the electrical resistivity of the particles.

The advantage of an ESP over filters with fibrous media is that it cleans the air as it flows through the electric field with no physical barrier. Energy costs of moving air through an ESP are lower as there is negligible pressure drop across the device. Although the collecting electrode requires periodic cleaning, this solution eliminates resupply of clean filters, which is important in logistics reduction especially for long-term missions. A self-cleaning electrode design can be attained with some engineering development. Performance is significantly enhanced by adding soft x-rays to the ESP flow path, thus improving charging efficiency leading to particle removal over a much larger size range. Studies have shown that the soft x-rays, coupled with the corona ion source, deactivate bacteria and viruses. Furthermore, they generate reactive species such as ozone, which oxidize and remove volatile organic compounds (VOC) and trace gaseous contaminants (Kettleson, et al., 2013, 2011). This enhanced ESP device combines particle control and trace contaminant gases removal, effectively reducing the number of subsystems for air revitalization and odor removal. Due to recent US government investment, there will be further improvements on this technology (NSF, 2016). Typically, a corona discharge, or non-thermal plasma, is undesirable on spacecraft, owing to the potential for electromagnetic interference (EMI) which may disturb electrical circuits of onboard computers or other electronic equipment. Incorporating shielding into the design can mitigate this effect. Optimal voltage and x-ray settings can minimize the potential for elevated ozone concentrations in the vicinity of the device (Kettleson, et al., 2013).

6.3.2. Water processing subsystem

For water processing, Starport 1 will use a biologically-based processor that NASA is researching. It is capable of treating a wastewater stream which includes urine, personal hygiene water, and laundry (Barta, et al., 2015). This biologically-based environmentally-friendly system does not require multiple filtration beds or large quantities of chemicals and uses membrane aerated biological reactor technology that has been proven in small-scale integrated waste water tests continuously for 500 days (Christenson, et al., 2013). While there are still technical challenges at this time, investment into engineering development will enable scaled-up operation that will be applicable to our station.

6.3.3. Solid waste processing subsystems

We recommend supercritical water oxidation (SCWO) as an environmentally-friendly and low upmass clean technology for solid human waste processing, without the use of chemical pretreatments. When water is above its critical point (extremely high pressure and temperature), many organic materials will dissolve and become soluble in it. The addition of oxygen (or air) to these solubilized organics creates a flame within the water, known as a hydroflame. This combustion entails many chemical reactions that break down the waste into CO_2, nitrogen, and water (with small amounts of oxygen as well). Recent studies have shown a >98% conversion rate and indicate that small-scale systems may be more economical than large-scale municipal plants (Miller, et al., 2015). A review by Qian et al. (2016) also outlines the economics of several municipal SCWO plants and the conversion of municipal sewage sludge to combustible gases. As with many new green technologies, SCWO has challenges such as corrosion, solids feeding and plugging of reactors. These can be overcome with some level of research and engineering investment. For Starport 1, gas products from human waste processing can be compressed and stored for future use or conversion to other gases.

6.3.4. Surface disinfection

Cleaning is an important aspect of a healthy living environment and the Mir space station is an example of the danger of negligence in this area (Satoh, et al., 2016). Microbial and fungal populations are also monitored in the ISS cabin environment (Kawamura, et al., 2001) and regular housekeeping chores include wiping walls and other surfaces. New technologies are emerging in surface disinfection with non-thermal plasmas which would reduce upmass and resupply by eliminating dependence on cleaning chemicals while effectively deactivating bacteria, fungi, and spores on surfaces. These methods are being explored in multiple commercial markets, for example, the gentle washing of fruits and vegetables or in the healthcare sector. Research has shown that the addition of water to plasma disinfection processes increases the deactivation of bacteria from 97% to 99.99% (Neuber, 2016). Under the effect of the plasma, the water undergoes chemical and thermodynamic changes which include active species such as hydroxyl radicals, ozone, and hydrogen peroxide that act on the microbes causing damage at the cellular level. The water can be in the form of a liquid film on the surface to be cleaned, or a specially designed nozzle sends water through a surface dielectric barrier discharge (SDBD) plasma and highly charged droplets emerge. One non-plasma method can also disinfect surfaces with a water electrospray (Pyrgiotakis, et al., 2015), creating a vapor of highly-charged droplets. As with the electrostatic precipitator recommended for airborne particle removal, plasma disinfection devices will need to be shielded properly to avoid electromagnetic interference with station electronics and communication infrastructure. Some work remains to scale up these plasma techniques for cleaning larger surfaces in shorter durations. We recommend this method for Starport 1, as it is a very safe, chemical-free cleaning method that would use water in very small quantities with no rinsing necessary. Less waste water will be produced while maintaining high standards of cleanliness and health for the residents.

6.3.5. Smoke and fire detection

Currently on ISS, the smoke detectors are turned off during housekeeping chores as dust from vacuuming often triggers the smoke alarms (Meyer, 2014). In the low gravity environment, the large particles that would settle to the ground on Earth remain airborne and can enter the sensing chamber of a smoke detector. Another issue on ISS is that smoke does not rise in the absence of air buoyancy, so there is no obvious location for smoke detectors. For Starport 1, the artificial gravity will create a density gradient in the air, and thus smoke and hot air will rise, making ceilings the logical location for smoke detectors, as they are on Earth. There is evidence that the current ISS smoke detectors in the US segments, which operate on the basis of smoke particles scattering light, cannot detect extremely small particles that are produced from overheating Teflon (Meyer, 2015). The optimal fire detector for future spacecraft will likely combine two types of detectors currently available. A typical household ionization detector which will perform well for small particles generated by flaming combustion, and a photometric (light scattering) detector which perform well for large smoke particles from smoldering materials (Meyer, et al., 2015).

Another improvement over the ISS in smoke detection is to couple smoke particle detectors with gas sensors to detect carbon monoxide or other gaseous smoke components with an algorithm, which will lessen the possibility of false alarms from ambient background aerosols. Post-fire clean-up is an important consideration for Starport 1 as well, and the soft x-ray enhanced electrostatic precipitator recommended previously will perform well as a smoke eater to remove particles and some toxic gases as well. The number of air changes in a smoke-filled area can be increased with temporarily larger flow rates, however, additional standalone units can be brought into an affected area and run continuously for faster results.

6.3.6. Additional topics

Specifying technologies for every life support subsystem is beyond the scope of this work. Therefore, the following ECLSS topics are important for the design but not addressed with specific new technology suggestions for Starport 1: thermal control subsystem, temperature, and relative humidity control.

6.4. Sustainability

Starport 1 aims to be as closed a system as possible, with the hope that one day very little outside assistance will be required to remain fully functional. While current technology makes this an unrealistic goal by 2040, with new developments and knowledge expected in the coming decades, we anticipate a rise in the percentage of self-sufficiency over the course of the station's lifetime. As a resort destination, there is no intention to have a closed loop with respect to food, as tourists expect variety beyond what can be produced on Starport 1.

Table 6-2: Water and air input and output per crewmember per day (Anderson, et al., 2015)

kg/crew member per day	Input	Output	Comment
Consumed water	11 to 28	-	Hygiene, laundry, and drink
Water vapor output	-	1.85	Accounts for exercise & resting during day
Sweat runoff	-	0.08	Accounts for exercise & resting during day
Wastewater	-	4 to 29	From hygiene, laundry, urine
O_2 consumption	0.82	-	Accounts for exercise & resting during day
CO_2 output	-	1.04	Accounts for exercise & resting during day

Table 6-2 gives the NASA baseline assumed quantities of water and air constituents (O_2 and CO_2) which are consumed and given off each day by one crewmember. Additional air is lost from leakage out of any spacecraft, and for ISS, this is assumed to be between 0.05% and 0.14% per day (Anderson, et al., 2005). Therefore, some make-up air must be provided to maintain the atmosphere. For a partially-closed loop life-support system, the most significant improvement is to recycle water, followed by CO_2 regeneration that recovers O_2. These activities are planned in the ECLSS and will reduce resupply by 80%. For current life on ISS, a crewmember needs approximately 5000 kg/yr of consumables to stay alive. The recycling activity for water and the CO_2-O_2 processing reduce that mass to 1000 kg/year. Additional incremental improvements towards closing the loop are very small in comparison to water and CO_2-O_2 sustainability, on the order of 2% to 4% (Eckart, 1996). Therefore, they are not pursued for Starport 1.

6.4.1. Waste disposal

Some waste products will be processed and re-used as done in the ECLSS system for human waste and laundry wastewater. However, for remaining waste products there are two main choices: recycling and reuse, or disposal outside the station.

There are a variety of technologies that will potentially be useful for minimizing waste in Starport 1, some of which are being developed by NASA's Advanced Exploration Systems (AES) program's Logistics Reduction and Repurposing (LRR) project (Ewert, et al., 2013). It is important to accurately plan the composition of the consumables on the station as this will determine what technology is best suited to process them.

There is currently no capability to wash clothes in space. Astronauts generally wear the same clothing as long as they find it tolerable. The gravity of Starport 1 will greatly simplify this area, so laundry services will be available for crew and guests, and the wastewater will be processed as mentioned in the ECLSS section. Anti-microbial treatment can be used to make clothes, particularly those of the crew, last longer between washes in order to conserve water (Ewert, et al., 2013).

The Heat Melt Compactor (HMC) is a device that is able to process wet and dry trash. Waste containing plastic can be processed into a tile that is microbiologically safe and can be handled by the crew. Water trapped in waste products can be reclaimed and sent to the water recovery system. The tile produced has a high hydrogen content, making it a material that could potentially be used for radiation shielding. (Turner, et al., 2014)

Many materials can be processed using trash to gas (TtG) technologies as they are manufactured using thermochemical processes. These TtG technologies can produce methane, gas for resistojets, and gases for non-propulsive venting as end products (Ewert et al., 2013). Other trash that cannot be processed might be ejected from the station and sent to burn up in the atmosphere.

