Antarctic Research Stations: Parallels for Interplanetary Design

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Prototype, simulation and analogy are crucial to the preparation process for future space missions. In this context Antarctic research station design, construction and operation can provide a useful analogue because the stations provide isolated living and working within extreme conditions in extraordinarily remote locations. The areas for collaboration between the space and Antarctic design communities have only recently begun to be explored and there is much greater potential to learn from each other. Through a review of the design of two Antarctic stations the paper establishes potential fields of collaboration and sets an agenda for this process in the future as a vital ingredient to the success of global and inter planetary scientific research.

Nomenclature

BAS	=	British Antarctic Survey
IGY	=	International Geophysical Year
FRP	=	Fiber reinforced plastic
CSIC	=	Consejo Superior de Investigaciones Científicas
UTM	=	Unidad de Tecnología Marina

I. Introduction

The vast unspoilt landscape of Antarctica provides a unique environment for the study of earth system science, helping us to understand a vast array of crucial scientific phenomena in the fields of geology, biology, meteorology, glaciology, astronomy and geospace science. To carry out this vital research, scientists must endure the harshest living conditions on our planet, living for prolonged periods in isolated and totally self-sufficient research stations subjected to extreme weather.

This isolation and the extreme environment make Antarctic research stations an excellent real life simulator[1] for many aspects of space architecture from project planning, to material delivery to construction logistics through to the study and application of human factors. In recent years this has been recognized by a series of experiments conducted at both physical and psychological levels by ESA and NASA in collaboration with Antarctic operators at bases operated by France, Italy and the USA, although the analogue has not been exploited to its full potential.

Fig 1: Visual of Halley VI with science modules in foreground and living accommodation in background

The author is the architect of two Antarctic Research Stations: Halley VI for the British Antarctic Survey and the remodeling of the Juan Carlos 1 Spanish Antarctic Base. This paper explains the progress of construction of Halley VI; introduces the design of the Spanish station; and considers the potential for greater collaboration between the space and Antarctic communities, in particular to monitor and develop concepts, which improve human factors in the design of isolated scientific installations.

II. Halley VI

Halley is the most southerly station operated by the British Antarctic Survey (BAS). It is located on the 150-metre thick Brunt Ice Shelf, which is flowing at 400 meters per annum out to sea. Snow levels rise on the site by around 1 meter every year. Temperatures drop to -56°C and the sun does not rise above the horizon for 105 days during the winter. In its coastal location the site is regularly buffeted by katabatic winds in excess of 160 kph. Logistics are managed through a brief 3-month summer season by ship and by plane. A research station has been occupied continuously at Halley since the International Geophysical Year (IGY) in 1957. In 1985 British scientists working at Halley first observed the springtime depletion in stratospheric ozone.

The current station is the fifth incarnation and was completed in 1992. The first four bases were designed to be buried by the snow, but Halley V was raised on steel legs, which are then re-aligned and extended each year to keep it free from the rising snow. Although successful as a design, the position of this base is now precarious, having flowed too far from the mainland to a position at risk of calving off the ice shelf as an iceberg within the next 5-10 years. As the station's legs are fixed in the ice it cannot be moved and so in 2004 the BAS organized an international competition to select designers for a new relocateable station for occupation by 52 people in the summer and 16 in the winter. The competition was won by Hugh Broughton Architects, working with Faber Maunsell (now AECOM). The modular concept was presented by the author at Space 2006 in San José and is featured as chapter 27 of "Out of this World: The New Field of Space Architecture"[2] and it is not the intention of this paper to re-state the credentials of the design. A brief summary of the design however serves to better understand the progress of the project.

Bedrooms, laboratories, office areas and energy centers are housed in standard blue modules of 152 square meters internal floor area and which weigh between 80-95 tonnes. Although the majority of core activities can be provided for using the standard modules, the requirement to combine the group social spaces for living, dining and recreation determined the development of a special two-storey central module of 467 square meters internal area weighing 160 tonnes.

Figure 2. Cut away visual of the central module, which provides space for recreation and relaxation. In the final design the gymnasium is placed on the upper level and the climbing wall was omitted for health and safety reasons (as it is also next to the bar!)

At the heart of this module is a double height light filled space clad with vertical and inclined high performance glazing and translucent nanogel insulated panels. It is planned to install a small hydroponics greenhouse in this space to provide up to 3 salads a week to the winter crew, who up to now have been starved of fresh food for 9-months a year.

The modules are arranged in a straight line perpendicular to the prevailing wind. Early design studies investigated attaching modules at node points to limit length of circulation, but this complicated snow models. In a straight line it is easy to predict that wind driven snow will deposit in long tails on the leeward side. All vehicles therefore track along the windward side.

