# Colonized Interstellar Vessel:
## Conceptual Master Planning

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## Abstract

The focus of this study is to assemble and evaluate necessary spatial components and considerations inherent to the potential development of self-sufficient communities capable of exploring interstellar space. Established psychological and spatial design knowledge will be discussed and expanded upon in an effort to better inform future design efforts surrounding perpetual spacecraft. Such studies are needed as a growing body of research suggests that "earth-like" planets may exist within just a few light years from earth, inviting human exploration in the physical form and the eventual establishment of research colonies. The first section of this document discusses general guidelines and predecessor studies, while the second section outlines a conceptual proposal for such a vessel. Furthermore, this study endeavors to utilize the aforementioned research to generate conceptual spatial diagrams representative of how specific occupiable spaces are related to one another, to generate considerations for the placement of such structures, and to explore how spatial design can influence the well being of its occupants.

This is a submission from the Project Hyperion Study Group.

# Contents

# I.

## 1 Introduction

The notion of humanity exploring distant worlds has long been the substance of dreams; from early Renaissance thinkers condemned for their heretical visions, to banal fodder for modern day science fiction plots. With humanity's insatiable appetite for knowledge and discovery, coupled with concerns surrounding the potential for an earthly cataclysmal event, it is only natural that armed with enough curiosity, we should seek to explore new horizons.

Yet despite centuries of study and attention directed toward the cosmos, only recently has humanity made significant strides toward actually attaining such lofty aspirations. Within the last half a century, we have reached from our terrestrial position so far as to set foot on the surface of the moon, orbit the earth for extended durations with aplomb, and detect even the faintest signatures of potentially habitable planets located light years away. Therefore, it seems only fitting that serious thought would now be directed toward developing a habitable colonial spacecraft, capable of sustaining life indefinitely while cruising at appreciable speed toward such a potentially sustainable second earth.

History has yielded numerous inspiring designs for colonized worldships, with images of suburban living among narrow lakes and fields of green, punctuated by the occasional industrial agriculture bay for community food provisions. [4] [7] The notion implies that life aboard such a vessel would closely emulate that found on earth. However, the cost implications and effort required to develop such a massive ship are staggering, likely rendering such dreams implausible for quite some time. Instead of striving to fully approximate earth like conditions aboard a spacecraft, this study endeavors to learn from predecessor designs and re-imagine a vessel capable of healthily sustaining humanity for extremely long durations, with the eventual goal of colonizing a neighboring solar system. As such, design proposals contained within this document aim to outline a smaller Colonized Interstellar Vessel (CIV), examining guidelines necessary to provide adequate living conditions for a given population, rather than envisioning how to encapsulate an exact visage of earth.

Certainly, such a CIV will require decades of planning, redesigning, and study before any semblance of a plausible vessel design emerges. In spite of this however, it will be the continuous advancement of designs and ideas that cumulatively ensures no opportunity is missed when design preparedness intersects with technological opportunity.

## 2 Developmental Focus

To date there have been many intriguing conceptual suggestions regarding how to achieve interstellar human travel, with the predominant contenders consisting of the following:

a) Embryo Colonization - sending a vessel populated with frozen human embryos to be raised robotically upon reaching a specific destination. [1]
b) Hibernation - as popularized in movies, suspending human activity for a given period of time, reawakening upon arrival at the target destination. [8]

c) Digital Brain - dispatching a ship containing the 'brain' in a digital format, to be reactivated or synthesized at the target destination. [2]
d) Colonized Interstellar Vessel (CIV) - develop a spacecraft designed to sustain human life as we know it, allowing for future generations to exist in perpetuity, until reaching a destination planet.

Arguably, options a) , b), and c) are wrought with ethical and technical issues that render them extremely unfeasible with comparison to option d), the Colonized Interstellar Vessel (CIV). Therefore, the intention of this document will be to advance the discussion surrounding the development of an immense yet appropriately scaled interstellar vessel capable of supporting human life indefinitely, bound for a terrestrial destination some light years away. Comprised of myriad sub-topics ranging from propulsion and energy technology, to the social engineering of a new style of community, the construction of such a marvel of engineering would be on a scale yet unseen by modern humanity. The focus of this discussion will surround the spatial considerations inextricably driving the master planning of such a Colonized Interstellar Vessel (CIV).

## 2.1 Designing for the Human Component

As a great deal of contemporary focus is commonly directed toward the technological requirements of space travel, designers of a CIV will need to be mindful that equal attention is allocated to the preservation of the mental and emotional human element. Without proper planning and thoughtful consideration to the physical, spatial, and psychological needs of the people tasked with living and operating in such a colony, even the most advanced technological achievements may risk failing at the human level. Design for the psyche and associated pragmatic daily functions should be of equal concern as those of cosmic radiation shielding, fuel supply, food procreation, etc. Should the precious human component be allowed to atrophy, the complete interstellar mission risks failure.

Thoughtful consideration must be exercised throughout the design phases to ensure a harmonious interconnection between infrastructure and its end users. Architecture and the interstitial spaces it creates should aim to promote healthy community living, while also meeting the basic territorial and privacy needs that human nature has become accustomed to on earth. Some methods for promoting psychological and physical well being through environmental design include:

- Allowing the user to modify the configuration and visual appearance of a space,
- Creating long vistas and distant focal points
- Using structure to choreograph space, allowing for discovery and 'unfolding'
- Varying materials, forms, shapes, textures, and colors to engage the mind
- Maintaining some semblance or connectivity to nature

The human brain will always be among the most advanced technologies aboard such a vessel; as such, the world designed around it should nurture and inspire, rather than simply function as containment.

## 2.2 Planning Considerations

Unlike predecessor space stations, such as SkyLAB, MIR, and the International Space Station (ISS), a permanent space settlement should much more closely emulate living conditions found on earth. While tremendous technological achievements have been realized aboard such celestial abodes, the nature of a CIV dictates a radically different approach to spatial design and materiality. Rather than a group of scientists coexisting for a specified amount of time, with a clear focus centered around research and experimentation, colonists living aboard a permanent vessel will require many more amenities and conveniences germane to everyday life.

Rather than simply constructing a megalopolis of metallic tubes in an effort to achieve a predetermined volumetric enclosure, initial design of a CIV could begin with a community-centric approach, as it is the opinion of this author that it will be the size and functionality of the colony that dictates the form of the vessel. Identifying the potential needs of the colonists and assembling a schedule of spatial uses will serve to inform designers, thus allowing for the development of appropriate spatial relationships and programming. As the nature of such a vessel will necessitate as compact a design as possible, a careful balance between minimal living quarters and maximal perceived space should be the goal.

The design and planning of a CIV intended to sustain life in perpetuity, or until arriving at a target interstellar destination, should begin at the diagrammatic level, first determining the various components required by the community and the circulatory relationships between them, then working outward to ultimately arrive at an optimal vessel design, much in the same way a modern city upon earth would be planned.

## 3 Urban Planning - Applied Principles

Effectively, the functionality of a Colonized Interstellar Vessel (CIV) at a given scale would closely resemble a small town or community found on earth, as least programmatically. Knowledge gained from centuries of bettering the human living condition when dwelling in dense quarters (i.e. cities, small towns, and universities) lends well to informing the conceptual organization of a CIV. Spatial needs of the colonist are likely to emulate those found within a typical medium-density urban environment. The predominant use of available space will be to satisfy the residential living needs of the colonists, with the second largest tenant being agriculture and animal husbandry. Tertial requirements will be sub-allocated among spaces utilized for functions such as civic activities, business, research, education, medical, utility, recreation, mechanical, and transportation. Of particular focus to the urban designer will not only be the creation of built structures, but also the resultant 'open space' for multi-purpose recreation and green park space. While such space may appear at first glance under utilized, the creation and preservation of adequate green space and generally open, unprogrammed space will be essential to maintaining healthy mental acuity among colonists.

Certainly much has been written and documented pertaining to good urban planning practices, a subject which is too vast to be fully explored within the scope of this document. However, the following subsections briefly highlight some considerations pertaining to specific land uses.

### 3.1 Residential Considerations

While extremely high residential 'dwelling unit' densities (DU / acre) could be achieved, such condensed living would be inadvisable due to the impending psychological effects such tight quarters are likely to impose long term. In contrast, there is simply too high of a spatial premium to allow for low-density residential situations more commonly associated with suburban or rural neighborhoods. The solution will be to develop varying residential modules, stackable in configuration, that meet the needs of all the user groups likely to occupy the ship. The ability for the colonists to periodically modify their living quarters and surrounding environments is an imperative element to be considered when designing such dwellings.

As a large number of residential units will be required, care should be exercised to create vibrant 'neighborhoods' aboard the vessel, populated with housing units for all social and familial structures. Proximal open space should be created, allowing colonists within a given block to feel a sense of identity and ownership over the spaces. As interaction with neighbors will be extremely commonplace and encouraged, sufficient private space should also be allotted. Ultimately, a diverse team of architects and designers should be engaged to aid in the development of such goals.

Circulation throughout and between residential districts and the remainder of the vessel should be carefully planned to be as efficient as possible, while still employing tactics to promote mental wellness. While traditional vehicular traffic will be non-existent, some form of light public transit will need to exist to ferry colonists longer distances throughout the community. Proportionally scaled pedestrian 'streets' should permeate the entirety of the vessel to promote health and exercise, and to create privacy separation between groups of dwellings.

## 3.2 Civic and Open Space Considerations

Providing space for colonists to gather and engage in social or recreational activities is of paramount concern with regard to mental health and well being.

Open space should be provided in numerous locations with a variety of uses in mind, from family gatherings and outdoor exercise classes, to small-scale sporting events or even larger gatherings such as 'outdoor' movie screenings. The key to each space will be to allow for the occurrence of multiple types of activities to encourage the most functionality of each space. Smaller spaces may be created to provide a bit of spatial relief from the density of urban living, while fewer larger spaces may even be able to accommodate sports such as soccer or football.

In a similar vein, civic structures should be constructed that permit ordered assemblies and a multitude of activities. These facilities should occur frequently within neighborhood communities and should be non-denominational spaces, capable of hosting events from art showings to performances and civic meetings. Architecturally, they represent opportunities for a unique visual departure from the modularity of the housing units, stimulating the mind and providing varied interest as the colonists move throughout the community. Additionally, the inclusion of non-spatial objects -- such as statues of commemoration, interpretive art installations, or even historical artifacts donated from earth's past would go far to embrace a richness in culture.

## 3.3 Agricultural and Food Production Considerations

Without a doubt, the ability to sufficiently generate food for the entire community and its projected growth needs is imperative. Adequate area must be allocated for agricultural germination and animal husbandry.

While certainly the topic of much further discussion, there will likely exist many viable methods for providing such agriculture, from traditional soil-based agriculture, to hydroponics and beyond. Careful planning will ensure that the maximum area available for food production is utilized, likely employing multiple tiers of staggered growing fields and other vertical solutions. The use of artificial grow lighting would likely also increase the achievable density within an agriculture district.