6.4.2. Farming

In the long term, Starport 1 aims to grow as much of its own food as possible. While many plants have already been successfully grown in microgravity (Meggs, 2010), we will not be relying on this as a source of nutrition initially. In 2040, we propose to have modules dedicated to agriculture supplying approximately 20% (conservative estimate) of the station's food supply needs, the remaining food requirement will be 3D printed or imported. We are expecting that by 2040 3D food printing will be fully developed (NASA, 2013). We expect the percentage of food supplied by the station to increase dramatically once agriculture technology and techniques are verified. One important factor for the tourism business aspect is that the food and drink should be abundant and varied, so these are expected to be ongoing cargo supplies over the life of Starport 1.

Growth of the station based food farming will be incorporated into the life support system. Basing our predictions on the Bios-3 (Salisbury, Gitelson, Lisovsky, 1997) and MELiSSA (Lasseur, et al., 2010) experiments, we assume that operation of a closed loop life-support system will become a viable option by 2060.

To minimize water use and volume requirements, we propose to use aeroponic farming (NASA, 2007a). Aeroponics proves to be an efficient way of plant growth and we can expect further developments in this area in the coming years.

6.4.3. Livestock, meat, and insects

Cultivating livestock in space will be very complicated as animals have a large requirement for many consumables such as animal feed and water. (Van Huis, et al., 2013). Their impact on the environment control system could potentially be significant. "Ten kilograms of feed yields one kilogram of beef, three kilograms of pork, five kilograms of chicken and up to six kilograms of insect meat." (Dicke, van Huis, 2011) This demonstrates how inefficient animals are at converting feed into body mass and food for human consumers.

Consuming insects is not popular in the western world, however it is already popular in some parts of the developing world and could be an effective source of protein and nutrients (Dicke, van Huis, 2011). Insects can more easily be raised in space than larger livestock and have a much higher feed-conversion efficiency than other animals. Greenhouse gas and ammonia emissions from insects are relatively low. They require much less water, there are fewer animal welfare issues, and can be grouped densely together improving efficiency. In addition, there is a lower risk of transmission of zoonotic infections. Insects could also be reared in organic side streams such as compost, which may lead to more space efficiencies within the agriculture modules of the station. (Van Huis, et al., 2013).

Another alternative to cultivating livestock is tissue engineering technology, which is being adapted from the medical field to develop meat. This has been applied to cultivate beef in the lab. A sample of fresh muscle from a cow will undergo a process that may take 10-11 weeks to produce donut shaped meat portions. This method has been already tested and life cycle analysis shows that cultured meat requires less water and power than livestock (Post, 2014). A start-up company in San Francisco called Clara Foods is currently working on creating eggs free from animals (Clara Foods, n.d.). There is a potential these could be one supply for meat and eggs in the 2040s and 2060s.

7. SOCIETY

Starport 1 will house people from different nations, bringing diverse cultural traditions and values into orbit. This section addresses questions related to the society onboard the space station, particularly in terms of its structure and governance, and raises ethical concerns that need to be considered. The ultimate question remains why we, as humans, should embark on this project of launching and operating the largest space station in history.

7.1. Societal ideology

In the process of designing the first large space stations, participating parties will take on the monumental task of deciding the social structures to be used in outer space. For decades, space settlement advocates have pointed to reasons for humans to establish communities beyond Earth's surface – the most common of these having to do with ensuring the survival of human life or intelligence. As humanity expands into the Solar System, our first outposts will determine what values our species will preserve and how individuals and communities will evolve in the future.

In the early stages of planning for large-scale commercial space stations, designers will need to decide the purposes that the station crew and visitors will serve, the activities that the station will accommodate, and the cultural values that the station's design and operation will reflect. All of these considerations will be rooted in the original rationales and ideologies of those developing the station. This section will provide a theoretical analysis of the current academic research on these issues and offer key ideological considerations for the societal design of Starport 1.

7.1.1. Social rationales for commercial space stations

An endeavor with the scope of Starport 1 will have long-term timelines, and as such, long-term returns on investment. While the project will be born out of a capitalist, private-sector initiative with significant government support, public stakeholders and financial investors will be motivated to support the project because of a demonstrated just and ethical long-term social imperative. Thus, gathering and maintaining support for the development of a station requires the use of compelling social rationales for why a commercially-run human outpost in LEO is necessary.

In the United States, space advocates often draw simultaneously upon rationales as diverse as "American libertarian understandings of government and economy and liberal appeals to the common good, on metaphors of the American Frontier and European colonialism, and on sources of speculative fiction" when arguing for the development of settlements beyond the Earth's surface through commercial space enterprises (Valentine, 2012). These decades-old rationales date from the earliest days of the space program, and can be problematic when planning an international space station with consideration of modern mainstream social ideologies. This is largely because such rationales represent a linear, and at times backwards-looking, approach to future planning; in a 2006 paper, Billings cites historian Stephen Pyne's observation that the case for space colonization is not compelling without the context of historical periods of imperialism or even enlightenment (Billings, 2006).

Contradictory to the practices of many commercial space advocates of the past half-century, social rationales largely on themes of colonialism and colonization will likely not necessarily resonate well with younger generations, or with most people outside of the space industry. Thus, it is necessary to develop new rationales based on modern social, political, and economic developments. Many of these developments oppose the continued and unquestioned expansion of capitalistic, Western ideologies into the Cosmos. Today, individuals dedicated to wealth and prosperity, humanitarian and environmental issues, or both, help to shape global communities. It is crucial to strike a balance between these considerations when developing the social structure of Starport 1.

The benefits for societies on Earth can be identified across various sectors. Developing countries can be a valuable source of qualified labor for the production of the components of Starport 1, thus fueling economic development while building high-tech infrastructure. Opportunities for manufacturing and scientific exploration onboard the microgravity section have the potential to benefit humankind across nationalities and cultures, while the cutting-edge character of the entire project can stimulate thousands of children and students to pursue excellence in the sciences. These rationales have been stressed by Logsdon (2004) as traditional drivers for governments to use their tax income to pursue human spaceflight, even with the associated risks.

We suggest focusing on ways to get the next generation of scientists, explorers, and dreamers excited about the possibilities outer space has to offer. What will likely resonate most with millennials and their successors are rationales concerning bringing societies closer together through international cooperation and the moral imperative to protect and rehabilitate planet Earth. The International Space Station (ISS) has provided a model for how cooperation on international space projects can propel human progress, development, and diplomacy (Manzione, 2002). Bringing more people to low Earth orbit also has potential for increased recognition for the unifying power of the overview effect, perhaps leading to a widespread scaling of this phenomenon that compels individuals to care for the human species and planet Earth. Finally, the potential for closed-loop technological development can help inspire the next generation to honor the elegance and complexity of the closed-loop systems of our home planet, Spaceship Earth.

7.1.2. Ethical considerations and implications:

Society building requires careful and ethical consideration of the evolution of human societies and options for humanity's future development. As we take the first steps toward expanding humanity's presence in the universe, we must ask ourselves:

- What values should we bring with us?
- What kind of opportunities and lifestyles should be offered in space?
- Who gets to decide these questions?

These ethical considerations greatly impact the geopolitical and economic challenges of organizing a space station of this scope. A strong adherence to one set of values or cultural institutions can severely alienate certain players from participating in the station.

When determining the crew composition, if the central reason for including the guests is to increase profit, tourists will largely include wealthier individuals capable of contributing continuous capital for the duration of their stay. If the goal is to expand humanity's reach into the Universe in the most diverse way possible, designers will need to sacrifice such profit making opportunities.

In the social design of Starport 1, there will undoubtedly be difficult decisions requiring tradeoffs between ideology and practicality. Designers will aid in timely and considerate decision-making by carefully planning the ideal social structure and identifying appropriate compromises.

7.2. Governance

This section will discuss some of the factors and variables affecting the governance of Starport 1. The space station will contain a semi-closed society from which one cannot immediately leave at will; its governance raises ethical and practical questions that future studies should address in detail. Ultimately, for the sake of insurance and legislation, it is necessary to ensure that every individual going to the space station, whether as a crewmember or in any other capacity, signs a legally binding contract clearly stating their rights and obligations prior to launch. We recommend a model of governance similar to ISS to be applied at Starport 1, jointly agreed upon by the operator. See Chapter 6 for legal and policy issues and recommendations.

7.2.1. Governance structure

The Starport 1 Officer in Chief, or Commander, who we plan to be an employee of the Starport 1 operator, will be the highest authority onboard and will be responsible for the overall management of the station and the security onboard. A code of conduct, similar to the code of conduct for ISS crew adopted by ISS partners on 15 September 2000 (Farand, 2001), should be drafted to detail the scope of the commander's authority over the crew, the spaceflight participants, and government astronauts, having due regard for applicable national legislation. The operator should require the commander to accept the provisions of this code of conduct, contractually, to ensure its enforcement. The commander onboard should remain under the authority of the flight director on ground, the latter also being an employee of the Starport 1 operator. The crew is responsible for on-site station management, station operation, and station maintenance.

7.2.2. Enforcement of authority

The enforcement of authority on Starport 1 will be comparable to that on ISS. Full-time guards and security personnel would require a substantial amount of the human resources to be available onboard, and therefore are not advisable. We propose a system whereby certain crewmembers will be trained in security measures on top of their regular duties. These crewmembers should be present at different locations in the station to ensure the best possible coverage at any time. In case of major disputes, for instance related to criminal actions, a court of justice on the ground will be available through telecommunications.

