# How does Extreme Climate Conditions Impact Building Envelope Design?

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**Abstract**

This study was carried out to gain a greater understanding of how extreme climate conditions can impact building envelope design. Through studying buildings located in the most extreme climate conditions on Earth, a better understanding might be gained into how Earth's extreme climate conditions compare to the extreme climate conditions on Mars which can then inform the design of the external envelope of a building designed for future architectural projects on Mars. Design choices made for a building envelopes form, construction type, U-Value and material specification can all be impacted by extreme climate conditions.

Two case study buildings on Earth were analysed. The first being the Halley VI, British Antarctic Research Station, located in an extreme polar climate. The second being the Nk'Mip Desert Cultural Centre, Osoyoos, Canada, located in an extreme arid climate. These two case studies were compared to the "Martian House" concept design by Hugh Broughton Architects, who also designed Halley VI. The analytical esquisse compared the annual weather data, design features, construction sequence, form and external envelope details for each case study. The data of each case study was run through digital simulation software. Firstly, a Revit model of each case study was created. A section of the external envelope was taken through the model and input into a thermal analysis plugin to calculate U-Value, fRsi, and Phi values achieved at the extreme outdoor temperatures. The case studies data also inputted into the Passive House Planning Package (PHPP) software to find the specific space heat demand to compare the results.

When designing a building envelope for an extreme climate, the designer should make themselves aware of the challenges the building will face pre and post-construction. For example, the Halley VI external envelope had to be modular to reduce the construction time on-site due to the extremely harsh working conditions. Halley VI raises itself above the snowdrift every year to avoid getting buried using its hydraulic legs.

***Keywords****: Mars, Extreme Climate, Building Envelope, Halley VI, Antarctica, Osoyoos.*

# Declaration

I hereby declare that the work in the dissertation is entirely my own and that all sources have been acknowledged and have not been submitted to any other sources or university.

Liam Deguara

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In memory of my grandfather Architect, Carmel Busuttil.

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# 1.0 Introduction

## 1.1 Aims

The aim of this dissertation is to investigate how buildings are designed for extreme climate conditions on Earth and show how designing a building on Mars compares to the extremes on Earth.

## 1.2 Motivation

Pushing the limits of architectural technology to the cutting edge of designing buildings for the most extreme environments on Earth and future architectural projects on Mars was a key inspiration. The researcher is also conscious that climate change may result in architectural technologists adapting their approach to designing buildings for harsher climates in the future. The author also has an interest in space exploration.

## 1.3 Objectives

The objectives planned out for this dissertation are as follows:

- To produce an analytical esquisse exploring how two case study buildings are designed for the most extreme climate conditions on Earth.
- To compare these two case studies to each other and to a subsequent case study concept building designed for Mars.
- To carry out interviews with experts in designing buildings for extreme climates.
- To carry out a thermal analysis of each of the case study building envelopes.
- To carry out an energy loss and space heating demand calculation for each case study.

## 1.4 Scope of Research

The research acknowledges the many design considerations faced with designing a building for extreme climate conditions and a building on Mars but focuses on the external envelope design and boundary conditions. Travelling to extreme climate locations to conduct field research of buildings could not be achieved. Neither could testing building materials in laboratories under extreme temperatures be accomplished due to the government's COVID-

19 restrictions prohibiting travelling more than 5 km outside of the researcher's home. Due to this, all research was either desktop research or performed using digital simulation software.

The research analyses a case study building located in an extreme polar and arid climate. These two case studies are then compared to each other and to a concept case study building designed for Mars as there are no buildings constructed on Mars currently.

# 2.0 Literature Review

## 2.1 Introduction

This study analyses how building envelope design is impacted by the most extreme climatic and environmental conditions. This review will survey literature about two case study projects located in two of the most extreme climates on Earth. The Halley VI, British Antarctic Research Station and Nk'Mip Desert Cultural Centre demonstrate how buildings are designed for Earth's most extreme climates. The design thinking behind these case study buildings might inform an approach to the future design of a building on Mars. These case study projects will be compared to a concept design case study building design called "Martian House" by Hugh Broughton Architects, who also designed Halley VI.

Most literature surrounding these case studies have been authored by architects such as Hugh Broughton and Ruth Slavid and published in books such as "Ice Station" and journals such as "The Architects Journal" over the past two decades in the United Kingdom and the United States.