To avoid the fate of previous stations, the modules are supported on giant steel skis and hydraulically driven legs. The hydraulic legs allow the station to mechanically “climb” up out of the snow every year to avoid being buried. And as the ice shelf moves out towards the ocean, the modules can be lowered, using the hydraulic mechanism, onto the skis and towed by bulldozers to a new safer location further inland. Utilizing the scouring effect of the wind, the geometry of the modules has been developed to ensure that the skis are kept free of snow for ease of movement.

Figure 3. Completed module raised up on hydraulics ready to withstand its first Antarctic winter

The Halley modules are constructed with a robust steel space frame substructure and braced portal frame superstructure and clad in pre-glazed painted fiber reinforced plastic (FRP) panels. The thickness of the panels is determined by the low U-value of 0.113 Wm^2K required to maximize thermal performance and minimize fuel usage. The outer skin is linked across the insulating body with resin infused fiber to prevent delaminating under wind load. Using FRP, panel sizes could be maximized and weather tightness could be achieved using a single skin, helping to minimize erection time on site. This is crucial as the construction season is limited to 10 weeks. This time limiting window for construction is a crucial shared design and logistic factor with space program development.

A. Prefabrication

Logistic constraints of the site were a significant factor in determining the modular design. As the ice shelf protrudes at least 20 meters above sea level, all materials delivered to Halley have to be unloaded onto the sea ice. They are then dragged across this and up man-made snow ramps created in natural creeks at the cliff-like edge of the ice shelf. The sea ice is precariously thin with a maximum bearing capacity of only 9.5-metric tonnes, limiting the size of construction components. The space frame sub-structure of the module was carefully designed within this limit so that it could be delivered fully assembled giving an excellent start to works on site. Similarly many of the station’s rooms and all the floors were designed to be prefabricated so that they could be finished in factory conditions and lifted into position on site ready to use.

B. Tried and tested v innovation

Survival in Antarctica is hard and it is crucial that the modern research station eases life for the teams at work. The life critical design of the station was therefore developed 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. All water at the station is made with a melt tank, which uses significant amounts of energy. Water usage at the base was therefore reduced from 100 liters / person / day to 50 liters / person / day through the introduction of aerated fittings and a vacuum drainage system, adapted from a marine environment, which was also the source of the bioreactor sewage treatment system. As space in Antarctica comes at a significant premium (approximately $38,2000 / square meter at Halley) the application of space saving devices was crucial for economic viability and the sources of these space efficient appliances inevitably came more frequently from the transport sector than the built environment.

Within the modules interior design will play a crucial part in determining the success of the project. For example the color scheme for the project was developed in close consultation with a color psychologist to help compensate for sensory deprivation, provide stimulation where appropriate and otherwise to help relax the residents. Within the bedrooms a special light fitting was developed to help combat the effects of Seasonal Affected Disorder. The lamp uses daylight simulation and an alarm function to slowly adjust peoples red / white blood cell balance as they wake up during the dark winter months, helping limit time keeping freefall which can often effect Antarctic residents when there is no outside daylight.

Figure 4. SAD light prototype

C. Research and development

In late 2006 the project was tendered to Galliford Try International, a British contractor who had previously worked in Antarctica with BAS. Initial stages of the contract involved significant research and development of key technical aspects of the project, in particular the steel structure and FRP envelope. The structure and envelope were procured using design drawings and a performance specification. The sub-contract was awarded to a South African consortium on economic, logistic and technical grounds, and because they had previously completed the envelope for a sub-Antarctic base on Marion Island. The early R&D stages focused on performance at extremes of temperature and achieving fire resistance of 30 minutes from both inside to outside and outside to inside with C-s3d2 EU Standard surface spread of flame on the outside and B-s3d2 on the inside. The combination of cost and fire performance dictated the use of filled polyester rather than phenolic resins. As the panels are large it was necessary to infuse them with the resin under vacuum. This combination of vacuum infusion and filled resins led to great difficulties early in the fabrication process because the density of the resin impeded successful vacuum infusion over large panel sizes with complex geometries. Eventually sufficient panels were completed to allow erection of a trial module. Within the module the prefabricated floors, service cassettes and two rooms were installed and hydraulics were successfully tested. Air infiltration was measured and achieved a rate of 0.1 metres^3 per metre^2 per hour at 50pa of pressure. The test module also gave site operatives an excellent opportunity to familiarize themselves with the assembly sequence and make minor adaptations to ease progress on the ice.