The commander of Starport 1 will ultimately enjoy the authority given by the code of conduct, which would be implemented by the operator as well as relevant states.

7.2.3. Ethical considerations

The United Nations Universal Declaration of Human Rights will apply to all people on Starport 1, and will be upheld. However, the way states interpret these rights varies. Today, states participating in ISS share, to a large extent, fundamental norms and values. In future scenarios, with a more diversified pool of space agencies and companies, this common heritage may no longer be self-evident. Other agencies and companies with different values may want their worldview influencing the governance of the space station, which again could affect the cohesion and society onboard.

7.2.4. A city in the skies

As we proceed towards year 2060, with potential residents living onboard the Starport 1, we need to address community and governance issues. The degree of autonomy requires particular attention. The ecosystem onboard will be less dependent on input from Earth as we move towards and beyond 2060 - is this also applicable for the society? As outlined in Section 6.1.1 and Figure 6-2, the modules for human living are arranged around a social center to accommodate human interaction on a day-to-day basis. This city will be dynamic in the beginning, as the number of people will fluctuate, but as we open up for residents, people will be able to stay for long terms. These people need jobs, whether directly related to the station or as remote workers in Earth-based companies or institutions.

7.3. The crew of Starport 1

The selection of appropriate individuals suited for long-term space missions is an essential component of a mission's success. Such selection procedures tend to focus on individual attributes, such as the ability to lead or to manage stressful environments, in addition to expertise in technical fields. While acknowledging the importance of individual performance in space, emphasis should also be placed on the role of the dynamics between humans onboard Starport 1.

According to Kring and Kaminski (2011), the crew composition is the most important factor affecting interpersonal relations onboard a long-term space mission, and gender seems to be the predominant variable. The complexity of a social structure depends on the number of people living within it. Larger groups are more complex and allow for larger social networks. Members tend to exhibit less hostility and get along better than in smaller groups. Each crewmember on the space station brings unique experience and an optimal team should foster both interpersonal and task cohesion. According to Kring and Kaminski's analysis of previously conducted space analog studies, a mix of female and male crewmembers is preferable to male-only teams, as each gender, on average, offers different skills and abilities to the mission. As smaller teams are more likely to struggle with tension, the gender mixture will be even more important during the early stages of assembly, when the number of crew members is limited compared with the operational stage.

From a societal perspective, taking into account the analysis by Kring and Kaminsky (2011), we recommend that the technical requirements of the mission should be the baseline for crew selection. As a result, planners should select the crew according to expertise, taking gender balance into account as a factor enhancing the team's performance.

According to Buckey (2006), mixed-gender crew compositions in hostile environments could have negative effects such as sexual rivalry, jealousy, and harassment. However, men and women are not exclusively driven by sexual desires, and the need for intimate intercourse can be overcome. Experience from analogs, such as long-term habitats underwater and on Antarctica, suggests that crew selection should ultimately be based on qualifications and ability to perform.

A key issue that needs attention is language and communication between the people onboard Starport 1. A certain level of English, or another language defined as the standard language of the station, is important to ensure ease of communication. Cultural sensitivity is another important aspect, as well as respect for other religions, beliefs, genders, and sexual orientation, among other concerns. This is important for crews as well as for guests. As outlined in Chapter 6, there will be no children onboard the station until we can sufficiently guarantee their safety.

7.4. A society in space - a glimpse into the future

When Starport 1 is completed, and the safety of long term stays can be ensured, it will be possible for people to live on the station as residents. Will we see the rise of a new culture, with its own traditions or even rituals, perhaps based on the existing cultures on Earth? If people live on Starport 1 for a long period of time, will they feel more connected to society onboard, compared to their communities on Earth? If people start living permanently on the station, they may want to buy property, create a “space currency,” or even arrange their own autonomous government. These questions seem far ahead today, but they will be of highest relevance 50 years from now and are worthy of further consideration.

7.4.1. Isolation, privacy, and social center at Starport 1

As the space station increases in size and capacity, the number of interpersonal relations onboard will increase. The social center will be the very core of the social activities onboard, and be designed to proactively address issues of isolation. People onboard will be able to move around between the different modules, unless concerns of safety or security deems otherwise. Guests onboard will be housed in modules on both sides of the social center, which will give easy access to facilities such as restaurants, spa, and the fitness center. The crew will be living on both sides of the station, one operating the station at night, the other during daytime. While we strive to avoid isolation, based on a general assumption of humans as fundamentally social beings, a certain level of privacy should be granted. This is particularly important for crew and guests staying for long periods of time. Increased social obligations can have both positive and negative attributes, as more complex relations would increase one's number of social duties (Palinkas, et.al., 2004).

Possibilities to do sports, particularly in teams, will be one of the measures implemented to keep the people onboard entertained and active. The Coriolis effect could, perhaps, lead to a new sport only possible to play at Starport 1.

7.5. Human resources over time

The number of people on Starport 1 will increase as time progress. Initially, most of the people onboard will work on assembly, research, manufacturing, and system maintenance. Therefore, little room will be available for guests. The first eight modules will only be for microgravity, and emphasis will be put on research and manufacturing. As the station is built and eventually starts spinning to create artificial gravity, more room will be given to accommodate guests, as illustrated in Figure 6-2. The period of stay will also change as the station develops. In general, the crew will stay longer than guests.

Figure 7-1 illustrates the potential for crew-guest compositions as the station develops. The station roles proposed below are broadly defined for the purpose of flexibility, and will be subject to change depending on the development of Starport 1.

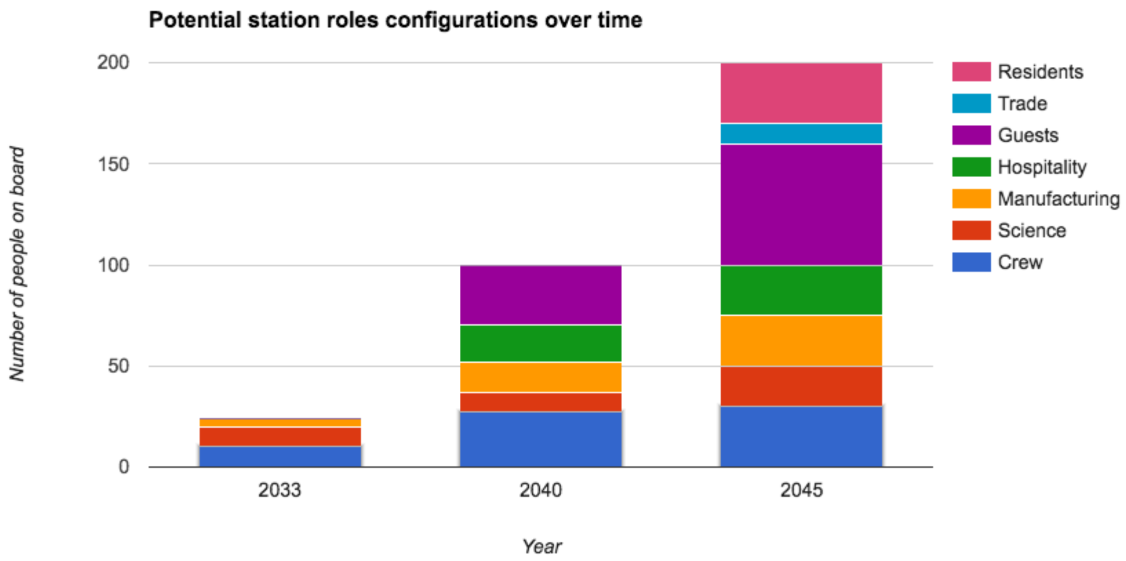


Figure 7-1: Crew and guest composition over time

In the early phases of Starport 1, the microgravity modules will potentially be able to house 24 people. As presented in Figure 7-1, these people will serve as crew, researchers, or manufacturers. Once measures are in place to mitigate the risks associated with traveling to and living in the initial modules, it will also be possible to house a limited number of tourists. By 2040, the station will have capacity for 100 people. As illustrated in Figure 7-1, new roles will have emerged on the station, most notably hospitality employees and guests. At this stage, Starport 1 will house up to 30 tourists. In 2045, the station will be able to house 200 people. With this configuration, there is a potential for increasing, perhaps even doubling, the number of guests. We account for new functions, such as trade workers or other residents, in this scenario.

"Crew" is here defined as people onboard working for Axiom Space, and whose primary purpose is the operation and maintenance of the space station. Roles within this category include pilots, I.T., communications, and management. The category *"Science"* refers to visiting researchers doing experiments in microgravity. *"Manufacturing"* mean people working in agriculture and high-value manufacturing industry onboard. *"Hospitality"* includes personnel working with the *"Guests"*, ensuring their comfort during their stay at Starport 1. The Guests category includes both tourists and families of personnel working onboard. *"Trade"* refers to people working onboard in marketing and sales, or commercial entities providing services onboard, and *"Residents"* includes people eventually taking residence at the space station.

The society onboard Starport 1 will become more complex as time progresses, and so will the potential for establishing an autonomous or semi-autonomous human ecosystem and society in orbit.

Overall, the cultural configuration onboard, as well as the society onboard, will depend on the countries, private entities, and individuals willing to take this project forward. We project a trend where more of the capacity on the space station will be allocated to commercial interests as the station develops.

7.6. Conclusion

The success of Starport 1 is not only dependent upon its technical configuration or the individual characteristics of the crew. The society created onboard can foster cooperation and performance, but conflicts and stress could be just as likely if the interpersonal relations and social structure on the station allow for them. Careful consideration should be taken to ensure optimal governance and social structures onboard. Assuming the society onboard will be diverse and multi-cultural, appropriate measures should be implemented to ensure cohesion, both before and during operation. We recommend joint training for crew and the ground segment prior to flight, including extensively language and cultural aspects. Tourists will also be subject to training before flight. The station will have a social center to foster human interaction, and will be governed following the model of ISS.

