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APOGEIOS, A SPACE CITY FOR 10.000 INHABITANTS

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Inspired by Gerard K. O'Neill's works on " Space Islands" in the '70s, *Apogeios* is a concept of a city for 10,000 inhabitants, located at Lagrange Point 5 of the Earth-Moon system. Built by robots with extraterrestrial material from the Moon and asteroids, protected from galactic radiation and solar wind, *Apogeios* must offer residents the comfort of a real city and a unique socio-cultural environment. The Sun provides all the necessary energy and brings warmth and light to greenhouses for food production and atmosphere recycling. As a prerequisite, an initial program of space industrialization will produce, locally and in large quantities, materials and equipment needed for construction and transportation. To this basic industry will be added later finished products, but highly processed products such as drugs or computer hardware will continue to be manufactured on Earth. Despite their high automation, minerals mining and processing, and first of all the construction of the city, will require the presence of man in situ. All the processes won't be remotely controlled. More than "site sheds", real living quarters will be needed. Larger and more autonomous than the current orbital stations, they prefigure the city to come. Besides their role in the industrialization and the construction, they will qualify number of essential functions such as artificial gravity, culture in greenhouses, recycling of air and water, ecosystem monitoring and safety. Time for such a project has not yet come, but this is more than science fiction according with today's space technology.

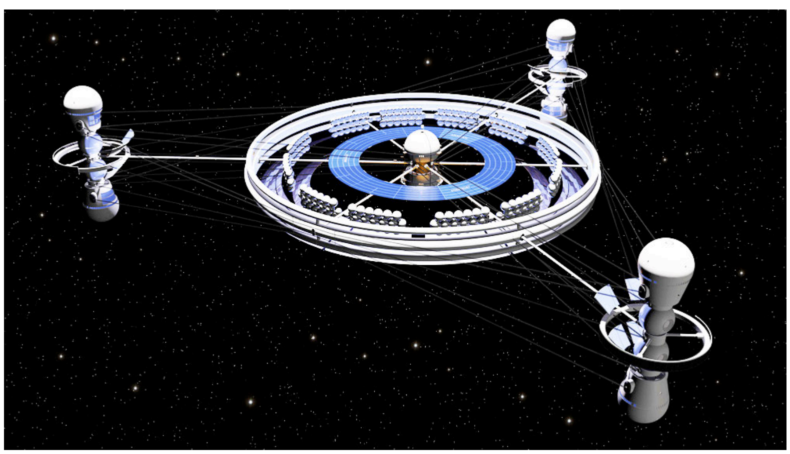

Fig. 1 : *Apogeios*, general view.

I. THE PROJECT

The aim of this project was to identify technological options, constraints, and hypotheses, in order to develop an architectural concept of space city plausible within the time horizon of one or two generations. It refers to Gerard K. O'Neill[1] early works on "Space Island" in the 70's, and is called *Apogeios*, the Greek word for "away from the Earth".

We do not, of course, pretend to describe in a comprehensive and realistic way a space city in all its aspects, but more modestly to identify basic guidelines for future researches. Some orders of magnitude, underlined in the text, were the subject of preliminary calculations (with a security margin when necessary). Some important points have been developed, others not yet. However, none of them determines the feasibility of the project. They are listed and commented in the last section of this paper.

Ten thousand inhabitants may live in *Apogeios* at first, maybe more later. Construction must, for obvious economic reasons, exploit extraterrestrial resources for materials, energy and agricultural production. Therefore, we have first to "industrialize" space in order to produce these materials at a reasonable cost, 3 to 4 orders of magnitude below the current space industry. This is the real techno-economical challenge of the project.

II. MAIN PRINCIPLES

II.1 A Space City in L5

The size of *Apogeios* is modest compared to the first habitat ("Island 1") described by O'Neill (derived from the Bernal sphere), which itself is very small compared to the cylinders of "Island 3". This is a real city and not some kind of Resort Park simulating a terrestrial "natural" environment. A smaller size has the advantage of avoiding gigantism that would amplify the difficulties of construction.

Only the initial configuration is defined in this project. Potential for future development should eventually allow residents to develop, transform, or even enlarge their habitat.

O'Neill's proposal to locate the city on the Lagrangian point L5 of the Earth-Moon system seems appropriate. Seen from the Earth, *Apogeios* follows the Moon from a few days and is therefore at an average distance of about 384,000 km. From the Moon, the distance is the same and the space city appears almost static in the sky, as our satellite rotate with the same period on itself and around the Earth. These circumstances facilitate the transport of lunar ore.

For a first "Space Island", this choice seems an acceptable compromise on the following criteria:

- Exploit the lunar regolith to produce different metals (mainly aluminum and iron), silicon and oxygen.
- Provide regular connections with the Earth, especially during the construction, which will require the transport of persons and specific equipment still manufactured on Earth.
- Have a permanent solar flux (ie 1.4 kW/m2) for lighting, electricity generation and heat.