Although it may seem economical to generate all of the colony's agriculture from within a centralized location to capitalize on shared resources and mechanical support systems, an arguably safer approach would be to provide several scaled regions at opposite locations aboard the CIV in an effort to safeguard against famine resulting from a disaster. In the event of a total decimation of crops within a given facility -- whether due to disease, life-support failure, or even a cataclysmic structural failure -- it would be advantageous to have multiple independent areas of agriculture to supply controlled food rations while repairs were undertaken. The ability to fully manage the food production environment, and more importantly enact quarantine as needed, is an extremely important design consideration when planning such a community.

## 3.4 Transit Considerations

Colonists throughout the community, although encouraged to walk or commute via bicycle as much as possible, will certainly encounter situations where their homes and their daily occupations are far enough apart to necessitate the use of a low-impact transit system. The average person is generally willing to walk approximately 500m (1/4mi), and thus an effort should be made to provide basic daily amenities within such a radius, including parks, grocery, social opportunities, etc., as well as access to public transit stops. Such transit could be small in scale, resembling small 'pods' on fixed tracks, or larger light-rail transit cars looping throughout the community. Additionally, provisions for small personal electric vehicles should be made when designing pedestrian streets. While transportation demands should not resemble those found on earth, additional methods of commuting long distance (which could be several kilometers) should be provided.

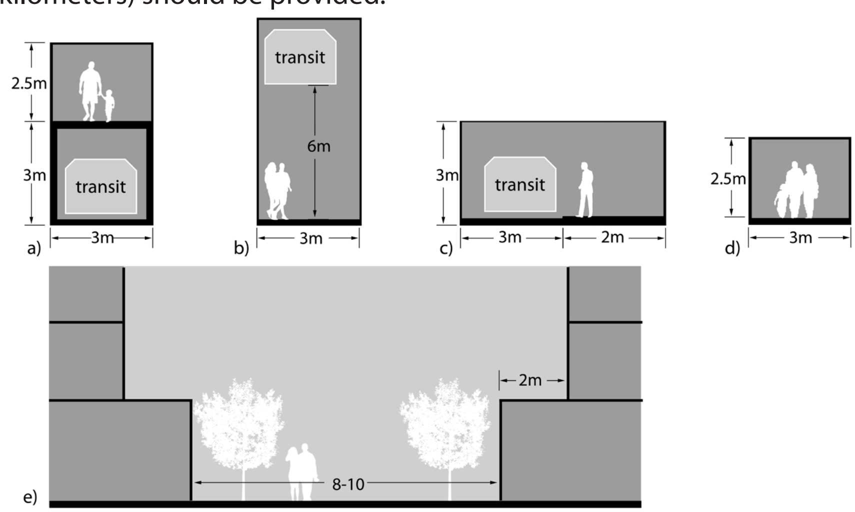


Figure 3A - Example transit setbacks and dimensions commonly used: a) transit below pedestrian street [7], b) transit elevated above pedestrian thoroughfare[7], c) transit adjacent to pedestrian walk [7], d) typical comfortable walk width [7], e) typical comfortable pedestrian width between structures

# 4 Precedent Design Analysis

Over the last several decades, significant design studies for space colonies and worldships have been generated, proposing ideas ranging from mammoth spheres and groupings of cylinders, to large ring shaped structures with large reflective mirrors. [4] As each idea is born and analyzed, the discussion expands and the design process matures. While every concept -- including the eventual final concept -- will be subject to both praise and criticism, the core idea is to promote research, imagination, and the chipping away at the seemingly insurmountable challenges inherent to such an undertaking. The purpose of this section is to briefly touch on some of the most popular predecessor designs to date, and to engage in a discussion surrounding each concept. It should be noted, however, that every subsequently mentioned proposal is a remarkable design achievement in its own right, has significantly contributed to the cause, and is held in esteemed regard.

## 4.1 Predecessor Colony Design Studies

Of the many studies conducted and the numerous artist renderings in existence, the three following proposals were chosen as case studies for influential derivation:

- Bernal Sphere (*1929*) [4]
- O'Neill Cylinder (*1974*) [4]
- Stanford Torus (*1975*) [4]

### 4.1.1 Bernal Sphere

SPHERE Concept: First proposed in 1929 by British scientist John Desmond Bernal, the original ‘Bernal Sphere’ consisted of a hollow spherical shell approximately 16km (9.9mi) in diameter, within which a population of between 20,000 to 30,000 colonist would live. The vessel would exist in permanent earth-orbit, utilize mirrors to reflect sunlight into the colony, and employ subtle rotation to produce approximately 0.7g (70% of earth’s gravitational effect). Unique to this design, the vessel actually consisted of two nested spheres: one outer ‘shell’ to protect the colonists from harmful radiation, and an inner rotating ‘shell’ within which the colonists would live. [4]

### 4.1.2 O’Neill Cylinder

CYLINDER Concept: In his 1976 book “*The High Frontier: Human Colonies in Space*,” American physicist Gerard K. O’Neill wrote of a space settlement (also known as ‘Island Three’ as there were three design schemes) which consisted of two counter-rotating cylinders measuring approximately 8km (5mi) in diameter, and nearly 32km (20mi) in length each. The two cylinders also utilize mirrors to reflect the sun’s rays into the habitat and rotate to maintain positive solar orientation. Unique to O’Neill’s design was the specification of an atmospheric pressure of just 50% of that found at earth’s surface in an effort to reduce the outward structural load exerted by the gas upon the cylinder’s walls. Additionally, O’Neill concluded that due to the large volume of air within the habitat, sufficient protection against cosmic rays would be provided with minimal shielding effort. [4]

### 4.1.3 Stanford Torus

TORUS Concept: During the 1975 NASA Summer Study, conducted with researchers, students and professors at Stanford University, speculation surrounding just what developing a permanent space colony would entail produced arguably the most comprehensive research document pertinent to worldship master planning to date, and is available as NASA research document "*SP-413*." [7] Expanding on predecessor designs and forging new horizons, the Stanford team released comprehensive designs and research outlining the development of a ring or torus shaped colony, ideally scaled to accommodate 10,000 inhabitants (but scalable to nearly 140,000 persons). [7]

Consisting of a single torus 1.8km (1.1mi) in diameter (10,000 colonists), the Stanford design rotates to produce about 1.0g, utilizes a mirror for sunlight reflection and agriculture, and allows for central axial hubs of zero-g environments or research and study purposes. Included within '*SP-413*' are detailed population calculations, land use studies, and other relevant technical findings supporting the design. [7]

## 4.2 Carrying Forward

The aforementioned studies offer significant contributions toward the advancement of worldship or Colonized Interstellar Vessel (CIV) design and thinking. Although much has changed in the decades since their respective publications, many of the parameters explored by each study are still extremely relevant, perhaps none more so than the planning studies contained within NASA document '*SP-413*', cataloging the Stanford Torus study. [7] As such, knowledge gained from '*SP-413*' will serve as the basis of further exploration and development in the next section of this document.

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II.

# 5 Proposal for a Colonized Interstellar Vessel (CIV)

The remainder of this research report intends to synthesize the findings of the Stanford Torus study, introduce plausible modifications or areas for further study, and to ultimately propose a new conceptual Colonized Interstellar Vessel (CIV) design and diagrams derived from the author of this document's experiences as an urban and master planner.

The ensuing research and conceptual diagrams are intended to provoke thought and discussion pertinent to the master planning of an inhabitable CIV, and should be considered as working ideological concepts. Figures and diagrams contained herein are derivations from predecessor research, the author's professional experience in planning, and the general design process whereby a conceptual hypothesis is proposed and developed in order to both fully test its viability and to enhance the body of knowledge through resultant studies and discussions. Certainly the content will be subject to debate, and while illustrative renderings will allude to more technical aspects inherent to spaceflight (propulsion systems, life support, structural elements, etc.) they should be regarded as illustrative placeholders at best, and not evaluated for their designs or technical plausibility. It is the author's opinion that CIV design development should be approached from many facets -- one of which being the development and scaling of the vessel from the perspective of colonial and human needs, establishing what sort of ship configuration would be ideal, and then working backward to establish technical and propulsive needs.

A significant amount of comprehensive research and detailed hypothetical testing will be required to fully develop a practical CIV design, which is ultimately out of the scope of this research document. For the sake of literary real estate, much of the technical data provided within NASA document '*SP-413*' will not be included, as the reader is encouraged to peruse '*SP-413*' for further detailed basis of design information. [7] A re-evaluation of the data will likely be required at some point in the future as humanity progresses toward developing a truly functional interstellar human spacecraft.

However, every idea begins somewhere.

## 5.1 *NASA 'SP-413'*: Pertinent Research from The Stanford Torus

This section will briefly outline the planning guidelines established within '*SP-413*', as they will serve as the basis of design moving forward. [7]

### 5.1.1 Geometric Considerations

While many geometries have been explored for vessel formation, the most popular include the aforementioned sphere, cylinder, and torus. However, previous studies concluded that both the sphere and cylinder were less efficient compared to the torus with regard to spatial usability. It has been established that in order for humans to inhabit outer space, some form of gravity must be provided or else the human body will atrophy and experience myriad other health problems. With the universally accepted solution being the introduction of centrifugal force through single-axial rotation, all worldship or CIV designs are predicated on the contingency of available 'projected space,' (defined as a planar space perpendicular to the axis of rotation, occurring within the interior of a given rotating geometry).

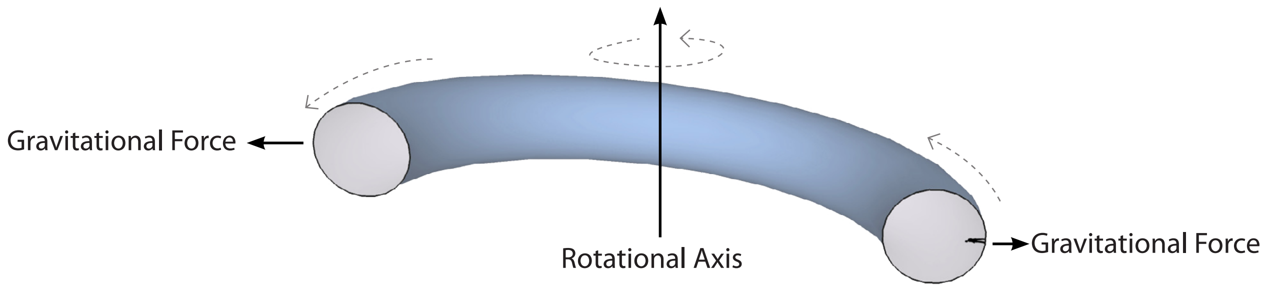
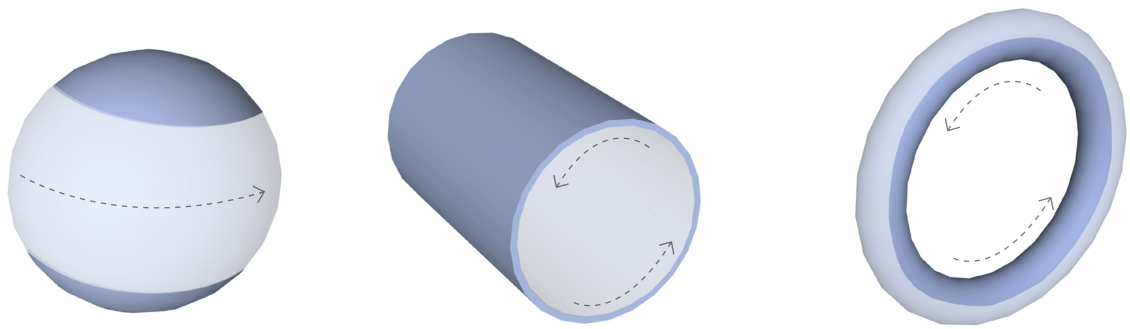



Figure 5A - Projected space diagram

The most popular geometries result in the following projected space (lighter color):



Sphere:

- High structural material and volume requirements.
- Minimal available 'flat' projected space.
- Approaching the poles of the axis of rotation, gravitational effects proportionally diminish.
- Surprisingly small area of ideal projected living space.
- Would require a diameter measuring several kilometers in order to mitigate a continuously curved living plane.