## 2.2 Case Study: Halley VI, Antarctica

The Halley VI British Research Station (Figure 1) in Antarctica is the world's first fully relocatable research station, which is built on the floating Brunt Ice Shelf, one of the most remote and isolated locations in the world, where temperatures can plummet to -55°C. Pushing the boundaries of design in a life-critical environment. The station was designed by Hugh Broughton Architects and AECOM for the British Antarctic Survey. Construction in Antarctica was carried out by Galliford Try over four summers from 2009 to 2013.

**Figure 1**

*Halley VI side elevation photograph*

*Note.* From *Ice Station: The Creation of Halley VI. Britain's Pioneering Antarctic Research Station*, by R. Slavid, 2015, Park Books. Copyright by BAS.

Antarctica has one of the most extreme climates on Earth. There is around 1.2 m of snow build-up a year. The temperature is very low; in winter it can drop to -50°C, with the lowest ever recorded temperature being -55°C. The snow never melts, therefore, and blown by the prevailing wind (that can exceed 160kph), it builds up against buildings and other obstacles (Slavid, 2015).

Not to mention Antarctica has just two seasons: summer and winter. Six months of total daylight in the summer and six months of total darkness in the winter. This is psychologically challenging for people living in Antarctica who are liable to induce SAD (Seasonal Affective Disorder).

Designing a building suitable for this climate is challenging. Halley VI, as the name suggests, had five predecessors. The first was built in 1956 and like its three immediate successors had to be abandoned when buried or crushed by a build-up of snow (Slavid, 2015).

In tandem with the extraordinary demands of the harshest climate on Earth, the construction and operation of the new station must meet the stringent requirements of the Environmental Protocols of the Antarctic Treaty. Delivery of construction materials to site also poses a significant challenge. As the ice shelf protrudes 20 meters above sea level, all materials must be unloaded onto fragile sea ice with a maximum bearing capacity of only 9.5-metric tonnes. They are 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 (Hugh Broughton Architects, 2014).

The solution the design team came up with envisioned a modular building consisting of several independent but linked units, mounted on skis for transport to new locations (Slavid, 2015).

The team developed skis that were very robust and able to lock in place to rotate independently. The skis are attached to the bottom of the module's hydraulic legs that raise the station above the snowdrift each year (Slavid, 2015).

The design team opted for a modular design not only to allow for each module to be relocatable but also for the construction process itself. With a summer season lasting a maximum of 12 weeks, the construction time was bound to be limited even when spread over several years; so, prefabricating as much as possible off-site was desirable (Slavid, 2015).

The modules are constructed with a robust steel structure and clad in a highly insulated airtight composite GRP 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 pre-construction activities in South Africa, where a full-scale trial erection of modules was undertaken (Figure 2) before shipping to Antarctica by an ice-strengthened cargo ship (Hugh Broughton Architects, 2014).

**Figure 2**

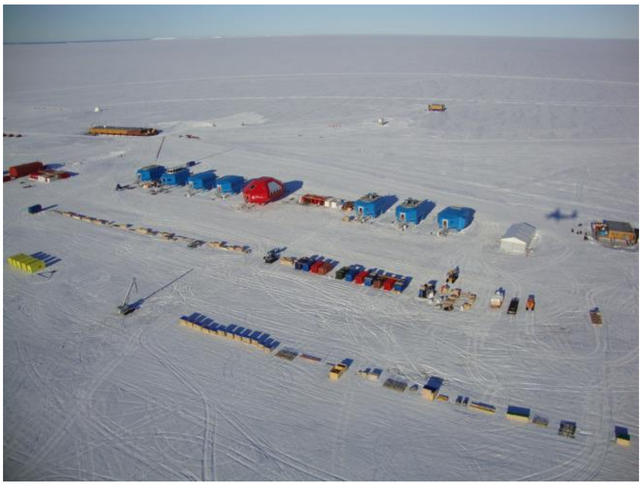
*Halley VI mock-up module in South Africa photograph*


*Note.* From *Ice Station: The Creation of Halley VI. Britain's Pioneering Antarctic Research Station*, by R. Slavid, 2015, Park Books. Copyright by Dave Southwood.