II.2 Extraterrestrial Materials

Materials used for building *Apogeios* must be supplied at acceptable technical and economic conditions. Therefore, it is excluded to provide the heavy and voluminous one from the Earth. This implies that even before the beginning of the construction, raw materials are extracted from ore found on celestial bodies with low gravity and orbits located "close" to L5, as the Moon (1/6 g) or asteroids.

The lunar regolith consists mainly of alumina (aluminum for construction), silica (glass and silicon for solar cells), of iron oxide (for steel), rutile and magnesite (titanium and magnesium alloys). Oxygen is used for the atmosphere, industrial processes (steel, welding, etc..) and as a propellant (combustive). However, there is neither carbon nor nitrogen on the Moon, maybe hydrogen, but without yet evidence of this.

Concerning asteroids, their number and diversity are inexhaustible resources of iron and nickel. Comets could also provide carbonaceous chondrites, water (and hydrogen), nitrogen, carbon, etc… But if the Moon is relatively well known, this is not the case for asteroids. NEOs (Near Earth Objects) are an interesting category, at least those orbiting relatively close to the Earth [5].

Ore will be extracted and send to the site of the city. The first step will be to install extraction units, associated equipment (for basic life, energy production, transport, storage and packaging) and transfer systems (mass drivers, bulk carriers , ..). As a guide, it takes 10 T of lunar regolith to produce 1 T of aluminum.

II.3 Terrestrial Processes

Apogeios protects its inhabitants in large pressurized structures covered with a thick layer of protection against ionizing radiation. This means that the walls are those of a battleship. This is not current aerospace industry, especially if we want to use low cost materials, and today's imperatives for minimizing size and weight of equipment cannot be seen as "design drivers" anymore. *Apogeios* will be built like large modern ships [4] or terrestrial building, where the economy of construction materials is not the first priority.

The essential problem is to "spatialize" means of production and construction, to suit the very specific conditions of a construction site in space. We believe that architects and construction companies will carry out this transformation, developing skills they already have in some of these domains (lunar concrete, for example).

The construction will require all kinds of materials, components, ingredients, tools and equipment in large quantities. If it is excluded to bring all of them from the Earth, it will be the case at the beginning and later for some specific manufactured goods.

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The presence of man will be necessary, to manage and supervise the site. Subsequently, there will be frequent exchanges between the Earth and the city. If we may assume that the return journey is inexpensive, this is not the case for the launch from Earth : space transportation from the Earth is today 1,000 times more expensive than air travel, and it could remain at a high level in this future.

II.4 Solar Energy

In space, the only two sustainable sources of energy are the Sun and nuclear fission (waiting for fusion). Given the situation of the city, the choice of solar energy makes sense.

Sunlight will be used first to light greenhouses used for food production and regeneration of the atmosphere (biological recycling of CO_2 by photosynthesis). But the Sun is also providing heat, directly usable for industrial processes, agricultural greenhouses and air conditioning habitats. We may also, according with O'Neill's idea, open large windows on certain areas of the habitats, receiving the light of the Sun properly filtered and reflected by mirrors.

For electricity, the photovoltaic conversion is preferable to the thermo-solar power. This was the technical choice for all the satellites until now, and for most of the projects of Solar Power Satellites (SPS).

II.5 And a lot of Robots !

The transposition in space of terrestrial processes of production, manufacturing and construction, is a real challenge. The experience of Extra-vehicular Activity (EVA) demonstrate the great difficulties for astronauts to perform the simplest operation of assembly / disassembly, the risks and the resulting physical stress. We can hardly imagine to build *Apogeios* in such conditions! Therefore, we have to use robots, from extraction of minerals and production of materials and fluids, to final assembly, through the development of semi-finished products.

We can imagine a fully automated process for collecting the lunar regolith, transporting, and extracting metals and oxygen. The assembly would be the task of an army of robots, autonomous and versatile enough to cover all the range of operations required. First of them would be sent from the Earth, but a second generation could be manufactured in space.

III. ARCHITECTURE

III.1 Structure

The city is composed of :

- Three habitats, protected from cosmic radiation and solar particles emitted by the Sun, with residential areas in "terrestrial" conditions: temperature, atmosphere and gravity.
- The industrial and logistic area, highly automated (human supervision only) and operating partly in space environment: vacuum, low temperature, 0-g, radiation. They include "docks" and main access points to the city.
- Agricultural greenhouses lit and heated by the Sun (atmosphere and lighting optimized according to the kind of crop).

And :

- The solar power station,
- The radiating panels for thermal regulation,
- The cables connecting these elements.

Elevators and traffic corridors provide appropriate carrying and communication capacities between these elements. Each zone has an access adapted to its functions (sas).

The three habitats, situated at the apexes of an equilateral triangle, are connected by cables to the central industrial area and between them. The whole structure has a spin of one rotation per minute, to recreate Earth's gravity in the habitats located at a distance of 900 m from the axis. This solution, very constraining compared to the absence of gravity (as in the International Station ISS) or a reduced gravity (like the Moon or Mars), seems an essential condition for maintaining long-term health for inhabitants and the possibility of their return to Earth.

