Polar Research Facilities: Living in isolation

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The paper describes the design of three polar projects and reviews the lessons learnt from each. It also describes a collaboration between the author, human factor experts and NASA JSC advising on net habitable volumes for astronauts on long duration missions. The paper concludes by exploring common themes between designs for terrestrial extreme environments and for space and suggests that these lie in the age-old design principle, crafting light and volume around human activities. In the preparation of the paper the author has drawn upon his experience as the architect of Halley VI Antarctic Research Station for the British Antarctic Survey, the Atmospheric Watch Observatory at Summit Station in Greenland for the National Science Foundation (USA) and the remodeling of the Juan Carlos 1 Spanish Antarctic Base.

I. Introduction

Scientists working in the Polar Regions have to survive for long periods without physical contact with the outside world. In the northern hemisphere, access is possible on an infrequent basis through the winter, depending on weather conditions but in Antarctica scientists can be cut off for up to 9-months of the year when the continent is isolated by up to 600 miles of impenetrable sea ice and temperatures are so low that access by plane is too dangerous. The level of isolation therefore provides an excellent terrestrial analogue for human factor research for future space missions. The implications of periods of prolonged darkness and of being forced to stay indoors during extreme weather, allied to the social impacts of living with a small number of crew are examples of factors which will resonate with those designing for habitability in space.

Traditionally polar research facilities built on the ice were basic structures, which needed to be regularly replaced as they succumbed to the extreme environment. Living conditions were cramped with little thought given to the impact of design on the well being of the crew. The earliest structures were timber huts, which became buried by the ice and snow. The second generation of facilities was therefore designed to be buried. Examples of these structures include the dome at South Pole (designed by Buckminster Fuller), Neumayer 2 German station and Halley III and IV. These structures were irreparably damaged by the inextricable movement of the ice and eventually abandoned.

More recently structures built on the ice have tended to be elevated to escape the impacts of rising snow levels. This has also allowed the introduction of natural light into the buildings and far greater thought to be given to the overall welfare of the crew. Whilst the first generation of elevated structures, such as Halley V (1992) and the South African SANAE IV (1997) remained staunchly pragmatic in their design, the postmillennial structures have become increasingly sophisticated. Examples of this new generation include the extensive US South Pole Station, the twin drums of the Italian-French Concordia Station, the zero carbon Princess Elizabeth Belgian Station and the elegant Bharathi Indian Station. While the design of these stations does now consider human factors, their designs are also a balance between engineering issues, scientific requirements, logistic limitations, and environmental considerations alongside the comfort of the residents.

The balance between these factors depends on the nature of the installation and its primary focus, i.e. the science being conducted. This paper provides an overview of the issues, which has determined the design of three polar research projects, designed by the author. The primary focus of the paper is on the Halley VI Antarctic Research Station, which is now fully operational on the Brunt Ice Shelf. The paper also includes descriptions of two other installations – Juan Carlos 1 Spanish Antarctic Base and the US Atmospheric Watch Observatory at Summit in Greenland. In the latter two cases however the projects are not complete and therefore analysis of the projects in use is not possible although the differing requirements and design considerations provide useful additional information to add to the analogue database.

II. Halley VI Antarctic Research Station

Halley is the most southerly science research station operated by the British Antarctic Survey (BAS) and is located on the 150-metre thick floating Brunt Ice Shelf, which moves 400 metres per annum towards the sea. Snow levels rise by 1 metre every year, and the sun does not rise for 105 days during winter. Temperatures drop to -56˚C and winds blow in excess of 160 kph. Access by ship and plane is limited to a 3-month summer window. A research station has been occupied continuously at Halley since 1957 and in 1985 scientists working there first observed the hole in the ozone layer. Halley V was completed in 1992. Its occupation became precarious, having flowed too far from the mainland to a position at risk of calving as an iceberg. As the station's legs were fixed in the ice it could not be moved and so in 2004, BAS organised an international competition to select designers for a new station. Hugh Broughton Architects and AECOM won the competition with a modular design concept, developed to meet the client's key objectives:

- To be relatively easy to deliver to site, build, operate and ultimately decommission
- To allow for the replacement of individual facilities without significant interference to the whole station.
- To minimise through-life environmental impact from construction to decommissioning
- To support 16 people in the winter and 52 in the summer in a safe, comfortable and stimulating environment
- To be fully relocateable inland when there is risk of the site calving off as an iceberg
- To minimise snow management and allow the station to climb above the annually rising snow levels

Figure 1. Halley VI Antarctic Research Station on the Brunt Ice Shelf

A. Environmental and logistic constraints

In tandem with the demands of climate, the construction and operation of the new station has to meet the stringent requirements of the Environmental Protocols of the Antarctic Treaty. Delivery also posed a significant challenge. As the ice shelf protrudes 20 meters above sea level, all materials had to be unloaded onto fragile sea ice with a maximum bearing capacity of only 9.5-metric tonnes. They were then dragged on skis and sledges across this and up man-made snow ramps created in natural creeks at the cliff-like edge of the ice shelf.

