Environmental Control and Life Support (ECLSS) for Large Orbital Habitats: Ventilation for Heat and Water Transport and Management.

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Abstract.

Modelling data from a largely biological ECLSS for orbital habitats is used to model heat and energy transport and management for an outline but realistic habitat design. This allows a more detailed analysis than was possible in most theoretical precursor studies and enables comparison and validation of aspects of the design with relevant space-based and terrestrial examples. Biosphere 2 is especially pertinent and provides valuable input data.

Photovoltaic panels covering the sun facing end-cap provide electricity while lighting is mainly from sunlight. The ventilation system transports large amounts of waste heat absorbed as latent heat during evapotranspiration in the food growing areas and recovered when hub mounted air conditioners condense water vapor for recycling. The waste heat is dumped via external radiators. The main "housekeeping" power demand, mainly for fans, air-conditioning and lighting, is 83% of the 264 MW generated, leaving 17% (46 MW or 4.6 kW pp), more than enough to run elevators, internal transport, other machinery as well as for personal use and some light industry. The power needed to run the ventilation and cooling systems as well as limitations in the capacity of the internal waste heat transport mechanisms are significant constraints on habitat design.

Plants are especially important; they not only provide food, clean air and water but evapotranspiration also helps cool the habitat and enables heat transport (as latent heat) in the circulated air. A combination of regulations and mechanical air circulation and pollution abatement systems is necessary to maintain high air quality and comfortable levels of temperature and humidity. The power required for ventilation with minimal atmospheric circulation is significant (50% of that available) so actively cleaning the atmosphere would be prohibitively expensive and pollution control becomes essential. Continuous illumination is convenient for shift working and enables some electricity to be generated internally while avoiding the complication of simulating night-time with mechanical blinds.

Key words.

Orbital habitat, environmental control and life support, ECLSS, heat and water transport, waste heat management.

Acronym definitions.

Environmental control and life support system (ECLSS),
Photovoltaic (PV),
Light emitting diode (LED,
Infrared (IR),
Ultraviolet (UV),
Photosynthetically active radiation (PAR),
Daily light integral (DLI),
Personal protective equipment (PPE),
Control of Substances Hazardous to Health Regulations (COSHH),
Local exhaust ventilation (LEV),
Air Changes per Hour (ACH),
Air conditioning (A/C), latent heat (LH),
Relative humidity (RH),
High efficiency particulate air filter (HEPA).

1. Introduction.

A largely biological ECLSS has been described previously and mass balances demonstrated for water and the principal nutrients [1]. An outline habitat design is now modelled to show how heat and energy balance might be achieved using input data from the ECLSS model. This is important because it allows a more detailed analysis than was possible in most theoretical precursor studies. This in turn enables comparison and validation of aspects of the design with relevant space-based and terrestrial examples (reviewed in the Appendix) of which Biosphere 2 proved especially valuable and provided input data. Finally, to permit the study of ventilation and waste heat transport, management and disposal in big open habitats, a scale comparable to O'Neill's Island 1 [2, 3] is used. To further aid comparison with the early work a population of 10,000 is assumed and to maximise deck area at constant pseudogravity (~1g) a cylindrical geometry is selected [4]. To support and feed the chosen population a radius (r) ~500m and length (l) ~650 m is required, the proportions chosen to comply with the rotational stability limit ratio of $l/r < 1.3$ [4]. Although there is no attempt to describe a complete habitat design the general appearance of a realistic architecture is shown in Figure 1. The stability constraint on the geometry implies that all cylindrical rotating habitats will have the hull shape shown in Figure 1 regardless of size.

Spacecraft dock at the two poles from where passengers and freight transfer to inboard spaceports at the hub, which is surrounded by a large air-handling duct. One end-cap always faces the sun and is covered with photovoltaic panels to provide electricity and shade the habitat. Cooling pipes buried in the radiation shielding distribute heat from the interior plus long wavelength IR passing through the PV panels to be emitted from the shaded parts of the hull. Sunlight is reflected from a mirror ring at each end and brought through the radiation protective hull via corresponding sets of radiation blocking chevrons (Figure 1). Secondary mirror rings within the radiation shielding distribute light evenly throughout the interior. Space facing radiators dump waste heat.

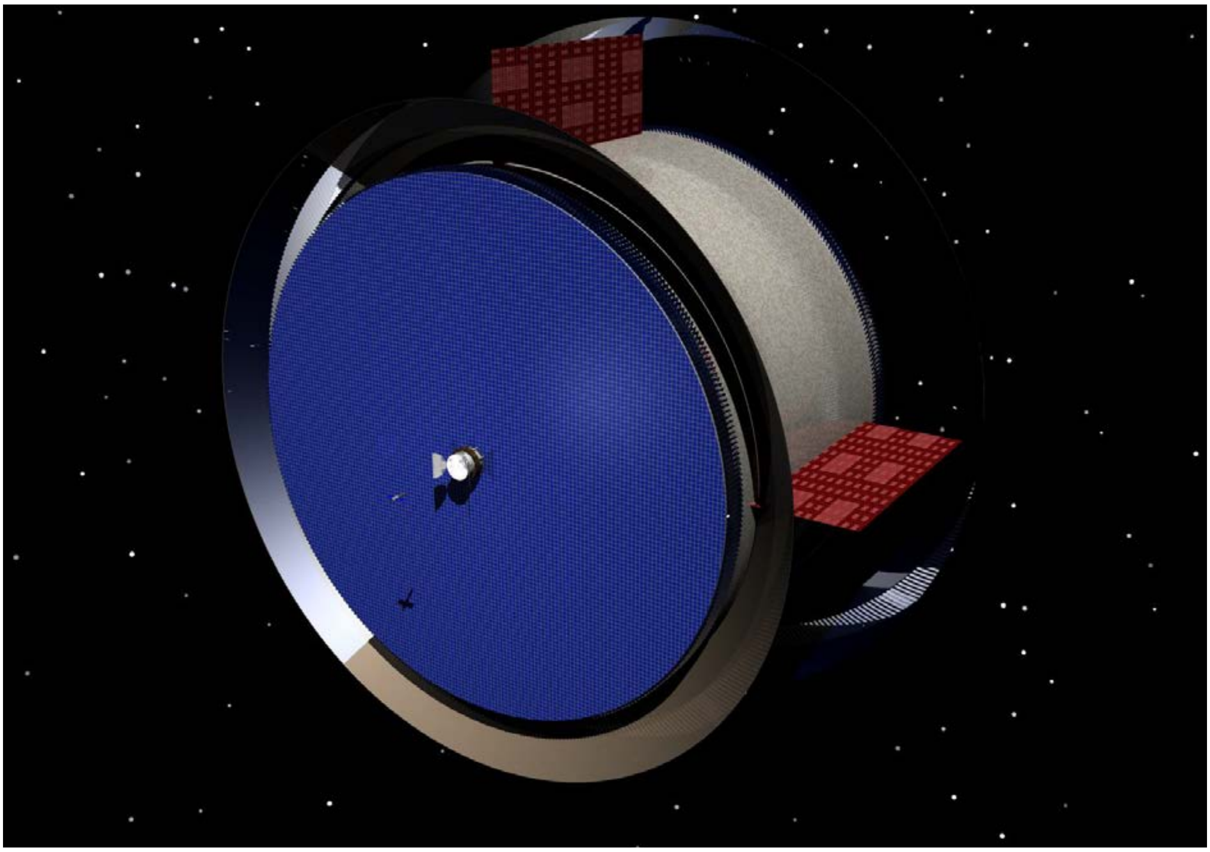

Figure 1. External view of the sun-facing end of the habitat showing photovoltaic panels (blue), radiators (red), mirror rings and hub spaceport.

A sub-tropical climate is good for growing many plants and a temperature of about 25°C is comfortable provided the relative humidity (RH) is kept within a range of 30%-70%. A temperature of 25°C and RH of 50% is therefore chosen for the habitat.

2. Main elements of habitat architecture, lighting, power and waste heat management.

Ventilation and heat transport is highly dependent on the internal architecture and size of the habitat as well as the distribution of heat sources and location of the radiators. Consequently, direct comparison between alternative designs with different geometries may be difficult although much of the data should be generally applicable. Light is required in different areas for different purposes but all possible lighting methods produce significant amounts of waste heat the management of which drives much of the design and forms the bulk of this paper.

External navigation and work lights radiate their waste heat directly into space and are not considered further. Similarly, docks for visiting spacecraft require good lighting but are shaded from the sun and in vacuum so the waste heat lost by radiation has a negligible effect on the structure.

The spaceports and other hub facilities are illuminated to levels similar to that of airports and other large enclosed public spaces. The waste heat is kept to a minimum with white light LEDs but still needs to be managed and is removed by ventilation systems and dumped to the external radiators.

The biggest lighting challenge within a large open habitat is to illuminate the interior to a level commensurate with human comfort and wellbeing and sufficient for food crops without generating unmanageable amounts of waste heat.

There are four decks (Figure 2) containing the ventilation, machinery and living space with the growing capacity to feed the inhabitants. The convention used to identify each deck is as follows. The top (4th) deck is at ground level where some crops are grown in "open air" farms situated between separate urban areas. (Soil depth is 0.6 m but not shown in the diagram.) Housing and offices are therefore situated in the illuminated interior where windows and light-pipes provide most lighting.