Every person who visits Starport 1 will have a unique experience. Upon arrival, everyone will contribute, in all kinds of ways, to the highest-velocity society in the world. When their stay is over, and it is time to return to Earth, the very same people will carry something special back with them – a piece of the experience, a piece of the culture in the skies, a piece of Starport 1.

8. BUSINESS

As a commercial venture, Starport 1 needs to generate revenue and produce long-term profits, which will also make it a more attractive investment for public and private actors.

This chapter explores a number of potential sources of revenue including the marketing of modules, areas for research and manufacturing, selling products and naming rights, and tourism opportunities. It also identifies potential competitors and the key areas of risk for business ventures on the station.

8.1. Leasing and selling artificial gravity modules

The highly modular nature of Starport 1 offers an opportunity to allocate some of the modules without fixed functions to be marketed in a variety of ways including leasing or selling.

Leasing modules either in part or in entirety would provide a source of income for fixed periods of time. It would also avoid relinquishing ownership of parts of the station.

Selling modules would reduce the investment needed to build the station, as the owner of the module would pay for its assembly, but would require the station operator to relinquish ownership. It could provide a recurring source of income, as the station operator would provide utilities to the module such as power, water, and life support services.

The main clients will likely be governments wanting to establish a presence in space, commercial enterprises aiming to offer services or manufacture products in orbit, and private individuals interested in space tourism.

8.2. Supporting research and manufacturing

Microgravity represents a unique environment for the manufacturing of particular goods and allows for the development of new manufacturing techniques.

8.2.1. Research and development in space

A source of income on Starport 1 will involve the leasing of the microgravity section for research and development purposes.

Scientific research could constitute one such source of income. The ISS is only expected to remain in operation until 2024, after which there will be a market niche for scientific research in space. This presents an opportunity for Starport 1 to provide similar opportunities in microgravity as well as other space environments. A component of leasing the station for research will involve housing researchers as station visitors.

Starport 1 facilities will also be marketed to commercial companies interested in developing new products in space. Pharmaceutical companies may be early adopters for such opportunities. Some commercial research has already occurred on ISS. For example, Procter & Gamble is working with the ISS program to create liquid pharmaceuticals and products that are easy to use and have a long shelf life (NASA, 2015c). The goal is to apply this technology to health, beauty, and household products. Procter & Gamble allocated $2 billion on research and development in 2014 (P&G, 2014). We estimate that research carried out on ISS accounts for between 1 and 1.5% of total expenses on research and development, accounting for at least $20 million spent on ISS research. With larger modules and easier, more frequent access to space, Starport 1 would allow companies to increase their R&D expenditure in the microgravity environment.

8.2.2. Manufacturing for terrestrial markets

The project sponsor identified manufacturing in orbit as a key source of revenue for Starport 1. A variety of products manufactured on the space station can then be sold at a high profit on Earth because of novelty or improved functionality. We identified a number of potential manufacturing applications, which are described below.

Fiber optics

We have identified fiber optics as a key product for manufacturing onboard Starport 1. ZBLAN has a large terrestrial market in excess of $7.56 billion annually (NASA, 2011). Its value per kg exceeds the cost of launch, and current research indicates a large performance increase associated with manufacturing this product in a microgravity environment. The team found no other product that satisfied those conditions to the same degree as ZBLAN optical fibers did.

ZBLAN is a family of fluoride glasses whose name is in reference to the chemical composition of the different types of glass $ZrF_4/BaF_2/LaF_3/AlF_3/NaF$. The major drivers of demand are the fast moving nature of the telecommunications industry and the advances with laser based communication systems, which could eliminate the need for mass-market optical fibers in national infrastructure. A NASA report (2011) showed that $7.5 billion of the $7.56 billion market was in telecommunications, with military and medical applications making up the remaining $0.06 billion.

Initial research by NASA suggests that the quality of optical fibers is greatly improved by manufacturing in a microgravity environment (Dooling, 1998). Figure 8-1 shows the differences between Earth's gravity (left) and microgravity (right) fabrication of ZBLAN optical fibers. The quality enhancement is in large part due to the optimum formation of crystal structures in a microgravity environment.

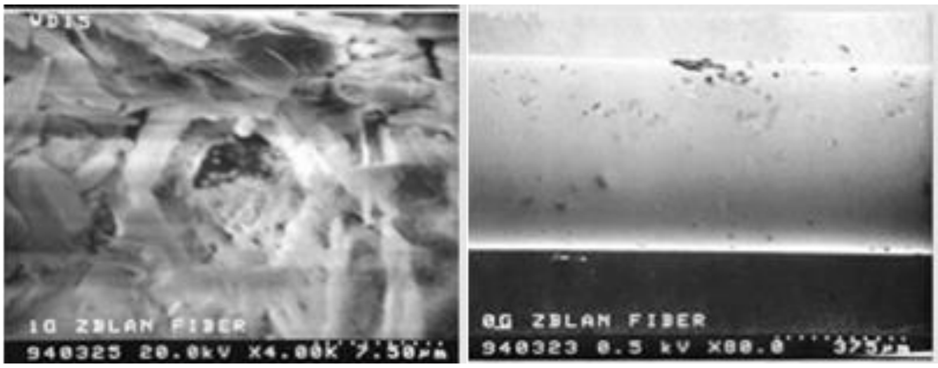


Figure 8-1: ZBLAN optical fibers produced in Earth's gravity (left) and microgravity (right) (Dooling, 1998)

There has been a large amount of commercial interest in microgravity manufacturing by companies such as Made In Space, Inc., who plan to launch a prototype manufacturing facility to the ISS in the first quarter of 2017. This facility will manufacture at least 100 meters of ZBLAN optical fiber (Projects, 2016). The business case for this is further enhanced by the high value per kilogram of ZBLAN fibers, as Andrew Rush, CEO of Made In Space, Inc. explained: "its value per kilogram is significantly higher than current launch costs, it has a strong existing terrestrial market and research indicates that microgravity-manufactured ZBLAN can open large new markets as well as more effectively serve the current market." Made In Space, Inc. has also developed a ZBLAN fiber optic printer prototype (Projects, 2016).

We researched the production capabilities of a ZBLAN fiber optic manufacturing facility in the microgravity section of Starport 1, based on the design of a Bigelow 2100, a 2100 cubic meter concept version similar to the Bigelow 330 set to be launched in 2020. For this study, we assumed the speed of production at 800mm per second per cubic meter. This is based on an analogy with the most widely available 3D printers as of 2016. However, this throughput may prove higher because of advances in technology over the next two decades.

As per the calculations in Table 8-1, the assumed conditions would allow a production of 644.75 kg of pure optical fiber a day. This means that the annual production would be 235 metric tons. Multiplying this annual production by the fraction of the global production (1.54%), then dividing the global market value by global production we can estimate a generated revenue of approximately $116 million per annum.

Protein crystal growth

There is demonstrated commercial interest in the growth of high purity protein crystals for study using x-ray diffractometry on Earth, and to apply the findings in the field of drug design and manufacturing. This has been considered for the pharmaceutical design of insulin regulators (National Research Council, 2000). Protein crystal growth is under ongoing investigation on ISS and is a promising future revenue stream given the value of terrestrial pharmaceutical research and sales, with an estimated small share of the global spending on medicine by 2020 of $1.4 trillion (Statista, 2016).

Bio-printing

Future applications for commercial space manufacturing include printing with biological materials. Space-borne bio-printers will allow printing tissue and organ constructs with unique functions such as biomonitoring of the negative effect of cosmic radiation (Zero G Corporation, 2016).

The advantage offered by space bio-printing is that complex structures such as the heart can be printed without the need for cellular support structures in the product, which are essential to prevent collapse under Earth gravity. This results in an organ or biological structure completed with only the required bio-inks, ready to be delivered and applied to humans in space or on Earth.

Luxury products

Certain objects manufactured in space could potentially be sold on Earth at a premium price. The novelty of being manufactured in space would make these luxury products. This manufacturing application has attracted lot of attention. The most notable category of luxury products is jewelry, where 3D printed rings could constitute one of the earliest available and most profitable products.

Future areas of study

Space manufacturing opportunities recommended for additional future investigation include microencapsulated products and manufacturing of biologics.

8.3. Manufacturing for the space market

8.3.1. Structural components

Starport 1 provides the opportunity to produce structural components in orbit, reducing launch mass and costs. Structures can also be designed and optimized for the space environment, instead of being designed to survive the launch.

The internal racks, dividers, and furnishings used in the habitat of Starport 1 will be extruded in composite polymer material from fused deposition modeling (FDM) printers. An example of this is the additive manufacturing facility (AMF) of Made In Space, Inc., which optimizes mass, shape, and functionality for structural components in the space environment. A good reference for the type of structures that are made in orbit are the ISS payload experiment racks and the examples in Figure 8-2 (Snyder, 2016)

Starport 1 could also produce trusses using a vacuum additive manufacturing device and assembly robots, such as the Made In Space, Inc. ESAMM/Archinaut (Snyder, 2013), and extrude them from carbon fiber reinforced polyether-ether-ketone (CFRPEEK) material. This could be used to manufacture other structures in space for external customers or to repair sections of the station that were damaged.