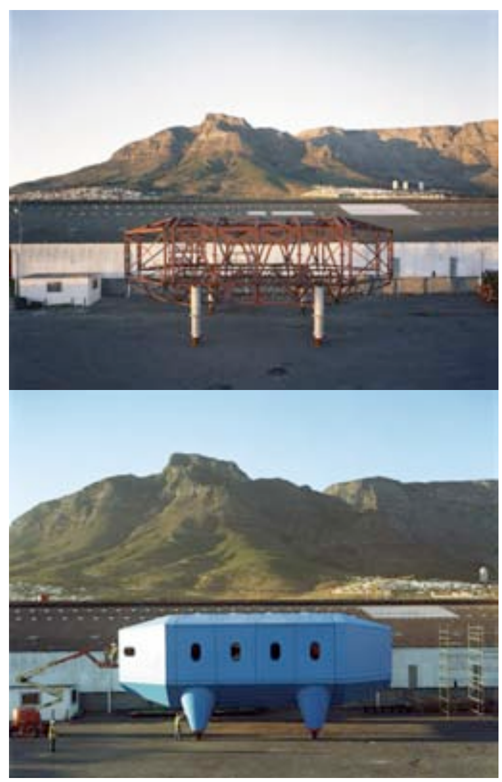

Figure 5. Test module erected in Cape Town as proof of concepts

Figure 6. Space frames were unloaded from the ice strengthened Russian vessel, Anderma, and dragged across the sea ice using lightweight transit skis. Once at site (right side) the hydraulic legs and permanent skis were installed, followed by prefabricated services, floor cassettes, prefabricated room pods and the superstructure

D. First Season Construction 2007-2008

In November 2007 construction materials for the new station were packaged in line with the stringent requirements of the Antarctic Treaty Environmental Protocol and shipped to Halley. As a result of slow progress in panel production only the FRP for one bedroom module was included in the cargo. On arrival in Antarctica the designed construction process proved a success with the sub-structure and super-structure frames for all standard modules erected; pre-fabricated room modules, timber floors and service cassettes installed; and primary energy components fitted. Six of the modules were then encased in PVC laminated vinyl fabric designed to withstand the Antarctic winter, while the seventh module was clad in the one set of completed FRP panels.

E. Benefits of on-site trials

Almost immediately after the panels were installed significant superficial cracking became apparent predominantly on the edges of the panels but also in other areas, although without a logical pattern. The design incorporated a silicone gasket sealing the joint between panels between precise FRP lips. As soon as the defect was observed investigations were begun in South Africa, which revealed that the fabrication of the lip did not match original samples and was excessively rich in resin. Further investigations showed that there were other areas of panels where the infusion process had been poorly controlled causing resin rich areas. The analysis established that the resin rich areas were suffering from thermal shock on arrival in Antarctica causing the cracking. Over the following two winters the module was monitored on site and no further cracking developed, confirming the source of the problem. This has demonstrated the benefit of trials when building in extreme environments, which is a crucial and well documented factor to consider in the development of installations for space environments

Figure 7: One module was clad with large FRP panels, while the others were temporarily protected in fabric

Figure 8. Relocating module with BAS plant

F. Product development

To overcome the defect a remedial process was instigated in the fabrication works in South Africa. The joint configuration was changed to incorporate an aluminum cover strip. All the panels were laminated with an additional 2 layers of glass fiber and a polyester resin to produce a tough crack resistant exterior. Changes were also instigated to the manufacture process to improve quality control in the factory and the geometry was simplified to ease the vacuum infusion process using filled polyester resins. These revisions had immediate positive benefits in the manufacture process of test panels, which were proven by a further series of structural and thermal shock tests. The tests were carried out before whole scale manufacture of panels could re-commence.

G. Second Season Construction 2009-2010

By September 2009 all the panels for all the modules had been completed and a second test erection of the large red central module was conducted. This trial was completed ahead of program and demonstrated the high level of quality, dimensional control and ease of erection, which can be achieved with large FRP panels. The second construction season was also very successful and by the end of February 2010, when the season completed, all the modules had been fully clad, including re-cladding the original bedroom module. This season also proved design concepts for snow management, elevation and relocation. The first clad module had survived two winters with no snow build up underneath, as a consequence of designed wind scouring. On arrival for the second season the module was jacked using the hydraulic legs and towed to the construction line, all as conceived in the original competition design. The 2010-11 season will concentrate on interior fit out. Although much thought has gone into this aspect of the project, evaluation cannot begin until occupation in January 2012. The format of post occupancy evaluation is to be determined and input from human factor specialists within the space architecture community would be welcome.

