Design of a Containerized Greenhouse Module for Deployment to the Neumayer III Antarctic Station

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Designs for an Antarctic plant production system to be deployed at Germany's Neumayer Station III are presented. Characterization and testing of several key controlled environment agriculture technologies are ongoing at the German Aerospace Center's Institute of Space Systems. Subsystems under development at the Evolution and Design of Environmentally-Closed Nutrition-Sources (EDEN) laboratory include, tuned LED lighting, aeroponic nutrient delivery, ion-selective sensors and modular growth pallets. The Antarctic greenhouse module baseline form factor is a standard sea shipping container, which allows for use of nominal Antarctic logistics networks. The facility will be fixed onto a specially constructed platform and co-located near the Alfred Wegner Institute's Neumayer Station III. The plant production facility will be operated year-round with maximum production per unit volume achieved through the deployment of modular grow units in a stackable rack architecture. In such a configuration the greenhouse module system can provide several kilograms of fresh edible biomass per day. Forty foot and 20 ft container configurations are described as well as the general design requirements, including specifics relevant to operations at Neumayer III. Successful deployment of such a facility will further the technology readiness and operational experience of space-based bioregenerative life support systems. Finally, the general design is presented in the context of an historical review of past Antarctic plant production facilities. This first known inventory of documented Antarctic plant production facilities, organizes the facilities with respect to Antarctic station, dates of operation, internal/external configuration and estimated production area.

I. Introduction

Crews operating in remote regions, such as Antarctic and Arctic field sites, operate under constraints analogous to those faced by astronauts operating on-orbit or on other planetary surfaces. These constraints can include extreme environments, challenging resupply logistics, and psychological isolation. In order to maintain operations, these isolated research facilities need to import consumables at typically high or subsidized costs.

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Further, the deliveries to these remote facilities are often sporadic. In such circumstances, in-situ plant production often represents the only solution remote station crews have for fresh produce.

Numerous Arctic communities and research facilities have constructed growth chambers or greenhouses for plant production. Arctic greenhouse facilities have been implemented in Russia, Alaska, Canada and Norway (Svalbard) [1, 2]. Facilities have also been constructed in Antarctic locales and although plant production in the Antarctic is governed by stringent environmental regulation, numerous countries have justified and deployed plant production systems. In particular, Australia [3], Chile [4], Germany [5], India [6], Italy [7], Japan [8], South Korea [9], New Zealand [10], Poland [11], Russia [5], United Kingdom [12], United States [13] have implemented Antarctic plant growth facilities.

Although several of the more recent systems have achieved greater sophistication, the bulk of Antarctic greenhouses/growth chambers have been simplistic in design. Many facilities have been developed by expeditioners, often developed solely with materials found on-site [5, 12]. The often piecemeal construction of these systems, or the historical growth of decorative plants within Antarctic stations such as that reported by Antarctic Treaty and Environmental Protocol inspection reports, demonstrate the benefit and the desire humans have to see and be exposed to plants in environments that are naturally devoid of such sensory input [4, 14, 15]. More recently, with the inception of more detailed environmental regulations (e.g. the Madrid Protocol) plant growth activities in the Antarctic have come under increased scrutiny. In particular, current plant production systems, including those currently under development, must abide by a suite of environmental regulations that essentially necessitate advanced plant production technology. These types of regulations, the harsh Antarctic environment, and the demanding operations of remote Antarctic outposts are in many ways analogous to future space/planetary greenhouses. Given the fidelity of this analogy, reviewing previous, current and planned Antarctic facilities provides useful input to current bioregenerative life support system test-bed design efforts.

Although the regulatory environment within which Antarctic plant production systems operate under is stringent, this has in no way inhibited countries in developing and deploying such facilities over the long-term. Further evidence of the benefit of local plant production is demonstrated by the list of documented Antarctic plant production systems in Table 1. The contained information only includes systems that were specifically designed to grow crops in a designated greenhouse or plant growth area. It does not include references to the growth of single or the small numbers of decorative/house plants that were common during the early establishment of long-duration Antarctic bases. It is also important to note that to the knowledge of the authors, no comprehensive review of Antarctic production systems has been conducted. The results compiled here are an initial attempt at such a survey but as evident in Table 1 various pieces of information are still lacking. Furthermore, much of the early plant growth activities in the Antarctica were conducted by expeditioners for personal interest and not as a primary station or science activity, as such there is little or no documented description of the systems. It is known that much of the early plant production activities were unreported and in many instances as is apparent from the references provided in Table 1 the sole source of information for some of these activities stems from Antarctic Treaty and Environmental Protocol inspection reports. Indeed, other facilities beyond those listed in Table 1 may still exist, in particular those implemented before the Antarctic Environmental Protocol.

Table 1. Summary of documented Antarctic (south of 60°S latitude) plant growth facilities.

Station Name	National Program	Latitude (DDM)	Longitude (DDM)	Facility Type	Active	Dates of Operation	Full Facility Area	References
Casey*	Australia	66° 16.941' S	110° 31.608' E	Int.	No	1980	6.6 m^2	[16]
				Ext: Cont. type	Yes	Opened: Summer 2000-2001	27.7 m^2 (2 x 20 ft cont.)	[3, 17-19]
Davis*	Australia	68° 34.556' S	77° 58.171' E	Ext: Cont. type	No	1984	13.9 m^2 (1 x 20 ft cont.)	[16, 20]
					Yes	Opened: 2000-2001	13.9 m^2 (1 x 20 ft cont.)	[3, 17-19]
Mawson	Australia	67° 36.159' S	62° 52.382' E	Ext: Wood building	Yes	Opened: 1995	28 m^2	[3, 17-19]
Eduardo Frei Montalva	Chile	62° 12.014' S	58° 57.758' W	N/A	N/A	Pre-2000	N/A	[4]
Dakshin Gangotri	India	70° 5.000' S	12° 0.000' E	Int.	No	1986	N/A	[5, 14, 21]
Maitri	India	70° 46.010' S	11° 43.847' E	Int.	No	1986	N/A	[5, 21]
				Int.	No	Opened: 1990. Closed: Between 2002-2009	28.2 m^2	[22-26]
				Ext.: Dome	No	Opened: 1991. Closed: N/A	7 m^2 (estimated from [27])	[27]
Mario Zucchelli	Italy	74° 41.688' S	164° 6.796' E	Ext.: Cont. type	No	Opened: 1997. Closed: 2002	1997-1999: 13.9 m^2 (1 x 20 ft cont.) 1999-2002: 31.4 m^2 (2 x 20 ft cont. w connecting module)	[28-30]
Novolazarevskaya	East Germany	70° 46.650' S	11° 51.050' E	N/A	No	Opened: Mid 1970s. Closed: 1993	Small greenhouse	[5, 31]
Syowa	Japan	69° 0.247' S	39° 34.910' E	Int.	No	1966-1967	0.2 m^2	[8]
King Sejong	Rep. of Korea	62° 13.394' S	58° 47.190' W	Ext.: Cont. type	Yes	Opened: 2010	13.9 m^2 (1 x 20 ft cont.)	[9, 32-34]
Scott Base	New Zealand	77° 50.966' S	166° 46.037' E	Ext.: Cont. type	No	Opened: 2000. Closed: 2005	27.7 m^2 (2 x 20 ft cont.)	[10, 17, 35]
Arctowski	Poland	62° 9.586' S	58° 28.399' W	Int. (science building)	No	Opened: 1977-1978. Closed: Late 1980s. Later reopened and re-closed	37.9 m^2	[11, 32, 36-38]
Novolazarevskaya	Russia	70° 46.616' S	11° 49.420' E	Int.	N/A	N/A	Mid to large sized system	[5]
Halley I	UK	75° 34.789' S	26° 43.717' W	Int.	No	Opened: 1962. Closed: 1963	0.54 m^2	[12]
				Ext.: Wood construction	No	Opened: End 1962. Closed Early 1963	2.75 m^2 (estimated from [12])	[12]
Amundsen-Scott South Pole Station	USA	89° 59.850' S	139° 16.370' E	Int.	No	Experiments commenced in Winter 1957	<1 m^2	[39]
				Ext.: In station dome	No	Opened: 1990. Closed: 2005	Approx 3 m^2	[13, 40, 41]
				Int.	Yes	Opened: 2004	50 m^2	[13, 17, 42]
McMurdo	USA	77° 50.893' S	166° 40.105' E	Ext.: Wood building	No	Opened: 1989. Closed: End 2010-2011 season	66 m^2	[13, 17]
Previously or currently planned facilities								
Comandante Ferraz	Brazil	62° 5.077' S	58° 23.554' W	Int.	No	N/A	N/A	[43]
Bernardo O'Higgins Riquelme	Chile	63° 19.257' S	57° 53.987' W	Ext.: Specialty constructed	N/A	N/A	24.2 m^2	[44, 45]
Halley VI	UK	75° 34.789' S	26° 43.717' W	Int.	No	N/A	10 m^2 (estimated from [46])	[46-48]