The greenhouses are located in the plane of the triangle, at an intermediate distance (a minimum gravity is needed in agricultural areas). This is the case too for solar panels. This means maintaining the rotation axis of the city "pointed to the Sun" throughout the year, while the "gyroscope effect" of rotation has a tendency to keep it in a fixed direction relative to the stars. An "attitude control system" (ACS) has thus to be used in order to rotate the city 360 degrees a year, and correct continuously the orientation of the main axis.

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Fig. 2 : *Apogeios* - Isometric View

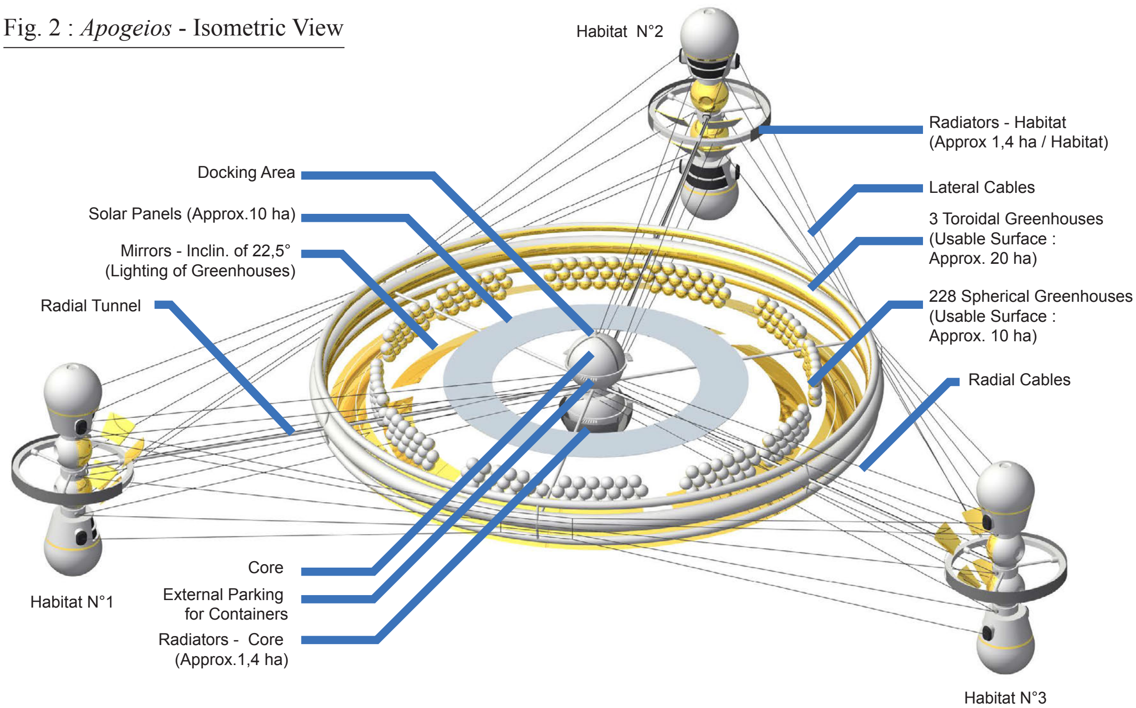

Fig. 3 : *Apogeios* - TopView

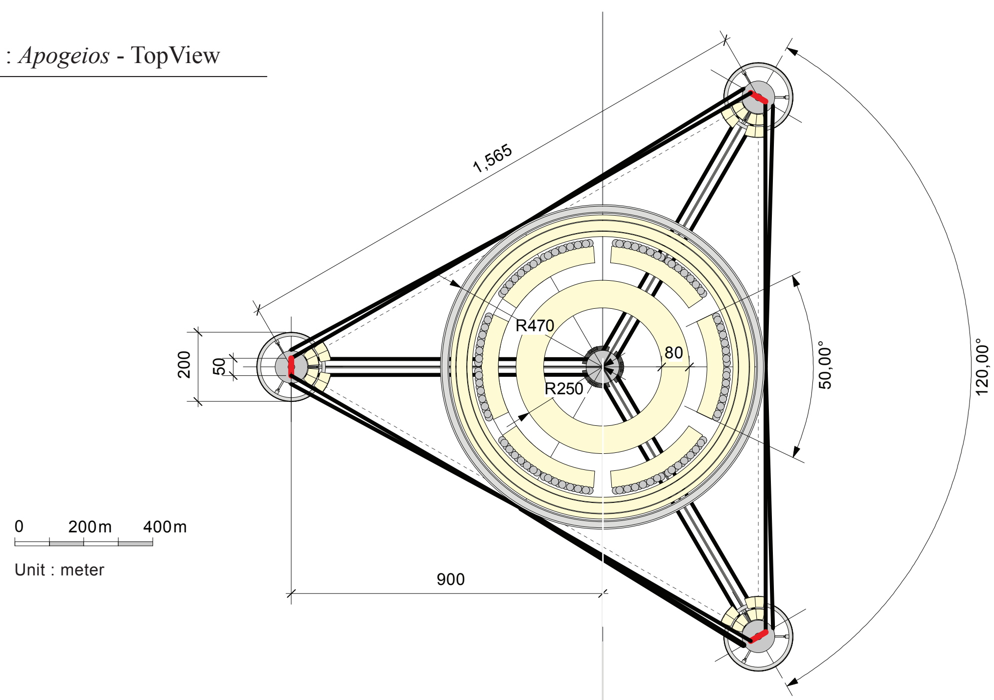

Fig. 4 : *Apogeios* - Side View

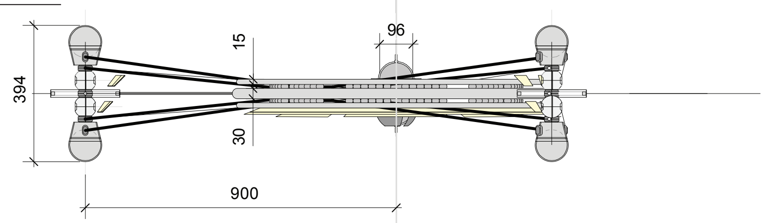

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Fig. 5 : *Habitat* - Isometric View

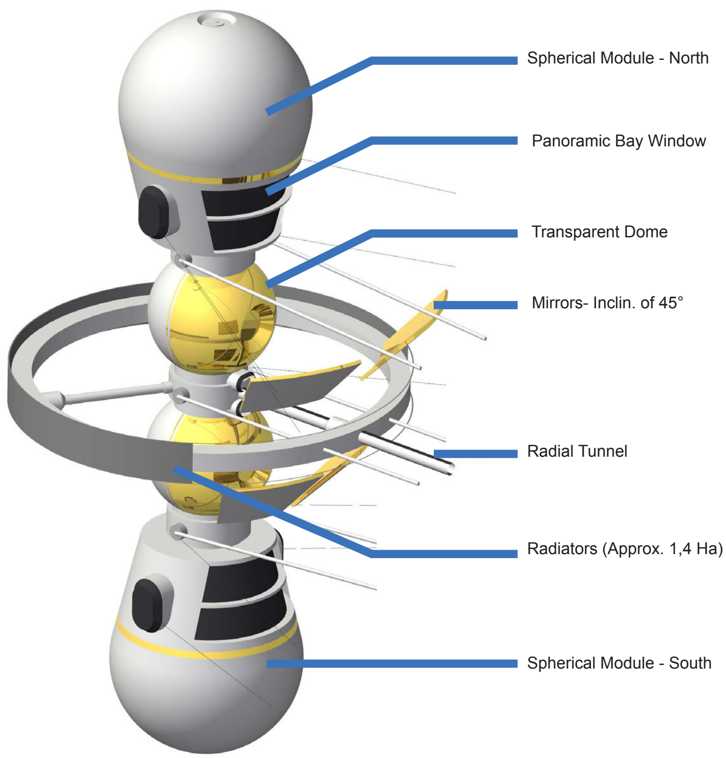


Fig. 6 : *Habitat* - Front View

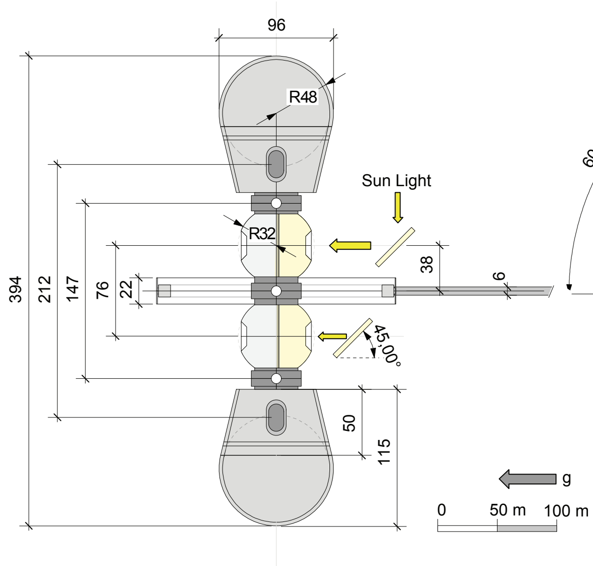
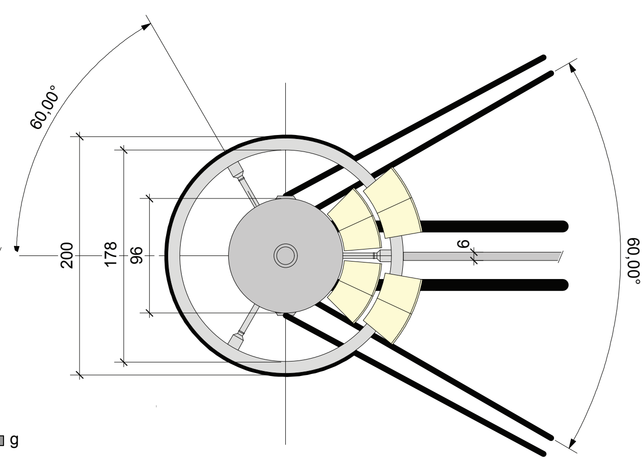