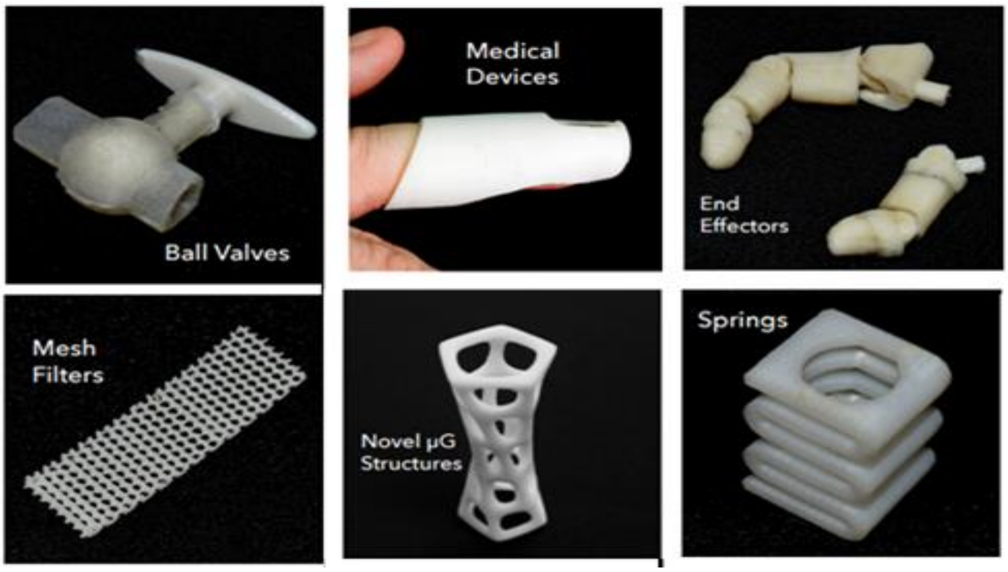


Figure 8-2: Made In Space, Inc. AMF example structures (Snyder, 2016)

Other space-printed components

In addition to the manufacturing of internal structural elements, Starport 1 could supply the spacecraft and satellite systems market with multi-layer radiation and thermal shielding panels. These structures made with a “design for load/function” or “bionic design” philosophy are highly desirable.

An example of the unique structures enabled is a bi-static earth observation (eg. synthetic aperture radar) spacecraft where the two optical payloads are separated by a long thin boom (Goel, 2015). As the confidence in microgravity printed parts grows, Starport 1’s manufacturing capabilities could provide highly integrated end-to-end spacecraft solutions for Earth observation, telecommunications, and space exploration.

Other areas of manufacturing that would benefit from being in microgravity are crystal formation processes such as precision optics and mirrors, and silicon for electronics. This would allow for the manufacturing of structures that are too delicate or too large to easily launch from Earth.

8.4. Marketing naming rights

Naming rights to portions of the station could be sold to interested parties, including commercial organizations, institutions for education and research, governments, and wealthy individuals. This could also be used for various forms of advertising similar to how sports stadiums host advertisements. Prices for sports stadium naming rights are in the millions of dollars per year (New York Times, 2013).

8.5. Tourism

Space tourism will be an important source for generating revenue onboard the station. As an example of this, Cirque du Soleil founder, Guy Laliberté, reputedly paid $35 million to spend 12 days on the ISS (Financial Times, 2015). Tourism aboard the station will directly contribute to revenue generation. Further public interest may have an indirect effect as existing tourists encourage more people to travel to the station and/or consume products that were created on the station.

8.5.1. Flight duration

Having a reasonable length of stay would help to offset the high initial cost of launching individuals to Starport 1. Since there will be a wealth of activities to take part in on the space station, in addition to simply experiencing being in space, we believe that a fourteen-day stay is sufficient for tourism onboard the station. This will align with resupply missions to the space station in the beginning of its development.

8.5.2. Cost

To determine the cost of a tourist trip to Starport 1, we developed a financial model based on the costs associated with the construction and maintenance of the station, and the percentage contribution of space tourism to each of these aspects.

Based on our hypothetical model the approximate price for a fourteen-day stay on Starport 1 would initially be at least $7 million per person in 2040, assuming launch of six tourists in each Crew Dragon capsule. This could fall to $2.25 million per person if 30 tourists are launched in a Skylon space plane (Reaction Engines, 2015). This price would drop further over time as economies of scale are realized.

8.6. Competitive landscape analysis

Competition to Starport 1 from crewed space stations could come from sources that already exist or are currently under development, namely the ISS or the Chinese space station, Tiangong 2, provided they are still active at the time Starport 1 begins operations.

In areas such as manufacturing, there could be competition from non-crewed space stations. Manufacturing in space will be in competition with similar manufacturing options on Earth, and will need to provide significant advantages in order to be profitable. Examples of such advantages have been described above in Section 8.2.2, e.g., ease of manufacturing fiber optic cables under microgravity conditions.

Some of the potential revenue streams are directly connected to humans in space (campus in space, space tourism, television and other media related to astronauts, research on the effects of space upon humans). Each of these fields may have competition with similar fields on Earth.

8.7. Funding

8.7.1. Business model operations

Based on the recommendations for public-private partnerships (PPP), we require a more detailed investigation of the optimal structure for debt and equity investment, including an exploration of government multiparty co-operational models and structures.

To help structure the funding for Starport 1, especially in early development stages, we suggest accepting ticket pre-sale reservation payments from companies and future Starport 1 tourists. As demonstrated by Virgin Galactic for flights aboard SpaceShip2 (Virgin Galactic, 2016), this technique builds excitement and interest in the public, and psychologically links the buyers to the development process and progress.

8.7.2. Crowdfunding

Crowdfunding can be used to raise small amounts of funds while raising awareness of the project. Crowdfunding could be used as a means of raising funds for the assembly of modules, or to support and launch astronauts and their supplies. The largest crowdfunding campaigns for products have exceeded over $100 million. For example, Star Citizen, a space themed video game, raised $108 million via online crowdfunding campaigns (Cieslak, 2016).

Astronauts can be an effective draw for crowdsourcing, especially for small contributors. National and international media campaigns could increase public interest and funding from small and large donors. This could be done in a raffle type way of winning a ticket to space.

9. POLICY AND LAW

In this chapter we examine the international legal relationships among all stakeholders involved through all phases of Starport 1, from its development up to its end of life. The main objectives are to characterize the geopolitical context and opportunities for funding, provide clear definition of the rights and obligations of all stakeholders while avoiding legal ambiguity, and minimize regulatory uncertainty.

For convenience, we refer to the station's governing entity as the *Starport 1 operator,* regardless of the model under discussion. The French Space Operations (Act 2008-518, adopted on June 3rd 2008) defines the term space operator as being "any natural or juridical person carrying out space operation under its responsibility and independently".

The general scheme of stakeholders concerned with Starport 1 is summarized in Figure 9-1.

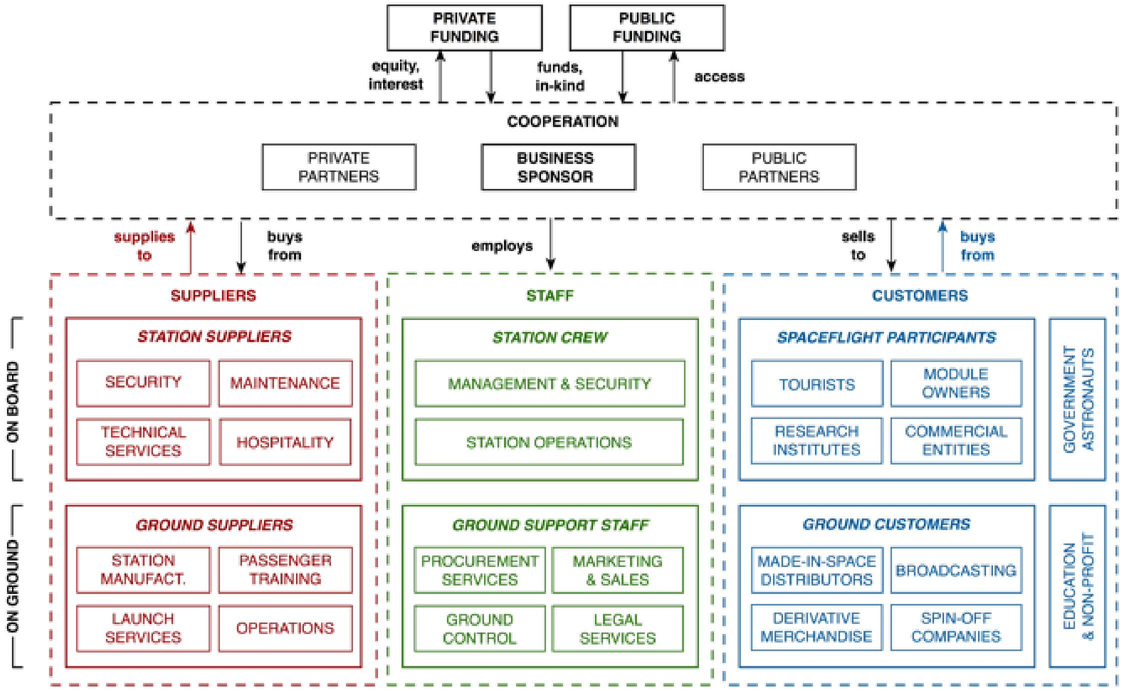


Figure 9-1: Starport 1 relationship scheme

9.1. Funding policy and international cooperation

9.1.1. Space funding policy

Governments design their space policies to encourage benefits both in space and on ground, including economic growth, national security, and technological innovation. Until recently, governments have been the main drivers of the space sector, with industry unable to initiate major development programs. In recent years, the model for space development has begun to shift—now commercial platforms are being developed whose primary customers are governments as well as businesses and consumers. In 2014, NASA declared its intention to transition LEO from primarily government activity significantly more private sector involvement. In this scenario, space research and technology requirements are private sector need driven, and the supply-side transportation and microgravity capabilities are private sector provided (NASA, 2015a). Starport 1, is intended to be commercial in the sense that it is a profit-seeking entity using private capital to carry out activities. However, in the early stages of station design, construction, and operation, we expect public funding to play a role. Governments have historically served as early investors to initiate economically and politically favorable projects that are not yet developed enough to attract commercial interest. (Bravo-Biosca, et al., 2014).