*Int. = internal, Ext. = external, Cont. = container, *Australian plant growth activites at Casey and Davis were commenced at least as early as 1969 [49][§§]. Several different projects (not included in summary table) were conducted at Australian stations between 1969 and 1989 when Australian Antarctic hydroponic activites were temporarily halted [17, 20, 50].*

[§§] Private Communication. Gillies J. (Aurora Journal) "Casey Station plant growth activities." 2014

Early published references to organized plant production activities in the Antarctic date back at least as far as 1957 when a hydroponic growth system was set up in the newly constructed US South Pole Station [39]. A simple growth apparatus was constructed out of an aluminum baking pan and a number of breadpans in which philodendron, sweet potatoes, watercress, radish and clover were grown [39]. In mid-1962 an overwintering expeditioner at the UK Halley I Station constructed both an internal hydroponic growth system within the station's radio office and later that same year, a small wooden greenhouse that permitted the use of natural sunlight [12]. The author also suggested that around the same time, expeditioners at other British Antarctic Survey stations were using small conventional greenhouses [12]. The first deployment of plant growth hardware to Japanese and Australian stations occurred soon afterwards. In 1967, Japanese developed 'Plant Boxes' were utilized to grow fresh vegetables on both the S.S. Fuji Japanese Antarctic vessel and subsequently at the Syowa Antarctic Station [8]. The ship installed production system included a 2.7 m^2 plant production area and operated onboard from November 20, 1965 to when it returned from its Antarctic resupply trip to Tokyo on April 8, 1966 [8]. The Syowa Station system had a production area of 0.2 m^2 and was operated from 1966-1967 [8]. Australia first conducted on-site plant growth activities at its stations in the late 1960s [17]. For example, in 1969 a spare Davis Station room was converted to a grow chamber and an external greenhouse constructed [49]. Australian interest in Antarctic hydroponics dates back to the late 1970s [16, 17]. A large and well-known greenhouse at the Polish, Arctowski Station was first constructed during the 1978-1979 timeframe [36]. This greenhouse, like the Australian units and those of a number of other nations, were later suspended to ensure that environmental regulations could be appropriately addressed [3, 4]. A number of these facilities have subsequently been reopened or reemployed in different forms, such as those at Australian stations of Casey, Davis and Mawson in addition to the sub-Antarctic Macquarie Island Station [3, 18].

As evident from Table 1 approximately half of the total Antarctic plant production systems have been setup external to the primary station structures (i.e. separate devoted structures for plant production), with the other half setup internal to the primary structure. Internal systems have been built both in the main living/common areas of the stations as well as in sub-sections of existing station buildings. Internal configurations are highly visible and as such are more likely to enhance psychological well-being. Further, they can be implemented in isolation from the extremes of the external environment. External buildings/structures benefit from the isolation that the extreme environmental conditions provide in that they are somewhat protected from the introduction of non-native species and cross-contamination from either the main station into the greenhouse or from the greenhouse into the station and subsequently into the Antarctic environment.

External plant production facilities typically are based on one of two basic design platforms. Approximately half have been constructed within standard shipping containers, with the remaining systems constructed from wood or other specialized building materials. In almost all instances, these containers and other structures were previously used for some other purposes and then outfitted on-site with hydroponics equipment [3]. Alternatively, the Republic of Korea's new Plant Factory was specially developed and outfitted off the Antarctic continent before shipment to Antarctica station King Sejong [34]. Along similar lines, as previously stated, many of the early stations utilized on-site hardware for the construction of the plant growth hardware. In these instances such things as empty cigarette tines, cooking supplies, penguin guano (as fertilizer), and other general hardware has been utilized [4, 12, 39]. These basic systems have more recently been replaced with more highly automated and sophisticated systems such as the Republic of Korea's Plant Factory or the US South Pole Food Growth Chamber (SPFGC) [13, 34]. These systems have been built on advances in controlled environment agriculture technologies and past Antarctic experience and strive to produce maximum output for minimum inputs.

Table 1 also summarizes growth systems that were planned but never built, or are currently planned and at some stage of implementation. Indeed plans were made to incorporate a specially built external plant production facility exploiting natural light into the Chilean O'Higgins Station and more recently designs of Halley VI Station included an internal hydroponic system within the station's main common area [44, 45, 48, 51]. Construction of the latter facility was eventually terminated on economic grounds*. During the rebuild planning of Amundsen-Scott South Pole Station, another plant production system (cf. to the implemented SPFGC) was studied and a prototype constructed at NASA Ames Research Center. Although not implemented at South Pole, this crop production system was part of an advanced life support tested design that also incorporated aquaculture and waste treatment facilities [52-55]. Brazil currently has plans to implement an internal hydroponic growth system in the [rebuilt] Comandante Ferraz Antarctic Station [43].

The design and deployment of an advanced container-based plant production system to the German Neumayer Station III is discussed and elaborated here. Various subsystems are presently undergoing test at the German Aerospace Center's (DLR) Institute of Space Systems as part of the Evolution and Design of Environmentally-

* Private Communication. British Antarctic Survey. "Status of Halley VI plant growth activities." 2014.

Closed Nutrition-Sources (EDEN) initiative. Although the plant production facility is in actuality a growth chamber, the term ‘greenhouse’ will be used interchangeably with growth chamber for the purposes of this review. The facility will provide a non-negligible addition to the small over-wintering team’s diet, while becoming the first plant production facility to be deployed to a Neumayer Station thus benefiting the crew from a psychological perspective. The deployment and operations at Neumayer III will help advance the readiness of the discussed controlled environment agriculture technologies and better position them for use in future space-based bioregenerative life support systems.

II. Neumayer Station III

The proposed deployment site for the greenhouse module is the Neumayer Station III operated by the Alfred Wegener Institute for Polar and Marine Research (AWI). The station (Figure 1), like the former Neumayer I and II stations, is located on the Ekström Ice Shelf in Antarctica’s Atka Bay [56]. Neumayer III was constructed during the 2007 – 2009 summer seasons. The two-story, above ground portion of the station is situated on an elevated platform 68 m long by 24 m wide and provides 2118 m^2 of living and working area. The elevated platform is constructed on 16 hydraulic struts that allow the station to be raised to accommodate snow accumulation, thereby extending the station life expectancy [57]. The Neumayer Station III has been selected as the best candidate for deployment of the greenhouse module based on logistical, infrastructure and environment properties. The bulk of Neumayer III resupply occurs once a year by ship [58]. Each December the AWI research vessel Polarstern, delivers resupply and research equipment from Bremerhaven, Germany, via Cape Town, South Africa, to the coast of Antarctica in the vicinity of Atka Bay. The supplies are then moved over the ice with Pistenbullys (tracked vehicles) to the station. Smaller items such as crew exchanges and certain foodstuffs are provided through air service to the station via Novo Air Base or Troll whose ice runways serve as hubs for stations and field sites within Dronning Maud Land. Nominally, 15 to 18 months of foodstuffs are maintained at the station [58]. Neumayer III is crewed year-round. In summer (December to February) typically 40 to 50 people work at the station, whereas only 9 crew members are present during the winter period (March to November). The crew size and composition during the winter season is analogous to a crewed spacecraft in that the Neumayer III crew is typically composed of e.g. a commander, a doctor, a cook, mechanics and researchers [58]. The importance placed on the Neumayer crew’s psychological well-being has been demonstrated by a number of activities, including the deployment of a 20 ft external container nicknamed “library on ice” that provides a comforting environment that crew members can retreat to, in some sense as they could with an external greenhouse module [59].