Cylinder:

- More efficient projected living space.
- Requires a very large diameter in order to mitigate the "curved floor" effect.
- If actually built to the scale of the O'Neill Cylinder (8km dia. x 32km L), the curved floor effect would be minimal.
- O'Neill scale dwarfs most cities and is likely implausibly large with regard to construction and propulsion.

Torus:

- With sufficent radii, provides a reasonable balance between structural / volumetric constraints and projected space.
- Subject to the same psychological ramifications resulting from "endless view" effect, whereby no real sense of depth is ever established and the colonists risk entering a confusing mental dream-like state called solipsism.
- The propulsion of a massive ring throughout space would require significant material ad structural considerations.

Figure 5B - Aforementioned geometries (Sphere, Cylinder, and Torus respectively). The lighter regions indicate the available 'projected living space'

However, researchers at Stanford also explored smaller combinations of said geometries in an effort to make their designs more compact, resulting in one such permutation known as the "banded torus." While the banded torus itself is not entirely a practical configuration for a CIV, it serves as an inspirational basis for the CIV geometry explored in the next sections.

## 5.2 Geometric Configurations Derived from Circulation

Alone, the banded torus is plagued with the problems of the torus, only magnified by the constricted radii. Projected living space is subject to a radically curving landscape and limited X-Y movement due to the curvature of each individual torus. The chief advantage, however, is the compact nature of the resultant form.

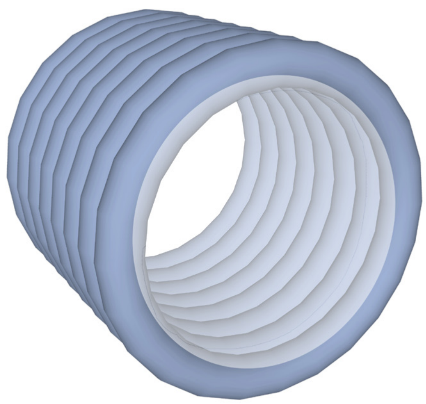


Figure 5C - Banded torus massing, the lighter area indicates 'projected living space'

When considering circulation throughout all three axes (X-Y-Z), free from practical constraints, the following circulation pattern occurs within a cylindrical geometry:

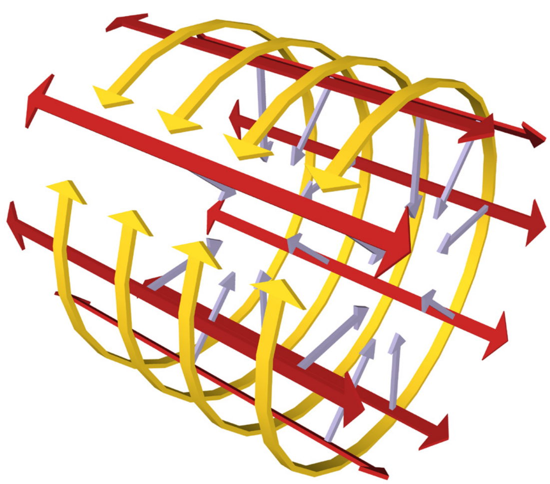


Figure 5D - Proposed colonist circulation throughout X-Y-Z planes in a cylindrical environment

Rather than developing the predominant projected living plane throughout the toruses in a banded fashion, a simple 90-degree reversal of thinking results in a different geometry resembling 'banded cylinders'. Reducing the cost and developmental restrictions of curved planes, the primary living spaces are designed to have flat bottoms and faceted extrusions, extending into long linear structures, referred to as 'bays'. This makes it possible to provide sufficient colonial living space while maintaining a compact vessel design that should allow for more feasible propulsion and life support systems engineering.

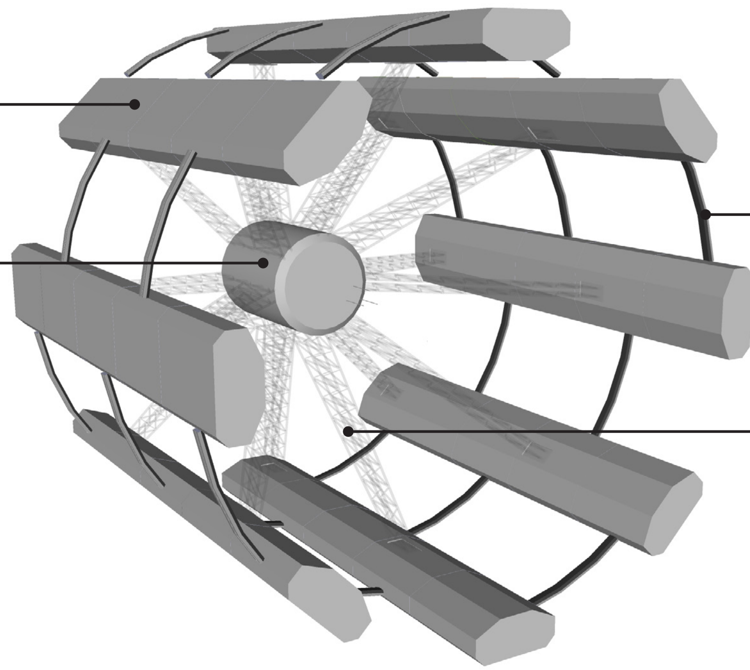



Figure 5E - CIV massing (excluding propulsion and life support considerations)

Such a configuration of interconnected bays rotating about a central axial zero-g hub, with each bay containing dwellings, agriculture facilities, civic structures, open spaces, and places of work and research, will be the basis of design moving forward.

One drawback associated with the rotation of a given geometry pertains to the t effect, or the deflection of a moving object when viewed within a rotating space. This effect would be most noticeable when a colonist turns his or her head, or perhaps drops an object, watching it land a few centimeters to the side of where it would otherwise be expected to land. According to research contained within '*SP-413*', an ideal space colony should not rotate faster than a couple of RPM in an effort to minimize the Coriolis effect. [7] Using the following formula to calculate the centrifugal acceleration experienced (in earth G's) allows for scaling the radius of such a vessel in an effort to minimize rotation rate while achieving a near-earth gravitational force of 1.0g. [11]

$F = (0.0011)W^2R$ **F = Centrifugal Acceleration (g), W = Rotation (RPMs), and R = Vessel Radius* [11]

As a result, 1.0g can be achieved at approximately 1.5RPM, with a radius of 400 m (other variations exist approaching 2.0RPM, but increase the presence of the Coriolis effect).

## 5.3 Scaling the Vessel: Urban Planning Populations and Considerations

The very nature of community planning entails the creation of a scaled, comprehensive community plan that effectively meets and addresses the needs of the people who will ultimately live and interact within it. In order to do so, preliminary steps must be taken to appropriately determine the scale of such a community and its particular needs. Among the primary design parameters to consider will be the target population size of the community.

As a benchmark established by previous studies and for the purpose of relative comparison, a target population of around 10,000 people will be used for this study model. Although some measure of a commitment to population control will have to be implemented within the community, a real working population number could vary from between 10,000-12,000, and CIV design should allow for such swells in order to avoid dangerous overcrowding or under-performance of resources as a result.

A population of 10,000 is generally considered to be the minimum size at which a dynamic community can exist, though further research is still being conducted. Some would argue that a minimum of 100,000 persons would be required to sustain a flourishing community, but given the enormity of the vessel required to support such a population, such high numbers are impractical. However, on earth there are many examples of healthily functioning communities with populations numbering approximately 10,000 persons -- from small universities and colleges, to many small towns throughout the world. While the topic of internal societal dynamics and population management requires deeper exploration, such research is outside the scope of this document. Moving forward however, design proposals contained herein will assume a target population of 10,000 colonists, while incorporating provisions for upward scalability as needed.

### 5.3.1 Establishing Programmatic Uses

The Stanford Torus study established data that was well researched and sourced, and despite several decades having passed, many of the figures proposed are still relevant. However, moving forward with a greater focus being levied on quality of life and the preservation of mental health, some modifications to the land use numbers are proposed. Below is a table derived from the study outlining such calculations, with occasional modifications made to reflect personal experiences and speculations that will be used to scale the ensuing vessel design.