Fig. 7 : *Habitat* - Top View



This architecture is not arbitrary. It focuses on three basic forms - sphere, torus, and triangle - to optimize structural constraints:

- The sphere (for residential areas and greenhouses of vegetable crops) has the best surface/volume ratio, and minimizes the mechanical structural constraints (forces related to containment of pressurized areas, control of low frequency vibrations).
- The torus, with less interesting mechanical properties than spheres, appears however to be the best solution for large areas (20 ha of extensive fields for agricultural production) on a circumference at intermediate gravity.
- The triangle, forming isostatic structures for stretched cable bundles. Greenhouses' tori are in the incircle of the triangle structuring the general form of the city.

III.2 Habitats

Each habitat is composed of four main areas interconnected by bushings composed of cylinders or truncated cones. The length of the whole is about 400 m with a maximum diameter of 100 m.

The structure resists to internal pressure, and protects inhabitants against ionizing radiation and micrometeorites. It includes an aluminum alloy frame coated with an aggregate of lunar regolith and epoxy resin 50 cm thick. In this structure is added a liner internal elastomeric sealing.

Inside, the usable surface is about 350,000 m2, spread over several levels for private areas, social activities and public facilities (education, health, sports, leisure,…). The population density is comparable to the density in a contemporary metropolitan area (about 100 m2 per inhabitant).

Habitats are pressurized at 800 mbar. The composition of the atmosphere is the same as on the surface of the Earth, with the average temperature (20°C) and the humidity rate (60%) of a tempered zone.

Unlike O'Neill Space Islands using only the Sun, the light in habitats is partly artificial. The potential for adaptation to different situations (day / night cycle, annual variations, physiological optimization, etc..) are virtually endless, without requiring a direct capture of sunlight, technically complex.

Spheres are linked by three sections. In these sections are anchored stiffened cables connecting habitats with the central area. Large transparent bays are provided on the inner faces of truncated cones, offering a panoramic view to the rest of the station.

At this stage of the project, we do not preconize any interior design in the habitats. Do we have to be inspired by cruise ships, troglodyte villages or Asimov's Caves of Steel ? We do think that it should be the choice of the inhabitants. Their architects, planners and decorators will design and build living areas and, subsequently, adapt and change their choices in the respect of basic technical standards (masses, structures, networks, health, security, ..). The challenge will be to provide spatial diversity and temporal change in this confined space, and compensate the absence of wide horizons.

However, we may start looking at ways to solve these questions. For instance, residential areas could be located in the two largest spheres of each habitat, each one accommodating about 1700 inhabitants. In the center of the habitat, the two smaller spheres would contain various public spaces, including "natural areas" in transparent hemispherical domes (gardens with water and vegetation) lightened by mirrors oriented 45 ° outside the habitat.

III.3 Industrial Zone

This zone includes:

- Small industry: food processing and packaging, production of components and equipment (including furniture, clothing, .., excluding art and crafts.), maintenance and repair of the city, testing laboratories and control, etc
- Storage of materials, shipping containers, equipment, liquid and gaseous elements, silage and conservation of agricultural products,
- Transport of passengers and freight: docks, transit areas, maintenance and repair of the vehicles, storage and refueling of propellants and fluids.
- Leisure center in zero-g, which could by used as a shelter in case of a serious accident in a habitat requiring the evacuation of all or part of the population.

The industrial area is composed of two large hemispheres, with a pressurized volume of approximately 100,000 m3 each. Except low gravity (maximum 0.3 m/s2 to the periphery), the industrial area has the same characteristics as habitats in terms of atmosphere and protection. Containers and materials requiring neither atmosphere nor protection can be stored on an external parking area.

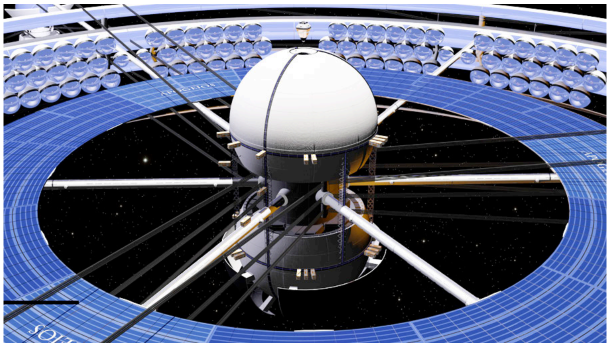


Fig. 8 : Industrial Zone

III.4 Greenhouses

Trying to transpose terrestrial food production methods would be unrealistic, as the ecosystems of the city couldn't survive, and because of the "low yield" of usual agriculture and animal husbandry. Ecosystems of the city should be as simple as possible, isolated from each other, and strictly controlled. At least at the beginning, the staple of the diet will be purely vegetable, produced in high-efficiency greenhouses. Given the current progress in this field, we may assume that the inhabitants of *Apogeios* will draw balanced diet and delicious meals.