Figure 1. Neumayer III Antarctic research station operated by the AWI. Photo credit: Stefan Christmann / AWI.

In addition to benefiting from the already established AWI container transport logistics network, the containerized greenhouse module permits greenhouse systems to be installed and fully tested in the module before it is deployed. The container format also allows for easy return to Germany should some severe event damage it beyond local capacity to repair.

III. Justification

Justification for Antarctic in-situ plant production at stations operated year-round is anchored in the provision of improved crew nutrition and dietary variation. A compelling and tangible benefit beyond dietary considerations is the use of plant production units as horticultural therapy tools that can help alleviate some of the psychological stressors commonly experienced during isolation [3, 60]. The following outlines the advantages of the Neumayer

Station III as a test site for the deployment of an advanced greenhouse module. Focus will be given to the maturation of the greenhouse module's technological and operational readiness for use on future space exploration missions.

A. Crew Size

The Neumayer Station III crew size varies with the season. During the summer season a team of approximately 40 to 50 people is maintained at the facility. During the Antarctic winter, a small team of approximately nine crew members remains to maintain systems and continue annual science data collection. The size and duration of the overwintering team aligns well with current ISS crew sizes as well as those proposed in Moon/Mars design reference missions.

B. Crew Dynamics

Typical resupply schedules for an Antarctic station are very similar to current space station resupply schedules. There is a typical 9 month lag between resupply missions to Neumayer Station III, which exposes the crew to strong isolation pressure and the associated psychological responses. Unlike laboratory-based long-duration isolation studies, Antarctic crew members must count on technology to survive as there is no door that can be opened to 'end the simulation' in an emergency. Furthermore, although crew members are provided traditional recreational opportunities, growing plants is an activity where the output of a few interested crew members can be enjoyed by the entire crew. From this perspective, effects on the psychological well-being of the crew can be compared with real long-duration space exploration scenarios, where some members of the crew can enjoy passive psychological benefits provided by the efforts of their crew mates.

C. Extremely Low Biodiversity Environment

The Antarctic continent is not only an extremely cold and arid desert, it is also one of the most protected, and biologically sparse environments on Earth. The Neumayer Station III greenhouse module is a high fidelity testing environment for microbiological experiments aimed at refining planetary protection protocols for long-duration human habitation of extra-terrestrial planetary bodies (e.g. Mars). Microbial contamination and distribution patterns can be accessed, as can remediation protocols and preventative practices.

D. Inhospitable Environment

The harsh environmental conditions typical of Antarctic research stations can only be found at a select few places on Earth. High winds, heavy snow fall (site dependent), low temperatures and seasonal dark periods lasting several months make this an environment where successful plant production requires advanced controlled environment technologies.

E. Habitat Interface

The means by which a plant growth module interfaces with the main habitat is an essential design consideration. As an additional subsystem to the main facility, power requirements, data collection and transmission, food and waste handling, and water demands need to fit within the carrying capacity of the station. As greenhouse systems advance and are considered at the design phase of new station facilities these integration considerations will become seamless.

The proposed analogue test site provides the opportunity to validate complex integrated systems under conditions relevant to the long-term goal of operating plant production facilities on the surface of the Moon and Mars. The operation of highly integrated systems can be simulated in a laboratory. An actual deployment to a site as analogous as possible to future space missions is the only way to truly evaluate system(s) performance, and experience the unforeseen challenges associated with field deployment. The Neumayer III greenhouse module will serve to confirm the functionality and applicability of concepts and technologies developed to realize plant production in extreme environments; thereby adding another degree of security and risk mitigation for future bioregenerative life support systems.

F. Advancements over the Current State-of-the-Art

1. Advancements over other Antarctic Facilities

In addition to being the first production greenhouse to be deployed to one of the German Neumayer stations, the greenhouse will provide several advancements over past and current Antarctic facilities:

- **Incorporation of advanced CEA technologies**. Although a number of more recent Antarctic plant production systems have incorporated advanced CEA technologies, the proposed Neumayer III greenhouse module incorporates several technologies that provide significant advancement over historical Antarctic systems. In particular, the greenhouse module will incorporate technologies such as aeroponics, tuned LEDs, ion-selective sensors to enhance yields and reliability while reducing waste (power, water, nutrients). These technologies and other novel monitoring systems will also permit the greenhouse to better meet the stringent Antarctic environmental regulations than many of its predecessors.

- **Substantial test program prior to deployment.** Due to the fact that the system is being incorporated into a shipping container and not being built in the Antarctic, the greenhouse can undergo a significant test campaign prior to deployment. This will enhance overall system reliability and provide a considerable advantage over previous, more expeditioner led systems constructed on-site.
- **Non-negligible production output.** Unlike several past Antarctic production chambers, the Neumayer III greenhouse will provide biomass output levels that will be sufficient to provide a non-negligible effect on the food requirements of overwintering crews. Additionally, unlike certain Antarctic facilities that operate only during summer months when sufficient light levels are available, production in the Neumayer III greenhouse module will be conducted year round. Although situated externally to the main station and thus potentially visited less often than station-integrated production systems, the greenhouse module due to its relative size and output will have considerable capacity to provide psychological benefits to the crew from visual, crop tending and fresh food output perspectives.
- **Pull of space technology and operational strategies.** As the greenhouse is being developed with the conjoined goal of advancing bioregenerative life support systems, numerous technologies and operational strategies that may not otherwise be implemented in more traditional greenhouses will be utilized. This includes extensive remote monitoring equipment and built-in autonomy thereby reducing on-site workload while enhancing production reliability. Backroom experts will take the downloaded monitoring data and collaborate with the on-site crew to ensure efficient operations.

2. Benefits to Furthering the Goal of Space-Based Bioregenerative Life Support Systems

The main benefit to the advancement of space-based bioregenerative life support systems provided by the Neumayer III greenhouse module will be with regard to the accumulation of mission relevant operational experience. In particular with regard to the following:

- **Operating individual hardware systems.** The operation of each of the respective CEA technologies within this relevant operational environment will, based upon successful demonstration, enhance their respective technology readiness level (TRL) for future utilization in space-based systems.
- **Integrated hardware operations.** The integration of the novel CEA technologies in this fully operational production system will provide further long-term operational knowledge of these technologies and their interaction with other greenhouse systems. Overall system reliability evaluation over the long-term operation of the system will also be conducted.
- **Crew time assessment.** The quantification of realistic crew time requirements over the long-term operation of this greenhouse within this mission relevant environment will have considerable benefit over laboratory extrapolations.
- **Contribution to per square meter production literature.** The precise quantification of greenhouse module inputs and outputs will be evaluated and will contribute to the literature on expected productivity per square meter in future space-based systems.
- **Remote operational experience.** The incorporation of a remote backroom operations team that can collaboratively interact to monitor and control aspects of the locally tended greenhouse will contribute new knowledge about requirements and potential efficiency improvements from this regard.