Note: Figures assume target population of 10,000 persons.

| Land Use | Surface Area per Person ($m^2$) | Total Colony Surface Area ($m^2$) | Approx. Number of Floors | Projected Surface Area per Person ($m^2$) | Total Colony Projected Surface Area ($m^2$) |
|---|---|---|---|---|---|
| **General** | $m^2$ | $m^2$ | qty. | $m^2$ | $m^2$ |
| Residential Dwellings [1] | 50.00 | 500,000 | 4 | 12.50 | 125,000 |
| Transportation Facilities | 12.00 | 120,000 | 2[a] | 6.00 | 60,000 |
| Open Space | 10.00 | 100,000 | 1 | 10.00 | 100,000 |
| Storage (Misc.) | 5.00 | 50,000 | 4 | 1.25 | 12,500 |
| Waste / Mechanical | 4.15 | 41,500 | 2 | 2.08 | 20,750 |
| Educational Facilities | 4.00 | 40,000 | 3 | 1.33 | 13,333 |
| Service / Utilities | 4.20 | 42,000 | 2 | 2.10 | 21,000 |
| Business (Retail, Offices) | 3.30 | 33,000 | 2 | 1.65 | 16,500 |
| Misc. Space | 3.50 | 35,000 | 2 | 1.75 | 17,500 |
| Civic / Assembly Halls | 1.50 | 15,000 | 2[b] | 0.75 | 7,500 |
| Recreation (Athletics) | 1.00 | 10,000 | 2[c] | 0.50 | 5,000 |
| Medical Facilities [2] | 0.30 | 3,000 | 3[d] | 0.10 | 1,000 |
| Subtotal | 98.95 | 989,500 | | 40.01 | 400,083 |
| **Agriculture Specific** | $m^2$ | $m^2$ | | $m^2$ | $m^2$ |
| Agriculture | 44.00 | 440,000 | 3 | 14.67 | 146,667 |
| Agriculture Drying | 8.00 | 80,000 | 3 | 2.67 | 26,667 |
| Livestock + Husbandry | 5.00 | 50,000 | 3 | 1.67 | 16,667 |
| Processing + Collection | 4.00 | 40,000 | 3 | 1.33 | 13,333 |
| Subtotal | 61.00 | 610,000 | | 20.33 | 203,333 |
| **Total Tabulations** | $m^2$ | $m^2$ | | $m^2$ | $m^2$ |
| Surface Area ($m^2$) | 159.95 | 1,599,500 | | 60.34 | 603,417[e] |

Departures from '*SP-413*' Surface Area figures

1 Area slgihtly increased to round off calculations and slightly expand living space
2 Calculations based on 50 beds, approximately 58$m^2$ per bed

Departures from '*SP-413*' Number of Levels figures

a Transportation needs will be stacked or elevated
b Civic insitutions will be multiple floors
c Recreation facilities can exist on rooftops or within multi-story structures
d Hospital and medical facilities will be multi-story except for the emergency deparment
e Proposed design utilizes additional floor stacking, resulting in a lower 'Total Colony Projected Surface Area' as compared to the 670,000$m^2$ called for by '*SP-413*'

Table 5F - Modified land use tabulations to be utilized for proposed CIV planning

### 5.3.2 Establishing Population Densities

Urban planners and architects typically use quick benchmarks to assess the possible density and functionality of a given piece of land. The first measurement assesses how many dwelling-units can exist within a given acre of land, known as the D/U. A second common figure employed by planners is the FAR, or floor-to-area ratio. Essentially, an FAR quickly describes the ratio of total building surface area (adding up all floors) in relation to the total site (land) area. For instance, a 1-story, 10,000$m^2$ building on a 10,000$m^2$ site would have an FAR of 1.0. The real power of the FAR is to enforce density / open space control measures. Establishing that a site must not exceed an FAR of 0.5 for example, prohibits the complete development of the site. With that said, an FAR of 1.0 does not necessarily indicate the complete development of a site; a 4 story structure with each floor footprint set at 2,500$m^2$, results in an FAR of 1.0 on the aforementioned 10,000$m^2$ site, but a building with a full 10,000$m^2$ floor footprint may not exceed 1 story in height. When combined with a mandatory percentage of the site dedicated to open-space, the FAR / open-space combination is a powerful guideline tool when establishing planning guidelines.

| Land Use | FAR Range | Reference Source | Reference City |
|---|---|---|---|
| Single Family Residential (Detached) | 0.35-0.65 | Seattle Municipal Code [9] | Seattle, WA, USA |
| Medium Density Urban Residential | 1.0-1.5 | Seattle Municipal Code [9] | Seattle, WA, USA |
| Mixed Use (Retail + Residential) Urban | 1.0-2.5 | Seattle Municipal Code [9] | Seattle, WA, USA |
| Mixed Use (Retail + Residential) Urban | 5.0 | Atlanta Code of Ordinances [3] | Atlanta, GA, USA |
| High Density Urban (City) Residential | 10.0 | New York City Planning [5] | New York, NY, USA |
| COLONY DESIGN TARGET (medium density urban residential) | 1.25-1.75 | | |

Table 5G - Typical urban planning FAR values for various U.S. cities

## 5.4 Accommodating Land Use Through Modularity

In an effort to design for maximum vessel modifiability, modularity and program become intimately engaged. For any early concept to have any sustainable longevity, it must be able to adapt to a constantly evolving set of parameters -- both technical and programmatic -- that demand reactive scalability. Establishing a clear module that can easily be replicated, accommodate scale flux, and provide for an efficient use of space becomes a key nodal component. A whole composed of many modifiable parts lends well to an organic evolution of design.

As the majority of space aboard such a vessel will be dedicated to housing the colonists, providing adequate space for proper neighborhood development is chosen as the driver behind initial module planning. Working from known planning practices germane to residential design and the interrelationships between dwellings, it is possible to arrive at practical minimum dimensions for such a module.

It is important that the colonists have the ability to modify their dwellings and neighborhoods from time to time, necessitating the development of several different, but dimensionally related, prototypical homes that can be reconfigured periodically while still functioning as healthy neighborhoods. In order to permit such flexibility, a typical 'residential corridor' is established, within which various arrangements are possible. For this CIV concept, a double-loaded aisle is used, assuming each aisle to include a 'pedestrian street' with residential units on each side of the street. The units will be stacked 3-5 high to achieve sufficient mid-rise density, and can be terraced back as they ascend to promote an open spatial feeling at the street level. The figure below established typical dimensionality for the width of a module, represented by one type of diagrammatic building layout that would be varied throughout the rest of the module.

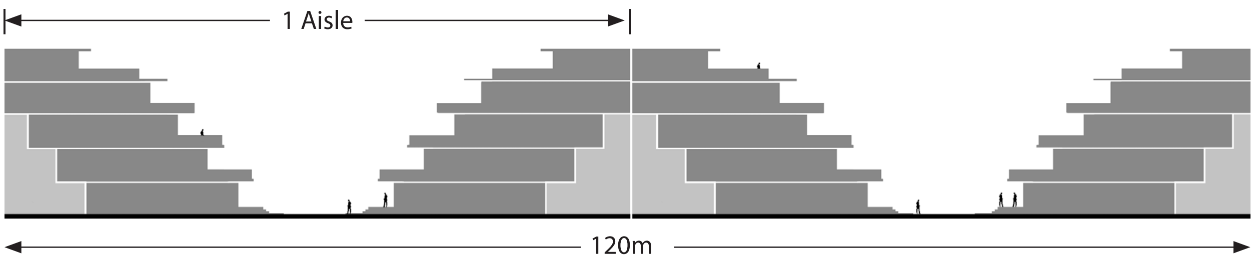



Figure 5H - Diagrammatic elevation showing relationships between units and pedestrian corridors

As a result, it is determined that an internal width of approximately 120m will provide enough room for many different neighborhood configurations.

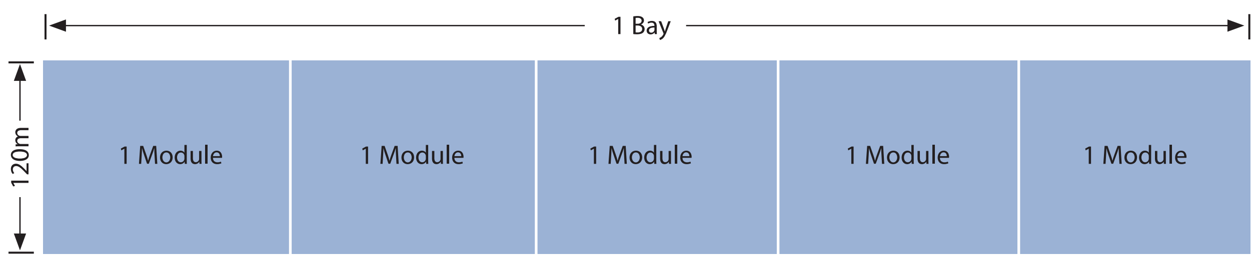



Figure 5i - Diagram of Bay and Module components

### 5.4.1 Module Dimensionality

Utilizing community surface area requirements established in 'SP-413' in conjunction with the establishment of the aforementioned module width, trial and error renders a workable module interior footprint of approximately 120m in width, and 155m in length. [7] The length is debatable, but derived from a series of tests whereby certain variables were manipulated until satisfactory dimensions resulted that fit the design parameters of module count, maximum bay length, and supportable density.

| Parameters | Proposed | '*SP-413*' Interpretation for Comparison |
|---|---|---|
| Projected Area ($m^2$) | 740,000 | 670,000 |
| **Required to achieve projected area:** | | |
| Number of Modules (Total) | * 40.00 | 35.00 |
| Number of Bays | ** 8.00 | 7.00 |
| Number of Modules per Bay | 5.00 | 5.00 |
| **Assumes:** | | |
| Area per Module ($m^2$) | 18,500 | 19,143 |
| Area per Bay ($m^2$) | 92,500 | 95,714 |
| **Results In:** | | |
| Total Bay Length (m) | 775.00 | 775.00 |
| Total Module Length (m) | 155.00 | 155.00 |
| Total Bay and Module Width (m) | 119.35 | 123.50 |
| Total Habitable Length (m) | 6,200.00 | 5,425.00 |

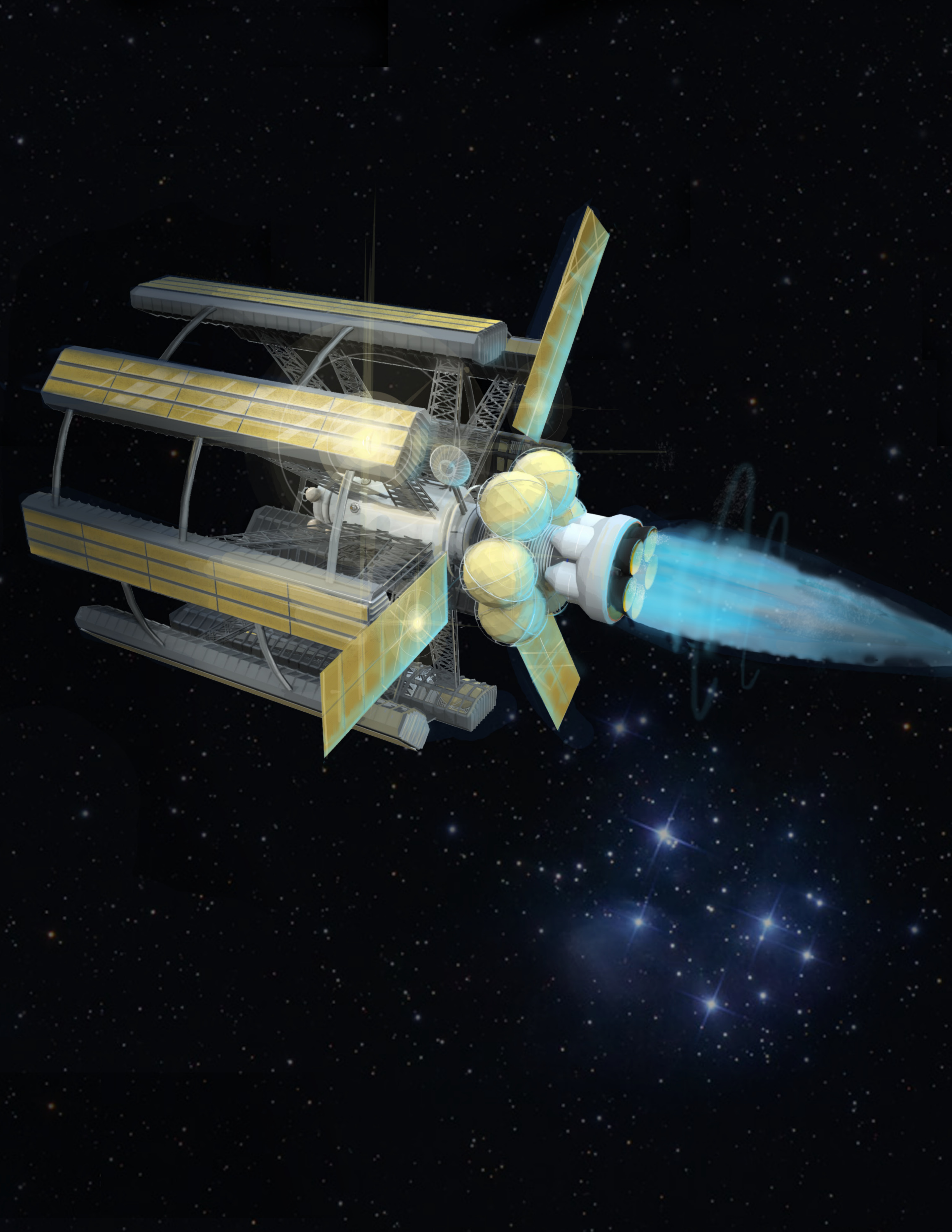
* Assumes 5 additional modules
** Assumes 1 additional bay