B. Design concepts

Bedrooms, laboratories, office areas and energy centres are housed in standardised blue modules**.** A larger two-storey light-filled red module provides the social heart of the station and is used for living, dining and recreation. The main window to this module combines clear triple glazing with nanogel insulated glazing to maximise light penetration whilst minimising heat loss. The lower level is open plan to encourage a sense of community. The upper level rooms include special domed rooflights providing spectacular views of the Aurora Australis in winter. The layout also incorporates medical operating facilities, air traffic control systems and CHP power plants and is a microscopic self-supporting infrastructure-free community.

Figure 2. Naturally lit social area within the station's Central Module

The station is arranged in a straight line perpendicular to the prevailing wind so that snow drifts form on the leeward side, reducing snow management requirements. The base is split in two for life safety. Each half has its own energy centre and is self sustaining in case of emergency. A bridge link allows sharing of power, drainage and water. The modules are supported on giant steel skis and hydraulically driven legs that allow the station to mechanically 'climb' up out of the snow every year. And as the ice shelf moves out towards the ocean, the modules can be lowered and towed by bulldozers further inland, and eventually taken apart when the time comes.

C. Technical solutions

The life critical design of the station is reliant on tried and tested technologies, although by necessity often applied in innovative ways from sectors apart from the construction industry. For example the silicone rubber connectors between the modules have to allow significant positional tolerance but a company, which usually makes connections between train carriages, was appointed to develop and manufacture these to suit the low temperatures and wider dimensions appropriate to a building. Drawing inspiration form the marine industry, many of the station's rooms were prefabricated so that they could be finished in factory conditions and lifted into position on site ready to use.

The key to the energy strategy is reduction in fuel use. Heating is provided by CHP plant contred by BMS. Water usage has been cut from 120 litres / person/ day at Halley V to 20 litres at Halley VI through the introduction of a vacuum drainage system and low water use devices. Sewage is treated in a bioreactor. Sludge is incinerated and clean water effluent is returned to the ice.

D. Interior Design

Alongside technical innovations, the design also employed old-fashioned architectural principles organizing light and space around human activity. Within the modules a myriad of interior design features were developed to help support the crew through the long dark winters. Bedrooms were designed to be comfortable, but not so comfortable as to erode the sense of community. A quiet room has been included at the north end of the station to provide a space for smaller groups. Large areas of high performance glazing allow views onto the ice and skywards to experience the spectacular auroras. Wherever possible opportunities were sought to address the sensory deprivations suffered by the crew. For example, a spiral stair leading to the upper level of the red module is lined in Lebanese cedar panels, which give off a pleasant natural scent in a place where there are no plants; a colour psychologist was employed to develop a special palette to help combat the debilitating influence of Seasonal Affected Disorder; and within the ergonomic bedrooms, a special alarm clock was developed incorporating daylight simulation lamps to stimulate mood enhancing serotonin production during the long dark winter.

Figure 3. Typical bedroom at Halley VI

E. Construction

The modules are constructed with a robust steel structure and clad in a highly insulated airtight composite fiber reinforced polymer (FRP) panel system. Prefabrication of structure, cladding, rooms and services was maximised within the limitations of the sea ice. Products were sourced from all over the world with the centre of preconstruction activities in South Africa, where full-scale trial erection of modules was undertaken prior to shipping to Antarctica by ice-strengthened cargo ship. The modules were erected over three 12-week summer seasons using a factory line approach at Halley V, which was used to support the construction crew. Once they were fully clad, the modules were moved 15 kms inland to the Halley VI site, proving the relocation strategy. Fit out was completed in the final season.

F. Lessons learnt

During the design stages of the project it was necessary to carry out value engineering to reduce the anticipated costs. The modular basis of design eased this process. The proportions of the modules also made re-planning relatively straightforward and demonstrated the value in systematic analysis of project programme preceding design.

The design of Halley VI demonstrates the value of investment in the interior architecture of a polar station to sustain and inspire the crew, particularly in the winter months when they face the trauma of Seasonal Affected Disorder.