IV. Requirements

The top-level requirements of the Neumayer III greenhouse module include the following:

- Conform to Antarctic environmental regulations
- Install external to and meet Neumayer III environmental/climatic conditions
- Utilize a standard shipping container as the structural form-factor
- Operate year round and provide a non-negligible contribution to the diet of overwintering crews

Greater details related to these requirements as well as an overview of the basic greenhouse module subsystems is provided in the sections to follow.

A. Environmental Regulations

The original Antarctic Treaty was signed in December 1959 and came into effect in 1961 [61]. In order to further enhance protection of the Antarctic environment and strengthen the Antarctic Treaty to ensure that the Antarctic will be used for peaceful purposes, the Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol) was signed on Oct 4, 1991 and came into effect in 1998 [62]. The protocol designates Antarctica as a "natural reserve, devoted to peace and science". These two documents in addition to the Annexes of the Madrid Protocol detail such requirements as the implementation of environmental impact assessments, prohibition on mining activities, protection of native species, handling and disposal of wastes, inspections and liability. A number of the requirements stemming from the treaty's protocols, as well as the summary manuals compiled by the Committee for Environmental Protection, dictate the feasibility, design and operations of potential on-site plant production facilities [63].

A number of specific restrictions on Antarctic plant production systems are derived from the Treaty and are often incorporated into law in countries who have national Antarctic programs. Such laws have been previously well-summarized [3]. As a brief example, according to the Australian Antarctic Treaty (Environmental Protection) Act (1980) a person may not bring into, or keep in, the Antarctic: (i) any animal, plant, virus, bacterium, yeast or fungus that is not indigenous to the Antarctic (ii) non-sterile soil, or (iii) any pesticides [64]. Exceptions to (i) include importation of food into the Antarctic Treaty area provided that no live animals are imported for this purpose and all plant and animal parts and products are kept under carefully controlled conditions and disposed of in accordance with appropriate regulations [64]. Furthermore plant growth facilities/a person shall not carry on any activity that results in: *(i) the habitat of any species of native seal, native bird, native invertebrate or native plant being adversely modified to a significant extent; (ii) any population of native seals, native birds, native invertebrates or native plants being adversely modified to a significant extent; (iii) cause or permit to escape from his or her control or the control of any other person an animal, plant, virus, bacterium, yeast or fungus that is not indigenous to the Antarctic and has been brought into the Antarctic by virtue of a permit or to be used as food*.

The risk of typical crop species surviving beyond the confines of the controlled greenhouse environment, especially during the winter season, is considered negligible [3]. That said, greenhouses also provide ideal conditions to many species of insect, bacteria and fungi, many of which are considered plant pests. These pests may stand a better chance of survival beyond the controlled environment than the more benign crop species.

The high humidity, warm temperatures, and available light and nutrients actually make the greenhouse an environment that is vulnerable to 'non-native' species brought into the research stations through normal resupply of potentially contaminated produce and other organic materials. The concern surrounding the introduction of non-native species into the Antarctic environment requires careful assessment of the broader picture of import processes. In actuality, if the primary entry of foreign species is the regular resupply chain then it can be argued that the delivery of a sanitized plant production system, complete with sanitized seeds, would reduce the risk of non-native species introductions in two ways. First, reducing the amount of produce that needs to be imported through in-situ produce production would reduce the probability of pest introductions. Second, the incorporation of good management practices, and monitoring programs would reduce the risk further. Indeed, Antarctic plant production facilities would actually be more easily inspected (including the output produce) and/or quarantined for introduced organisms than other typical Antarctic station organism refugees, such as sewage outlets, water production sites, around packing crates and in cool and warm store housing person luggage, equipment and foodstuffs [3].

As previously discussed, a well-controlled plant production program could actually reduce the risk of non-native species introduction compared to the current practice of direct importation of fruits and vegetables. Indeed, although meat is generally supplied frozen with long-term storage at -20°C, which itself likely kills introduced microorganisms, imported fruit and vegetables can easily include non-Antarctic soil residue, insect pests (including eggs and early instar stages) and microorganisms [65]. It is estimated that Antarctic fresh foods are sourced from 750 different locations and that the specific locations can vary from year to year [47]. In a recent study more than 11,000 fruit and vegetable items destined for nine different research stations were examined for the presence of significant soil, invertebrate and microbial contamination (51 food types from approximately 130 locations). A total of 12% of the items had soil on their surface, 56 invertebrates were recorded (primarily from leafy produce) whereas 28% showed microbial plant pathogens. Estimates suggest that approximately 90 different soils may be introduced to the Antarctic Treaty area each year. Reducing such fresh food import though in-situ production may actually benefit conformance to environmental regulations.

B. Environmental Conditions

Typical weather conditions at Neumayer III are provided in Figure 2. The presented air temperature (Figure 2A) and wind speed data (Figure 2B) were collected using the Air Chemistry Observatory (Raw data obtained from [66]) and suggest the greenhouse module will experience minimum temperatures of approximately -50°C in the dark season, and summer temperatures reaching just over 0°C.

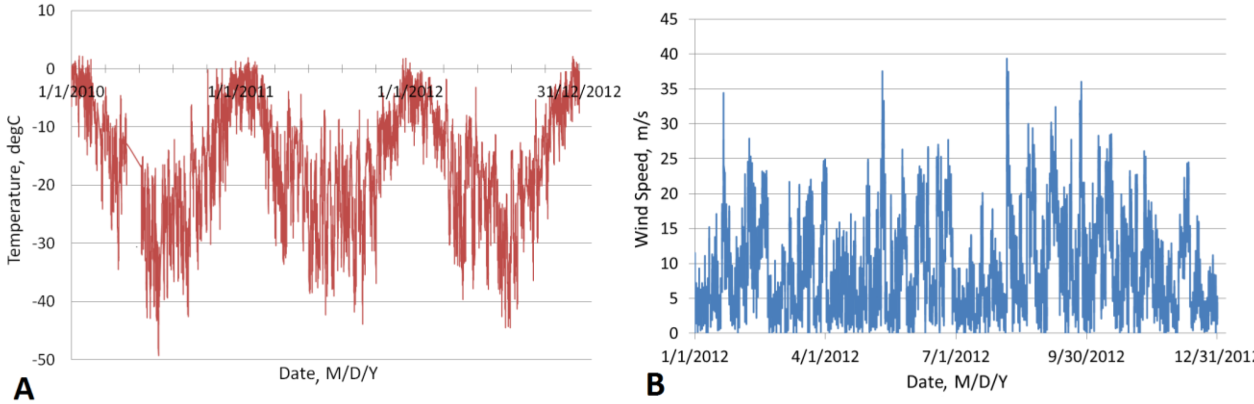

Figure 2. Neumayer III recorded air temperature and wind speed. Air temperature (A) is provided on an hourly average from Jan 1, 2010 to Dec 31, 2012, whereas wind speed (B) on a one minute logging rate is plotted from Jan 1, 2012 to Dec 31, 2012.

Due to the approximate two months of darkness (end of May to end of July) at Neumayer Station III, any plant production facility operating year round must incorporate electrical lighting. Additionally, the low sun angles at such low latitudes imply reduced overall light intensities and suggest the use of supplemental lighting for greenhouse facilities operating outside of the long dark season. Snow accumulation and drifting is another factor that must be addressed by any external Antarctic plant production facilities.