The modules were erected over three 12-week summer seasons using a factory line approach at Halley V (Figure 3), which was used to support the construction crew. Once they were fully clad, the modules were moved 15 km inland to the Halley VI site, proving the relocation strategy. Fit-out was completed in the final season (Hugh Broughton Architects, 2014).

**Figure 3**

*Aerial photograph of construction line and stores at Halley V*



*Note.* From *Ice Station: The Creation of Halley VI. Britain's Pioneering Antarctic Research Station*, by R. Slavid, 2015, Park Books. Copyright by BAS.

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. Inspiring interior design provides an uplifting environment to sustain the crew through the long dark winters, helping to combat the debilitating influence of Seasonal Affected Disorder. Halley VI incorporates medical operating facilities, air traffic control systems and CHP power plants and is a microscopic self-supporting infrastructure-free community (Hugh Broughton Architects, 2014).

The energy strategy for Halley VI was a part of the core requirements of the project brief. The key ingredient to achieving this strategy was to minimise fuel usage. In Antarctica, there is no infrastructure. Everything needed to operate a research station must be imported by sea or air (Hugh Broughton Architects, 2014). The building envelope for Halley VI was designed with this restraint in mind.

Modules are clad in highly insulated pre-glazed painted glass-reinforced plastic (GRP) panels. The thickness of the panels is determined by the low U-value of 0.113 $Wm^2K$ required to maximise thermal performance and minimise fuel usage. Using GRP, panels could be made as large as possible and weather tightness was achieved using a single skin, which reduced erection time on-site as shown in Figure 4.

**Figure 4**

*Halley VI cladding installation of a standard module photograph*

*Note.* From *Ice Station: The Creation of Halley VI. Britain's Pioneering Antarctic Research Station*, by R. Slavid, 2015, Park Books. Copyright by Andy Cheatle.

GRP has a very low coefficient of thermal conduction ensuring consistency of thermal performance across the whole panel with minimum heat loss compared to metal or timber SIP panels (Hugh Broughton Architects, 2014).

The cladding system forms an airtight, monocoque enclosure for each module. The centre of pre-construction activity was in South Africa. Before shipping to Antarctica, a trial erection was carried out in Cape Town of both a blue (Figure 2) and the red module (Figure 5). Air infiltration was measured and achieved a rate of 0.1 $m^3m^2h$ at 50pa of pressure (100 times better than current UK Building regulation limits) (Hugh Broughton Architects, 2014).

**Figure 5**

*Halley VI mock-up of the central module in South Africa photograph*

*Note.* From *Ice Station: The Creation of Halley VI. Britain's Pioneering Antarctic Research Station*, by R. Slavid, 2015, Park Books. Copyright by Hugh Broughton Architects.

Within the parameters of the energy balance, glazing is maximised throughout the station for the wellbeing of the crew and to reduce lighting demand during the 24-hour day lit summer. Windows are triple glazed using high-performance glass. Within the atrium of the central module, the glazing (Figure 6) incorporates translucent nanogel insulated panels with a U-value of 0.6 $Wm^2K$ and 38% light transmittance, filling the volume with a gentle diffuse light whilst minimising heat loss (Hugh Broughton Architects, 2014).

**Figure 6**

*Halley VI atrium glazing panels photograph*

*Note.* From *Ice Station: The Creation of Halley VI. Britain's Pioneering Antarctic Research Station*, by R. Slavid, 2015, Park Books. Copyright by James Morris.

Construction for the building envelope on-site did not go without its issues. When the panels were on-site in Antarctica small cracks opened in the surfaces. Many of these were around the complex moulding in the joint between panels, but some were also in the panel centres.

The contractor continued with the erection, but also appointed David Kendall, a structural engineer specialising in composite materials, to investigate the problem and help devise a solution. Kendall's investigation showed that none of the cracks were structural and that in fact, the structural performance of even the worst affected panels was very good.

The source of the problem was 'resin-rich' areas where the resin had pooled, without adequate fibre, because of the difficulty that the filled resin had in passing through the moulding. Working with the architects and structural engineer, he came up with a solution that allowed many of the panels, which had already been fabricated, to be remediated rather than having to be entirely remade.