In addition to food production, greenhouses ensure regeneration of the atmosphere in habitats (CO2 absorption and oxygen regeneration by photosynthesis). They are of two types:

- 20 hectares of "fields" for the extensive culture of cereals (wheat, corn, sorghum) and various proteins (soy, flax, rape).
- 10 hectares of "garden" for fruit and vegetable farms.

These surfaces have to be increased by about 10% due to the immobilization required for the periodic regeneration of greenhouses. Every three years, a greenhouse should be fully cleaned, the ecosystem destroyed, and equipment sterilized by vacuum and UV sunlight. The greenhouse will be then cultivated again with strictly controlled seeds. This is the price to pay to ensure the sustainability of these closed ecosystems.

The greenhouses are designed to:

- Provide a wide variety of fruits, vegetables and cereals (at least the 120 most important produced), on the basis of 0.62 kg of food per person per day [2], 2300 T / year for 10,000 people (6 T per day).
- Provide flax and cotton for clothing (quantity to be defined).
- Provide the basis of vegetable cosmetics and pharmaceuticals (quantity to be defined).
- Recycle carbon dioxide on the basis of 1 kg per person per day [2], about 4,000 T / year for 10,000 people (10 T per day).

Culture is essentially aeroponic / ultraponic. The plants are fixed to metal grids and immersed in a light nutritious mist: water, fertilizer, micronutrients, and pesticides.

- Optimum lighting (intensity, spectrum)
- 1/6 g minimum
- Atmosphere: T = 32 ° C, O2: 168 mbar, N2 and humidity to define, CO2 : 300 to 1300 ppm.

This kind of agriculture allows, in some cases, an increase of the yield by a factor of 8 compared to the culture on substrate (130 inhabitants / ha). We take the factor of 2.5, thus 30 m2 / person.

The greenhouses are inflatable transparent polyethylene structures, toroidal (extensive culture) or spherical (fruit and vegetable farms). Because of the gravitropism of plants, cultivated areas should be perpendicular to the direction of gravity. This implies reflecting sunlight with mirrors. For a Sun about 45 ° to the zenith, like in tempered latitudes, we may optimize the surface of usable floor thanks to a terraced arrangement.

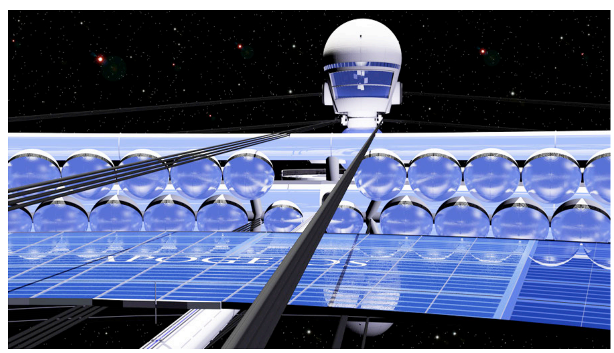


Fig. 9 : Solar Panels and Greenhouses

All greenhouses consists in three torus with a mean radius of 455 meters for extensive culture (two 20 m section, one 30 m), and 228 spheres of 25 m diameter divided into 12 clusters of 2 x 19 greenhouses. The level of gravity is about 0.5 g, atmospheric pressure is low (corresponding to a terrestrial altitude > 4000 m).

The atmosphere is tropical, with a high rate of CO2. GCR protection is reduced, the plants being more tolerant to ionizing particles than human organism. Only robots work there. When necessary, men operate with mask and full-body suit, slightly pressurized to compensate the low atmospheric pressure.

III.5 Water

While important, the water issue was not addressed at this stage of the project. We believe that this raises no major problem, neither for supply, storage or recycling. We can estimate the global consumption for all needs (individual and collective, agricultural and industrial) at about 2000 m3/day. The water can be recycled quite easily and almost entirely by simple physico-chemical processes (steam condensation, nano-filtration and reverse osmosis of liquid waste [2]) .

Water is also a very effective protection against Solar Particles Events (SPE) [3]. Therefore, it is conceivable to use it as a protection for inhabited area exposed to the sunlight, in a double wall enclosing a layer a few centimeters thick. This protection would also be a provision of water of a few thousand m3.

III.6 Solar Power Station

Based on current French consumption in 2010, 500 TWh / year (60% for the residential and tertiary sector), the average power required for the city is about 5 MW. Adding industrial and agricultural applications and considering peak demands, the power requirement of about 7 MW, an order of magnitude between the ISS (100 kW) and SPS projects (at least 1GW).