C. Mobile Facility

A recent DLR market study determined that there is a viable market for mobile plant production systems in a variety of sectors including remote research stations, isolated communities, research vessels, cruise liners, off-shore installations, military camps and remote mining operations. The primary benefit to these sectors is the provision of fresh food (fruits and vegetables with low storability) that are otherwise difficult or impossible, in any practical sense, to resupply. In order to take advantage of current supply chains, the mobile greenhouse module design was based on 20 ft and 40 ft shipping container form factors. Such a containerized system simplifies transport requirements to the bulk of the aforementioned locations. Although the logistics chain for the Neumayer III is based upon 20 ft containers both the 20 ft and 40 ft container designs have been considered. The elaboration of the 40 ft design remains relevant, as upon arrival at Neumayer III two separate 20 ft containers can be joined together to form a module with the larger footprint. Sea container sizing is based upon International Shipping Organization (ISO) standards. In particular, ISO 668 specifies standard external dimensions, whereas ISO 1496 specifies minimum internal dimensions. Containers come in standard and high-cube versions [67]. These have identical footprints (length and width) but the high cube version is one foot higher. The greenhouse design is based upon the high-cube version as it permits greater total plant growth area when utilizing a stacked plant tray configuration. The dimensions of such a container are provided in Table 2. The ISO specified internal dimensions should actually be considered the worst-case internal sizing data. In actuality more nominal internal dimensions are several centimeters larger than this worst-case; more realistic sizing assumptions based upon several common transport providers are also included in Table 2 [68, 69]. Including an assumption of 80 mm thick internal insulation on all sides the final internal working volume considered is also presented in Table 2.

Table 2. External and internal dimensions of 20 ft and 40 ft shipping containers.

Container Type	Length (20 ft)	Length (40 ft)	Width	Height
External	6058 mm	12192 mm	2438 mm	2896 mm
Internal (minimum)	5867 mm	11998 mm	2330 mm	2655 mm
Actual assumed	5895 mm	12022 mm	2350 mm	2700 mm
Assumed after insulation	5735 mm	11862 mm	2190 mm	2540 mm

Initial external and internal conceptual designs based upon the 40 ft containerized greenhouse concept are illustrated in Figure 3. It can be seen that the internal arrangement of the greenhouse module is separated into a plant module and service module. The specifics of each, and their relevant subsystems, are discussed.

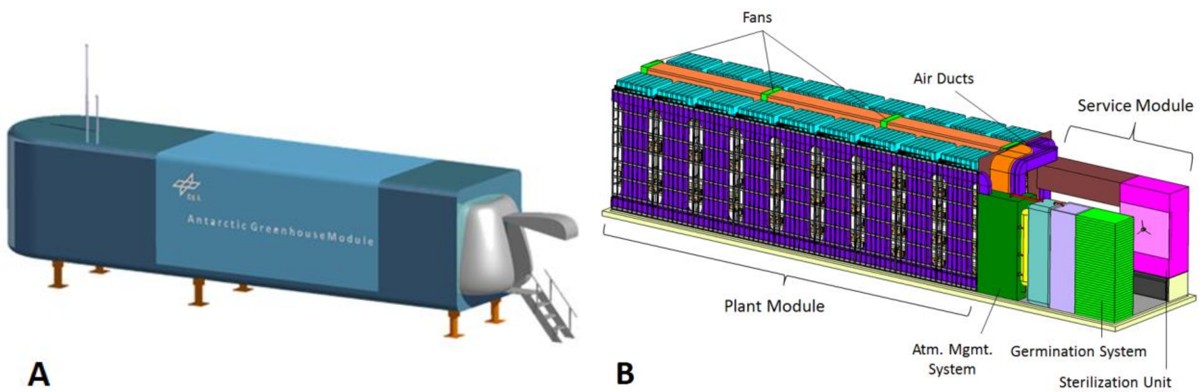

Figure 3. (A) Exterior and (B) interior of the 40 ft Antarctic greenhouse module concept.

D. Structure

The Antarctic environment necessitates special considerations for the use of standalone buildings. The majority of recently built and future planned structures, including plant production facilities, are built on elevated platforms. This design criterion is necessitated by snow accumulation and drifting. Indeed, wind carried snow has resulted in several previous stations being abandoned. Examples include the closure of the original South Pole station that was buried under 30 ft of snow and ice [70], a number of Halley Antarctic bases [48], and India's Dakshin Gangotri Station [71]. The annual snow accumulation at the South Pole is approximately 8" per year, at the location of Halley VI approximately 1 m. In comparison, accumulation at Neumayer III is approximately 1.2 m annually [48, 70]. Although a great deal of this accumulated snow can be removed in the summer months (winter removal also possible) when large crew complements are available and the weather is more amenable to such activities, this requires significant work and involves some risk of damage to buried structures. Installation on an elevated platform allows fast moving winds to move beneath the platform helping to scour snow from the area and reducing manual excavation requirements. The greenhouse module platform will be based upon AWI developed platforms such as that used for the Air Chemistry Observatory shown in Figure 4. As the wind direction at the Neumayer III site is primarily from the east, the entrance to the greenhouse module will be oriented westward.

Figure 4. Neumayer III Air Chemistry Observatory installed on elevated platform. Photo credit: AWI.

To combat the harsh environment and -50°C winter temperatures the greenhouse module will be appropriately insulated. Although several options are being considered to gain additional internal volume by limiting the physical insulation space, polyurethane foam or mineral wool are the fallback options with outfitting to be similar to past or the current Neumayer III Air Chemistry Observatory, in which thermal conductivity K-value requirements of less than 0.3 to 0.35 W/m^2K were utilized[72, 73]. Other relevant considerations for the external/internal container structure include a snowstorm-proof ventilation system and material selection that will ensure all interior container surfaces can be washed. Appropriate external corrosion protection will be applied to resist the wind carrying salt spray due to the site's proximity to the coast.

E. Grow Units

The plant module in the 40 ft container configuration includes 18 grow units. Figure 5A depicts a subset of five grow units from one wall. Each of the grow units incorporates shelves with integrated air and nutrient solution handling lines. Light Emitting Diode (LED) light banks are installed directly under each of the shelves providing light for crops below. An early concept of this stacked arrangement under in development in the EDEN laboratory is illustrated in Figure 5B.

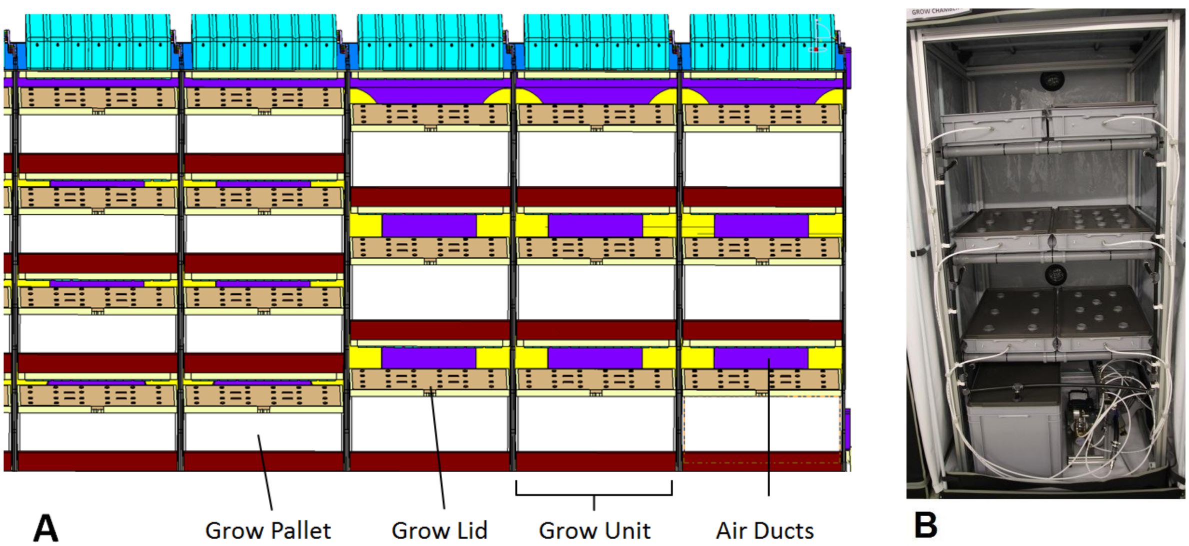

Figure 5. (A) Configuration of the interior of the plant module showing five example growing racks. Each grow racks includes a number of levels depending on crop type and age. (B) Stacked growth arrangement undergoing test in EDEN laboratory.