The station has now been occupied for three years and is running a full science programme. Post occupancy evaluation was planned but, due to significant financial cuts within BAS, the programme was abandoned. Questionnaires comparing Halley V with Halley VI were issued to the crew in February 2013. The results were generally positive however a disagreement between some crewmembers and their employer distorted the results. Verbal reports from the station over the following seasons have been very positive with residents enjoying all aspects of the design, particularly the quality of the main social space and the high levels of natural light in summer. Whilst these reports are useful the author feels that a measured Post-Occupancy Evaluation would be of enormous value to the wider community of designers working in extreme environments and could foster closer collaboration between architects working in space and their terrestrially charged peers.

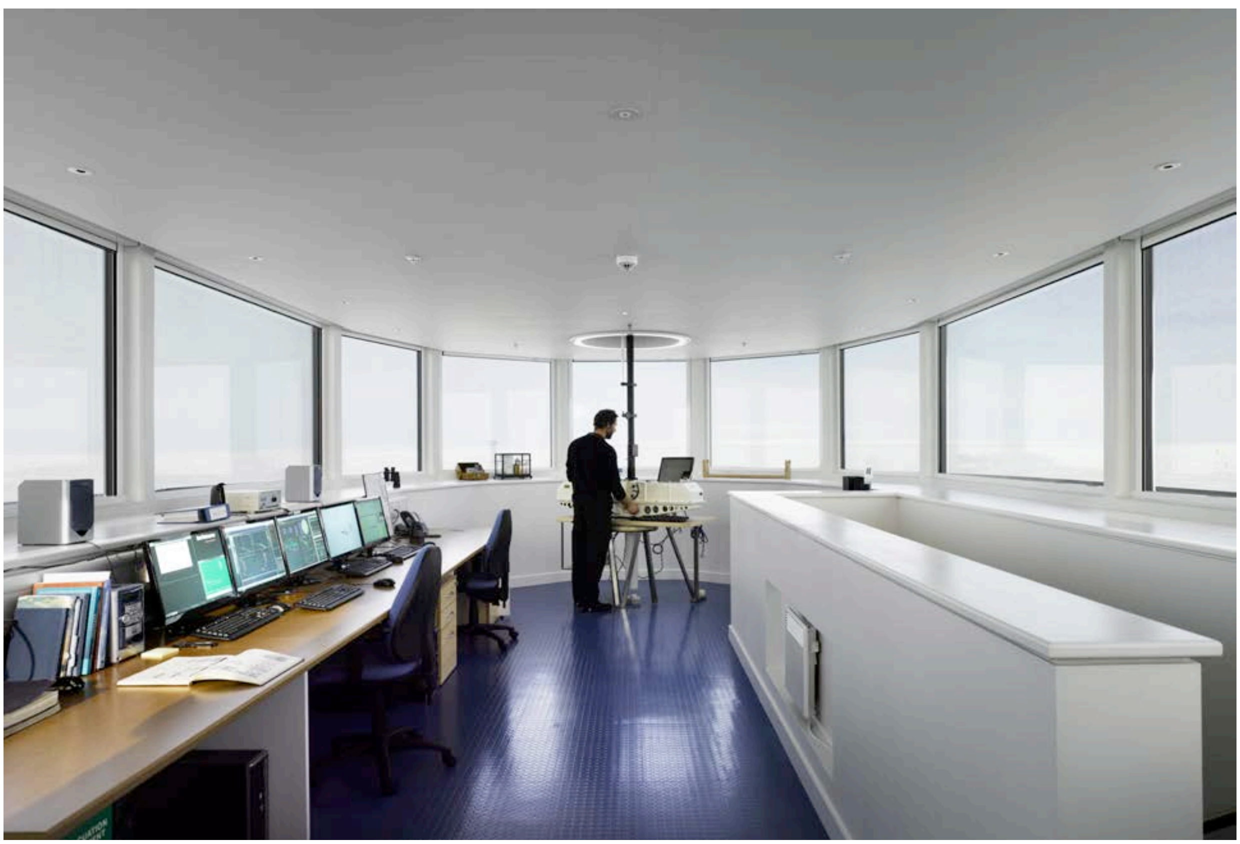

Figure 4. The meteorological observation deck at Halley VI has 360º views of the surrounding environment

III. Atmospheric Watch Observatory, Summit Station, Greenland

Located at the top of the Greenland ice cap, at 72 degrees north, 3225m above sea level and nearly 400 km from the nearest point of land, Summit Station is a scientific research station sponsored by the U.S. National Science Foundation under a permit with the Government of Greenland and operated by CH2M HILL Polar Services. The station is the home of the Greenland Environmental Observatory, which monitors key climate variables. Snow levels rise by 700mm per annum and temperatures drop to –60ºC in winter. Unlike Halley however, the station remains in location and does need to be relocated.