The joints between the panels were redesigned to be much less sharp, and the original gaskets replaced with aluminium cover plates. The joints were ground down to create the new shape, and a similar joint was designed for the red panels, which were yet to be fabricated. The outer faces were also ‘re-skinned’ using resin without filler since only the interior face of the panels are vulnerable to fire. The new panels underwent extensive fire and thermal testing and all were ready for shipping for the 2009/2010 season.

The new joints are crisper than the original gaskets, which had proved to run into difficulties where they had to turn corners. Valuable knowledge has been accumulated on using materials in extreme conditions (Slavid, 2010). See Figures 14 and 15 in chapter 4.2 for a graphical comparison of the defective and amended panel joint detail.

This case study shows how the extreme climate conditions impacted how Hugh Broughton designed the building envelope. The extreme temperatures in Antarctica meant that construction time on-site should be limited, so a modular design that was quick to construct was adopted. The remote location on a fragile ice shelf limited the size and weight of the pre-fabricated cladding panels. The defects in the cladding panels proved how designing exposed building envelope materials for extreme temperatures can lead to unforeseen failures in the materials.

### 2.3 Case Study: Nk’Mip Desert Cultural Centre, Canada

The Nk’Mip Desert Cultural Centre (Figure 7), designed by DIALOG is located in Osoyoos, Canada, one of the most spectacular and endangered landscapes in North America. Its rare desert condition is the northernmost tip of the Great American Desert, which extends southward as far as the Sonoran Desert in Mexico (Valenzuela, 2014). The building opened to the public in 2006.

**Figure 7**

*Nk'Mip Desert Cultural Centre front elevation photograph*

*Note.* From *Nk'Mip Desert Cultural Centre / DIALOG*, by K. Valenzuela, 2014, ArchDaily. Copyright by Nic Lehoux Photography.

The project's concern with deep sustainability grows out of the fragility of this landscape and reflects the core values and history of the Osoyoos Indian band. The extreme climate made sustainable design a very particular challenge. Hot, dry summers and cool, dry winters see average temperatures ranging from -18°C to +33°C and often reaching +40 °C on summer days (Valenzuela, 2014).

The building features indoor and outdoor exhibits that celebrate the culture and the history of the Osoyoos Indian band. It is designed to be an extension of the remarkable site and reflects the band's role as stewards of the land. The desert landscape flows over the building's green roof, held back by a rammed earth wall. The partially submerged building is sited very specifically to focus the visitor's eye away from the encroaching development of Osoyoos to the west, with the height of the wall set to create a layered view of the desert rising up in the middle ground, receding to the riparian landscape adjacent, and the mountains in the distance (Valenzuela, 2014).

The building's siting and orientation are the first strategic moves toward sustainability: the partially buried structure mitigates the extremes in temperature, and its orientation optimizes passive solar performance, with glazing minimized on the south and west sides. The project's ambitious approach towards sustainable design achieved building the largest rammed earth wall in North America.

At 80m long, 5.5m high, and 600mm thick, this insulated wall stabilizes temperature variations. Constructed from local soils mixed with concrete and colour additives, it retains warmth in the winter, its substantial thermal mass cooling the building in the summer much like the effect the surrounding earth has on a basement (Valenzuela, 2014).

The choice to use rammed Earth for this project primary building envelope material is significant. Firstly, the on-site soil used to create the wall is a sustainable material because there was no embodied energy in local soil. Secondly, the rammed earth thermal mass properties act as a heating/cooling device. Heywood (2013) describes how thermal mass works as buildings with heavy walls, which have high thermal mass, will absorb heat slowly and store it. The stored heat will then be released slowly into the building. In high-thermal-mass buildings, the highest indoor temperature will occur in the early hours of the morning, many hours after the highest temperature has been reached. Heavy buildings are therefore said to have a slow response time. This is also known as the "thermal flywheel effect", and it relates to the patterns of use of buildings. In hot, arid locations, thermal mass is needed in walls and roof to balance large diurnal temperature differences.

The wall consists of local dirt, with organic matter filtered out, combined in a mix of 10 per cent concrete and colour additives (to get that clean, layered look). Contractors from British Columbia's Terra Firma Rammed Earth Builders laid down each strip and then mechanically tamped it down to 50 per cent of its original height. Haden says it was more labour intensive and expensive than concrete, but he hopes to encourage more rammed earth architecture in the region by training locals in the construction methods. "If this could become a more generic material, it could foster a modern and regional aesthetic," Haden says (Fortmeyer, 2018).