To accommodate two rows of grow units within the container while maintaining enough space to move around and insert and remove grow pallets from the grow units, the width of the grow units was limited to 720 mm. This leaves 750 mm for the walkway down the middle of the container. A small part of each grow unit is reserved for air handling ducts, resulting in a working height for each grow unit of 2500 mm. The length of the grow unit came about after several iterations and is set to 970 mm. Within each grow unit are a number of stacked grow pallets. The grow pallets are installed within the grow units by way of a simple rail system permitting ease of user modification of the height between each respective grow pallets. In particular, this allows maximum use of the internal grow volume with height adjustments made based upon crop age and type. Running the length of the sides of the grow units are piping and cabling that serve to connect the grow unit with the service module and subsequently to each of the respective grow pallets.

Each grow pallet has a length of 900 mm and a width of 600 mm. The height of the grow pallets depend on the crop of interest so as to provide sufficient root zone height for the particular crop. For example the grow pallet for lettuce includes a light tight enclosure box with sufficient height to accommodate roots with a height of 150 mm and thus the total box height is 230 mm. When the LED panels are integrated into the bottom of the boxes the total thickness is 320 mm. The basic grow pallet layout includes an interchangeable grow lid that can be exchanged to optimize crop spacing (Figure 6).

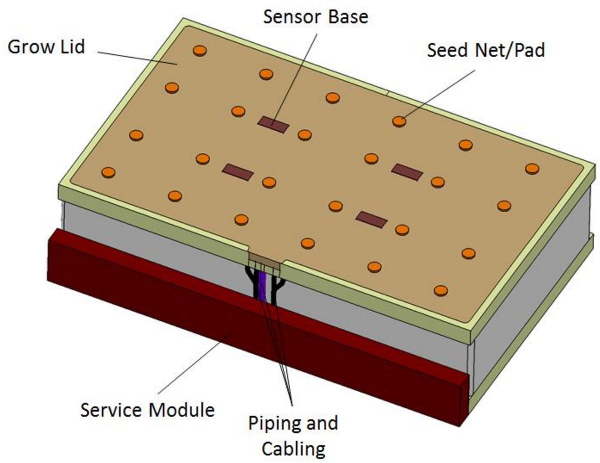

Figure 6. Schematic of basic growth pallet. Nominal dimensions are 900 mm length, 600 mm in width and a flexible height defined by the particular crop.

In this arrangement each growth pallet provides a growth area of 0.48 m^2. A total of 8 grow units can be contained in the 20 ft container configuration. This assumes a service area in the 20 ft container of approximately 60% the size of the service area within 40 ft container (i.e. 3132 mm service module width in the 40 ft container is reduced to 1855 mm in the 20 ft container) so to include some potential losses due to scaling.

F. Lighting

LEDs with their increased application to the horticultural sector are typically described as advantageous over more traditional greenhouse lighting systems due to their small size, ballast-free operation, solid-state electronics, near monochromatic emission, improved reliability, power conversion efficiency and reduced operating temperatures [74, 75]. Indeed, reduced touch temperatures permit the LED panels to be located in the tightly stacked arrangement of proposed grow units. LEDs provide near monochromatic emission allowing for the selection of light emission spectra best matching the absorption spectra of plant pigments [76]. The light quality and quantity can be adjusted for each individual greenhouse module tray based on the crop and growth phase. EDEN laboratory-based testing is on-going with several commercially available and custom LED lighting systems e.g. Heliospectra (Göteborg, Sweden) and OSRAM (München, Germany).

As lighting is often the largest power draw of a plant growth chamber an estimate of their associated power requirements is important. Considering a light:dark 16:8 photoperiod, and the worst-case scenario in which lighting for all racks is activated at the same time, a power estimate can be made for both the 40 ft container with its 18 grow units and the 20 ft container with its 8 grow units. An average of 5 shelves per grow unit is assumed. A total power consumption of 400 W per growth rack LED system is assumed based on a review of numerous horticultural LED systems. With such assumptions the LED power consumption alone is estimated as 36 kW for the 40 ft container and 16 kW for the 20 ft container. Adopting a staggering of the photoperiods between racks and the relatively low light intensity requirements of the currently proposed crops (e.g. lettuce) a more appropriate estimate for the lighting power requirements is 18 kW for the 40 ft container and 8 kW for the 20 ft container (assumes 300 W power consumption per panel). As roughly half of the required LED power would be given off as heat it is unlikely that a supplemental heating system for the greenhouse module is necessary and analysis will be conducted with respect to potential cooling requirements, especially in the Antarctic summer season.

G. Power

Neumayer III uses three diesel generators sets, each an electrical output of 160 kW. The waste heat from the generators is used to heat the station (at approximately full load each provides approximate 200 kW heat). The required power of Neumayer III in the winter is approximately 140 kW with the thermal power required under 200 kW [77]. Thus, only one generator is nominally required to fulfill the electrical and thermal requirements of the station in winter. Greenhouse power will be taken directly from the Neumayer Station III. This is assumed to be easily feasible due to the fact that the Air Chemistry Observatory which is situated 1.5 km south of Neumayer III is powered by a hard-wired cable connection to the main station. The station also includes a 30 kW wind turbine and it is expected that subsequent turbines will also be deployed [58].

H. Nutrient Delivery

Based upon the aforementioned Antarctic environmental regulations the greenhouse module will employ a hydroponic nutrient delivery system. To further minimize waste generation the system will not utilize growth media and instead employ an aeroponic nutrient delivery system. In this configuration, the plants will be seeded into circular neoprene pucks and installed within custom top plates (i.e. plant spacing based upon a particular crop). Between crop cycles the neoprene pucks will be appropriately cleaned for reuse. Plant nutrients will be transported in salt form to the Antarctic. Nutrient solution will be made up by greenhouse operators on-site. Fresh water will be taken from the nominal Neumayer III water supply. This water is generated from snow melt using excess heat from the diesel generators [58]. As the nutrient solution will incorporate UV sterilization, ozone disinfection and be monitored for pH, electrical conductivity as well as for several ions for which reliable sensors exists (e.g. Ca^{2+}, K^{+}, NH_4^{+} and NO_3^{-}) the nutrient solution will be recirculated to the greatest degree possible [78]. Nutrient solution pH, conductivity and ion concentration will be adjusted accordingly. Four weeks or more of recirculation is expected. A total volume of 180 L of bulk nutrient solution is estimated for the 40 ft container and 80 L for the 20 ft configuration (i.e. approximately 10 L of nutrient solution per rack). The baseline nutrient solution recipe will be the half strength Hoagland recipe (solution two) [79]. The present aeroponic design incorporates four stainless steel misters from AFT GmbH (Oberasbach, Germany) with a 0.5 mm diameter orifice in each growth pallet. The aeroponic system will operate at 10 bar and utilize FLOJET Triplex Hi-Pressure Pumps from Jabsco (Letchworth, UK). Aeroponic tubing employs 4.0 mm inner (6.0 mm external) diameter LLDPE high pressure hosing. This and the nominal reservoir and nutrient delivery piping materials avoid the use of PVC as directed by Annex III of the Madrid protocol [62]. In addition to several rinsable fine filters, misters will undergo a regular cleaning program to reduce issues of clogging.

Three separate nutrient solutions reservoirs are incorporated into the 40 ft container design, whereas two separate reservoirs are included into the 20 ft container. Due to the periodic nature of the aeroponic watering system (baseline 10 seconds on every 10 minutes) one high pressure pump will be co-located with each reservoir and serves several grow units.