In 2012 the National Science Foundation commissioned the design of a new laboratory for atmospheric research within a clean air sector. The module will be sited about 1 mile from the main base to minimize impact of pollution on experiments. It needs to be easy to build and allow for constantly rising snow levels and drifting. Internally the focus is on flexibility as the laboratory will be used by multiple organizations conducting an ever-changing range of scientific experiments.

The project is currently awaiting final government funding. It is eventually planned that it will be prefabricated in the USA, shipped to Thule in Greenland from where it will be hauled in sections 730 miles across the ice cap to the station for assembly and commissioning.

G. Design Concept

The Atmospheric Watch Observatory (AWO) has been designed to provide year round state-of-the-art laboratory facilities for atmospheric and snow chemistry research. The energy efficient, aerodynamic design maximizes flexibility to suit the ever-changing needs of the scientific research. Internally the layout provides an open plan laboratory, warm-up lobbies for personnel and cargo, a plant room and a small WC and emergency store (in case scientists have to stay over night in the module due to bad weather). As the laboratory conducts sensitive aerosol experiments it is crucial that air pollution is kept to an absolute minimum. All personnel need to either walk to the module from the main base (over a mile away) or use electric powered skidoos.

Figure 5. CGI visual of the Atmospheric Watch Observatory at Summit Station

H. Technical Solutions

The design draws upon our experience working on the larger Halley VI Research Station and develops systems to ease construction and minimize impact on science. Hydraulic legs help the module climb above the rising snow levels. These are supported on steel feet, which spread load onto the ice and allow for dragging the module into place following assembly. The more expensive skis used at Halley are not however necessary as the module will not be relocated. Highly insulated fiber reinforced polymer cladding is used to enclose the module and integrates photovoltaic arrays to reduce reliance on electricity produced by generators at the main camp. The cladding was designed to allow a progressive installation from end to the other, simplifying installation compared to Halley VI. All materials have had to be scrutinized by the National Oceanographic and Atmospheric Administration (NOAA) to ensure no risk of pollution through off gassing to their highly sensitive aerosol experiments contained within the module.

I. Interior Design
A large window maximises natural lighting and creates a pleasant outlook, which is important as scientists can spend up to 6 hours a day working within the AWO. The interior design has however been developed for flexibility and practicality to suit the scientific requirements – this is a working laboratory not a habitat. A small window provides an alternative means of escape in case of fire via spring loaded descender. An external cargo deck incorporates a small electric crane. A pultruded GRP roof deck provides space for the installation of science equipment. Access is arranged downwind to minimise impact on aerosol experiments. No access is allowed on the upwind side of the module.

J. Lessons learnt
The project demonstrates the benefits of developing systems applied in one design to the advantage of the next. The design of Polar Research facilities must respond to the requirements of the science and of the site and these can vary significantly. There are however inevitably also many similarities between installations. By working on a series of closely related commissions, the designers have been able to learn from each and apply the lessons learnt to the next. In the project in Greenland this has manifested itself in a simpler cladding installation strategy, the application of newer technologies for a lighter floor construction, enhanced scientific flexibility and a greater reliance on sustainable energy. The module has also been designed mindful of the proportions of habitat modules so that the same modular approach can be applied to a larger station development, which may take place at Summit in the medium term future.

IV. Juan Carlos 1 Antarctic Research Station
The Superior Council of Scientific Investigation of Spain (CSIC) has been operating a summer only research station at 62º South on Livingstone Island since 1988. Livingstone Island is the second largest island in the South Shetland Islands archipelago, to the north west of the Antarctic Peninsula. Research at the base focuses on geology, meteorology, glaciology and biology with visiting scientists spending up to 4 months on base.

K. Environmental and logistic constraints
In winter temperatures drop to around -25ºC and in summer rise to an average +2ºC, when the majority of snow on site melts to reveal the glacial morraine substrate. Strong winds buffet the station, regularly exceeding 160kph. The station is run by the Maritime Technical Unit (UTM) with logistic support provided by their supply ship, the Las Palmas. Logistics are managed through both Punta Arenas in Chile and Ushuaia in Argentina, both of which are around 600 miles and 4 days sailing away. The original base provided accommodation for a maximum of 20 people and was constructed using containerised and modular igloo accommodation. After 20 years in use the buildings had reached the end of their useful lives and were in desperate need of replacement. The CSIC therefore organised an international competition for the concept design for the total remodelling of the base. In October 2007, Hugh Broughton Architects and AECOM were selected as winners of the competition.