At L5, the power radiated by the Sun is the same than on Earth, about 1400 W/m2. But photovoltaic panels still have a poor performance. Based on a power output of 65 W/m2, more than 10 ha of panels are needed to provide the required 7 MW. It is likely, however, that this performance will be improved.

Many types of structures are possible. One of the simplest is a ring of panels centered on the axis of the city, with a small outside radius to be as light as possible.

III.7 Radiators

The city produces heat mainly from electricity consumption. The only way to dissipate this heat is to radiate into space.

As habitats are very well insulated thanks to GCR protections, there must be specific radiating surfaces using diphasic fluids in a cooling circuit (vaporization exchangers in the habitat, liquefaction in the external "radiator"). Using ammonia (NH_3) which liquefies at -33 ° C (under a pressure of 1 bar), about 4 hectares are needed to radiate the 7 MW of energy consumed.

Unlike the solar power station, this surface is distributed on the three habitats and the central area, allowing shorter circuits and therefore reducing the power of pumps. Each habitat is surrounded by a cylindrical sector of radiant panels at a temperature of 240 ° K, in such a way the radiation is perpendicular to sunlight. In the central area, radiant panels are only on one hemispheric sector, on the side opposed to the Sun.

III.8 Cables

Each housing is connected to the central area with cables (like suspension bridges) of metal or carbon fiber. 24 cables of high strength steel, 60 cm in diameter and 900 m long, can hold twice the weight of a habitat, estimated at 150,000 T.

Cables grouped in sets of four are rooted in the structures connecting the spheres, distributing the important constraints concentrated at the attachment points, and limiting the mechanical freedom of habitats. These cables also support light structures of communication tunnels, solar panels, and other devices such as hoists. By cons, a specific system is designed for greenhouses. Habitats are also linked together for reasons of dynamic stability and / or safety.

During the construction, a scaffold will be used to connect the cables, and removed once the structure, gradually rotating, will have a sufficient rigidity.

IV. OTHER ISSUES

IV.1 Security

Living in Apogeios is probably less dangerous than living on Earth. Being well protected from cosmic radiation and solar storms, the only external natural risk is the impact of a meteorite. Considering the size of habitat, a "pebble" makes only a negligible leakage, difficult to estimate in the long term. Only a "rock" may cause a rapid depressurization, but the probability of such an event is extremely low.

By cons, the city is facing risks such as fire or explosion, pollution or epidemic. Therefore, it must be designed to prevent any kind of disaster. A first solution is, as for greenhouses, to compartmentalize inhabited areas in order to distribute the risk. And in a crisis situation, the population of a habitat could be temporarily moved in the shelter of the industrial zone, or evacuated thanks to hundreds of inflatable spherical rescue boats.

IV.2 Mass

On the basis of preliminary calculations and estimations, the following table gives the magnitudes of the masses for the different components of the city.

Habitats	3 x 150,000 T	Including 3 X 90,000 T of GCR and SPE protections
Industrial Zone	40,000 T	Including 30,000 T of GCR protection
Greenhouses	60,000 T	3 torus + 228 spheres
Solar Power Station	5,000 T	
Cables	3 X 2,000 T	3 x (6 + 2) groups of 4 cables
Other	10,000 T	Radiators, connections with cables, …
Total	625,000 T	
Margin	125,000 T	20%
Total (with margin) :	**750,000 T**	**Including 300,000 T of GCR / SPE protection**

Table 1 : Mass of Main Components

This means 75 tons per inhabitant. By comparison:

- With the ISS : 67 tons / astronaut (6 maximum for a total of 400 tons).
- With the famous cruise liner "France": 19 tons / person (for a total of 57,000 tons, 300 m long, 34 m width, 12 decks, 2,000 passengers and 1,000 crew members).
- With the Montparnasse Tower in Paris : 30 tons / person (209 meters high, 150,000 tons, 59 floors, 1,700 m2, about 5,000 persons).

IV.3 Transportation

Different kinds of vehicles will ensure the specific needs:

- Bulks and/or catapults for transporting minerals and raw materials from the Moon and asteroids,
- An equipment fleet for surveillance and intervention on the site, and on the Moon and asteroids.
- “Liners” for links between the city and Earth, via a relay station on Low Earth Orbit.

Shuttles for freight and passenger can dock on the two stations located at the axis of rotation. From there, it is possible to load / unload cargo containers parked outside. Airlocks can transfer passengers and freight within the industrial area (pressurized) and then be transported to habitats via communication tunnels.

IV.4 Construction

A long and important preparation must precede the construction of *Apogeios*. This initial program of "space industrialization" will first produce, locally and in large quantities, aluminum structures, steel cables, concrete protection for GCR, silica and silicon and glass for solar cells, nitrogen, water and oxygen for residents and ecosystems, plastics and oxygen and liquid hydrogen for rocket propulsion.