Table 5J - Calculations used to scale the module and bay configurations and alternate values. Simply adding an additional bay provides room for growth and resource storage

Developing a vessel comprised of smaller pieces provides a great deal of flexibility, both during construction and while in flight. Creating numerous bays within the colony, rather than one enormous open space, permits a greater degree of control in the event of a significant adverse event (such as a medical emergency, agricultural disease outbreak, or mechanical systems / hull failure).

In an effort to manage the significant hurdles associated with constructing and deploying such a vessel, assembly could occur in stages at stable near-earth orbit locations. As a design parameter, modules or complete bays of modules could be partially inhabited during construction as the entire ship comes to fruition, permitting on-site design improvements as necessary and thorough testing before engaging in flight. Certainly, it makes sense to study the inner-workings of a fully inhabited colony in near-earth proximity for some time before dispatching it on a one-way mission, thereby ensuring to the highest degree possible that all systems will perform as designed. A phased construction plan would also permit the adoption of the latest technologies -- which may emerge during the colony construction phase -- such as promising interstellar propulsion systems akin to those being proposed in studies like 'Project Icarus.' [6]

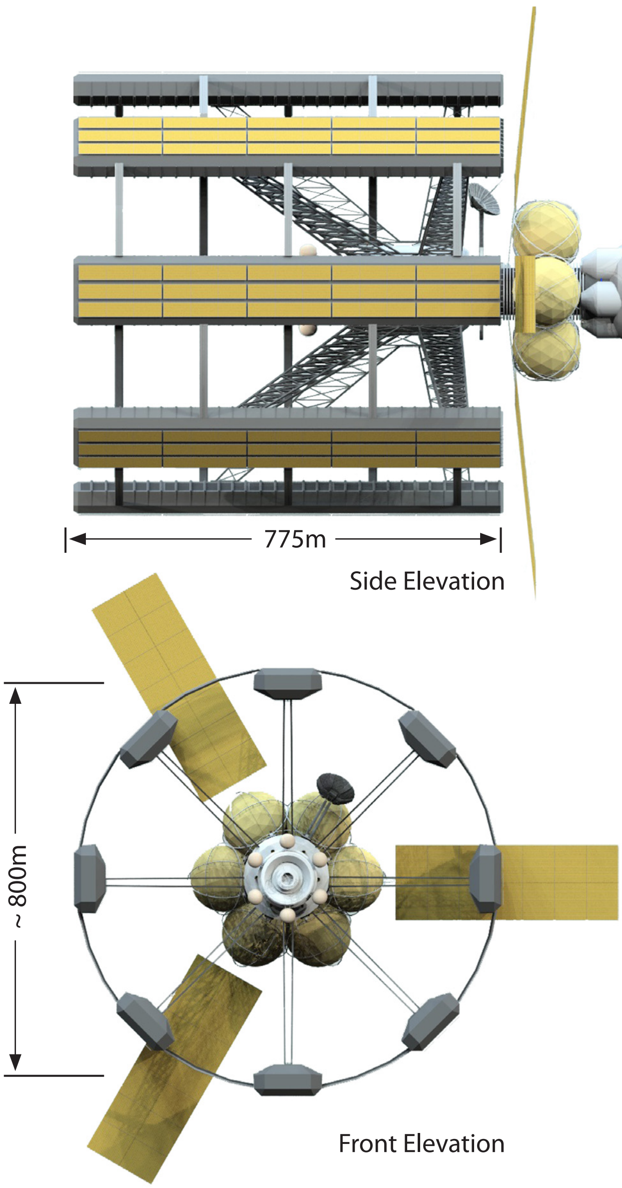
At this point, an organized system of module, bay, and total vessel has been outlined as a way of progressing forward. However, the geometric arrangements serve only to describe the majority of the inhabitable regions within the proposed CIV; the next two sections explore the design scheme at a macro-level, as well as at the pedestrian urban planning level.



# 6 Colonized Interstellar Vessel (CIV) Design Concept

In this section, the Colonized Interstellar Vessel (CIV) concept is explored at a macro level. The intention is to clearly convey the thought process behind such a design, convey the scale of the vessel, address specific technical issues at a conceptual level, and to highlight potential performance advantages.

## 6.1 CIV Conceptual Design Features




VESSEL CHARACTERISTICS

- Radius: ~400m
- Target Population:10,000-12,000
- 1.0g @ ~1.5 RPM
- 40 Initial Modules: 120m X 155m
- 8 Bays (5 Modules / Bay) 775m

– Interconnected through 15-25m wide pedstrian viaducts.

– Vertical elevators embedded within armatures provide tranist to central core.

– Central hub for operations, mechanical equipment, and low-g experimentation / recreation.

– Accomodation of leading propulsion system at the time of vessel inception.

– Minimal cross section exposing leading vessel edges. Edges are beveled and reinforced to reduce damage from particle impact, a situational threat to all interstellar travel.