L. Design Concept
The habitat comprises three wings of accommodation arranged around a central core while the science building is a separate structure far enough away to provide a refuge in case of a fire within the habitat. When the station is complete, the habitat will provide sleeping accommodation for 24 people in single rooms, with the option to double up and increase the population to 48 in the future. Open plan areas at the ends of buildings have fully glazed end elevations. Ancillary modular single storey buildings arranged around the site provide space for technical equipment, waste management facilities and stores.

Figure 6. CGI visual of the new Juan Carlos 1 Antarctic Research Station

The location and orientation of the buildings makes best use of the site topography and aspect, with windows framing views of the surrounding land and seascapes. Within the buildings the modular approach maximises flexibility for growth and change so that the new station can continue to respond to the changing needs of Antarctic scientists for 20 years or more.

M. Technical Solutions

Initially the habitat and science buildings were designed to comprise highly insulated modular FRP monocoque rings supported on FRP legs, with ancillary space suspended below. Precast pads form the foundations for the legs. The foundations are set into the morraine, which is easily excavated. The project was designed to a developed concept stage and then tendered to contractors. Once the contract was let, the contractor therefore was able to choose to modify the design. As a monocoque structure had not been used previously on a large scale project in Antarctica, they chose to incorporate a steel frame structure but retained the FRP cladding system originally designed. The ancillary buildings are also constructed in a similar fashion. The curvaceous form of the building exterior was also modified to create a more rectilinear design which better suited the use of steel structure, although losing some of the aerodynamic preformance of the original design.

N. Interior Design

The contemporary interior has been designed with areas for recreation and relaxation within a comfortable, uplifting environment which will sustain both the community and the individual alike. Walls will be fabricated in cassette form to ease construction. All services will be easily accessible. Rooflights and glazed entrance areas will maximise daylight, reducing energy consumption and allowing the crew to continually engage with their surroundings. Although the project was tendered for construction at an ealier stage of design than Halley VI, extensive interior design documentaion was included to ensure fitness for purpose. Final fit out of the station has however been delayed. Budgets of the CSIC were severely effected by the global and national Spanish economic crisis and funds for the interior installation are still awaited.

O. Lessons learnt

The project was designed after Halley VI, and many of the lessons learnt from that project were successfully applied at Juan Carlos. As a result, the design was able to proceed very rapidly towards tender and construction stages. However, it was quickly apparent that the location of Juan Carlos 1 provided many different challenges and opportunities, in terms of environment and logistics. As a result, different design solutions were applied.

- At Halley the construction process was largely determined by the bearing capacity of the sea ice. At Juan Carlos the determining factor was the size of landing craft, which can land on the beach without the need to construct an expensive pier head. Once landed, the design allows for a rapid construction process to suit the limited season.
- Water production at the base is more complex. For parts of the summer a stream runs next to the site, fed by melt water from lakes. At the start and ends of the season however the stream does not run. The scheme therefore includes both treatment of the stream water and a reverse osmosis treatment plant to purify seawater for consumption for when the stream is not running.
- Halley is founded on ice, whereas at Juan Carlos foundations are set into the moraines and are made in prefabricated concrete. The overall building weight was therefore minimized to reduce excavation in rock for foundations.

Figure 7. View of the construction site for Juan Carlos 1 Antarctic Research Station

V. Applying lessons learnt in Polar Regions to space architecture

Whilst the details of the engineering solutions applied to the described polar research facilities may have minimal value to the space community, the principles of integration and coordination of engineering and architecture are common to both fields. Of particular relevance is the experience working in a remote and extreme environment, isolated from the outside world for long periods, which does provide an excellent analogue to space exploration. By necessity polar research facilities need to be designed to be as ergonomic and space efficient as possible and provide facilities which can help sustain the crew through prolonged periods of bad weather, when they may have to stay inside to remain safe.

On the basis of the human factor experience working on polar research bases, in March 2014, the author was invited to take part in a collaboration with NASA to help determine the acceptable minimum net habitable volume for astronauts on long duration exploration class missions[1]. Alongside the NASA team, the working group included two architects, an environmental psychologist, an ergonomics expert and epidemiologist with experience of effects of environmental stressors.