I. Atmosphere Management

A ventilation loop is provided to each side of the plant module. Each loop incorporates its own fans, filters, and piping. Whereas more centralized dehumidifying, cooling, CO_2 injection and UV/ozone systems are incorporated into the service section. Hot and humid air is sucked from the top of the plant compartment and pumped into the dehumidifier/cooler. Dehumidifier cooling liquid is provided by an external heat exchanger, which cools the liquid to a defined temperature before returning it to the dehumidifier. The cool dry air is then pumped into the grow compartment from the bottom. Figure 7 shows a longitudinal cross section of the 40 ft container with the various atmospheric management components displayed.

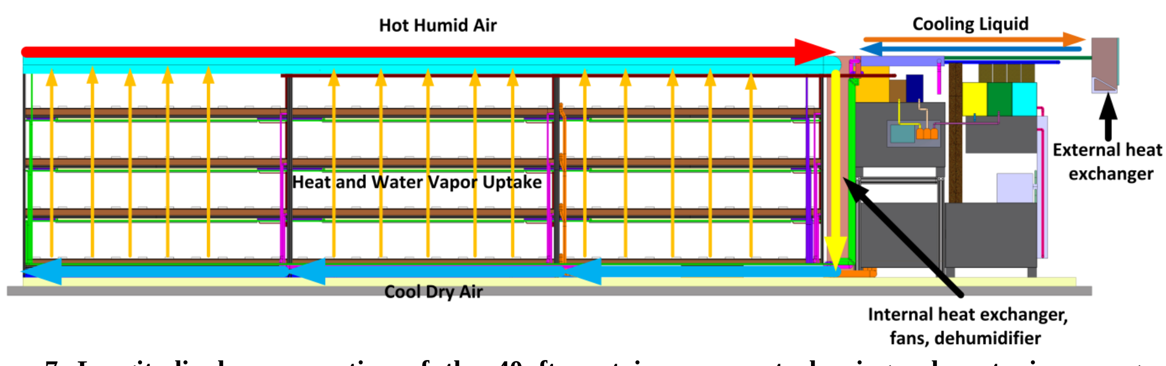

Figure 7. Longitudinal cross section of the 40 ft container concept showing relevant air management components and pathways. Arrows indicate air flow direction.

Designs are also being considered for a partitioned internal container volume. Although adding increased complexity and further reducing growth area, added partitioning permits the aerial environment to be better tailored for different crops and growth phases. This includes segregated control of temperature and CO_2 partial pressure. This partitioning also would reduce the spread of any plant pests and permit rigorous sanitation of isolated sections without affecting the entire production volume.

J. Cleaning and Monitoring

A detailed cleaning and disinfection program will be an important part of the plant production facility's routine operations. Due to the Neumayer III sewage treatment facility only biodegradable substances can be utilized for cleaning purposes [58]. Based upon past experience with other Antarctic plant production systems, isopropyl alcohol or diluted bleach will be utilized to clean and swab growing containers after each harvest or when algal deposits are apparent [3, 29, 80]. Full-scale greenhouse cleaning will also be conducted on an annual basis in which all walls, surfaces, lighting systems and plant growth containers will be cleaned with isopropyl alcohol or diluted bleach.

Crew members entering the facility shall follow defined hygiene protocols in accordance with the biosecurity plans developed for the facility. The stringency of this protocol is borne from the potential introduction of pests and pathogens from imported produce and other commodities and shipping containers. Pest scouting activities will be a component of the daily maintenance routine. Should pests be found in the greenhouse, the module will be closed down and all plants double bagged and then contained in garbage transport containers and added to the station food waste stream (placed into the cold part of the station). Once the plants have been removed a rigorous greenhouse cleaning will be conducted. Other relevant lessons from past Antarctic greenhouses will be incorporated into the cleaning and monitoring program of the proposed facility, including training for all expeditioners who will accessing the facility and other relevant considerations described previously [80].

K. Waste

Waste streams from the greenhouse module include wastewater, inedible biomass, packaging (seeds, nutrient salt containers, etc.) and failed components. Solid waste components will be dealt with through the existing Neumayer III waste handling systems/protocols including sorting, stabilization/storage, labelling, reporting and subsequent shipment off the Antarctic continent [58]. Waste biomass generated in the plant production facility will be handled similarly to kitchen food waste. Once appropriately packaged it will be placed in the cold part of the station/garage in waste containers where the low/freezing temperatures will prevent the generation of odours. All efforts will be made to avoid and minimize packaging and unrequired shipping supplies required for the transfer of the greenhouse module, equipment and supplies from Germany to the Antarctic.

After several weeks or recirculation through the production system it may no longer be possible to maintain the nutrient solution ionic balance in a state appropriate for optimal plant production. Once this condition is reached the solution will be deemed waste and a new batch will be made-up. The waste nutrient solution will be transported by sledge or hand carried from the greenhouse into the main station in tightly sealed containers. The water will be added to the nominal Neumayer III waste stream. An average daily general wastewater consumption volume per crew member of 100 L is assumed based upon some improvement with respect to historical Neumayer II crews that utilized approximately 117 L/day [58]. With a worst-case nutrient solution regeneration cycle in which 180 L of nutrient solution is discarded every 4 weeks (equating to an average contribution of 6.4 L/day) as well as a rough total facility estimate of 10 L/day of water a day for cleaning related activities, the increase to the wastewater stream of a 9 member crew remains less than 1%. Minor water losses due to non-complete closure of the atmospheric management condensate recovery system (i.e. transpirational losses) and through the opening of the facility entry door during operator access to the facility are not considered. Detailed analysis of water losses with respect to storage in plant tissue is also a factor to be evaluated in future design work. Post-harvest water could also be considered, but this contribution should be essentially the same as the water utilized for the preparation of nominal station foodstuffs.

The discharge from an Antarctic plant production systems into station sewage treatment systems has been considered by other countries operating such facilities and is generally considered an insignificant burden on the overall system [3]. Grey and black water from the Neumayer Station III is cleaned and disinfected in a containerized sewage treatment plant before being disposed of into a snow pit in the vicinity of the station [58]. The 20 ft containerized waste treatment plant is biological reactor based and utilizes ultrafiltration membranes [81].

L. Data Acquisition and Control

Greenhouse control will be conducted using National Instruments (Austin, Texas, USA) CompactDAQ data acquisition system running LabVIEW. All sensors and actuators will be connected and controlled utilizing this system. The nominal operations of the facility will require limited tending but operational parameters will be modifiable both by on-site means as well as through a satellite link utilizing the main Neumayer III communication infrastructure. Indeed the greenhouse module will be connected to the station through a wireless connection, in a manner similar to that wireless link between the even more distant Air Chemistry Observatory and the station. The nominal Neumayer III satellite connection will be utilized for real-time data transmission of greenhouse data and for remote commanding. Unlike examples of other past analogue plant production facilities [1, 82], the DLR greenhouse module will benefit in that it will be constantly human tended and thus in addition to the advanced sensing suite, operators will quickly be able to address off-nominal conditions. Operators will gain operational experience through considerable pre-deployment testing of the greenhouse module in Germany.

V. Estimated Output

Although the greenhouse module will likely incorporate as many as 10 different crops over its operational life, lettuce and tomato are representative and as such used for the subsequent illustrative analysis of the estimated module biomass output levels. The growing properties used for the output calculations were taken from the NASA Baseline Values and Assumptions Document [83].

Lettuce (*Waldmann's Green*): Maturity phase of 28 days, a maximum mature height of 0.25 m, a fresh edible biomass output of 131.35 $g/m^2/d$ and a fresh inedible biomass output of 7.30 $g/m^2/d$ [83].