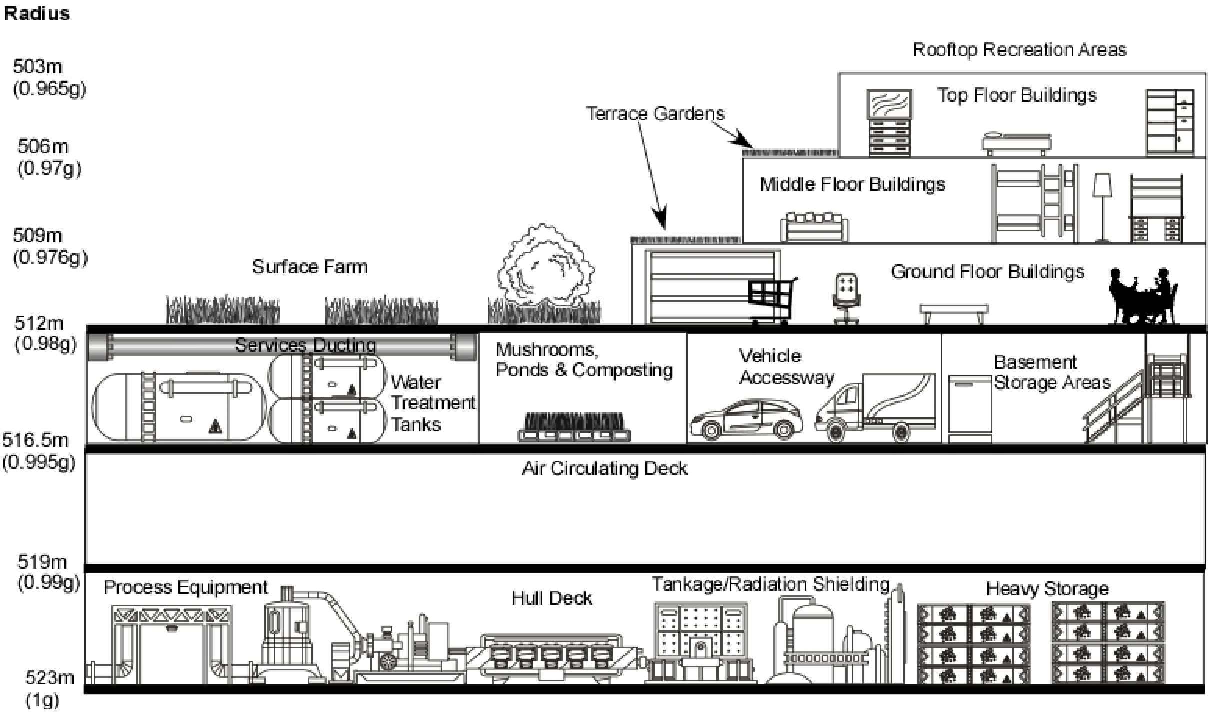

Figure 2. The habitat deck layout (detailed in the text).

The 3rd deck immediately below ground level is filled mostly by the water treatment tanks and vermiculture /mushroom /composting units [1]. These are largely autonomous and only need lighting during inspection and maintenance visits, using white LEDs controlled by motion sensors so only areas being visited are illuminated.

The 2nd deck (air circulating or air-deck) is one continuous ventilation duct but needs illumination during occasional inspection and maintenance visits for which portable lights are adequate. The 1st (bottom or hull deck) contains machinery and storage; lighting is provided by white LEDs controlled by motion sensors so only areas being visited are illuminated.

The circulating air carries the relatively small amounts of waste heat produced by the lighting systems on the lower decks plus the larger amounts from machinery on the 1st deck and fan motors on each deck. This air is vented all around the rim into the interior through ground level gratings. Air from the interior (the atmosphere) is steadily drawn into the hub ventilation chamber where excess moisture and waste heat are extracted by the air conditioners.

To maximize use of the interior lighting for crops, greenhouses are attached to the end-caps with hydroponics units facing the bright interior. Figure 3 shows the end-cap greenhouses and the hub air-handling duct with tower blocks connecting to the urban and farming areas at "ground level." Also shown are end-cap window rings to admit sunlight reflected from the external mirrors. The overall impression is of a brightly lit large open green space.

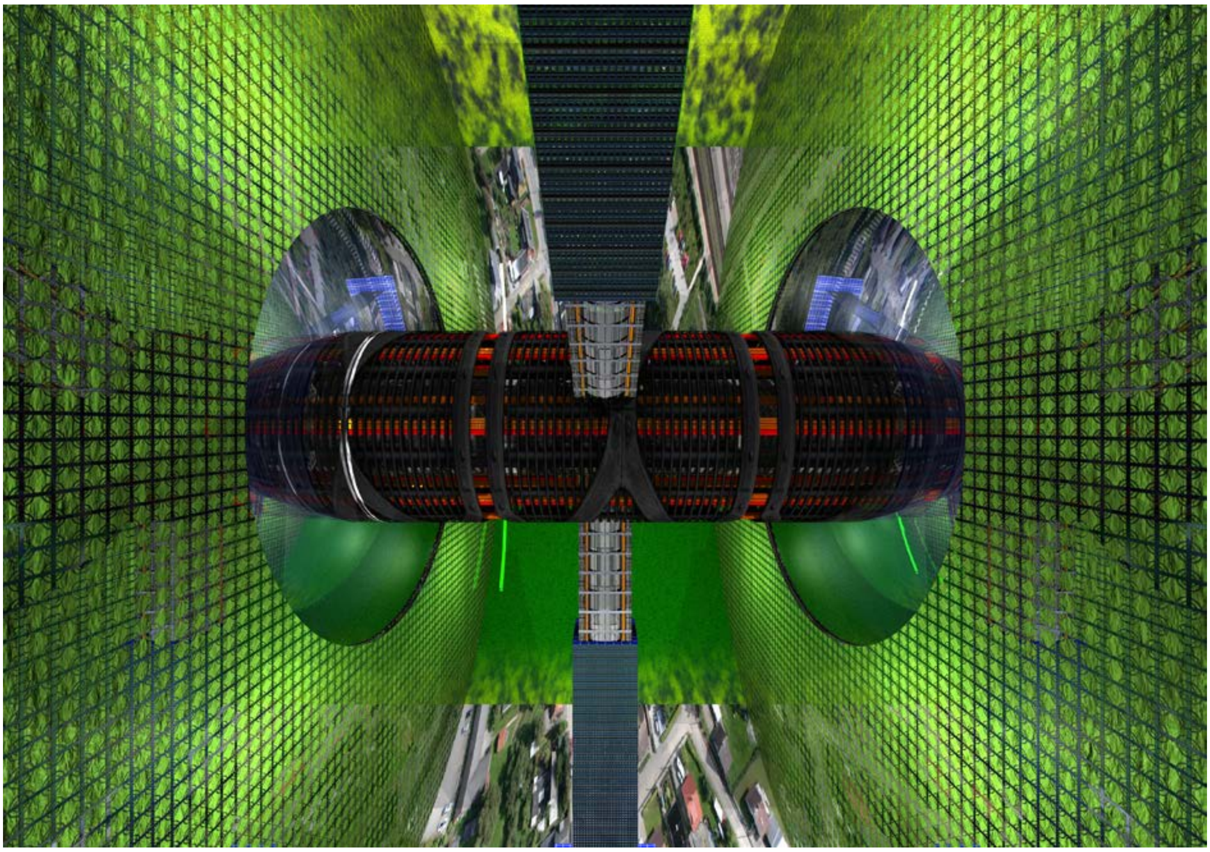

Figure 3. Interior view showing end-cap greenhouses and window rings surrounding the hub air-duct. Transfer shafts within the tower blocks connect to "ground level" urban areas separated by farms.

Greenhouse lighting is boosted by a mirrored back-wall behind which are the fish tanks of combined aquaponics systems. Fish culture water is circulated through the grow beds where waste fertilizes the plants before the cleaned water is recycled. The sunlight is augmented by narrow band LED grow lights for fruiting plants (section 2.3.2.1); windows in the mirrored wall are sufficient for the fish. Food animals, namely poultry, pigs and goats, need near Earth gravity so are kept on the ground floor behind the greenhouses in the small space necessary for the few animals involved. Although animals need much lower light levels than plants, they do need some light to be healthy, with light levels similar to barns with natural lighting. Waste heat, together with moisture, CO_2 and NH_3, is extracted by air drawn up from the animal pens at ground level, through the backspace with the fish tanks, to ventilate the greenhouses where gasses are exchanged before venting into the interior.

2.1 Heat management systems.

No internal heating is necessary; indeed, so much waste heat is generated from solar radiation and electricity consumption from external PV panels that it must be dumped to avoid overheating. Some long wavelength IR passes through the sun-facing panels to warm the hull, which is also warmed by heat lost from the interior as well as hull-mounted facilities that use power.

Since temperatures and humidity levels are always maintained within comfortable limits there is no need for house heating or cooling, and windows can provide most ventilation. A humidity level of 50% is low enough to inhibit mold growth but permanently damp enclosed spaces such as bathrooms need forced ventilation to prevent problems.

2.1.1 Radiators.

The waste heat must be transferred outside the hull and dissipated via space-facing radiators. Much waste heat is lost from permanently shaded parts of the hull but, for simplicity, radiating areas are calculated without specifying their layout, although Figure 1 shows one possible arrangement.

For an emissivity of 0.9 the radiators should shed 284 Wm^{-2} at 0°C (coolant starts at the internal ambient temperature of 25°C and cools to ~0°C). Radiators with a total area of ~3,500 m^2 are therefore needed to dump each MW of waste heat. Shaded radiators emitting from both sides would require half this area (~1,800 m^2).

Internal heat transport and radiator size are major constraints on the design and every effort is made to minimize power consumption.

2.1.2 Cooling system.

Of all the components in air conditioning the compressors consume the most energy and industry is moving away from refrigeration-based systems towards "free cooling" with cold outside air providing a heat sink. Such systems are less efficient but simple and robust and use less power. The habitat has the advantage of proximity to space as the ultimate heat sink so free cooling has been chosen as a reliable low-tech solution. Water (with some antifreeze) has a relatively large heat capacity, is non-toxic and readily available so is used as the coolant.

2.2 Lighting requirements.

2.2.1 Day length.

Day length is an important parameter affecting plant growth as well as human sleep patterns. Any combination of light and dark is possible so the optimum regimen must be selected. Modern cities operate continuously using artificial lighting and an orbital habitat need be no different, facilitating interaction with all Earth time zones. Also, since the many support staff are on different shifts the imposition of an arbitrary light/dark cycle is counterproductive. Continuous illumination is therefore selected with blinds or windowless bedrooms enabling dark sleeping periods to promote a healthy work/sleep pattern. It also means that neither sunshades for artificial night nor street and interior lighting are needed. A further important benefit is that heat flow is no longer cyclic and a steady state more readily achieved.

A wide range of crops are increasingly being grown north of the Arctic Circle in heated greenhouses to take advantage of the 24 h growing conditions during the summer months. Plants can be divided roughly into three groups according to their response to day length. Short-day plants require the alternation of 10-12 h light and dark periods to come into flower. For long-day plants the transition to flowering is hindered by a dark period of 10-12 h. Day-neutral plants flower independent of day length. It has been shown that continuous illumination can be effectively used in growing many crops, including radish, wheat, barley, pea, carrot, beets, turnip, cucumber and onion [5]. In addition, for wheat grown with a photoperiod of 16 h, not only was the photosynthetic system shown to be "idle" during dark periods, but also there was unnecessary expenditure of previously synthesized substances for dark respiration. Some crops such as potato, tomato, soybean and rice, however, failed to give satisfactory results in continuous illumination and need 12-16 h light and 8-12 h dark periods [5]. Some long-day plants, notably strawberries, are bred to be day-neutral, and so greatly extend the cropping season, and it seems reasonable to assume that the same can be achieved for most other crops.