Figure 6A - Vessel characteristics examined

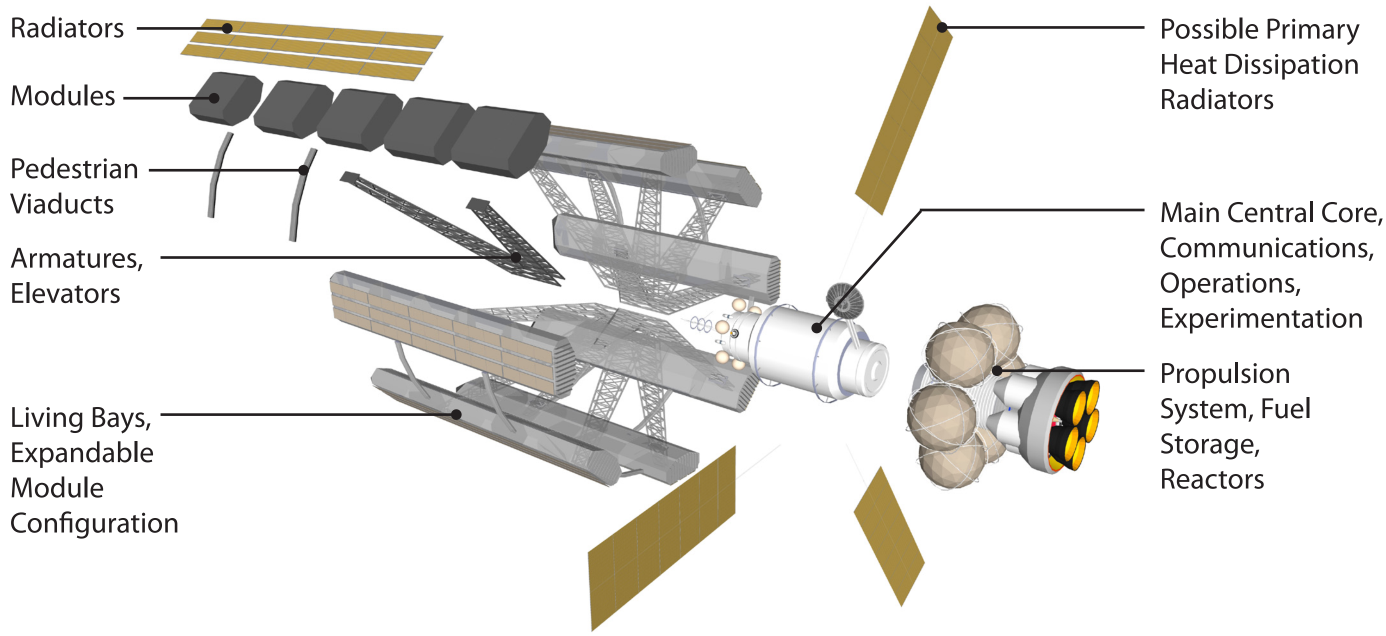



Figure 6B - Exploded view of the macro components comprising the vessel

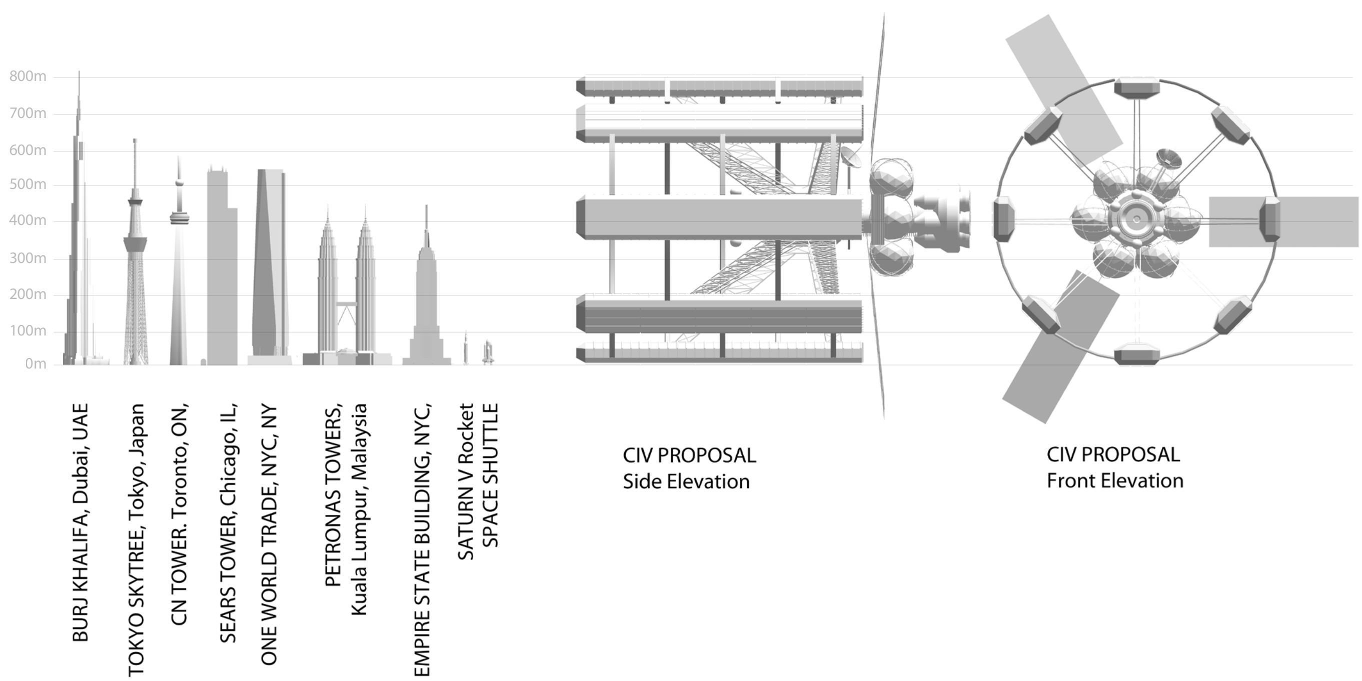



Figure 6C - Proposed vessel in scale comparison to notable buildings on earth

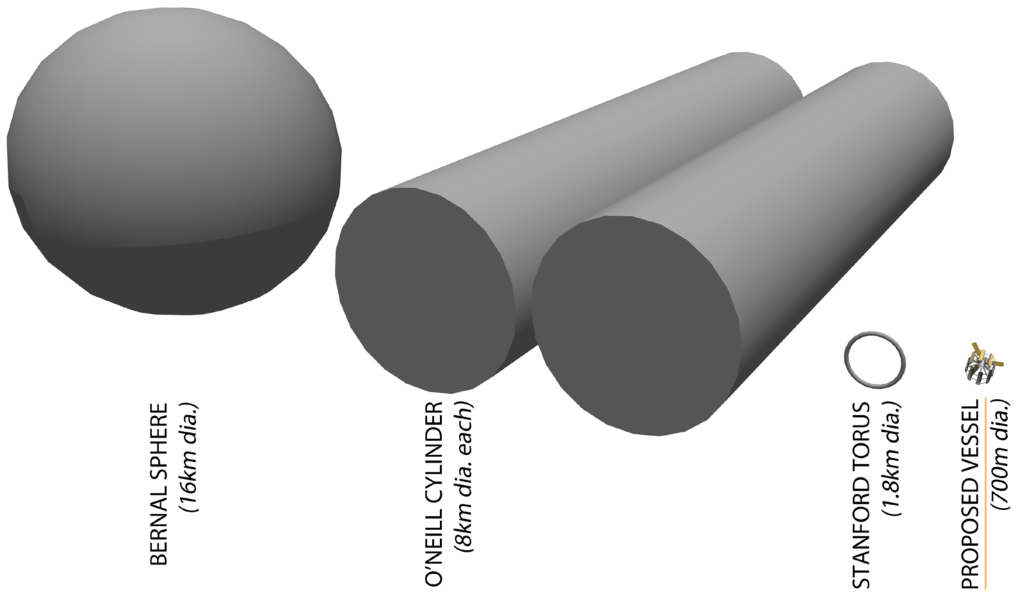



Figure 6D - Proposed vessel in scale comparison to predecessor design concepts

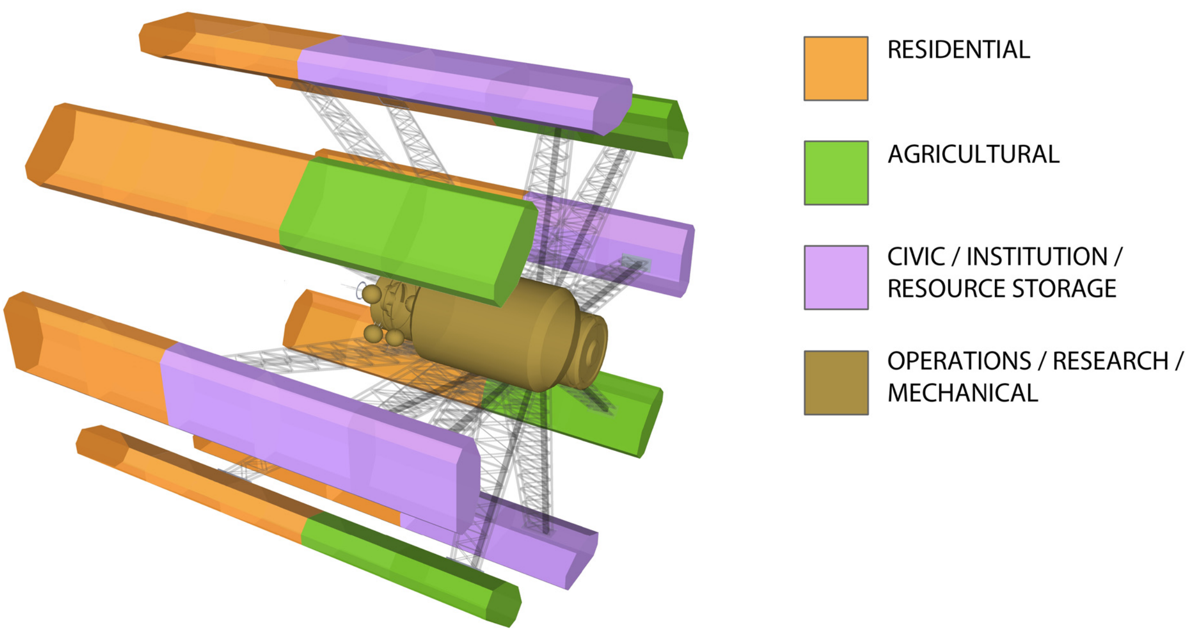



Figure 6E - Diagram showing overall percentage allocation to general land uses (Note: This is NOT a spatial land use diagram, nor does it necessarily indicate final locations for land uses)

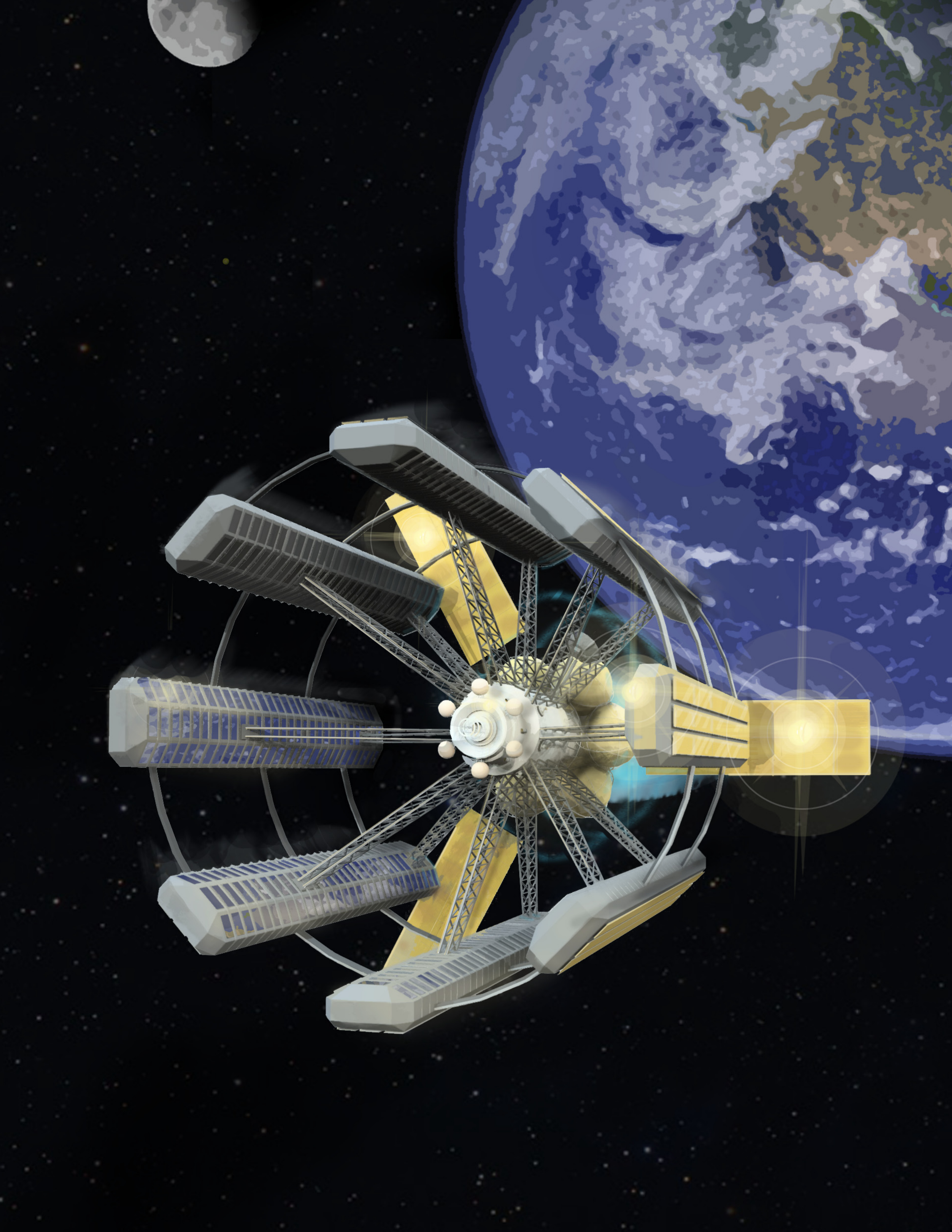
## 6.2 CIV Conceptual Design Summary

The preceding diagrams and illustrations describe a design concept that strives to find a balance between ideal human living conditions, and practical technological provisions within the conceivable near-term future. The vessel is appropriately sized to accommodate a target population of 10,000-12,000 colonists, employs modularity as a remedy for uncertainties in the design process, and is of a scale that is seemingly plausible, as buildings of similar size to the proposed bays have been built on earth.

The design assumes near total power generation resultant from nuclear fusion reactors or similar, as solar power will quickly become unfeasible as the sun recedes into the distance during the sojourn. Large heat dissipating radiators are shown in the illustrations, but further studies should be undertaken to determine the maximum effectiveness of heat recapture as a source of colony heat, rather than simply assuming it to be a waste by-product and dumped into space.

A potential advantage to a vessel of this design scale and configuration may pertain to protective shielding from harmful radiation. Any CIV and its colonists would be subject to cosmic radiation, necessitating some sort of protective measures—on earth, this is accomplished with an atmosphere and magnetic field. One such method of protecting colonists involves the utilization of thick shielding. Such shielding would certainly be opaque in nature, which brings up the issue of translucency among colony roofing structures. A colony orbiting about the earth would surely benefit from allowing natural sunlight to permeate the roof into the inhabitable interior, but as a CIV would quickly depart from the effective illumination range of our sun, the benefits of retaining such translucently becomes an issue for further study. However, it could be argued that an 'open-sky' may provide considerable benefits to the colonists, as distant and changing vistas would be experienced throughout the journey, and a new notion of what comprises the sky may emerge. For the sake of this discussion, a translucent roof is shown in the accompanying illustrations.