Tomato (*Reimann Philipp)*: Maturity phase of 85 days, a maximum mature height of 0.4 m, a fresh edible biomass output of $g/m^2/d$ and a fresh inedible biomass output of 127.43 $g/m^2/d$ [83]. A mature root zone depth of 0.15 m for lettuce and 0.2 m for tomato was also assumed. For simplified, early stage analysis, plant growth was approximated as linear over the growing cycle and the following two production strategies were compared:

> Static stacking: The static stacking production strategy holds a fixed grow pallet arrangement within the grow units. For example, the grow pallet spacing for lettuce is based upon its maximum mature growth height (aerial zone) of 25 cm. This 25 cm height in addition to the grow pallet height of 23 cm (defined by the maximum mature root zone height) and LED panel thickness height of 9 cm define the spacing required between each stacked growth panel. For lettuce, this necessitates that within the 250 cm available height, that 4 grow pallets can fit within each grow unit. The static crop production strategy is the simplest in terms of operation (no manipulation of pallets during grow cycle), but the least optimized in terms of crop yield.

> Dynamic stacking: The dynamic stacking production strategy assumes a fixed grow pallet height based on the maximum root zone height (23 cm for lettuce) and LED panel thickness height (9 cm) but considers that the spacing between grow pallets can be modified over the crop cycle. In particular, a minimum distance between the LED panel and plant canopy is defined. This minimum distance will be maintained over the growth cycle through a movable grow palette. This allows a greater numbers of grow pallets to be installed in a given grow unit. For example, in this configuration an average of 5 pallets can be configured into each grow unit. Disadvantages of implementing this technique is an increase in complexity of the grow unit and the increase in crew time (should automation not be built in). Further stacking density could be achieved if variable root zone/grow pallet heights were employed so that their height could follow the growth of the particular crop over its lifecycle. This latter option is not considered due to the additional increase in complexity.

The results of the greenhouse module biomass output estimate based on the assumptions above are summarized in Table 3. As evident, the dynamic production strategy allows approximately 25 – 30% increase in total plant growth area and thus biomass output.

Table 3. Estimated greenhouse module outputs for 40 ft and 20 ft container options growing lettuce or tomato. Static stacking and dynamic stacking production strategies are compared. The 40 ft container assumes 18 grow units whereas the 20 ft container assumes 8 grow units.

Crop	Production Strategy	Container Type	Number of Palettes	Total Growth Area (m^2)	Fresh Biomass Output (kg/day)		
					Edible	Non-Edible	Total
Lettuce	Static	40 ft	72	34.56	4.54	0.25	4.79
		20 ft	32	15.36	2.02	0.11	2.13
	Dynamic	40 ft	90	43.20	5.67	0.32	5.99
		20 ft	40	19.20	2.52	0.14	2.66
Tomato	Static	40 ft	54	25.92	4.50	3.30	7.80
		20 ft	24	11.52	2.00	1.47	3.47
	Dynamic	40 ft	72	34.56	6.00	4.40	10.40
		20 ft	32	15.36	2.67	1.96	4.63

When considering a lettuce monocrop with staggered planting and the dynamic production strategy, it is estimated that the greenhouse module will generate 5.67 kg or 2.52 kg of fresh edible biomass per day in the 40 ft and 20 ft container configurations respectively.

VI. Additional Opportunities

Also being explored is the incorporation of two International Standard Payload Rack (ISPR) based plant production systems (Figure 8). The Antarctic greenhouse module deployed at the Neumayer III is considered a useful test venue for several relevant technologies but even more importantly, for testing the operations of such plant growth rack systems/salad machines. Although there remains significant differences between microgravity and planetary-based subsystems, particularly fluid flow subsystems, there remains much in the way of operational experience that can be gained in this environment. Further, several of the discussed key technologies can be suitably trialed in a ground-based system to advance their readiness for on-orbit utilization.

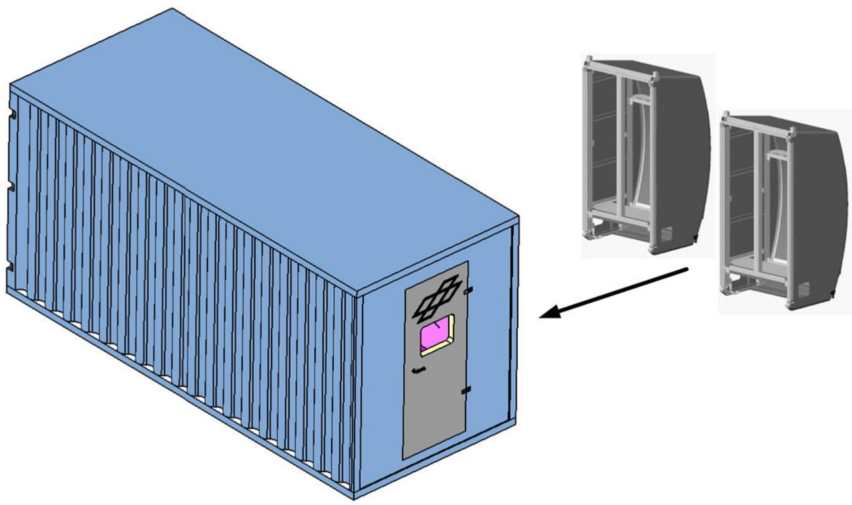

Figure 8. 20 ft container with integrated ISPR based plant growth chambers.

A concept being explored is the segregation of the container into a service module section, a 'future' planetary greenhouse section, and a section incorporating ISPR-based growth systems. The service module and planetary greenhouse sections would be based upon the previously described arrangements and hardware. Alternatively, the ISS rack-based section would house racks with the form factor of nominal ISPR systems and as many relevant ISS-to-rack interfaces as deemed appropriate so that lessons can be learned with respect to the operations of a full rack-sized plant growth facility/salad machine such as those previously proposed for on-orbit or in-transit use [84-87].

VII. Conclusion

A wide array of plant production systems have been deployed, by various nations, to the Antarctic. These systems have ranged from early small-scale systems to more recent, larger-scale systems. In all instances, it is known that the on-site provision of fresh produce to over-wintering crews can not only supplement crew diets but also provide psychological benefit. Although only relatively minor supplementation is presently possible, further advancements in controlled environment agriculture technologies is making it possible to further extend the contribution of such production systems so that they can begin to realistically alleviate some of the logistics requirements of Antarctic stations. Additionally, Antarctic resupply constraints, small over wintering station crews and general station operations provide a relevant analog for the operation of a future space-based bioregenerative life support system. The trialing of certain Antarctic greenhouse module technologies and operational strategies will advance the readiness of such systems for future utilization.

A containerized plant production system installed externally to the German Neumayer Station III will benefit both the Neumayer III crew but also enhance European technology and operational experience in this domain. Forty and 20 ft containerized greenhouses using stacked grow units, LED lighting technologies and advanced nutrient delivery and control systems will ensure operations that meet Antarctic environmental regulations while maximizing biomass output per unit energy and volume. A 20 ft container with a monocrop of lettuce is expected to output 2.52

kg of fresh edible biomass per day when operating in the dynamic stacking production mode. The incorporation of ISS standard racks as a subset of the container also positions the facility as a venue for operationally relevant testing of candidate ISS plant growth hardware technologies and advances their technical readiness. The mobile greenhouse in combination with laboratory-based testing in the EDEN laboratory and in other consortium laboratories provides a useful technology development pathway for on-orbit and planetary surface-based bioregenerative life support technologies. Further elaboration of greenhouse module subsystem designs and concepts continue. The DLR team, with its design consortium, is planning several upcoming design studies within the DLR Institute of Space System's Concurrent Engineering Facility in combination with continued subsystem development and testing within the EDEN laboratory. This will be followed by the outfitting of the winterized container and with it, system levels tests on the grounds of the Institute of Space Systems. Deployment to the Antarctic is presently planned for the end of 2016.

Acknowledgments

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