2.2.2 Lighting for plants and people.

Humans and plants see visible light differently. Humans see green light most easily (peaking at 550 nm) and require a relatively small amount of light to see well. For photosynthesis, plants use light between 400-700 nm, and the higher the intensity the greater the rate of photosynthesis (up to a limit). Consequently, ways of measuring light for humans are different to and not appropriate for plants. Nevertheless, it is necessary to provide a comfortable level of lighting for the inhabitants while at the same time ensure that there is sufficient for plants to grow reasonably efficiently while managing the waste heat burden. To resolve these conflicting requirements, the method used below assumes that 100 lux (the unit used to measure light for people) is approximately equivalent to 2 $\mu mol.m^{-2}s^{-1}$ (the unit used for plants).

2.2.3 People.

To minimize the waste heat, light levels within the interior are determined by the minimum requirements of people. In fact, people are comfortable in a wide range of light intensities although full sunlight (~100,000 lux (lumens/m^2)) can be painful and very low levels (<750 lux) make close work difficult. Some people can suffer depression (Seasonal Affective Disorder, SAD syndrome) because of low light levels during Northern Winters. A level of 10,000 lux, equivalent to shade illuminated by a bright midday sky in Summer, has been selected as a good compromise. Although this light level is comfortable for people it is barely sufficient for some crops and inadequate for others. It does, however, reduce the waste heat burden by a factor of 10 compared to full sunlight and is much more manageable.

2.2.4 Plants.

Plants use light energy between 400 and 700 nanometres, the region known as Photosynthetically Active Radiation (PAR) measured in watts per square meter (~300 Wm^{-2} is typical). Plants can respond to different colours of light by changing their growth form (phytomorphology). For example, a high fraction of far-red light (from incandescent lamps or shade from other plants) causes plants to elongate excessively. Conversely, a high fraction of blue light (such as from fluorescent or metal halide lights) causes shorter plants. Fixation of one CO_2 molecule during photosynthesis, with a quantum requirement of ten, gives a theoretical maximum efficiency for white light in the PAR region of ~13% although, in practice, it is ~5%. Furthermore, because plants actually use light of narrow wavelength bands within the PAR region for photosynthesis, overall efficiency is nearer 2% [2]. Consequently, 98% of white light energy becomes waste heat and just 2% is used by plants and stored as biomass. Since most of the energy converted to biomass is "burned" as food, or released during composting, the stored energy is largely recycled and the very small amount of energy remaining as recalcitrant carbon compounds can be ignored when calculating the heat balance.

An alternative and more fundamental unit for measuring instantaneous light for plant growth is micromoles per square meter per second ($\mu mol.m^{-2}s^{-1}$), the amount of energy (photons) hitting a square meter each second. The Daily Light Integral (DLI) is the accumulation of all the PAR received during a day measured in units of $mol.m^{-2}/day$. On a sunny day in summer, at noon, there is about 2,000 $\mu mol.m^{-2}s^{-1}$ (equivalent to 100,000 lux) of instantaneous light with an accumulative total of 65 $mol.m^{-2}/day$. In contrast, at noon on a cloudy winter day, there may be only 50 $\mu mol.m^{-2}s^{-1}$ (2,500 lux) of instantaneous light and cumulatively ~1 $mol.m^{-2}/day$. For a constant light intensity of 10,000 lux (200 $\mu mol.m^{-2}s^{-1}$) accumulated over a 24 h day (paragraph 2.2.3), the DLI is 17 $mol.m^{-2}/day$.

The amount of light that plants need depends on species, but in general terms, propagation of plugs and cuttings requires 8-12 $mol.m^{-2}/day$, vegetables, such as hydroponically grown lettuce, 15-17 $mol.m^{-2}/day$ and tomatoes at least 30 $mol.m^{-2}/day$. The amount of light at an intensity of 10,000 lux should therefore be sufficient for propagation and for growing leafy vegetables, but tomatoes will need some supplementary lighting to ensure fruiting and maximum yield. This is especially so for tomatoes because they need a period of >8 h of darkness [3] resulting in <16 h of light during which they will receive <12 $mol.m^{-2}/day$.

2.3 Light sources.

2.3.1 Sunlight.

2.3.1.1 Illuminance.

Some 1.361 kW of sunlight pass through each square meter of space normal to the Sun in Earth orbit (defined as the solar constant) [6]. To calculate the level of illuminance (visible component only), 1.361 kWm^{-2} is multiplied by 93 lumens per watt to give ~126,600 lux on a perpendicular surface. A reflecting surface coated with Al is 98%

efficient so about 10% is lost during the multiple reflections necessary to bring light through the radiation shielding. A further 10% is lost to absorption in the hull windows so 80% of the collected radiation enters the habitat. The external mirrors (Figure 1) must therefore intercept 295,700 m^2 of sunlight to achieve the target light intensity of 10,000 lux averaged over the internal illuminated area (2,812,000 m^2).

2.3.1.2 Power.

About half (53%) of the solar flux is IR, about 8% is UV with visible light accounting for the remaining 39%. Cold light mirrors are used which reflect visible light inside but transmit UV and IR. The 295,700 m^2 area intercepted by the collecting mirrors is illuminated with a total of 157,000 kW (157 MW) of visible light. After allowing for 20% lost during multiple reflections and transmission through windows, 126 MW enters the habitat. The average rate of visible light intensity is then 42 $W.m^{-2}$, ~8% the maximum ~500 $W.m^{-2}$ hitting the surface of the Earth.

Using cold light mirrors means that all the energy brought inside from sunlight is in the visible range so light production is 100% efficient. In contrast, the best white light LEDs are just 50% efficient so they double the heat burden should they be used. For this reason, sunlight illuminates the interior where white light is necessary for human comfort. The situation is different for plants, however, because they utilize only narrow bands of red and blue light and this is discussed next.

2.3.2 Artificial lighting.

2.3.2.1 Grow lights.

Wavelengths for red and blue light are between 630-700 nm and 400-450 nm, respectively, but plants efficiently absorb narrow bands within each range (precise wavelengths depend on type of chlorophyll). Modern LED grow lights are available that produce light in exactly the narrow bands utilized by plants so are much more efficient than white lights which produce light in the entire visible spectrum. High efficiency (50%) LEDs of the optimal red and blue wavelengths need ~40 Wm^{-2} of electrical energy (a factor of 7.5 less than full spectrum white light in the PAR region) to replicate the plant growth rate of full sunlight. This is for vegetative growth only as flowering appears to require additional wavelengths, also efficiently provided by appropriate narrow band LEDs.

Both the hydroponics (in greenhouses) and farming areas are located within the interior and illuminated by sunlight, which is sufficient for vegetative growth but needs to be supplemented by narrow band LED grow lights to promote flowering and fruiting in the greenhouses. It is estimated that 10% of the greenhouse area needs supplementary illumination by LED grow lights at any one time and it is assumed that the same amount of power is required for this purpose in the farmland.

2.3.2.2 Lighting for people.

Permanent sunlight minimizes lighting requirements but white light LEDs are used where necessary. The main areas requiring lighting are rooms without windows or light-pipes such as bedrooms and the lower decks which are unlit except for brief periods during occasional visits.

3. Management of air quality and the ventilation system.

Air quality is important in both the bulk atmosphere in the large open interior of the habitat and in the air within enclosed compartments, but there is a qualitative difference between the two situations. On Earth, occupied buildings can be ventilated continuously by fresh air from outside where natural processes keep the atmosphere in balance. Similarly, enclosed compartments in the habitat can be ventilated with air from the bulk atmosphere but this cannot be changed because there is no possible replacement supply.

On Earth, we are beginning to suffer the consequences of assuming that, because of the massive dilution of contaminants entering the atmosphere, natural processes would take care of any amount of pollution. However, the natural atmospheric cleaning processes, although effective, are slow and we now understand that it will take many decades if not centuries for the atmosphere to clean itself. It is therefore much better to prevent atmospheric pollution at source when it is most concentrated than to attempt to clean it up afterwards when it has been hugely diluted. By analogy with Earth, the habitat requires scavenging processes to clean the atmosphere but these will be slow given the great bulk of material to be processed and especially because of the huge amounts of power required to circulate it. It is therefore paramount that the atmosphere of very large habitats starts clean and is never allowed to become contaminated. This factor becomes ever more important the bigger habitats become and, although the early designs [2,3] had very large open interiors, no prior work on air quality management can be found as a guide.

The following approach to maintaining high air quality and comfortable levels of temperature and humidity in the habitat atmosphere follows best practice on Earth. The first line of defence is a robust regulatory regime to ban all but the most essential polluting processes from the habitat and severely constrain any permitted ones. These constraints include efficient mechanical containment for polluting processes and local exhaust ventilation (LEV) with appropriate filters in the air extraction systems. Together these measures minimise the potential for atmospheric contamination. As a last resort, however, personal protective equipment (PPE), such as breathing apparatus and/or respirators, is provided in the few potentially hazardous areas while safe havens are provided throughout the habitat wherever people are expected. The habitat is naturally divided into compartments, principally the lower decks, hub facilities and tower blocks that can all be isolated by shutting down the ventilation systems to prevent the spread of contamination. This does not apply to the endcap greenhouses where plants form a key part of the atmosphere-wide pollution abatement system and need to continue working. In addition, all habitable compartments, such as those housing offices and other workplaces, can be temporarily sealed off, giving time to evacuate people to the nearest safe haven.

Regulations therefore ensure that all necessary highly polluting processes take place outside the habitat and, apart from separate orbital factories for heavy industrial processes such as metal smelting, may include small chemical plants co-located with the air liquefaction equipment [1] in the docks, allowing toxic fumes to be vented to space. Highly toxic chemicals, apart from small quantities needed for drugs and other medical purposes, are not allowed inside the habitat while less toxic, but potentially harmful materials are restricted in quantity. Kitchens have their own LEV systems and all cooking uses microwaves, electric hotplates and ovens.

Fire can be a major source of air contamination so its prevention is very important throughout the habitat. Large quantities of flammable materials are banned in general and flammable plastics and elastomers in particular. Finally, all unnecessary polluting processes, such as bonfires and barbeques, are banned.