Government contributions can come in many forms, including:

- cash-flow;
- in-kind contributions, such as launching services, radiation hardening and testing services, space analogs and simulation environments, and advanced production technologies; and
- financial benefits, such as tax benefits, loans with favored conditions, or government guarantees for investments to encourage private investments.

Any form of government funding will increase the valuation and decrease risk factors to pave the way for the private sector's capital investment.

9.1.2. The geo-political environment

The particular national policies and space capabilities of governments will determine their desire to participate in Starport 1, their preferred contribution, and their expected economic, political, and societal returns. We consider involvement by four major categories of governments: major spacefaring nations, other established spacefaring nations, emerging space nations, and other governments expressing interest in space.

Major spacefaring nations

With ISS's end of life planned for 2024 (NASA, 2014b), its partner space agencies might want to use the Starport 1 station as an alternate venue for their research. Other nations might also be interested in the venture. For example, China is developing its own series of space stations and has expressed interest in participating in international orbital collaboration. Some of these space faring nations could also contribute launch capabilities. In exchange, these countries might want a degree of autonomy in their operations on the station, meaning they have control of their own modules, similar to operations on the ISS (ESA, 2013).

Other established space faring nations

Other long-time players with proven capacities in space or with niche advanced technological and scientific capabilities include nations like India and Israel. These nations may be interested in contributing their space capabilities and funding to demonstrate their space industry and provide station access to their researchers. These nations might want their national businesses to become suppliers for the construction and operation of the station in return for their funding contribution to the Starport 1 venture.

Emerging space nations

Emerging space nations, such as the United Arab Emirates and South Korea, have allocated substantial government funding to in an attempt to become more involved in space activities. For instance, the United Arab Emirates established its space agency in 2015 "to prepare generations of highly skilled professionals and to develop research, space programs and strategic partnerships in the field of space"

(UAE, 26 May 2015). Participation in Starport 1 will provide these nations an opportunity to acquire hands on knowledge in space mission design and execution in return for investing government funds.

Other governments expressing national interest in space

Other governments with national interest in space include the LATAM alliance initiative of Brazil, Mexico and African programs in South Africa, Egypt, and Tunisia. these nations, participation in Starport 1 could jumpstart involvement in the global space community. In exchange for funding they would gain prestige, promotional abilities for their countries, and enhanced international relationships benefiting political domains outside of space. These governments may also support involvement of their citizens in the Starport 1 initiative as tourists and onboard workers.

9.1.3. Private investors

The founders of Starport 1 hope to raise a significant portion of funding from private investors. Noting also that the source of funding is one of the main criteria to set up the legal scheme among concerned stakeholders. These investors include venture capitalists (VCs), business angels, and private equity investors. In the early stages of such a high risk project, the founders of Starport 1 should target mainly governments and as minority funding - business angels and VCs. In later stages, more VCs and private equity investors may be approached for a second round of funding. These equity investors may become shareholders of the Starport 1 enterprise, as is reflected in the consortium structure referred to above.

9.1.4. Public-private cooperation models

A common model for cooperation between government and private entities are public-private partnerships (PPP). In this model, the government initially assumes a substantial financial load, allowing the private entity to proceed with the technical and operational aspects of the project until private investors or customer revenues can support an increased percentage of funding.

The purpose of this section is to identify under which legal status the operator may act in the frame of this project. Some of the potential cooperating models, each entailing cooperation between public and private sector include:

- A *Starport 1 operator-centered model*, in which Starport 1 is the only legal entity in direct contractual relationship with each of the stakeholders;
- A *consortium model*, whose membership would be open to funding entities and organized under a consortium agreement signed by all partners. Such a consortium would not have any legal personality. Consequently, the contracts made with third parties could be signed by all its members, or preferably one of them (e.g. Starport 1 operator) mandated to sign on behalf of the other members (e.g. H2020 DESCA model agreement, 2014); or
- A special purpose company (SPC) model, which utilizes a legal entity with the Starport 1 operator and its funding partners as the shareholders. The SPC could be registered in any nation that seems most suitable. Contracts with suppliers and customers will be signed by the SPC (Report on Special Purpose Entities, 2009).

9.2. General legal framework

All activities related to Starport 1 must comply with both international law and applicable national legislation.

9.2.1. International law

As with any space endeavor, the legal foundation for Starport 1 starts with the five United Nations treaties on outer space: the Outer Space Treaty, the Rescue Agreement, the Liability Convention, the Registration Convention, and the Moon Agreement. Additionally, the United Nations declarations, principles, and guidelines establish provisions for the conduct of activities in space and are therefore applicable to stakeholders taking part in the development and operation of Starport 1.

Three major notions result from this international legal framework.

(a) Launching States

A launching state is defined by both the Liability Convention Article I and the Registration Convention Article I as follows: "the term 'launching state' means: (i) A state which launches or procures the launching of a space object; (ii) A state from whose territory or facility a space object is launched." The identification of the launching state(s) is fundamental to identify the state(s) (i) to be held liable in case of damages (Articles II and III of the Liability Convention); and (ii) having to register the space object (Articles I and II of the Registration Convention).

(b) Jurisdiction and control

If Starport 1 was fully owned by its operator, one government would retain jurisdiction and control over the spacecraft and any personnel within. Starport 1 could also be owned by a private company in conjunction with other entities, including individuals, other private companies, and possibly governments. In this case, several governments might register their contributed sections and retain jurisdiction and control over their nationals, the model typically used by ISS (International Space Station Intergovernmental Agreement, 1998).

(c) Use of nuclear power sources

A major liability of the space station will be the nuclear power source. The United Nations Committee on Peaceful Uses of Outer Space drafted the Principles Relevant to the Use of Nuclear Power Sources in Outer Space (1992). Starport 1 should comply with the contents of this resolution. Because powering the station with a nuclear reactor is the most effective and realistic power source, it is not in violation of the above-mentioned principles to use it on the station. First and foremost, the concern is to protect life on Earth of uninvolved third parties. The Principles dictate that launching parties should mitigate all risks concerned with nuclear power and radiation, stating that "the appropriate radiation protection objective for the public recommended by the International Commission on Radiological Protection shall be observed. During such normal operation there shall be no significant radiation exposure." Before use, the launching state must also conduct a safety assessment detailing possible risks, which should be made publicly available and open to consultation by other states.

9.2.2. Applicable national law: criminal jurisdiction, contractual law, and tax issues

Assertion of jurisdiction can come either from governmental regulation or contractual acceptance by stakeholder to abide by certain national laws. For example, ISS partners contractually agreed that governments exercise criminal jurisdiction over their nationals regardless of which component the national was in. Any "alleged perpetrator" would be subject to the jurisdiction of the state of which he or she is a national (International Space Station Intergovernmental Agreement, Article 22, 1998). We recommend a similar approach to be applied onboard Starport 1.

Regarding tax issues, all company individuals retain their nationality of origin and they will naturally need to comply with domestic laws, including tax regulations. It might be envisaged to apply a specific tax regulation onboard Starport 1, but this would be subject to regulations to be adopted by the government(s) retaining jurisdiction and control over Starport 1 or its elements. Such specific regulation, if advantageous for the companies and individuals, could be an incentive to develop business onboard Starport 1.

9.3. Stakeholder rights and obligations

The purpose of this section is to further detail the specific rights and obligations of the main stakeholders identified in Figure 9-1, i.e. the operator of the station, its staff, its suppliers and its customers (including tourists, module owners, research institutes, and commercial entities providing services onboard).

9.3.1. Starport 1 operator

Registration

Registration covers both incorporation of the company operating Starport 1 and registration of the Starport 1 craft itself. It is likely that the station operating entity will register Starport 1 in its nation of incorporation, but it is advisable to keep the question of nation of registration open. Other locations might offer more favorable conditions for this project based on tax issues, political stability, commercial barriers, liability schemes, and other regimes related to spaceflight. In that respect, the US offers a specific legal regime for the conduct of space activities. The nation of incorporation will also impact the registration procedures required for the station to comply with the UN Registration Convention.

Liability

The launching state, as defined in the Liability Convention, will be liable for damage inflicted to third parties by or in the use of the station. However, the operator's liability through traditional legal frameworks cannot be excluded, e.g. in its relations with its suppliers and customers. In addition, the Inter-Agency Space Debris Coordination Committee (IADC) has recommended guidelines to reduce the threat of orbital space debris and preserve the safety of on-orbit activity (IADC Space Debris Mitigation Guidelines, 2007).

In accordance with the guidelines, we recommend the development of a Space Debris Mitigation Plan for Starport 1. The Guidelines suggest that the plan should be adopted in the early mission requirement analysis and definition phases, addressing any issues and mitigation measures that should be considered, as well as a plan for disposal at end of life. Minimization of debris generated during operations is also a crucial aspect of this plan (IADC Space Debris Mitigation Guidelines, 2007).

The mitigation plan entails disassembling the station at end of life and de-orbiting it over a period of 10 years after Starport 1 end of life. The targeted de-orbit area is a spot in the South Pacific Ocean. We selected this location to reduce the risk to people or property on Earth during de-orbit procedures.

Moreover, if the station is de-orbited in sections with the help of active maneuvers or the use of a drag sail to slow the descent and increase atmospheric drag, the current mitigation plan would further comply with paragraph 5.3.2 of the IADC Mitigation Guidelines which provides that "[a] spacecraft or orbital stage should be left in an orbit in which, using an accepted nominal projection for solar activity, atmospheric drag will limit the orbital lifetime after completion of operations."