**Figure 8**

*Nk'Mip Desert Cultural Centre rammed earth wall & formwork photograph*

*Note.* From *A Rammed-Earth Wall for the Ages at Nk'Mip Desert Cultural Centre*, by R. Fortmeyer, 2008, Architectural Record. Copyright by Brady Dunlop/HBBP.

The habitable landscaped roof reduces the building's visual imprint on the landscape and allows a greater percentage of the desert landscape habitat to be re-established on the site (replanting uses indigenous species). The roof also provides further temperature stabilization and insulation. The choice to specify a green roof is significant because the green roof dissipates the heat better than a typical concrete flat roof which would absorb the summer heat causing overheating.

In-slab radiant cooling and heating in both ceiling and floor slabs create an even, comfortable environment that avoids blasts of air, noise and dust. Coupled with 100% outdoor air displacement ventilation, the system will result in savings of 30-50% over a forced-air system. This is worth noting because the heating/cooling system is embedded into the inside face of the building envelope which heat/cools the fabric as well as the indoor air.

Water is precious in the desert. A channel of water at the entrance along the rammed earth wall introduces this theme. Less visibly, demand on the site fed well is reduced by 40% by incorporating low-flow faucets, waterless urinals, and dual flush toilets (Valenzuela, 2014). This is like how Halley VI was designed to consume low amounts of water in its isolated location. A vacuum drainage system was integrated to reduce water usage to 20 litres per person a day. An average person in Europe uses 160-180 litres of water a day (Slavid, 2015).

This case study shows how on-site materials can be utilised as construction materials for the building. This in turn impacted the design of the external envelope to utilise the rammed earth thermal mass properties to cool the building in the scorching summer and stay warm in the freezing winter.

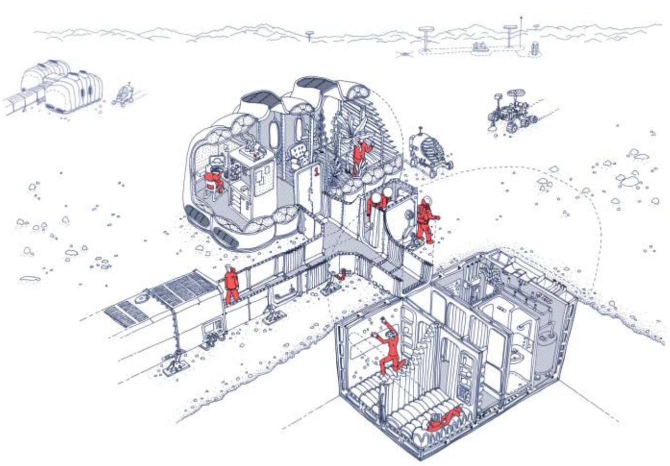
**2.4 Case Study: Martian House, Mars**

Hugh Broughton Architects is working with multidisciplinary studio Pearce+ and the artists to produce the concept design of a Martian House (Figure 9) based on the public's ideas.

The prototype for the house has been granted planning permission and is due to open in Bristol, April 2022 and be taken down in August of the same year (Pitcher, 2020).

**Figure 9**

*Martian House concept design cutaway 3D sketch*



*Note.* From *Gold inflatable house for Mars designed by Hugh Broughton Architects and Pearce+*, by C. Carlson, 2020, dezeen. Copyright by Hugh Broughton Architects.

Occupants will make use of a hydroponic living room, small-scale lab, bedroom, toilet, shower and a kitchenette.

The house will comprise two levels. The lower level of the house is designed to be built below the ground will be designed to be fully buried to maximise protection and would likely be made of reused rocket components.

The upper level, designed to sit on a Martian landscape, will be formed using a pressurised inflatable gold-coated foil, making it lightweight enough to be transported to the fourth planet from the sun and filled with regolith (Martian soil and rock) to provide protection from galactic and solar radiation (Pitcher, 2020). This is worth noting because firstly, the architects have specified lightweight materials which indicate there will not be able to transport typical heavy construction materials transported from Earth to Mars on a rocket. Secondly, the choice to use the mass of the on-site Martian regolith as a primary building envelope is significant because it will be used to block occupants exposure to the dangerous amounts of radiation on Mars. This is an impact the climate on Mars has had on the building envelope design.