With polluting processes under control, the main potential air borne hazard is CO_2 exhaled by people and animals but, conveniently, it is consumed by plants to fix carbon and release O_2. The main method for maintaining air quality therefore relies on crops situated throughout the habitat mainly in the hydroponics greenhouses and farms, with some in urban areas. In fact, because some carbon from CO_2 becomes sequestered in organic materials that are not recycled, the O_2 released in the process increases its concentration in the atmosphere while CO_2 becomes depleted [1]. Consequently, rather than causing a problem from increasing concentration, the "lost" CO_2 must be replaced and the excess O_2 harvested from the atmosphere using air liquefaction and fractional distillation equipment [1]. Although true for the atmosphere the situation is different for enclosed occupied compartments (3.1.1.1) where CO_2 build-up could become a serious hazard.

Other than CO_2 management, which is somewhat different (3.1.1.2), local filtration systems prevent pollutants from entering the atmosphere while back-up systems continuously scavenge the remaining traces. Plants do much of the scavenging but the air liquefaction / distillation process also enables trace volatiles such as CH_4, SOx, NOx, solvents or hydrocarbons from lubricants to be removed.

If the air cleaning processes are successful, the atmosphere circulation rate per se does not matter although some cycling is necessary and it is not clear at this stage what this should be. It is therefore assumed that the airflow necessary to ventilate the enclosed compartments and circulate heat and moisture to the hub air conditioners while facilitating CO_2/O_2 gas exchange is adequate. Input data for the rate of evapotranspiration from crops comes from modelling the carbon/oxygen and water cycles in a closed ECLSS [1]. Therefore, if water evolution and transport is shown to be successful the linked CO_2/O_2 cycle will be too. Further, if these important parameters are circulated successfully then accompanying trace gasses and particulates should be also.

3.1 Ventilation for enclosed compartments.

In general, accumulations of warm, moist, stagnant air and the build-up of hazardous concentrations of CO_2 and trace amounts of toxic volatiles and particulates (especially allergens like pollen and fungal spores) must be avoided in closed spaces. However, there is a big difference between occupied enclosed spaces such as the lower decks, workshops, offices and housing and the hydroponics greenhouses, and these are discussed separately.

3.1.1 Ventilation rates for occupied compartments.

The O_2 partial pressure is unlikely to fall low enough to be hazardous even in unventilated spaces but the CO_2 concentration (nominally ~0.034%) could potentially increase to lethal levels so must be kept below safe limits. The situation in the habitat is essentially the same as it is on Earth and similarly managed by regulation and adequate ventilation. The UK Control of Substances Hazardous to Health Regulations (COSHH) 2002 [7] long-term exposure limit for CO_2 is 5,000 ppm (0.5%), more than 10 times the nominal concentration. The COSHH short-term exposure limit is higher at 15,000 ppm (1.5%) but safe only for short visits (~15min).

The accumulation of hazardous levels of CO_2 can be avoided in occupied enclosed spaces (not necessary in greenhouses, see 3.1.1.2) by changing the air. The number of air changes per hour (ACH) necessary depends on the activities inside a particular compartment with more polluting agricultural and industrial processes (Table 1a on next page) requiring better ventilation than community and domestic spaces (Table 1b).

The highest ventilation rates are for heat and moisture removal in greenhouses (25-60) and poultry sheds (4-40). Light industrial processes such as laundries (10-30), dye works (20-30), welding (15-30) and boiler rooms (15-30) are close behind whereas community and domestic spaces range from 1 to 15. Showers, kitchens and utility rooms need up to 20 ACH, also for heat and moisture management. Warehouses need less ventilation at 3-6 ACH.

The very highest rates shown for greenhouses are probably not necessary in the habitat because cold-light mirrors and LEDs minimize the waste heat load from lighting. Compared to the rest of the habitat, higher levels of RH and temperature are advantageous within the greenhouses to limit evapotranspiration and maximize plant growth rates, so 20 ACH is chosen (See 3.1.1.2).

A higher value of 30 ACH is needed locally for those industrial processes that produce heat and/or moisture but 10 is sufficient almost everywhere else except for warehousing where 5 is enough.

These, however, are average figures and do not preclude different local ventilation rates and specialist filtration systems for particular processes such as paint spraying. The success of this method depends on a ready supply of fresh replacement air from the atmosphere.

Agricultural/food processing/storage	ACH	Light industrial	ACH
Greenhouses	25 – 60	Factories/workshops	8 - 10
Mushrooms	6 - 10	Welding shops	15 - 30
Poultry remove dust/ammonia	4	Boiler Rooms	15 - 30
Poultry cooling (summer)	40	Compressor rooms	10 - 20
Dairies	8 - 10	Electroplating	10 - 12
Bakeries	20 - 30	Engine rooms	15 - 30
Kitchens	15 - 20	Paint shops (not cellulose)	10 - 20
Warehouses	3 - 6	Dye works	20 - 30
Cellars	3 – 10	Hospitals/sterilizing	15 – 25
		Hospitals/wards	6 - 8
		Laboratories	6 - 15
		Laundries	10 - 30

Table 1a. Suggested Air Changes Per Hour (ACH) for agriculture, food processing and light industry, credit Vent-Axia.

Community	ACH	Domestic	ACH
Conference rooms	8 -12	Living rooms	3 - 6
Offices	6 - 10	Kitchens	15 - 20
Banks	4 - 8	Bedrooms	2 - 4
Churches	1 - 3	Halls/corridors	3 - 5
Cafes/canteens	8 - 12	Bathrooms	6 – 10
Cinemas	10 - 15	Showers	15 - 20
Dance halls	12	Lavatories	6 - 15
Libraries	3 - 5	Utility rooms	15 - 20
Bars/Restaurants	8 - 12		
Shops	8 - 15		
Schoolrooms	5 - 7		
Squash courts	4		
Gymnasiums	6		
Swimming baths	10 - 15		

Table 1b. Suggested Air Changes Per Hour (ACH) for community and domestic spaces, credit Vent-Axia.

3.1.2 Ventilation for hydroponics greenhouses.

All plants grow well at ambient levels of CO_2 but as these are raised photosynthesis increases proportionately and for the majority of greenhouse crops this occurs between ambient (340 ppm) and ~1,000 ppm (0.034-0.1%) [8]. For any given PAR value, increasing the CO_2 level to 1,000 ppm increases photosynthesis for most crops by ~20% (Figure 4).

An actively growing crop in a greenhouse with little or no ventilation can reduce the CO_2 level during the day to as low as 200 ppm. However, the decrease in photosynthesis when CO_2 level drops from 340 ppm to 200 ppm is similar to the increase when the CO_2 levels are raised from ambient to ~1,200 ppm (Figure 4). In general, a drop in CO_2 level below ambient has a stronger effect than supplementation above ambient and must be avoided.

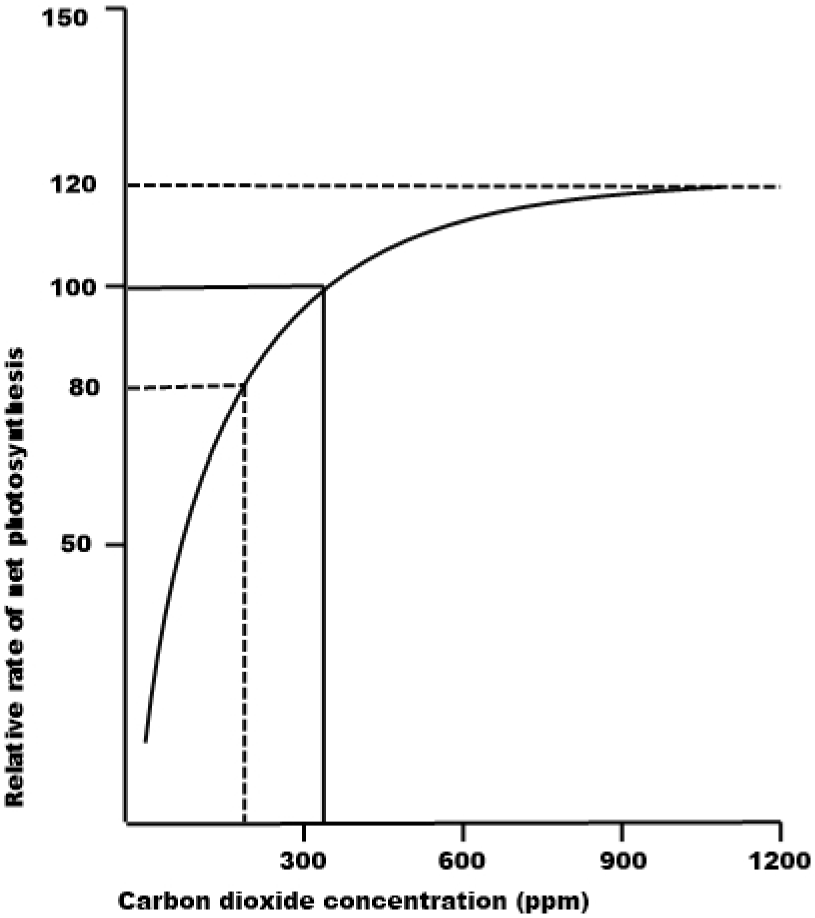

Figure 4. The effect of carbon dioxide concentration on rate of photosynthesis [8].

The habitat greenhouses therefore provide important routes for adding supplementary amounts of CO_2 to avoid depletion of this essential nutrient while replacing sequestered carbon and harvested O_2 [1]. Furthermore, higher than nominal CO_2 levels take advantage of increased growth rates in the main food production system. Happily, the CO_2 concentration necessary for maximum growth is well below (factor of 5) the COSHH long term exposure limit. It should therefore be possible to add CO_2 to the input air at a rate that enhances plant growth while maintaining concentrations close to ambient in the exhaust stream. Of course, different plants at different stages of growth require varying amounts of CO_2 and concentrations must be monitored and managed locally according to need and to maintain safe levels for workers. In addition, CO_2 concentrations must be monitored globally and adjusted as necessary to maintain the CO_2 / O_2 balance for the habitat as a whole.

The local ventilation systems move air over the leaves to facilitate gas exchange but also enable trace gases such as NH_3 and other volatiles to be absorbed. At the same time, particles, such as pollen, impact the plant stems and leaves and are removed from the air. Nevertheless, it may be necessary to fit high efficiency particulate air (HEPA) filters at the greenhouses' outlet vents to remove pollen and other potential allergens from entering the atmosphere.

3.2 Maintaining air quality in the atmosphere.

Water enters the atmosphere mainly because of evapotranspiration in the farmland and greenhouses and is condensed in air conditioners for recycling. The latent heat (LH) associated with evaporation and condensation is absorbed in the growing areas and released in the condensers transporting heat in the process. Humidity is maintained at the target level of 50% and temperature at 25°C by the dehumidifiers. Particulates not captured by the LEV filters impact on the wet surfaces of the dehumidifiers and are carried by condensed water into the main supply system where they can be removed if necessary.