It will also be important to take measures to neutralize the nuclear power source onboard to ensure that people or property on Earth is not damaged by loss of containment during or following de-orbit, as stated in the Principle 3 of the Principles Relevant to the Use of Nuclear Power Sources in Outer Space (United Nations General Assembly, A/RES/47/68, 14 December 1992).

Finally, it is also in the interest of the operating company not only to comply with these guidelines but also to support and contribute to debris-limiting policies.

9.3.2. Suppliers

For the purpose of this section, *suppliers* refers to companies and governments that will provide goods or services to the Starport 1 operator, onboard or on the ground, it also includes companies to which the Starport 1 operator sub-contract some activities to be conducted on its behalf but for the benefit of third parties. These goods and services include: Starport 1 subsystems; launch services; operation services, including telemetry, tracking, and command (TT&C); maintenance of Starport 1 or its associated ground elements; and training for crew, spaceflight participants, or government astronauts.

Supplier selection and industrial organization

Domestic distribution of industrial work could be a key motive for governments to fund Starport 1. In return for funding, governments would bring industrial work to their respective countries, helping them meet policy goals of attaining economic growth, scientific research, and expertise. These countries likely desire the opportunity for their industries to become suppliers for the construction and operation of the station in return for their funding contribution to the Starport 1 venture. This could happen in the form of the geographical return principle as in the ESA partnership, or of the competition based on excellence principle as demonstrated in European Framework Program (FP) for research and Innovation (Horizon 2020), or via a middle model as in European Southern Observatory (ESO) which does not set an obligation to deliver *juste retour* to its Member States, but from time to time impose limitations on competitive procurements to companies belonging to ESO Member States with a "low geographical return coefficient."

Supplier rights and obligations

Legally, many of the contractual agreements with suppliers will be similar to those found in traditional business law. We focus on issues like design authority, warranties, intellectual property rights, export control, procurement of launch services, and settlement of disputes.

(a) Design authority and warranties

The entity providing supplies and components to Starport 1 will also provide guarantees and warranties on their products, leading to a clear risk-sharing regime and ensuring compliance with expressed Starport 1 requirements.

(b) Information, data, and intellectual property

This section refers to the information, data, and intellectual property regime that the Starport 1 operator should implement with its suppliers. The applicable regime between the Starport 1 operator and its customers (see Figure 9-1) is further detailed below on the section related to spaceflight participants.

New technologies will result from Starport 1 development activities. Contracts with suppliers will provide Starport 1 with the option to acquire information, data, and intellectual property rights in the time frame of those agreements. In some situations, however, we advise the Starport 1 operator to secure use of the technology, but allow developers to retain property rights. This approach could reduce costs by allowing suppliers to have an interest in the development of the technology. There could be more business opportunities associated with the commercialization of the intellectual property rights, giving suppliers an incentive to invest in the technology, not just deliver against a contract.

(c) Transfer of goods and technical data

Each government is free to implement the export control regime it deems appropriate. From a commercial perspective (i.e. Starport 1 operator's perspective) the choice of export controls can either be dealt with through lobbying for legislative change or with contractual provisions agreed upon with the customer. When drafting contractual agreements between Starport 1 and its supplier, it is important to ensure that: (i) all activities of stakeholders should be carried out in accordance with applicable laws and regulations, especially those pertaining to export control and facilitation of classified information; and (ii) all suppliers, when entering into contractual relationships with the Starport 1 operator, shall make sure they have obtained necessary licenses needed to export goods and information in connection with business agreements.

(d) Settlement of disputes

The provision of any contract related to the settlement of disputes is fundamental considering especially that it will define the process to be followed in case of disagreement between the parties to a contract, i.e. in case it is alleged that a party is infringing its obligations. Such provision may finally be used everywhere the text of the contract does not provide sufficient details on the way forward and where the parties concerned are unable to find an agreement through consultation. Such provision will obviously apply where a party would not supply the products and services it is supposed to supply despite any safeguards which could have been foreseen (e.g. bank guarantees, being a preferred creditor, schedule of payment according to accepted deliverables).

9.3.3. Passengers

If the station was licensed in the United States, passengers onboard would be classified based on the American licensing scheme. Under current U.S. Federal Aviation Administration (FAA) law, humans on spacecraft fit into three categories: crew, government astronaut, and spaceflight participant. Different legal obligations are attached to each class concerning principles like regulation compliance and informed consent (Kleiman, Lamie, and Carminati, 2012).

Because of the assertion of national jurisdiction on the launching state's spacecraft, should a working environment be formed in LEO, it is likely that traditional federal employment law would apply based on the asserted jurisdiction. For example, Occupational Safety and Health Administration (OSHA) regulations on exposure to radiation might also apply to workers on a part of the station within U.S. control.

For handling liability, a contractual risk sharing scheme could be established which would reduce the financial burden on the passenger, fostering business and encouraging participation on the station. According to this scheme:

(i) Passengers can be held responsible for damages up to a predefined amount. They can also be advised to secure an insurance policy;

(ii) Beyond that limit, the operator of Starport 1 should obtain insurance that covers the financial consequences of potential damages for greater amounts; and

(iii) This scheme shall not apply, however, in cases of a passenger's willful misconduct. In such a situation, the passenger alone would be liable for the full amount of damage caused by their actions.

9.3.4. Crew

Crew members are employees of the Starport 1 operator. They are responsible for performing activities in the course of employment that are related to the operation of the vehicle. As a result, regulations require that crew members be adequately trained in their functions to reduce risk to third parties on Earth. Additionally, cross-waivers are not mandatory for commercial human spaceflight operators, so issues concerning liability should be addressed in contract form. (Kleiman, Lamie, and Carminati, 2012)

9.3.5. Spaceflight participants

A spaceflight participant (SFP) is defined as "any individual, who is not crew, carried within a launch vehicle or reentry vehicle." (51 U.S.C. § 50902 (17)). In the case of Starport 1, we have established four potential types of SFPs: tourists, module owners, and research institutes. In areas where US jurisdiction applies, the FAA has the power to impose medical and training requirements for SFPs, and requires that the operator obtain an SFP's informed written consent after being fully educated on conditions and risks of the launch. (Kleiman, Lamie, and Carminati, 2012)

Guests

Guests are short-term residents on Starport 1 who do not actively participate in research, manufacturing, or operations. Unlike crew and government astronauts, guests will not have any job capacities or employment responsibilities. Guests will be contractually required to comply with training procedures to mitigate risk to themselves and to the station.

Module owners

The rights of specific module owners will likely be addressed in the contractual agreement between the owner and Starport 1, similar to the use of Intergovernmental Agreements and Memoranda of Understanding to regulate rights on ISS (International Space Station Legal Framework, 2013). One approach is to treat module owners as a traditional tenant, but with added obligations based on the hazardous nature of a capsule's presence in space. Module owners would retain control of their actions on the module, but the module might also be subject to the instructions of Starport 1 based on safety concerns and on compliance with the functioning needs of the station.

Research institutes

Scientists working for a research facility that rents a Starport 1 module to conduct experiments falls into a gap in the current classification system. These individuals are not government employees or Starport 1 crew, so they can only be considered spaceflight participants, a role originally conceived with tourists in mind.

From a policy perspective, it may be worth exploring the creation of an alternate classification for this kind of person based on whether we would like to assert different licensing procedures or cross-waiver rights due to the differing nature of their work on the station. The FAA has already set a precedent for this process. Originally, there were only two classifications of persons onboard a spacecraft: crew and SFPs. However, in 2015 the FAA drafted a portion of the Commercial Space Launch Competitiveness Act adding “government astronaut” as a category for the existing licensing scheme (Commercial Space Launch Competitiveness Act, 2015). A similar process could be used depending on the needs of a commercial space station passenger.

Activities of research institutes onboard Starport 1 will undoubtedly lead to the development of information, data, and intellectual property. In the context of ISS, this matter is dealt with in the International Space Station Intergovernmental Agreement (Article 21, 1998). In particular, it is provided that for the purposes of intellectual property law, an activity occurring in an ISS element shall be deemed to have occurred only in the territory of ISS partner state of that element’s registry, except for ESA registered elements for which any European partner state may deem the activity to have occurred within its territory. It should be assessed whether such approach constitutes an appropriate frame or if should be improved to enhance commercial activities.

Government astronauts

Some of the passengers onboard the station may be government employees conducting research in the scope of a PPP or for national space research. As a result, certain cross-waivers normally required to protect the government from claims would not apply (Commercial Space Launch Competitiveness Act, 2015).

10. ROADMAP

The Starport 1 roadmap lays out the chronological plan we need to develop technologies, establish legal and policy regimes, build a market, and prepare crew members to launch, assemble, and operate the space station. This roadmap should be used as a guide to plan the development of the station and to coordinate its stakeholders.

10.1. Phase I: Development (Today to 2030)

In Phase I, we lay the groundwork for the political and legal foundation of Starport 1, the engineering design, funding mechanisms, and communication strategy. Most of the activity will be centered on manufacturing station components and setting up the multi-national, multi-entity PPP framework designed to boost investment and enable revenues and benefits to contributing partners. Starport 1 is commercial in the sense that it is a private entity seeking to use private capital to carry out activities and generate dividends for its shareholders. However, public funding will play a crucial role, particularly in the early stages of the station, when investments in the venture carry very high risk.

Habitat

The planning of the station's habitat, in terms of resident composition (people onboard) including medical station crew training, should begin prior to the launch of the microgravity modules, adopting procedures similar to those used on ISS. Codes of conduct will be defined on the station, with the commander in chief (employee of the Starport 1 operator) authorized to enforce this code. As the first onboard passengers are selected, contracts will have to be signed by each passenger including provisions relating to their liability and insurance, among other obligations. Here, the station's society should be modeled on the lessons learned from ISS, with cargo missions provided on regular intervals.