Hugh Broughton and Owen Pearce stated that "the gold is important for dissipating heat into the thinner atmosphere on Mars. For future use on Mars, a new polymer might need to be developed that is light enough to be transported to the red planet. The regolith within is set using biological solidification – the regolith becomes bonded using microbes and forms essentially Martian concrete. The inflatable formwork remains as a seal and final surface" (Carlson, 2020). This statement from the architects is important because it highlights that there is an opportunity for further research within this project. There is a requirement to find a polymer material that is lightweight enough to be transported to Mars and act as an inflatable formwork and provide an airtight seal for the building envelope.

This concept case study shows the thinking behind designing a building envelope on Mars. The choice to use lightweight materials was influenced by the fact that Astronauts going to Mars will have to bring as little amounts of building materials as possible. The use of regolith as a primary construction material was impacted by the fact that there are dangerously high levels of radiation on Mars.

### 2.5 Conclusion

To conclude, this literature review surveyed what authors have written about Halley VI, Nk'Mip Desert Cultural Centre case study buildings located in the most extreme climates on Earth. A concept design case study for Mars designed by the same architect as Halley VI was also reviewed.

The Halley VI case studies construction type was impacted by the fact that components could only have a maximum weight during transportation over thin ice and because construction time on-site was limited to a 12-week summertime slot each year due to the harsh winter working conditions in Antarctica. The hydraulic legs feature was implemented to avoid getting buried by snow like the previous five stations. The cladding design was greatly impacted by the cracking GRP found when the cladding panels arrived in Antarctica.

The Nk'Mip Desert Cultural Centres building envelope design was impacted by the climates hot summer and cold winter temperatures. The building envelope had to have thermal mass properties to absorb the heat in the day/summer and dissipate it during the night/winter. The sustainable design approach meant that using rammed earth instead of concrete to achieve this was selected.

The Martian House design concept was impacted by the extreme environment on Mars that has extremely low temperatures and dangerously high levels of radiation. This led to the building envelope having to have a high mass to block the radiation. Also, the choice to transport lightweight minimal construction materials to Mars was influenced by the fact that a rocket's cargo will have limited space.

# 3.0 Methodology

## 3.1 Analytical Esquisse

The purpose of the analytical esquisse was to graphically analyse how case study buildings are designed for the most extreme climate conditions.

Two case study buildings located in Earths most extreme environments were selected as well as the concept case study design for Mars. All three case study buildings were analysed under these key areas:

- Climate conditions.
- Architectural drawings (plans, sections, elevations and details).
- Phases of construction.
- How the building actively deals with the extreme climate conditions.

## 3.2 Interviews

Interviews with people who have had experience in designing buildings for extreme climates were chosen to highlight the challenges faced when designing a building located in an extreme climate.

Hugh Broughton was a key candidate for his work on Halley VI and the Martian House. Colman Billings from Billings Design Associates, who were the external envelope subcontractor for Halley VI was also nominated for his insight on the external envelope design.

## 3.3 Digital Simulation Software

### 3.3.1 Thermal Analysis

The purpose of the thermal analysis was to investigate how extreme temperatures affect the performance of the thermal envelope in an extreme climate.

The workflow of this process was as follows:

1. A 3D Revit model of the building is created using materials (with correct thermal properties associated with the materials) for the walls, floor and roof.
2. A 1:20 section drawing is created from the model.

3. The 1:20 section is then analysed by the Numfem plugin, which is a thermal analysis software that is directly synchronized with the Revit data to simulate the thermal behaviour of the external envelope of the building. The software calculates the building envelopes U-value, Phi (φ) value and fRsi value at the set temperature difference.

This process was done for all three case study buildings to compare the results.

#### 3.3.2 PHPP Calculation

The purpose of the PHPP calculation was to find out what effects the extreme external temperatures have on the specific space heating demand to maintain a comfortable indoor design temperature of 20°C all year round. A typical Halley VI modules area, volume, U-value and annual climate data was input into the PHPP excel spreadsheet to find the specific space heating demand (kWh($m^2$a)). For the purpose of this calculation, to do a more direct comparison of the case studies results, the area and volume of the typical Halley VI module was the same for each case study calculation.