Toxic volatiles and particulates arising from industrial processes on the lower decks are mostly prevented from entering the ventilation air flow by capture near the point of release by LEV fitted with activated carbon and HEPA filters as necessary.

Dust and pollen arising from processes both cultural (rotovating, harvesting) and natural (pollen from wind pollinated cereal crops) in the farmland is managed using temporary ventilated polytunnels with filters to clean the exit air. As described above for the greenhouses, supplementary CO_2 is also added as a key nutrient in the farmland and to replace that lost to the system. It is mixed with the exhaust air from the lower decks which emerges from ground level vents.

All these processes depend on the ventilation system circulating the atmosphere in order to efficiently transport water, CO_2, O_2 and heat from where they are produced to where they are needed.

3.3 A practical habitat ventilation and air conditioning system.

The only experimental data for a large-scale closed habitat came from Biosphere 2 (see Appendix) where the power required for air circulation was ~1MW for a flow rate of 624 m^3s^{-1}, 2,250,000 m^3h^{-1}. This provided ~14 ACH for a total volume of 164,300 m^3 for 8 crew, ie 20,500 m^3 pp. In the habitat there is 467,500,000 m^3 of atmosphere for a population of 10,000 or 46,800 m^3 pp, about twice as much as for Biosphere 2. Although the habitat geometry is quite different (especially the very large interior volume), and the solar input much lower, Biosphere 2 experience is invaluable in ensuring a realistic ventilation system.

A system of fans, radial ventilation shafts and ducting network moves air between the rim and the hub facilities. This ensures adequate flow through the lower decks, ventilates the farms and greenhouses and feeds the air-conditioners. The general layout of the air circulation system is shown in Figure 5. A large cylindrical ventilation chamber, to both control airflow and house the air-conditioner units, encloses the hub.

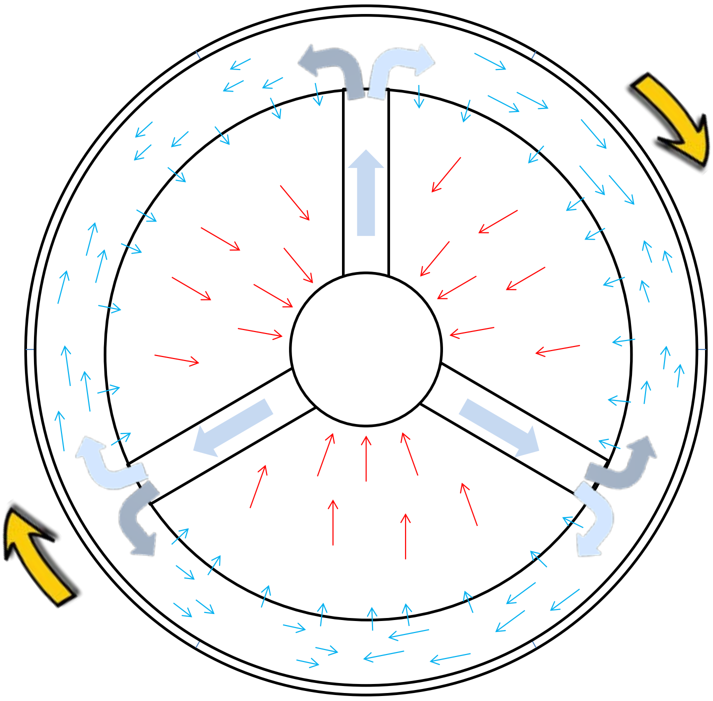

Figure 5. Idealized airflow patterns showing air-deck only

Large fans in the airshafts draw moist air through the air-conditioners where its temperature drops below the dew point and excess moisture condenses out. The LH absorbed when the water evaporated is transferred to the coolant fluid in the air-conditioners when it condenses. This waste heat is carried through the hull and dumped via space-facing radiators. The condensed water is collected into tanks, so clouds and rain are prevented. A relatively small amount of the clean water goes directly to the housing via the access/airshafts for human use before being recycled by the sewage units on the 3rd deck [2]. Most water, however, is used for irrigation, moving directly to the farms at the rim while the rest goes from the hub condensers down one floor at a time through the greenhouses.

The cooled dry air is blown down the airshafts and into the 2nd (air) deck and ventilates the other decks before being returned to the farms, greenhouses, lower decks and homes via a system of ducting leaving via grated outlets around the rim. This ensures that all the air is cycled through the hub facilities and gas exchange can take place in the crops without unventilated air pockets allowing stale air to accumulate.

The airshafts are cylindrical (to minimize turbulence) and form the center section of tower blocks containing offices and apartments.

Air moves into the greenhouses from the backspace through vents near floor level and is drawn out by fans mounted in a corresponding set of high level vents in the roof.

3.3.1 Power supply and consumption.

The sunward facing end-cap is covered completely with PV cells to generate 264 MW (~26 kW pp) and is the main source of electrical power. The review of the power requirements of Antarctic bases and Space Settlement studies in the Appendix (Table

A2) shows that the power requirements range from 3 kW pp (Stanford Torus), 60 kW pp (Kalpana 1), 40 kW pp (Kalpana 1 updated with LEDs, Al Globus personal communication), 30kW pp (UK Halley IV Station) to 88 kW pp (Biosphere 2). For the present habitat, the total power input including sunlight is 390 MW (~39 kW pp, the same as the updated value for Kalpana 1), which is lower than, but reassuringly close, to the figure for Biosphere 2, the best real-world model available. Indeed, it should be lower because Biosphere 2 used full sunlight whereas the model habitat has cold light mirrors (to exclude solar IR) and minimal lighting levels specifically to reduce cooling requirements.

The waste heat from the 264 MW of electricity brought inside requires a radiator area of 0.93 km^2 to add to the ~0.44 km^2 for sunlight i.e. a total of ~1.37 km^2 (Table 2).

Heat Source	Power, MW	Radiator km^2
Sunlight	126	0.44
Electric generated	264	0.93
Total	390	1.37

Table 2. Overall heat input and disposal.

3.3.2 Ventilation rates for housing, lower decks and hub facilities.

Data from Biosphere 2 shows that ~1 MW was required for a ventilation rate of 2,250,000 m^3h^{-1} and this ratio is used to calculate power demand in each of the following cases. Allowing for space lost to the airshafts, housing occupies an area of ~717,000 m^2. More space is lost to roads, paths and other open areas but most buildings are at least two stories high so a reasonable estimate of the ventilation requirement assumes the entire area is covered one room deep (2.5 m). The volume is therefore 1,793,000 m^3 requiring a ventilation rate of 17,930,000 m^3h^{-1} for 10 ACH using ~8 MW. Although cool fresh air is desirable in the inside rooms, the pleasant climate means that most people will prefer to live partly “outdoors” with windows and doors open most of the time. It is therefore assumed that only about a quarter of the ventilation requirement comes from the airshafts, mainly cooled air for bedrooms. Similar arguments apply to the apartments and offices attached to the access shafts which have a similar ventilation requirement resulting in a total demand of 9,000,000 m^3h^{-1} using ~4 MW of power.

Deck 3 has a surface area of 651,000 m^2, when space lost to the airshafts is accounted for, and a volume of 2,604,000 m^3. To achieve 10 ACH a ventilation rate of 26,040,000 m^3h^{-1} is necessary requiring ~12 MW. More than half (14,475,000 m^3h^{-1}) comes up from the warehouse deck and is made up with 11,570,000 m^3h^{-1} of clean fresh air from the air-deck.

Deck 1, the machinery and warehouse deck, is continuous all around the circumference so has a total floor area of 1,448,000 m^2 and a volume of 5,790,000 m^3 with the areas beneath the villages used for warehousing and those under the farms for production. The ventilation rate for the manufacturing space is high locally where machinery produces waste heat, fumes or moisture but much space is used for access and transport of raw materials and finished products and needs much less. An average of 10 ACH for the industrial spaces and 5 ACH for warehousing need 29,000,000 m^3h^{-1} (~13 MW) and 14,500,000 m^3h^{-1} (~6.4 MW), respectively.

A practicable habitat air conditioning system is estimated to be capable of achieving a flow rate of ~72,000,000 $m^{-3}h^{-1}$ (requiring ~32 MW) but the total ventilation rate necessary for the enclosed compartments is 64,000,000 m^3h^{-1}. This leaves 8,000,000 m^3h^{-1} (12.5%) spare capacity to take account of fluctuating demand, with the excess vented into the interior. This is sufficient to ventilate all enclosed spaces to the appropriate ACH value but is only 0.15 ACH for the entire atmosphere, about 100 times lower than the equivalent value for Biosphere 2. Whether this is adequate remains to be seen.

Separate vent and fan systems take air from the gap behind the growing space to ventilate the greenhouses and are independent from but complimentary to the main ventilation system. Air entering this backspace at ground level via floor gratings from the lower decks ventilates the animal pens. It also enters through the ground level access corridors through the greenhouses. Air moves into the greenhouses from the backspace all around the circumference past the fish tanks and through vents in the back walls just above each floor level to be drawn out by fans mounted in high level vents in the front walls. The volume to be ventilated on each floor decreases with height and by the time the top level is reached at 300 m all the air drawn up from ground level has been expelled. The greenhouse and fish tank floors together are just 4 m wide giving a total volume for both end caps of 5,278,600 m^3. For 20 ACH, a ventilation rate of 105,571,000 m^3h^{-1} is necessary requiring ~47 MW of power.

Ventilated space	Ventilation rate m³/h	ACH	Power MW
3 airshafts	72,000,000	N/A	32
2 greenhouses	81,900,000	20	47
Accommodation	9,000,000	10	12
Deck 3 (Vermiculture etc)	26,040,000	10	12
Deck 1 (warehousing)	14,480,000	5	6.4
Deck 1 (machinery)	57,900,000	10	13
Spaceports & hub	23,880,000	10	10.6
Pumps	N/A	N/A	1
Total	N/A	N/A	134

Table 3. Power requirements for the ventilation system.

The power requirements of the ventilation system, summarized in Table 3, consume half of the amount generated. The main "housekeeping" power demand also includes dehumidifiers and LEDs as shown in Table 4. This totals 83% of power available and is probably of the right order of magnitude. It is a clear limiting factor on habitat design. The remaining ~17% (46 MW, or 4.6 kW pp) of power has not been allocated but is required to drive the elevators, internal transport, other machinery as well as for personal use and some light industry. In 2011 the average power usage in the UK was

834 W pp (see Appendix) for all uses so the amount of power remaining should be more than enough.

	Power required MW	Fraction of input power %
Fans & pumps	134	51
Dehumidifiers	73	28
LEDs	11	4
Not allocated	46	17
Total	264	100

Table 4. Estimated "housekeeping power requirements.