Figure 9. Central module showing test erection in Cape Town (top left), under construction on site with pre-glazed panel being lifted into place (top right) and nearing completion (bottom)

H. Halley VI: The Future

When Halley VI becomes operational it will be the most advanced research station in Antarctica on technical, operational, environmental and social levels. Its flexibility will allow easy conversion of science modules to suit a rolling quinquennial science program while its state of the art architecture and interiors will both sustain the crew in unparalleled comfort and, vitally, attract cutting edge scientists to work in the Antarctic with BAS, justifying their radical approach to procurement and design. The key mark of success of the station will be the additional time and improved environment available for science research at Halley. Although it is already clear[3] that the ratio of scientists to technical staff will dramatically improve, currently there are no programs planned to determine improvements in human performance in the station, achieved as a consequence of design. It is the author's view that this could be an interesting area of collaboration between BAS and the space community, similar to programs under way at Concordia, which are run by ESA in partnership with the French and Italian Antarctic programs.

III. Juan Carlos 1 Spanish Antarctic Base

For our own part the immediate success of the Halley project was the commissioning of a second Antarctic station design for Spain. 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. In winter temperatures drop to around -25º C and in summer rise to an average +2º C, when the majority of snow on site melts to reveal the glacial moraine substrate. Strong winds buffet the station, regularly exceeding 200 kph. The ecology of Livingstone Island is extremely fragile. Alongside colonies of elephant seals, gentoo and chinstrap penguins the island is also home to the only flowering plants in Antarctica. The site of the station is also the location for extremely rare lichens and large areas are cordoned off to prevent human damage.

Figure 10. Existing Spanish Antarctic Base showing main habitat module (1), science labs (2), stores (3), sleeping pods (4), generators (5). Boat shed and fuel tanks are out of view

The station is run by the Maritime Technical Unit (UTM), based in Barcelona, 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 base currently provides accommodation for a maximum of 20 people and is constructed using containerized and modular igloo accommodation. After 20 years in use the buildings on the site have now reached the end of their useful lives and are in desperate need of replacement. The CSIC therefore organized an international competition for the concept design for the total remodeling of the base. In October 2007, Hugh Broughton Architects were selected as winners of the competition with an extruded section modular design.

A. Design of the new station

The habitat building comprises three wings of accommodation arranged around a central core[4] while the science building is a separate structure far enough away to provide a refuge in case of a major fire within the habitat. 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.

The location and orientation of the buildings makes best use of the site topography and aspect, with windows framing wonderful views of the surrounding land and seascapes. Balconies at each end also double up as means of escape and as access at the start of the season. Although the site is free from snow for most of the summer season, on arrival in November the site can be under 3 meters of snow. Raising the accommodation above ground allows the team to enter the buildings more easily without the need for major clearance operations before services are fired up. It also limits connections with the ground, reducing flood risk and impact on the rare lichens on the site.

Figure 11. Visualization, showing habitat modules in foreground and science module in background.

B. Construction approach

The habitat and science buildings comprise modular fiber reinforced plastic monocoque rings supported on legs, with ancillary space suspended below. Foundations are set into the moraines and are made in prefabricated concrete. The monocoque structure combines the inherent strength of FRP with the natural strength of a tubular geometry so that, for this project, steel structure is not needed. This is important in such a corrosive marine environment. The monocoque structure also delivers other benefits. Space is saved through adoption of a single system for structure and envelope; there are no complex structural interactions between materials with different performance characteristics; and the overall building weight is reduced minimizing excavation for foundations. Learning from experiences with FRP used at Halley, the jointing of the rings is designed with an aluminum cover strip, omitting risk of resin rich areas.

Figure 12. Balconies to ends of modules allow alternative means of escape and of entry at start of season. Glazing allows scientists to constantly engage with the stunning surrounding sea and landscape. In summer doors can be opened and scientists can use balconies for relaxation in the Antarctic sunshine.

As the outsides of the buildings are circular and the insides are rectilinear clear service distribution zones are created in fully accessible interstitial areas between the two geometries. This simplifies construction, detailing and fire protection, which can be achieved to the same standard as Halley using the inner cementitous based linings instead of relying on the panel constitution. In this way it is possible to form the FRP rings using unfilled polyester resins under vacuum, avoiding the issues of slow infusion associated with the filled polyester resins. This is a clear demonstration of successful application of lessons learnt in one environment applied to another.