### 3.4 Energy Loss Calculation

Similar to the PHPP calculation, a typical Halley VI cladding panel was taken and input into the formula: Area ($m^2$) x U-Value (W$m^2$K) x Temperature Difference (°C) = Heat Loss (W$m^2$h). The same area of wall fabric was taken from the Nk'Mip Desert Cultural Centre and Martian House case studies to compare the results. This was done to find the heat loss through a section of the building envelope, to find out how the extreme temperatures impacts the thermal performance of the building envelope.

# 4.0 Results and Analysis

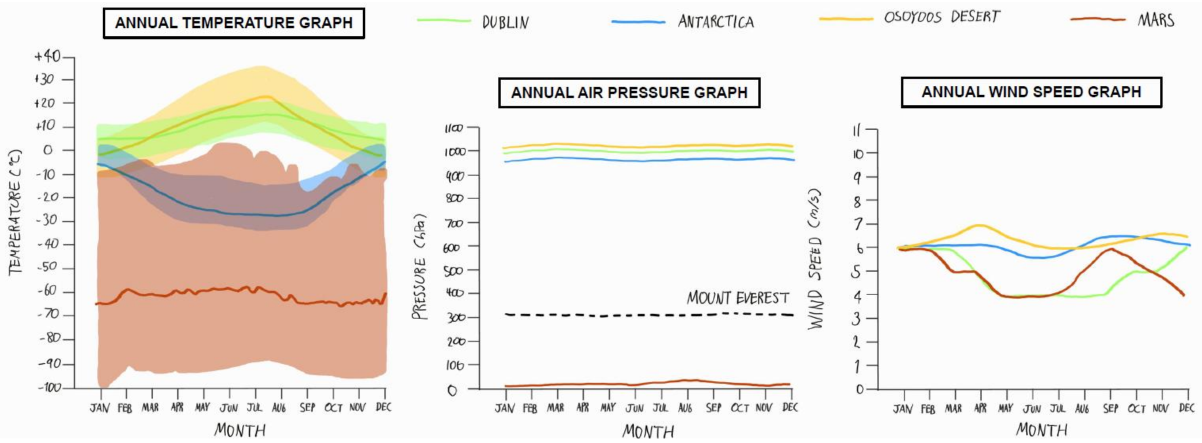
## 4.1 Analytical Esquisse

### 4.1.1 Climate Comparison

A climate comparison was undertaken to compare Dublin's baseline temperate climate to Antarctica's extreme polar climate to Osoyoos's extremely arid climate and Mars's extreme climate. The graphs shown in Figure 10 compared the air temperature, air pressure and wind speed annual weather data of each location.

**Figure 10**

*Annual weather data comparison graphs*




Note. Weather data from Weather spark and NASA's InSight probe at Elysium Planitia, Mars.

From this weather data, many conclusions can be made. Antarctica and Mars endure freezing temperatures all year round. This indicates that specified building envelope materials must be able to perform well under freezing temperatures. Osoyoos has freezing temperatures in the winter and hot temperatures in the summer. This determines that the building must be able to keep cool in the summer and warm in the winter. Mars has the greatest daily temperature swings than the other locations. A building on Mars must be able to adjust under the fluctuating daily temperatures. Also, Mars poses a new challenge in designing for an extremely low air pressure lower than that anywhere else on Earth. This means that the temperature difference between the inside and the outside will be high. The building envelope will need to be able to “flex” to allow for adjustment in pressure difference.

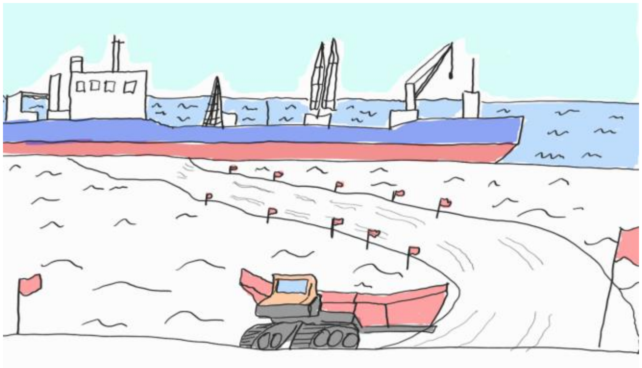
### 4.1.2 Case Study: Halley VI, Antarctica

The esquisse explored how Halley VI was constructed in Antarctica by sketching the construction sequence of the modular construction system designed for a fast construction time in an extremely remote and hazardous environment. How the building actively deals with the extreme climate and environmental conditions was also investigated.