Interestingly, Biosphere 2 used between 0.78 MW and 1.17 MW for ventilation from an average input of 0.7 MW and peak 1.5 MW (see Appendix). The fans clearly did not run continuously but when running at peak capacity to cool the habitat during the day they needed 78% of the available power. For this study, the total power requirement for all the separate ventilation systems is ~134 MW which is about half of the amount generated. This is not unreasonable given the steps taken to minimize waste heat with cold light mirrors, narrow band LEDs and reduced interior lighting levels compared to illumination by full sunlight for Biosphere 2.

Finally, despite 50% of the available power being consumed to ventilate the enclosed compartments, transport waste heat and manage the heat and water balance, the result is minimal circulation of the bulk atmosphere. Higher rates of atmospheric circulation are clearly unaffordable in energy terms so the approach of preventing atmospheric pollution instead of actively cleaning it is justified.

3.3.3 Fan noise and airshaft geometry.

Fan noise is a potential problem. Therefore, smooth circular airshafts with the largest practical diameters are used with the lowest possible flow rates to mitigate the effect. For a total flow rate of 20,000 m^3s^{-1} (72,000,000 m^3h^{-1}) and air speed of 3 ms^{-1}, the three main ventilation shafts need each to be of ~2,200 m^2 cross sectional area (~26.6 m radius). To allow this amount of air to spread out into the air-deck without restriction, the airshafts must flare out at the bottom like a bell mouth.

Figure 6 is a cross section of one half of the bell mouth as it descends past ground level through the 3rd deck before merging into the air-deck. It starts at the 26.6 m radius of the air-shaft at a height of 13.3 m above the floor of the air-deck, expands to 55 m radius at ground level, and has reached 150 m radius when it merges with the ceiling of the 2.4 m deep air deck. Much of the spread is taken up in the 4 m height of the 3rd deck, which loses space (212,000 m^2) in the process, and the portion rising into the interior climbs to a height of 6.9 m above ground level.

The ground therefore appears to slope upwards in a ring about 7 m high and 28.4 m wide around the bottom of each airshaft. This slope would probably be incorporated into the buildings surrounding each airshaft so they merge into the apartments of the tower blocks.

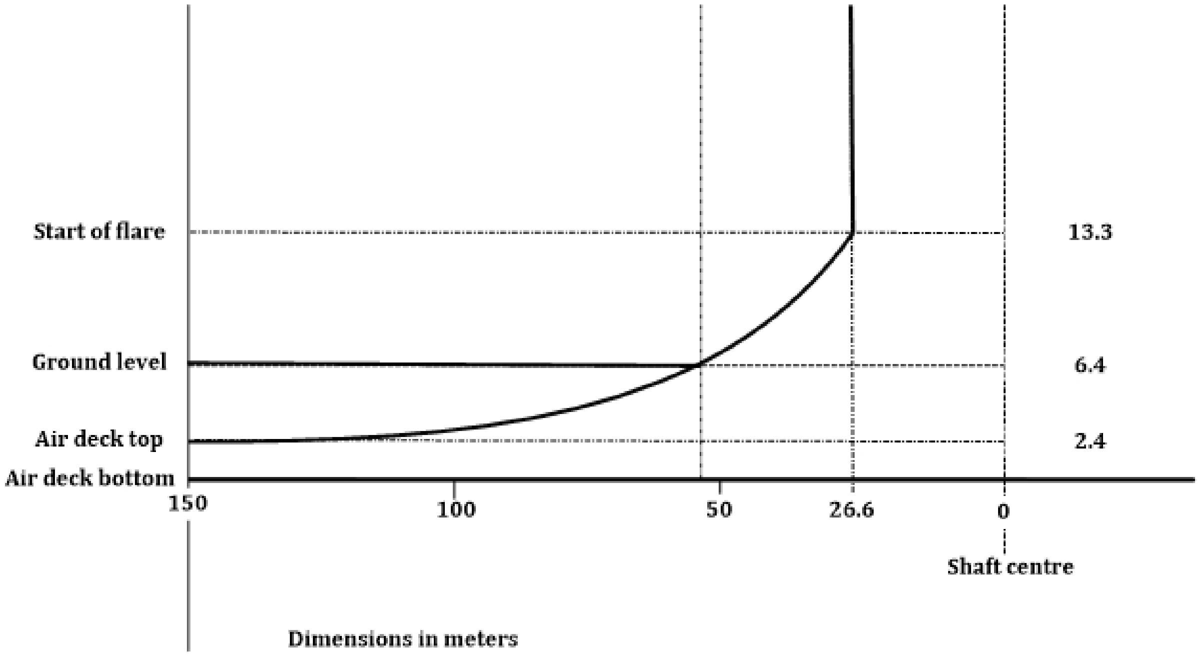

Figure 6. The shape of the bell mouth at the bottom of each airshaft required for constant volume airflow into the air-deck.

3.3.4 Coriolis effects on air movements.

Once spin-up is complete the bulk of the atmosphere moves around with the rotating hull but flowing air is subject to Coriolis effects. Specifically, air spreading out from the flared bottoms of the airshafts into the air-deck is affected; air moving East to West tends to be overtaken by the spinning deck and appears to slow whereas air moving West to East appears to speed up as it moves against the direction of spin. Air moving towards the North rotates clockwise but air moving to the South rotates anticlockwise analogous to winds on Earth; the airflow therefore sweeps all around the circumference of the air-deck, with vortices to North and South. Unlike Earth's complex surface conditions, the vortices generated by air flowing out of the airshafts towards the poles moves across the smooth, uninterrupted, surfaces of the air-deck. The "weather systems" are therefore fairly stable and ensure that fresh air spreads across the full width. The speed decreases as air moves away from the airshafts because it is being bled off into the other decks and into the farms and urban areas. Air emerging from the airshafts towards the West moves against the slowing circulation causing it to back-up to some extent.

Wind friction causes a small but continuous drag on the rotation which must be boosted periodically to maintain a constant rotation rate.

3.3.5 Alternative air circulation mechanisms.

There are several potential methods for circulating air without using fans. However, the unusual geometry, Coriolis effects and pseudogravity gradient affect airflow in ways difficult to predict without detailed computer modeling. Pseudogravity is produced by centripetal acceleration inside the rotating cylinder and appears to give "weight" to objects sitting on the rim (or less "weight" for those supported above the rim). The air is in contact with the rim so appears to feel a "force" due to pseudogravity and this "force" is felt to a continuously decreasing extent throughout the air column from rim to hub. It is this effect that is described here but for simplicity it is referred to as a pseudogravity gradient. Similar arguments apply to other continuous columns of fluids so a pipe full of water descending from the hub condensers will deliver water under pressure to the rim farms.

Detailed computer modeling of these effects is beyond the scope of this study, although some simple calculations show promise.

Method 1. Convection, driven by differences in temperature between adjacent masses of air is one possible mechanism. Pseudogravity ranges from Earth's 1g at the rim, to 0.41g (approximately Martian) at greenhouse roof height, falling to 0.22g at the air conditioners located above the windows. Although this should provide significant buoyancy at all levels, differences in air temperature are small throughout (Table 7) so convection in the bulk of the interior is minimal. However, the temperature in the airshafts is ~2°C lower than the surrounding air (resulting in an increase in density of ~1%) (Section 4.4.1, 1st paragraph) causing a "reverse stack effect" with the denser air sinking down the shafts, although it will warm a little as the pressure increases by ~1%.

The flow rate (Q m^3s^{-1}) induced by the stack effect can be calculated with equation (1)

$$Q=CA\sqrt{[2gh((Ti-To)/Ti)]} \quad (1)$$

where A is flow area, C is discharge coefficient (usually 0.65 -0.70 but 1 for unrestricted open ends), g is pseudogravity (ms^{-2}), h is height (m), Ti is inside temperature (°K) and To is outside temperature (°K).

Q depends, not only on the temperature difference, but also, on h and A which are both large. It also depends on pseudogravity, which ranges between 1g and 0.216 g so the average (0.5 g) is used.

Applying equation (1), the reverse stack effect (for three airshafts) causes the cooled air to sink at a total flow rate of -188,000,000 m^3h^{-1}. Similarly, if the solar input to the villages and the waste heat from electrical consumption were to be concentrated into similarly sized stacks, then the air would rise at a rate of 68,000,000 m^3h^{-1}. The required flow rate is 72,000,000 m^3h^{-1} so stack effect induced airflows are of the right order of magnitude and it is possible that careful design will allow air to be circulated by differential heating and cooling without using fans.

Method 2. Air flowing down the shafts will experience a sideways Coriolis force (C ms^{-2}) in the direction of spin given by equation (2)

$$C=2v\sqrt{(g/r)} \quad (2)$$

where v is air velocity (ms^{-1}), g is pseudogravity and r radius (m). Applying equation (2) at ground level for an airflow rate of $3ms^{-1}$, the acceleration due to the Coriolis effect is 0.265 ms^{-2} or 2.7% of pseudogravity (ms^{-2}) equivalent to a pressure of 2.7 kPa.

Air sinking down the airshafts has a higher pressure on the West side than the East so, if the shaft is not perfectly radial but slopes towards the West as it descends from the hub, this pressure difference should cause the air to accelerate. This may not be practical but air flowing from the shaft bottoms into the air deck will also be affected by the pressure difference resulting in equatorial winds from the West carrying air all around the circumference.

Method 3. Bernoulli's principle states that faster moving air has lower pressure. Air aloft is less obstructed, so moves faster than lower air and has lower pressure, helping suck fresh air through a building. Lower pressure air moving in the airshafts can suck air in through the tower block apartments. Similarly, the Coriolis driven equatorial winds in the air-deck suck air out from the bottom of the airshafts adding to the reverse stack effect. They also suck air from the lower decks. A simple chimney optimizes for the stack effect, while wind scoops optimize for Bernoulli's principle.

It might be possible to use a combination of these effects to help drive air circulation with reduced noise, power and maintenance requirements, mainly in the airshafts. However, fans will still be required to overcome friction and ensure that air moves throughout enclosed spaces (in the spaceports, greenhouses and villages), ventilates industrial processes and is expelled from the lower decks.

4. Modelling results and discussion.

The output from the model used to calculate mass balances for water and the principal nutrients for a closed ECLSS [1] is used as input to a new heat balance model for the habitat. The results are heavily influenced by the architecture of the habitat and especially the large open interior.