The next section attempts to convey a sense of what life living within such a CIV may look like, as the focus shifts from exploring the vessel as a whole, to provoking discussion about the inner workings of everyday life.



# 7 Interior Concept Exploration

Successfully establishing complete design guidelines for the vast interior spaces contained within such a vessel is an exercise that will take years of diligent work, conducted and reviewed by many professionals; as such, the information contained within this section is intended to promote the discussion surrounding such planning, rather than attempt to provide an all-inclusive design solution. The spatial planning component represents the careful interweaving of numerous delicate pieces, any of which have the ability to suddenly void even the most well conceived approaches. True success will demand comprehensive model creation and testing beyond the scope of this study.

## 7.1 Elements for Consideration

Several important factors must be addressed when beginning to layout potential land use arrangements. The very nature of attempting to create a false experience of living both indoors and outdoors, within the confines of a finite volume, presents numerous challenges.

### 7.1.1 Height

The interior height to the perceived "ceiling" must be determined with both structural and psychological components in mind. For this model, an interior height of 50m is chosen. The figure is derived somewhat arbitrarily, but considerations were made working backward from a model that assumed residential units stacked 3-5 units high, with volumetric accommodations on the rooftop for recreational sports, plus what felt like sufficiently comfortable overhead volume. The proposed ceiling would be comprised of some sort of translucent material and structural elements, potentially employing glazing tint that would filter incoming starlight to emit just the blue wavelength, when viewed from the interior. Predecessor colony designs employed mirrors to reflect sunlight into the colony; as the proposed vessel outlined above will not remain in permanent earth orbit but instead be receding from the sun, persistent starlight alone may not suffice for the needs of humans and agriculture, potentially necessitating the usage of auxiliary overhead lighting that emulates sunlight -- another issue for detailed study.

### 7.1.2 Pedestrian Streets, Open Space and Scale

Although traditional vehicular traffic will be non-existent, "streets" should still be provided within the colony to facilitate pedestrian interaction and circulation. Despite the likelihood that small, personal electric vehicles will be used, the space between residential dwellings and structures is given over to the pedestrian. Wide thoroughfares permit walking, socializing, slow electric vehicle circulation, and structured gatherings. Every so often, larger permanent open spaces (many with green space) are provided to accommodate light sporting events and general recreation. Perhaps however, the most significant impact of such open spaces will be their contributions to the mental psyche, as the presence of openness will be essential within such a colony.

While the most efficient manner of arranging residential structures may be double-rows of units, this practice should attempt to be avoided for long stretches. Each residential module should attempt to be uniquely laid out, staggered, and utilized as a means for controlling and creating long and short vistas. Moving throughout a residential neighborhood should be a mentally enriching experience, thoughtfully choreographed, and not quickly absorbed and discarded by the brain -- as would be the case if looking down a long corridor of homes. City planners on earth employed these tactics centuries ago; for example, medieval Italian city planners knew that one manner of creating a reprieve from very tight living conditions was to periodically provide large open squares. The psychological trick they employed to maximize the impact of the squares involved controlling the views -- the full vastness of the space was revealed only upon entering the square from small access points. The effect would create a dramatic unfolding of the space and a much richer experience for the mind. Similar tactics for controlling and presenting spaces of contrasting scales are essential aboard a Colonized Interstellar Vessel (CIV).

### 7.1.3 Tactile Natural Elements

Although life will be relegated to existing within an artificially created environment, it should not always feel as such. While wood and stone may not be conducive to spacecraft design, the tactile nature of such elements improves the quality of a space by creating a semblance of nature connectivity. Wood panels may be incorporated into the modularity of dwelling designs, lightweight stone veneers or similarly stamped or textured materials may periodically appear in open spaces, and soil should be accessible by means of agriculture and urban gardening practices.

### 7.1.4 Vegetation

Multipurpose vegetation should be utilized throughout the community. Serving to create a pleasing outdoor environment in the residential setting and softening the potentially overwhelming hard edges created by built structures, pedestrian streets are lined with trees in architectural planters that use lightweight soil specifically designed for lessening structural load requirements. In order to maximize efficiency, plant species should be used that provide edible parts or otherwise somehow contribute to the food or medicinal supply. Residents will be encouraged to engage in urban gardening as a means to remain connected to nature, as well as to produce a small portion of their food resources. Parks and open spaces may need to utilize synthetic turf for athletic purposes, but opportunities to provide passive strolling gardens should occur.

## 7.2 Characteristics of a Bay

Composed of many modules, each of the vessel's bays should vary in architectural character and functional layout. Interconnected by a series of semi-circular bridges (pedestrian viaducts), one could meander indefinitely throughout the entire colony, covering several kilometers (km). The proposed bay consists of 5 initial modules, creating a bay nearly 775m in length.

## 7.3 Characteristics of a Residential Module

In order to meet the needs of 10,000 colonists, nearly 24 different modules devoted largely to housing will be required. Although residential in nature, these modules also contain a bevy of facilities inherent to promoting a vibrant community -- dwellings, open spaces, civic structures, light transportation structures, occasional retail and dining venues, and minor medical facilities. Essential services such as mechanical, waste, HVAC, electrical, etc., will be concealed at every opportunity within 'basement' decks below the main level of living, as well as within the walls of the macro-bay. Much in the manner a luxury resort is run, back-of-house services will be removed from regular view wherever possible.

A potential diagram is shown for one residential module in the figure below, conveying the intent behind strategic neighborhood planning in an effort to embrace the aforementioned principles of varying scale, lines of sight, land uses, and visual interest.

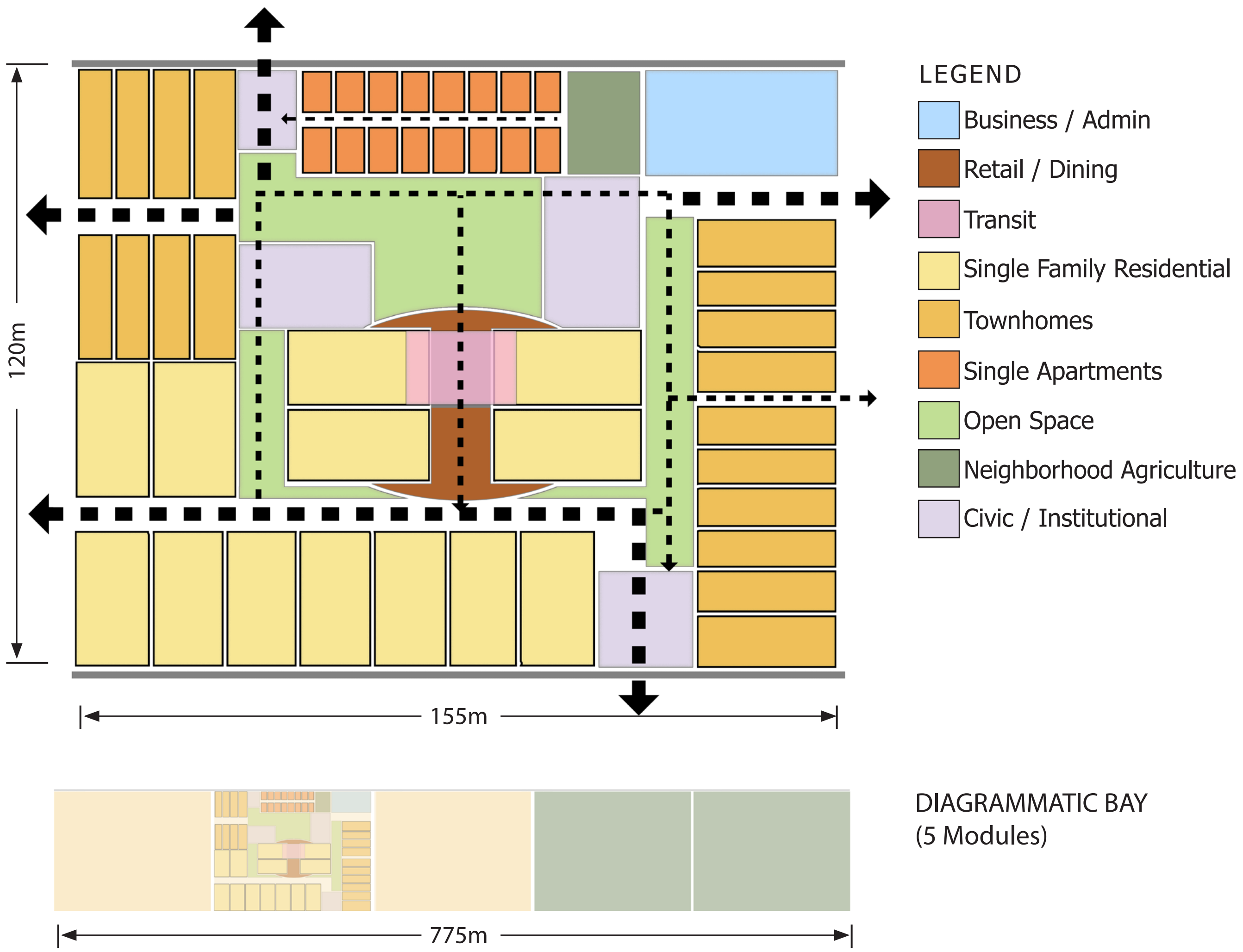



Figure 7A - Potential land uses within a given neighborhood module, (top: residential module, bottom: potential relationship with larger bay).

Different housing types will need to be developed to accommodate various expected community groupings, namely singles, couples, and small families. While the shape and form of such dwellings may vary significantly, for the purposes of this discussion the following unit modules are utilized:

| Type | # of Occupants | Floor Area ($m^2$) | Floors | Dimensions | # Colony Dwellings | Colony Occupants | % Colony Population |
|---|---|---|---|---|---|---|---|
| Single Dwelling | 1 | 50 | 1 | 5m x 10m | 2,000 | 2,000 | 20% |
| Couple Dwelling | 2 | 100 | 1 | 7m x 14.25m | 1,500 | 3,000 | 30% |
| Family Dwelling | 3-4 | 200 | 1 | 7m x 14.25m | 1,250 | 5,000 | 50% |
| | | | 2 | 14m x 14.25m | 1,250 | | |
| | | | | TOTALS | 4,750 | 10,000 | 100% |

Table 7B - Initial target demographics and colony dwelling-type allocations (based upon studies contained within 'SP-413') [7]

| Type | Units in Module | Population in Module | Module FAR | Residential Density DU/Acre (Units/Acre) |
|---|---|---|---|---|
| Single Dwelling | 74 | 74 | | |
| Couple Dwelling | 82 | 164 | | |
| Family Dwelling | 70 | 245 | | |
| TOTALS | 226 | 483 | 1.40 | 49.44 |

Table 7C - Sample dwelling unit calculations for aforementioned sample residential module

With space at a considerable premium in all directions, it is essential to preserve pedestrian corridors between units, and to enhance the perceived openness of the spaces. This can be achieved by allowing the residential units to step backward a couple of meters as they ascend, thereby creating a 'V' shaped corridor rather than a confining 'U' shape, while also having the advantage of creating private outdoor terraces for each unit.