Within the buildings the rooms, floors and service distribution will be prefabricated drawing upon the successes of Halley. This approach also maximizes flexibility so that the station can continue to respond to the changing needs of Antarctic scientists for 20 years or more – whether in terms of space planning or service requirements. In line with this strategy bedrooms, bathrooms and kitchens are planned as prefabricated pods whilst offices and labs utilize partition systems, which can be moved when needed to maximize flexibility. The contemporary interior will be packed with areas for recreation and relaxation within a comfortable, uplifting environment designed to sustain both the community and the individual alike. Rooflights and glazed entrance areas will maximize daylight, reducing energy consumption and allowing the crew to continually engage with their surroundings.

Ancillary modular single storey buildings arranged around the site provide space for technical equipment, waste management facilities and stores. Separation improves robustness of the station in case of fire. The ancillary buildings will also be constructed in FRP, raised above ground on precast concrete foundations and with timber cassette floors. Service distribution between these buildings will be managed in semi submerged service canals, which will provide easy access and maintenance. One of the key requirements of the brief is that the base is easy to open and close at the start and end of each season with a limited team from the UTM.

C. Service systems

Similar in approach to Halley, the proposed scheme utilizes the latest technologies from a broad spectrum of industry, ranging from the rail to the aircraft sectors. The design aims to limit the station's environmental impact while making best use of renewable energy. Solar and wind generated energy are already in use at Juan Carlos 1 to power scientific equipment during the winter months, when the station is unoccupied. The new designs will extend this power source to allow for expansion of science programs and utilization of renewable energy within the accommodation. As life safety is critical however the major power load will continue to be provided by four CHP generators in two modules. Sewage will be treated using a bioreactor. Water production at the base is 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.

D. Construction process

At Halley the construction process was largely determined by the bearing capacity of the sea ice. For the Juan Carlos base 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 rings of the station, which weigh between 2.5 - 3 tonnes each, can be erected relatively simply using a simple system of hydraulic lifts and temporary propping. The design for the new Spanish Antarctic Base allows for a fast and effective construction process, which maximizes off-site fabrication.

Figure 13. Cross sectional visualization taken through entry stairs showing service distribution at ground level between floors, service distribution across glazed stair foyers at first floor level, FRP legs supported on precast concrete foundations and lobbied entrances

IV. Learning from the Antarctic experience: a proposal for increased collaboration

The practice of architecture in Antarctica has enormous relevance to the emerging field of space architecture. Although technically the fields function to very different criteria, the case studies illustrated show that there are many similarities in terms of logistic, human factor and even technical issues. This paper has been prepared to provide a springboard for collaboration between the Antarctic and space communities. Initial steps could be established within the space architecture community. The first step could be a workshop to identify areas of collaboration and could be attended by representatives of some Antarctic missions and interested space agencies. A review of the areas of mutual interest demonstrates the potential value of this approach.

In both cases the habitats are isolated[5], established in extreme environments and predominantly serve a scientific mission. Logistic concerns are also shared, although distances are of course very different. To deliver materials to the Antarctic requires careful planning and programming, systemized packing regimes and great care in transportation. To ensure success on site, construction relies on extensive testing and trial erections to prove feasibility. Whilst maximizing prefabrication is crucial, this has to be tempered by significant logistic constraints, in weight and volume. Once delivered to site, erection is carried out by operatives wearing bulky, restrictive clothing in harsh weather conditions. When completed the stations survive within an infra-free environment with a requirement to create their own heat, power and water without any supporting infrastructure. These similarities offer fantastic opportunities to the space community to input to the success of Antarctic missions and for Antarctic missions to offer opportunities for the space community to trial new concepts. This level of collaboration is currently embryonic although notable exceptions to the rule are developing. The success of these collaborations can also contribute to appropriate technology transfer to other sectors ranging from outposts in remote locations to emergency shelter in disaster zones[6].

Looking beyond the logistic process, within the stations the residents remain in place for long periods (scientists stay for up to 2.5 years at Halley) without relief and are subjected to an intense array of human experiences exaggerated by prolonged periods of light in summer and dark during winter whilst conducting a combination of life preserving and scientific duties. Within this field the opportunities for exchange between the two communities are unparalleled[7]. This potential of this collaboration can only be properly understood through exchange of experience and ideas and a better understanding of respective missions. The recent completion and ongoing construction of a series of new Antarctic Research Stations (Belgium, France, Germany, India, Italy, Spain, UK, USA) can offer a remarkable opportunity to expand learning and improve upon levels of collaboration. The study of real-time simulation in these environments could be of huge significance[8] and to mutual benefit of the scientists who over decades to come will be working at the front line of both our planet's survival and of our quest to expand our knowledge of our surrounding solar system.

Figure 14. Halley VI module, seen against backdrop of the Aurora Australis – not so different to space?

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