4.1 Input data for water evaporation, condensation and LH transference.

Evapotranspiration has been measured at ~200 to 700 g of water per day per g of biomass produced by photosynthesis [1]. The output from the model used to calculate mass balances for water and the principal nutrients for a closed ECLSS [1] is used as input to a new heat balance model for the habitat (available as an Excel file). The environment above the farms is not controlled so evapotranspiration is assumed to be slightly above average at 500 g per day per gram of biomass for the open farmland. The average photosynthetic process fixes carbon at a rate of 5 g.m^{-2} per day and there is 5 g of carbon in 12.5 g of biomass (dry matter) [1] so 6.25 kg.m^{-2} of water are evaporated each day. If a 10% reduction in area is allowed for access, 65 ha of growing area remain available from which ~4,070 t/day (170 t/h) of water evaporates.

The higher RH in the enclosed greenhouses (Table 7) means that evaporation rates are lower than in the less well controlled farm environment but they have almost twice the growing capacity so together they evaporate 8,530 t/day (355 t/h) of water. The total amount evaporated and condensed during crop production is therefore 12,600 t/day (525 t/h).

Not all growing plants are in the farmland and greenhouses and amenity planting in the urban areas also make a contribution. These are the same area as the farms but in the urban environment planting will be much more restricted, say 10% of the farmed area, giving 6.5 ha evaporating 407 t/day or 17 t/h.

The average amount of water required each day for personal use is ~30kg of which the amount transpired and evaporated from sweat amounts to 2.2 kg/pp/day [2]. Assuming that a similar amount is evaporated from showers and during cooking activities then the total amount for the population is 44 t/day, about 2 t/h.

A rough estimate of evaporation from fishponds and swimming pools yields another 2 t/h while pressure washing and industrial processes produce, perhaps, another 1 t/h. Evaporation rates, and LH absorbed, for each sector are summarised in Table 5.

Evaporated	t/h	LH MWh	Condensed	t/h	LH MWh
Farms	170	107			
Greenhouses	355	224			
Amenity planting	17	10.7			
Personal use	2	1.26			
Other	3	1.89			
Sub-total	547	345			
Cooling	71.3	45	A/C units	618	390
Total	618	390	Total	618	390

Table 5. Water evaporated in farms, greenhouses and amenity planting and condensed in the air conditioners. The associated quantities of LH are also shown.

4.2 Heat transport.

The latent heat of vaporization of water is 2,257 kJ.kg^{-1} (0.63 kWh.kg^{-1}, 0.63 MWht^{-1}) so to evaporate 547 t during crop production absorbs 345 MWh, which is released again when the water is condensed and the waste heat dumped via the radiators. However, the total amount of waste heat that must be transported from throughout the habitat to the hub air conditioners is 390 MW so about 88% of the required waste heat transport and disposal is achieved by the water cycle.

Increasing ventilation rates in the hydroponics units would force additional evapotranspiration and so increase this fraction but would cause other problems, especially for CO_2 supplementation. To avoid this complication and achieve the necessary amount of heat transfer, an additional 71 t.h^{-1} of water must be condensed which requires an 11% increase in the capacity of the air conditioners. The excess 71 t.h^{-1} of condensate is returned to the dry air after the heat has been extracted and allowed to evaporate to absorb 45 MW.h^{-1} of LH as it moves down the ventilation shafts. Although the air has been cooled it has also been dried and is still warm enough to absorb large amounts of water. The specific heat of air (density 1.2 kg.m^{-3}) is ~1.00 kj/kg/K so to heat 1 m^3 by 1 °C, 0.000333 kWh of heat is required. An airflow of 72,000,000 m^{-3}h^{-1} must lose 24 MW each hour to reduce the temperature by 1°C, but removing 45 MW each hour cools the air by ~2°C (Table 7). The airshaft starting temperature is 21.5°C, which is cooled to 19.7°C; since both temperatures are above the dew point (14°C), all the water droplets should evaporate (Table 7).

To do this rapidly, however, it is necessary for the water droplets to be as small as possible and for the air to be mixed thoroughly. Also, Coriolis effects would cause large drops to "rain out" on the Western sides of the vertical ventilation shafts as the air/water stream moves downwards. To avoid these potential problems, the water is added as a fine mist to both greatly increase the surface area and produce drops too small to sediment out under the influence of either the Coriolis effect or pseudogravity.

Urban heat input (MW)		Farms heat input (MW)		Hub heat intake (MW)		Hub heat dump (MW)		Radiator required (km^2)
Sun	32	Sun	32	Farms	192	Sun	126	0.44
Fans	63	Urban & Deck 1	142	GHs	113	Electric	264	0.93
Deck 3	46	LEDs	6	Space ports	12			
		Electric unallocated	12	A/C & fans	73			
Total	142	Total	192	Total	390	Total	390	1.37

Table 6. How the waste heat from sunlight, LEDs, fans and pumps, is distributed throughout the habitat and dumped via the hub A/C units and radiators.

Fans designed to create turbulence and rapid mixing within the shafts also provide the downward force to assist the circulation.

The heat balance in Table 6 shows how the total heat of insolation (126 MW), plus the waste heat from electricity consumed (total electric 264 MW), is distributed and dumped via the radiators.

4.3 Cooling system.

Assume the coolant drops to 0°C in the radiators then warms up to ambient temperature (25°C) in the internal heat exchangers. The heat capacity of water is 4.2 kj/kg/K or 0.00117 kW/kg/K (0.00117MW/t/K) so a flow rate of (400/0.00117)/25 = 13,300 t/hr (3.7 t/s or 3.7 m^3s^{-1}) is required to achieve the necessary cooling effect. If there are two sets of radiators and each has a main cooling pipe 1.6 m in diameter, a linear flow rate of 1 m/s is required to move 2 m^3s^{-1} between the A/C units and the external 1.37 km^2 of radiators.

4.4 Heat balance and variations in temperature and humidity.

The data in Table 7 are based on the volume of air passing through the ventilation system in one hour and show how temperature and humidity vary as air moves around the interior. The numbers are reasonable estimates for the restricted spaces between decks, in the greenhouses, hub and airshafts, but air leaving the ventilation system and entering the interior is massively diluted so temperature and humidity will vary very little. The numbers in parenthesis are more realistic rough estimates of the average values above the farms and urban areas and outside the greenhouses. They are calculated by multiplying the vent value by the ratio of the airshaft and urban / farm /

greenhouse areas, respectively. The effect of heating and evaporative cooling is shown separately in each case.

It is assumed that much of the electrical consumption takes place in the urban areas and, for simplicity, the waste heat from the machinery space on deck 1 is also included and added to the solar heating. This produces a net heating effect despite the small amount of evaporative cooling from amenity planting.

In contrast, the farming areas receive less heating from the solar input, some LED lighting and a small amount of heat from composting on deck 3, so there is net cooling from the much larger quantity of plants being grown.

The enclosed greenhouses are heated not only by solar input but also from the supplementary LED grow-lights plus warm air from the animal pens and fish raising areas. Even so, the intensive hydroponic cultivation in a restricted volume produces some overall cooling. The large amounts of water evaporated in the greenhouses are reflected in the high RH value shown, but dilution rapidly returns it towards the target value.

	Leaving Urban areas	Leaving farms	Leaving greenhouses	Leaving hub	Leaving bottom of airshafts
Temp (°C)	(25)	21.9 (25)	21.5 (25)	21.5	19.7
Heating (°C)	+5.9 (+0.063)	+1.4 (+0.012)	+8.0 (+0.04)	+16.3	0.00
Cooling (°C)	-0.58 (-0.0053)	-4.46 (-0.041)	-9.3 (-0.09)	-17.1	-1.9
Change (°C)	+5.34 (+0.049)	-3.11 (-0.029)	-1.4 (-0.05)	0.00	-1.9
RH (%)	50	60.8 (50.6)	87.7 (51.0)	43.2	54.4
H_2O (g/kg)	9.98	10.00	14.11	6.96	7.78

Table 7. Temperature and humidity variations for ducted air leaving the various sectors. Numbers in parenthesis are rough estimates of the values in the main atmosphere, which vary little because of the large dilution effects.

The latent heat of water condensing in the dehumidifiers causes a temperature increase balanced exactly by the temperature drop from the waste heat dumping system. Air leaving the hub is cool and dry and readily absorbs moisture to cool further in the airshafts. The airshaft coolers complete the cycle and return comfortably moist, cooled (20°C) air to the villages, farms, lower decks and greenhouses.

After allowing for dilution, variations from the target values (25°C and 50% RH) in the farms and urban areas are very small, which demonstrates that the relatively few ACHs in the interior are sufficient to maintain equitable conditions. The rate of CO_2 / O_2 exchange is linked to evapotranspiration in the ECLSS model and implicit in the input data. Therefore, because the results show that heat and water vapour are efficiently circulated and exchanged by the plants, CO_2 and O_2 must be too. These data and arguments apply to the main interior volume and not necessarily to enclosed spaces which are ventilated separately at much higher rates.

The importance of plants inside the habitat is clearly demonstrated by these results. Some of the benefits of plants are fairly obvious but others less so. The benefits are summarized as follows:

1. nutritious food (from crops),
2. clean air (CO2 / O2 gas exchange and absorption of pollutants),
3. clean water (animal waste in dirty water metabolized and evaporated moisture condensed for potable water),
4. cooling (by absorption of LH during evapotranspiration),
5. heat transport (stored as LH in circulated moist air),
6. enable waste heat disposal (LH recovered in the condensers dumped via radiators).

For the present design, cooling enabled by evapotranspiration amounts to 88% of that required, with the remaining 12% provided by evaporation of water sprayed into the airshafts. The mechanisms required for internal heat transport are therefore significant constraints on habitat designs.

5. Conclusions.

This preliminary analysis of the heat and water balance in a large orbital habitat is based on published modelling results for an ECLSS and is therefore more detailed than has previously been possible. Data from Biosphere 2 has also been used and allows comparison and validation of the results against the only real-world example of a large closed artificial ecosystem.

The results show that comfortable levels of temperature and humidity can be maintained despite relatively few ACH. Rates of CO_2 /O_2 exchange are linked to the water cycle so they must be circulated adequately too. The successful heat and moisture management also provides a useful proxy for circulation and removal of trace pollutants. The power required for ventilation with minimal atmospheric circulation is significant (50% of power available) meaning higher cycling rates are unaffordable. Consequently, the strategy of preventing atmospheric pollution instead of actively cleaning it is shown to be essential.