The minimum acceptable net habitable volume was defined as the minimum volume of a habitat that is required to assure mission success during exploration-type space missions with prolonged periods of confinement and isolation in a harsh environment. The exercise presumed that the mission would spend 6 months in transit, 18 months on location and a further 6 months in return transit. The 6-person crew would comprise a pilot, physician, two scientists and two engineers. Communication delays would be 22 minutes with long black out periods with the mission enduring increased autonomy en route to Mars with an obvious decrease on return to earth.

The exercise analysed the minimum space required for sleeping, working, exercise, ablutions and recreation within a cylindrical volume. Volumes were proposed for each activity and then merged into a cohesive whole to determine an acceptable minimum of 25 cubic metres per person of free volume.

The exercise asked pertinent questions about the space needed for privacy; the location for areas of ablution relative to space for sleeping, working or social activity; the space needed for physical exercise; the activities which would take place in the social space and the need to be able to look out of a window. It distilled the requirements of life in a restricted volume to establish a list of requirements to support the best possible living environment for astronauts. Key features deemed essential for the support of the crew included:

- A zonal approach to the layout to separate work and sleep; noisy and quiet activities
- Maximization of opportunities for personalization of space
- Incorporation of sensory stimulation
- Individual sleeping quarters for each member of the crew with a minimum 5.4 cubic meters per berth which allow for sleep, self-care and recreation
- Sufficient dining and communal space to support the full crew and to foster team cohesion, whilst taking advantage of zero gravity to use all surfaces to support multiple tasks
- Task driven work space for up to four crew members with separation from the dining / communal space to prevent cross contamination
- Two separated hygiene and waste compartment areas located away from the berthing and galley for privacy
- Inclusion of partitions for visual and acoustic separation with pass throughs sized for suited crew members
- Stowage, radiation shields and engineering volumes were excluded from the calculation. The net habitable volume revolves around the zone available for human use

Reviewing these criteria against those applied to the design of Halley VI, its is clear that, apart from the opportunities offered in space by micro gravity, there are shared ergonomic and social factors apparent in both designs.

VI. Conclusion

Each of the described polar sites has its own unique set of challenges, and each base has different operational requirements. These issues need to be considered on their own merits to derive the optimum solution for that particular project. However, the design process, intellectual rigour, coordination requirements and fundamental understanding of how to design for such remote, extreme environments are common to all, and should be carried through into the design thinking for any other similar project.

This became apparent in the collaboration with the NASA NHV Workshop where it was clear that the design for optimal living conditions in space shared many common themes with the design of optimal living conditions in an isolated polar environment. The factors which effect crews in space are clearly similar to those which affect crews in Antarctica. In the projects discussed in this paper common themes have emerged, particularly:

- The balance between personal and communal space
- Separation of working and living space
- The relationship between different activities to ensure efficient circulation
- Appropriate environmnetal separation, particularly to create acoustic isolation of sleeping space from noisier activities
- The benefits of good views out to create stimulation and connection with the surounding environment
- The role of natural and artificial light in supporting the crew both in summer and in total darkness
- The role of ergonomic design to make best use of limited space
- The design of communal space which can foster the strongest possible crew cohesion
- Meticulous coordination of engineering designs with architecture to minimise overall construction volume and maximise space available for the crew
- The value in collaboration between design disciplines to ensure the best possible designs to sustain human activity in extremity. This includes the involvement in a wide range of specialists, for example a color

psychologist formed part of the Halley VI team whilst the expert in stressors was a key member of the NHV workshop

It can be argued that these factors are common to many design scenarios. The approach taken to the design of the living environments at Halley VI for example drew upon the first principles of architecture, designing for human activities in the same way that many buildings also do. The key therefore is to consider carefully how every space can be utilized to best advantage to create the most efficient design, which can sustain individual and crew alike for long periods in physical and psychological comfort.

VII. Acknowledgments

The author acknowledges the invaluable contributions of the following to the designs described in this paper:
My colleagues at Hugh Broughton Architects (http://www.hbarchitects.co.uk)
British Antarctic Survey (http://www.antarctica.ac.uk)
AECOM (http://www.aecom.com)
Galliford Try International (http://www.gallifordtry.co.uk)
Office of Polar Programs of National Science Foundation (http://www.nsf.gov)
Consejo Superior de Investigaciones Científicas (http://www.csic.es)
Unidad de Tecnología Marina (http://www.utm.csic.es)
NASA Johnson Space Center (http://www.nasa.gov/centers/johnson)

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