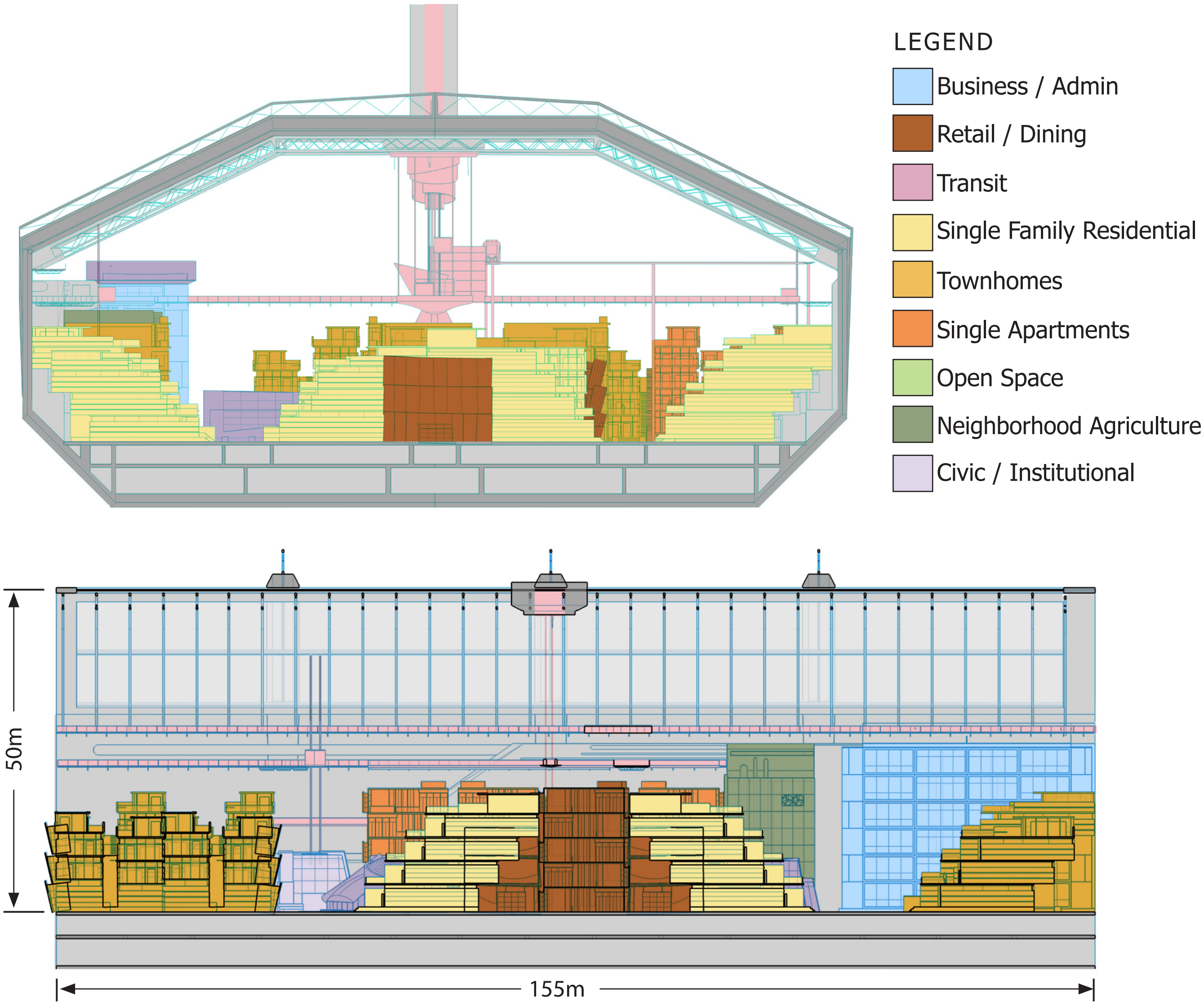
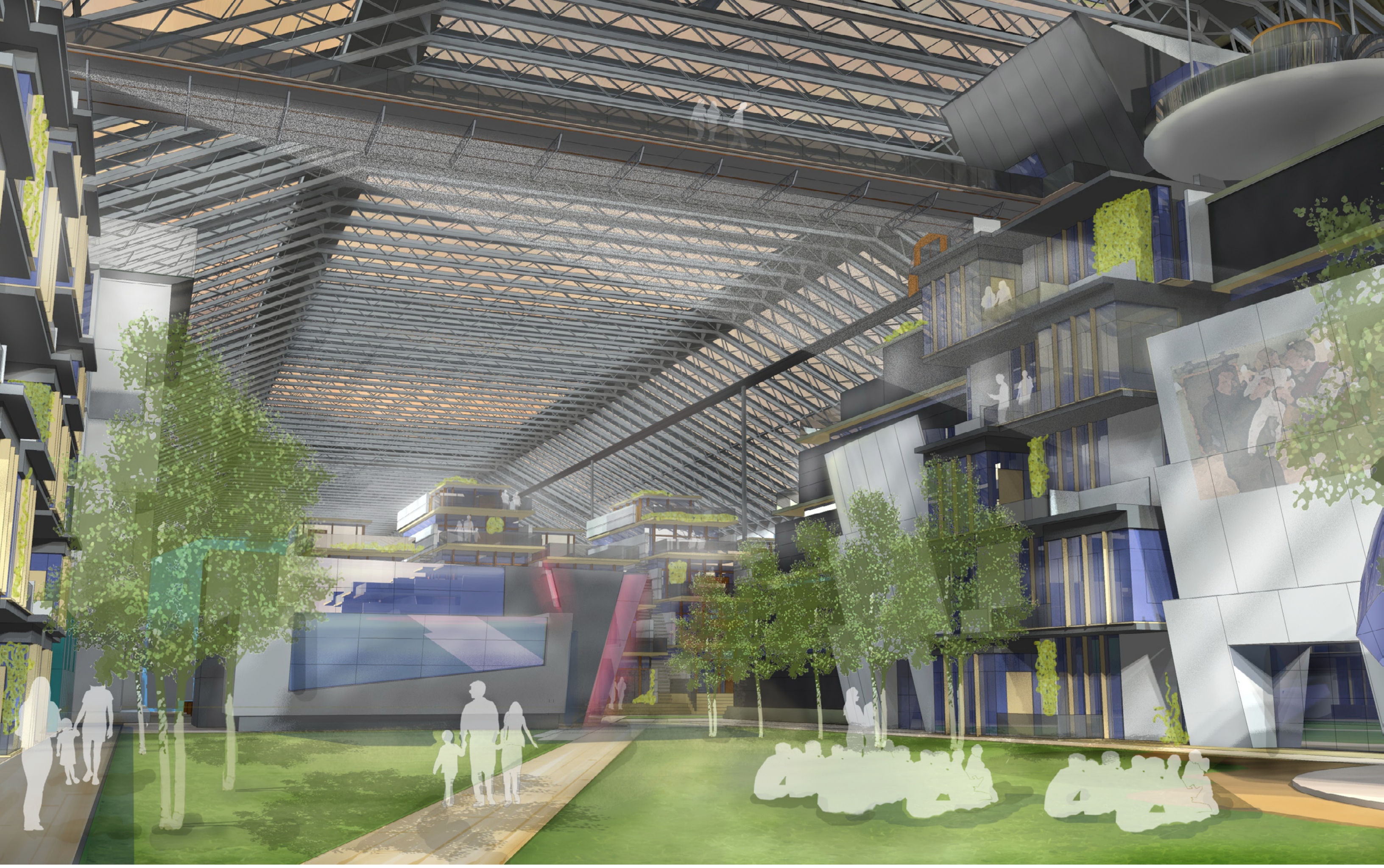



Figure 7D - Conceptual sections through a neighborhood scenario showing potential land uses

Access to transit is important and should be easily accessible, but also somewhat removed from, immediate spatial interaction. Transit stations and rail lines are locatable above and below structures, accessible by means of periodic elevators. Additionally, abundant 'roof' space atop dwelling units can be repurposed into recreational terraces and other outdoor active use spaces.

## 7.4 Cultural Identity

Periodically throughout each residential module should be places of multi-use civic functionality. These structures should be non-denominational and capable of facilitating everything from religious gatherings and community forums, to art exhibits, concerts, and any other community event. Architecturally, these structures allow an opportunity to inject character through design, departing from the modular reproducibility of the residential units in an effort to provide visual stimulation and contrast.



## 8 Conclusions: Progressive Evolution of a Design

Moving forward, the conceptual vessel outlined above should be viewed as an inspired concept for discussion, rather than a mandate for design. While functionally derived from a logical approach, the model is also subjectively designed and espouses nothing more than the thoughts and experiences of the author. To be sure, significant further research is to be concluded at a detailed and dedicated level, as this research paper only intends to concisely examine some of the issues inherent to worldship design.

Designing with the intention to sustain life in perpetuity helps ensure that the highest level of thought and quality are woven into the vessel's design, but realistically certain components would critically fail at some point. Therefore, the ultimate goal of such a mission would likely be to arrive at a predetermined planet within a specific period of time, perhaps on the order of hundreds of years. Throughout earth's history, explorers and settlers have all shared one commonality -- the provisions with which they embark are likely those with which they arrive. To this end, elements from the proposed CIV could be systematically dismantled upon insertion into orbit around the destination planet, and lowered onto the planet's surface (perhaps via space elevators) to be reconfigured into the beginnings of a new permanent civilization. Carefully designed enclosures that once housed colonists and shielded them from the hazards of space, now become terrestrial dwellings, mining facilities, and entirely new structures. Every piece of the ship should be designed with this repurposing in mind.

It is hoped that designers and engineers will derive inspiration from the concepts and illustrations contained herein. Perhaps some of the notions will endure, provoking further study into the feasibility of such devices and making clear a path for specific research and testing. Most likely, significant friction to progress will emanate from the singular issue of cost. Who will pay for the intense research and design documentation necessitated by such a project — let alone the construction costs? There is unlikely to be any significant attraction to venture capitalists, so funding may have to originate from government institutions or wealthy philanthropists, but the sheer amount of funds required provide a significant hurdle. Certainly the presence of a near-term threat to life on earth would provide sufficient impetus to develop such a vessel, but no sane person desires that opportunity.

As momentum behind pursuing such a monumental design challenge increases over time, it will be the cumulative effect of all the predecessor dreaming and design work that will ultimately allow such a marvel to be constructed. It may take decades, centuries, or even longer to fully realize, but all of humankind's immense engineering design ideas began somewhere.

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