The main "housekeeping" power demand is 83% of that generated, leaving 17% (46 MW) or 4.6 kW pp which should be more than enough to run elevators, internal transport, and other machinery as well as for personal use and some light industry. The power needed to run the ventilation and cooling systems, as well as limitations in the capacity if the internal waste heat transport mechanisms, are significant constraints on habitat design.

The importance of plants inside the habitat is confirmed and, besides the expected benefits of providing food, clean air and water [1], they also have a less obvious role in cooling the habitat and enabling heat transport in the circulated air. A combination of regulations and mechanical air circulation and pollution abatement systems is necessary to maintain high air quality and comfortable levels of temperature and humidity.

Simple calculations of non-mechanical means for circulating the air utilizing the reverse stack effect, Coriolis forces and Bernoulli's principle show promise as power saving and noise reducing measures but require detailed modeling work to confirm. Drag caused by Coriolis effects on air moving through the ventilation system must be countered periodically to maintain constant habitat rotation rate.

Continuous illumination is convenient for shift working and communication with Earth while enabling small, but useful, quantities of electricity to be generated while avoiding the complication of simulating night time with mechanical blinds.

6. Acknowledgements.

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APPENDIX: Precursor Studies and Practical Comparisons

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A key goal of this paper has been to deliver a space habitat design at one level of detail deeper than most theoretical precursor studies, a strategy which enables the comparison and validation of aspects of the design with relevant space-based and terrestrial examples.

This Appendix gathers together results of a survey of such examples.

A.1 Space Habitats

The International Space Station (ISS) [A1] is at present our only permanently inhabited space outpost, capable of supporting six crew for extended periods, with power from sunlight, and resupply of comestibles from Earth. This example offers no guidance as to the sustainability of ECLSS in space, but does offer a reference mark concerning life-sustaining power usage. The power per person figure quoted here (Table A2) is based on power supplied by the USOS solar panels; the Russian modules have separate panels. Power provided is given as 84-120kW, but the station spends 35 of every 90-minute LEO orbit in eclipse, working off batteries; the figures in the table reflect input averaged over the orbit.

Of significant theoretical space-habitat studies of the past, the Stanford Torus [3] (1975) was an 1800m-dia. wheel habitat with a crew of 10,000, supported by ECLSS sunlight-driven agriculture. The energy flow is summarized on pp102-3. The station has a large mirror (~600m radius) to collect sunlight, some of which is fed directly into the habitat, and the rest to feed a solar cell farm. The largest energy input into the habitat itself is the insolation of the agricultural and residential areas, with a smaller input from the solar cell station.

A more recent ECLSS study, Kalpana One [4] (2007), was a cylindrical habitat of 500m diameter with 3,000 inhabitants. Food produce was based on 'high intensity, controlled environment agriculture' using artificial light (p9).

Note that the present study attempts a greater depth of detail than either of these precursors. Regarding atmosphere exchange and cleansing, for example, such requirements are not made specific in the precursors, with any power requirements subsumed under global figures—though the Stanford authors did note the need to '[pass] the atmosphere . . . through a thermal processor several times a day' ([3] p99).

A.2 Ground-based Precursors

A.2.1 Biosphere 2

Regarding ECLSS studies the Biosphere 2 experiment, based on a sealed habitat in Arizona, remains to date the only example of a working large-scale long-running enclosed-biosphere human habitat [A2]. See Table A1 for key technical parameters.

The habitat was contained aboveground by a glass superstructure, and underground by a steel liner. Through each 2-year 'closure' experiment (1991-4), Biosphere 2 was virtually materially sealed (<10% air exchange per year) but open to the energy of sunlight, electricity and heat transfer. For food, Biosphere 2's eight-strong crew relied on the energy of the sunlight falling on their 2,000m^2 agricultural section. Mechanical support included systems to circulate and process air and water, to process waste, and to simulate tides, currents and waves [A3].

The solar flux through the glass roof on the agricultural area averaged at 267kW, or 138 W/m^2, or 33 kW/person. Electrical power for pumps, fans and all other internal systems was supplied by an external Energy Centre running on natural gas. The peak demand was 1500kW, averaging 700kW—that is, about 88kW per person [A4].

The largest demand for artificial energy was the maintenance of temperature and humidity conditions. Cooling within the habitat was achieved by having the air forced by a blower across heat exchangers in conventional air handlers [A5]. A 40-60 HP (~30-45 kW) blower was required to circulate the air through each of the air handlers' radiators. There were 26 air handlers in the habitat, each capable of airflow up to 24 m^3 /sec, so that power devoted to air circulation was 0.78-1.17 MW. This arrangement was sufficient to provide 14 ACH for the whole habitat.

A2.2 McMurdo Station and the Halley VI Research Station

McMurdo Station and the Halley VI Research Station are permanently crewed Antarctic bases. While unlike Biosphere 2 they make no attempt to sustain closed life support systems, they do sustain human populations for lengthy periods in essentially uninhabitable environments, and so can provide data in particular on necessary power usages. For the present study McMurdo is particularly relevant as it sustains a comparatively large population (~250) on artificial life support systems through the Antarctic winter.

McMurdo Station [A6], Antarctica's largest community, is situated on Ross Island. It is essentially a small town which has grown haphazardly in response to the needs of individual projects. In 2005 it consisted of ~100 buildings covering ~40,000m^2. Run by the U.S. National Science Foundation (NSF), the main purpose of the station is science. In Antarctic summer the station can host >1000 residents; it endures a winter 'closure' from February to August, when the ~250 (or less) 'winter-over' inhabitants must survive without resupply. The purpose of the winter-over crew is essentially maintenance.

At McMurdo, a distillation plant extracts fresh water from salt water. But food and power must be (mostly) imported. In the summer a weekly delivery, mostly by sea, provides 4,700 lb (2100kg) of fresh food per week. The major delivery of supplies for the winter-over residents, made by ship in early February, consists of 26 million lb (11.8 million kg) of goods.

According to a NSF briefing [A7] the input of stores includes, annually, ~1.3m gallons (5200 m^3) of diesel fuel, which delivers a power supply of 1700kW. So, in the winter the 250 staff draw 6.8kW each.

The British Antarctic Survey runs the Halley VI Research Station [A8], situated on the Brunt Ice Shelf. The station supports 70 staff in the summer, and 16 in the winter. Halley VI is powered by four combined heat and power (CHP) engines that run on aviation fuel. In the winter the total power delivered is ~480kW, or 30kW / person. Liquid water production is one of the station's greatest energy demands. The staff recycle water but not in a fully closed loop; they need to melt 20 liters of water from the ice per day per person.

A.3 *Discussion*

The key question regarding power in artificial habitats was posed by Fogg in 1995 [A9]: '*Most basic life support on Earth comes for "free." In space it will represent an additional power requirement. How much more?*'

A study of Table A2 suggests some answers. The purpose of the table is an order of magnitude comparison of the real-world stations with space habitat studies in terms of energy usage.

A starting comparison point for a discussion of power usages in artificial habitats is the power provided to citizens of modern industrial economies. According to the *Guardian* of October 16 2016, the UK National Grid anticipated an average peak demand of 52.7GW during that year's cold weather, with 55GW of supply capacity available. Meanwhile, according to the 2011 census, the total population of the United Kingdom was 63,182,000 [A10]. So, power usage was *834 W/person.*

Of the practical examples of habitats without ECLSS (ISS, Hadley and McMurdo), it can be seen that power usage ranges from ~7kW-30kW per person, so an order of magnitude larger than the UK reference figure. The Biosphere 2 number, in which ECLSS was supported, is an order of magnitude higher again.

But the figures for Stanford and Kalpana habitats, which did support ECLSS, are significantly *lower* than Biosphere 2. Stanford's estimate was based on 'doubling that of the current U.S. per capita consumption to account for the need to recycle all materials in the colony' [3] (p103). For Kalpana, the residual power supply estimated, like Stanford, 'total energy use per person in the U.S. today, including industrial use' [4] (p9).

Concerning agricultural growing area, Table A3 gives comparisons of the two ECLSS-based studies, Stanford and Kalpana, with the real-world example of Biosphere 2.

In the case of Kalpana One food produce was based on 'high intensity, controlled environment agriculture' using artificial light [4] (p9). This would have required 50m^2 per person and 50kW power, the latter in fact more than the Biosphere 2 solar power allowance per head.

In the case of Stanford, however, its agricultural area per head is given as 61 m^2 per head ([3] p61), with sunlight power per head scaled accordingly. The authors hoped that advanced farming methods and environmental controls would 'increase productivity to approximately ten times that of the average American farm' (p98).

In short, the Stanford study authors hoped that the torus's agriculture would be four times as productive per unit area as Biosphere 2, while using only 3% of the power per head for its support systems.

A preliminary conclusion is that at least some previous studies of ECLSS-based space may have been drastically over-optimistic concerning the provision of such essentials as power and growing area. These parameters do severely constrain any space habitat design—as noted in the main text, in the present design an extra megawatt of power requires an extra 3,520m^2 of radiator surface—but plausible allowances are necessary for any valid design, a plausibility that will come from increasingly detailed studies.

The data in Table A1 (Biosphere 2 Dimensions) is summarized from [A2]. The 'habitat' was the human living quarters. The habitat contained several biomes of which all were 'wilderness' save for the agricultural areas. The 'lungs' were large expansion valves intended to maintain an equalized pressure during temperature excursions. (Note: 'lungs' measured at 50% inflation.)

Section	Area (m^2)	Volume (m^3)	Soil (m^3)	Water (m^3)	Air (m^3)
Agriculture	2000	38,000	2720	60	35,220
Habitat	1000	11,000	2	1	10,997
Wilderness biomes	5900	106,000	14,000	3900	88,100
Lungs	3600	30,750	0	750	30,000
Total	12,500	185,750	16,722	4710	164,320

Table A1: Biosphere 2 Dimensions.

	Personnel	Power source	Input power	Power / person
Biosphere 2	8	Gas power station	700kW	88kW
McMurdo Station	250-1000	Diesel plant	1700kW	6.8kW
Hadley VI	16-70	CHP plant	480kW	30kW
ISS	6	Solar panels	56-80kW	9-13kW
Stanford Torus	10,000	Solar cells	30MW	3kW
Kalpana One	3000	SPS	30MW	10kW

Table A2: Energy in space habitats—comparison.

	Biosphere 2	Stanford Torus (ref 9 p103,96, Fig 5.18)	Kalpana One (Ref 8 p9)
Agricultural area / person (m^2)	250	61	50
Agricultural power / person (kW)	33 (solar)	6.6 (solar)	50 (artificial)

Table A3: ECLSS Habitat agricultural designs compared (figures given per person).

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