Station

In developing the spacecraft, the launching services for the microgravity modules will need to be contracted prior to completion (possibly contributed as in-kind contribution from partner governments). In terms of governance, the Starport 1 operator and its stakeholders should agree on a PPP model and establish contractual guidelines to govern funding mechanisms, legal jurisdictions, and states of registration for launch and space activities.

Business

In terms of business, multiple contracts will be signed with scientific research, manufacturing, and tourism commercial entities operating onboard. Moreover, the operator should begin signing contracts with research institutions, and begin advertising available lease areas. Customer business activities may include advertising and publicity, in addition to the presale of tourism tickets to the station.

10.2. Phase II: Microgravity construction (2030-2033)

Habitat

Phase II of the station development will establish its microgravity facility. During this time, the station would have the capacity to hold 44 people, but is expected to hold 24 people, with considerable space for habitat and medical countermeasures (as discussed in Section 7.5). The first people onboard Starport 1 will be categorized as either crew, scientists, or manufacturers. Here, the exact number of people aboard the station involved in research, manufacturing, and tourism on the microgravity modules, their roles, and the duration of their stay aboard the station would be determined by the arrangements made during Phase I, considering geo-return and priority access requirements to funding partners.

Station

The station will be initially composed of eight microgravity modules that will be launched into LEO from 2030 to 2033.

Business

The launching state could have an impact on the station legal registration and future liability. The completion of the microgravity facility will enable governments and commercial companies to begin research activities, and manufacturing (e.g. optical fibers, bio/pharmaceutical).

10.3. Phase III: Outer ring assembly (2034-2039)

Habitat

The twelve artificial gravity modules forming Starport 1’s initial outer ring will be launched to LEO between 2039 and 2040. Once installed, the station will have a combined occupancy capacity of 100 people, allowing the number of tourists, along with scientific researchers, and workers in the manufacturing section to increase. The habitat resident composition should begin to incorporate typical leisure facilities, medical centers, dining areas, etc.

Station

Prior to the launch of the twelve AG modules, the space station will have conducted an artificial gravity test sometime between 2035 and 2037. This test will be completed in less than a year and will involve spinning up and then spinning down the station. As the station technologies mature, the share of private equity funding increase.

Business

At this point, the nature of the station’s commercial business model could expand from mainly research and manufacturing to place more focus on tourism. This can include basic concepts such as cafeteria dining, water processing, and food research, in addition the inclusion of recreational modules. A larger number of tourists may begin to visit the station, while other business activities could include releasing spacecraft into orbit for industry and academic use. Other revenue-generating marketing activities could include using the station as an advertising platform for sponsors, along with using the newly completed initial station as a backdrop for film and media production.

10.4. Phase IV: Commercialization (2040-2045)

Habitat

As more modules are attached to the outer ring of the station, there will be increased potential to develop new enterprises such as space hotels and other commercial services. The onboard society will shift to a new model with commercial vendors and semi-permanent residents. The growing number of tourists will be able to participate in longer-duration stays. As the occupancy increases, tourism is projected to increase more than other sectors. Passengers will be able to eat food that was harvested on the station, in addition to exploring the use of 3D printed foods.

Station

An additional 20 modules will have been launched and attached to the station by 2045, increasing its potential occupancy capacity to 200 people, from 100 in 2040. At this point, the operator will have allocated the end use of the 12 modules that were attached to the station in 2040.

Business

From 2040 onward, there will likely be an increase in commercialization as new business options become available in the areas of tourism, agriculture, mining, and media. This will likely be accompanied by a transition from the traditional customers paying for research and manufacturing, to more funding stemming from private actors.

10.5. Phase V: Space city (2045-2060)

Habitat

Once Starport 1 is operating closer to full occupancy, the station's function will begin transitioning from primarily related to scientific research and manufacturing, to that of a true space city. This will be in accordance with Axiom Space's vision to construct an affordable, inclusive, state-of-the-art city in Earth orbit for people to live and work.

Station

At this time, the station will be fully operational.

Business

As revenues from scientific research, manufacturing and tourism activities reach a high point, support from governments may diminish.

10.6. Phase VI: Future (2060 onwards)

Habitat

Increased technology for radiation shielding will allow permanent residency. Station operators will need to re-evaluate human performance and society structure.

Station

Station designers and engineers will need to consider the need to begin replacing modules after 25 years in orbit, beginning in 2058. Towards end of life time of parts of the station, plans for disposal at end of life will be implemented according to international Space Debris Mitigation guidelines.

Business

They will also need to consider the commercial potential for construction of a second ring to expand capacity of the station.

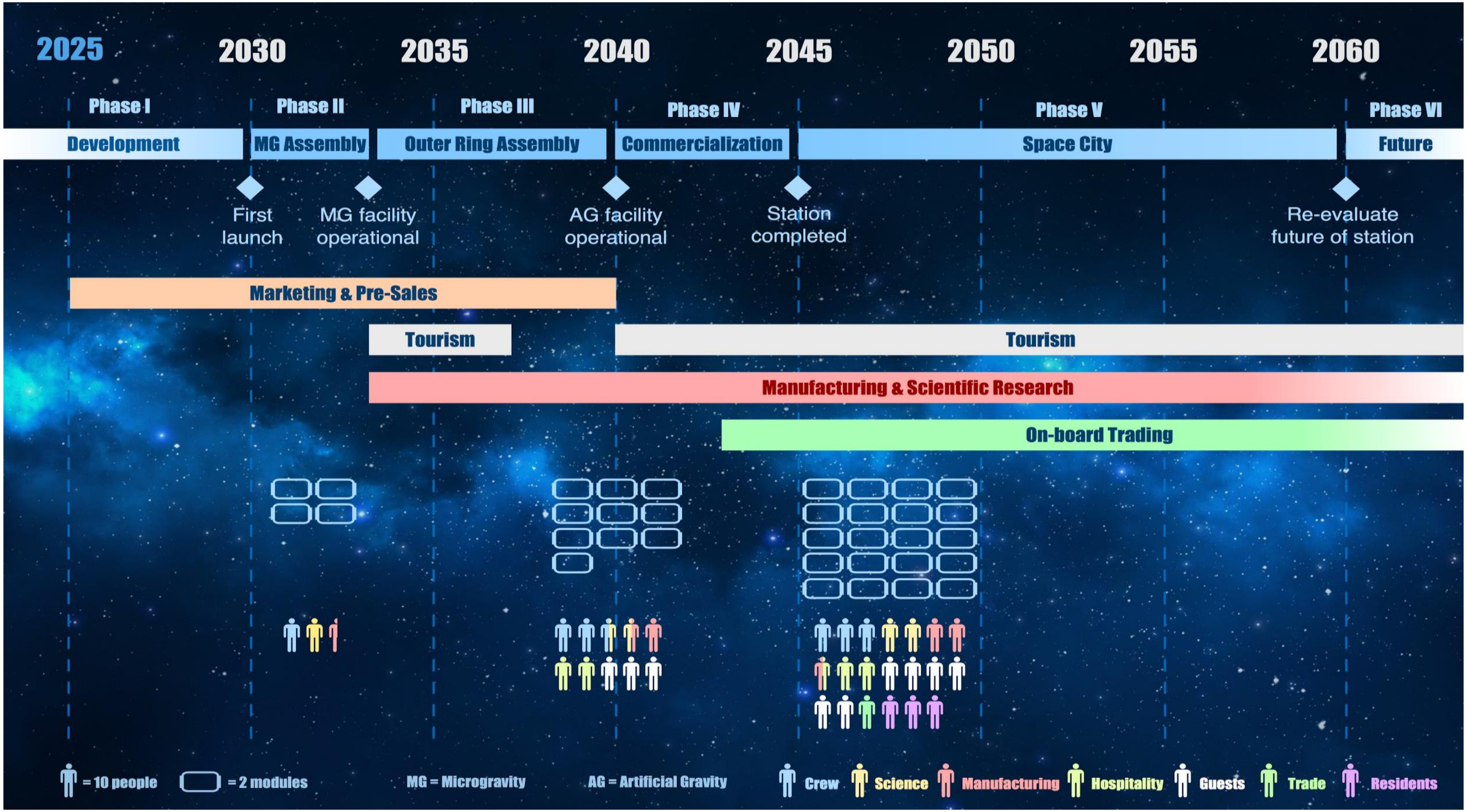


Figure 10-1: Roadmap for Starport 1

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APPENDIX A – BIGELOW MODULES

Table 10-1: Bigelow module specifications

Specifications	BEAM	Destiny Module (ISS)	B330	BA2100
General type	Inflatable	Rigid	Inflatable	Inflatable
Partial dimensions (m)	L = 2.16, D = 2.36			Requires 8m fairing (SLS II)
Expanded dimensions (m)	L = 4.01, D = 3.20	L = 8.53, D = 4.27	330 m^3	L = 17.8, D = 12.6
Expanded volume (m^3)	16 m^3	106 m^3	20,000 kg	2219 m^3
Mass	1360 kg	14,520 kg		70,000 kg estimate for module + interior: 100,000 kg
Occupancy		3 people	6 people	16 people
Radiation shielding	Proprietary flexible Kevlar-like material A middle layer was a closed-cell vinyl foam for radiation protection and thermal insulation.		Hull thickness, water.	Water based (mass include 10% of required water amount).
Source	(Bigelow, 2004; Seedhouse, 2014; Spaceref.com, 2011; Bigelow Aerospace, 2016)		(Bigelow Aerospace, 2016)	(Spaceref.com, 2011)

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