This basic industry will have to be complemented by the production of many finished products: metal alloys, fluids and various ingredients. But the highly processed products, such as drugs or microprocessors will continue to be manufactured on Earth.

Despite a high degree of automation, mining and processing and especially the construction of the city require the presence of man in situ. Everything won’t be remotely controlled and operated, as the capability for robots to face or foresee critical situation is yet a distant prospect (but can not be excluded).

More than "site sheds", "base camps" will be needed. Larger and especially more autonomous than the current orbital stations, they prefigure the city to come. Besides their role during the construction, they will qualify number of essential functions such as artificial gravity, culture in greenhouses, recycling of air and water, ecosystem monitoring and security.

IV.5 Growth Potential

On the long term, it will be possible to increase the capacity of the city, but building new cities could be a better solution (before spreading further). The idea of O'Neill was to create an archipelago at the Lagrange Point, for a population of hundreds of thousands or millions inhabitants. Like on Earth, cities would be specialized in different activities, and cultural aspects. Note that long distance transport between these cities could be done at low cost in energy or time.

In that way, new additional facilities (for energy, industry, leisure, …) could be build in the neighborhood of *Apogeios*. For example, a solar power station could transmit the energy produced by a microwaves or laser beam, as for the Earth, and livestock could be introduced in “space farms” without any risk to interfere with the ecosystems of the city.

V. CONCLUSION

The purpose of this reflection is to launch further researches, all these issues being real technological challenges. But the other challenge is human: *Apogeios* is not a resort hotel or a cruise ship for tourists looking for short stays in space, anyway for an unbearable cost. Our idea, on the contrary, is that inhabitants will want to stay and appropriate this new place providing a pleasant living environment, a unique socio-cultural space and the freedom to adapt and develop the habitat. But this assumes acceptance by the pioneers of a "new paradigm" in which the Earth no longer occupies the central place - a paradigm yet to be invented …

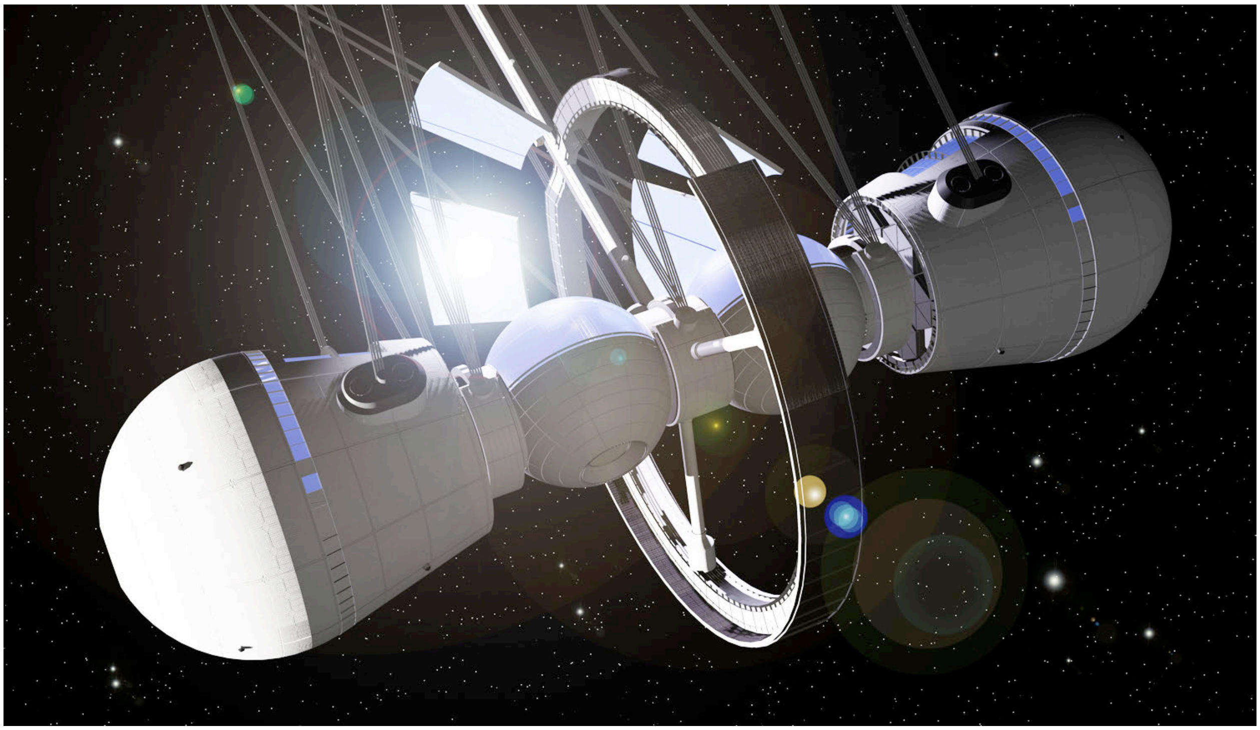


Fig. 10 : Habitat

Are only mentioned here the references used in this text :

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