The analysis shows that the modular construction method was adopted because the delivery of materials to the site had to be done by transporting the panels from South Africa to Antarctica of a giant ice-strengthened Russian cargo vessel as shown in Figure 11. The materials then had to be loaded onto a sledge on 2-3m thickness of ice so the load on this sledge could not be more than 9 tonnes to avoid the risk of the ice cracking. This meant that each module had to be constructed on-site using the prefabricated cladding panels and the steel space frame structure. The construction process is demonstrated in Figure 12.

**Figure 11**

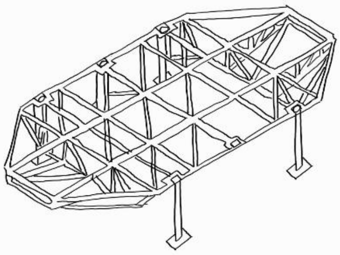
*Halley VI delivery of construction materials to site sketch*



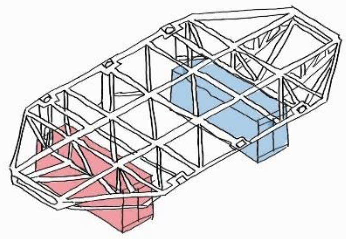
Note. Authors own, adapted from Ice Station: The Creation of Halley VI. Britain's Pioneering Antarctic Research Station (p. 47), by R. Slavid, 2015, Park Books. Copyright by James Morris.

**Figure 12**

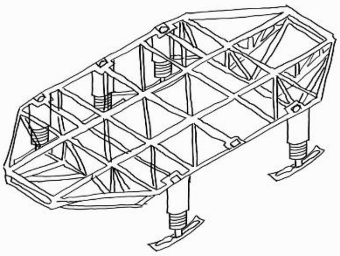
*Halley VI sequence of on-site construction sketches*



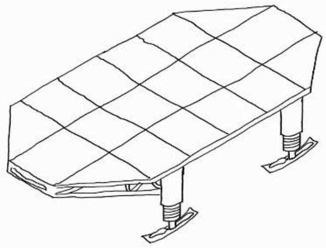
**Stage 1:** The space frame of a standard module supported on its transit skis, having just arrived at the Halley V site.



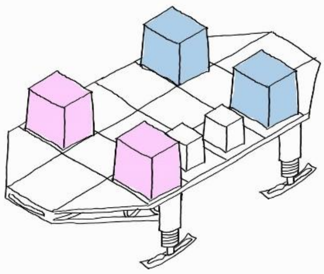
**Stage 2:** The module is raised on shipping containers to allow the hydraulic legs and Lehmann skis to be installed.



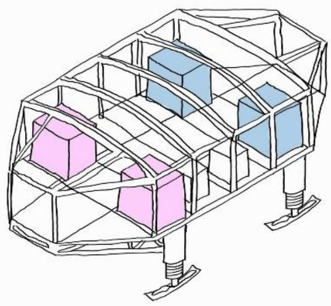
**Stage 3:** Hydraulic legs and Lehmann skis are installed, holding up the steel frame.



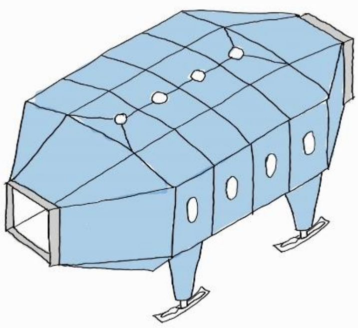
**Stage 4:** Prefabricated timber floor cassettes are installed onto the space frame, creating both a working platform and the floor of the module.



**Stage 5:** Prefabricated pods are installed onto the floors of the module. The pods installed include fuel tanks, generators, bedrooms. bathrooms, etc.



**Stage 6:** Steel superstructure is fitted over the pods, ready to receive the cladding.



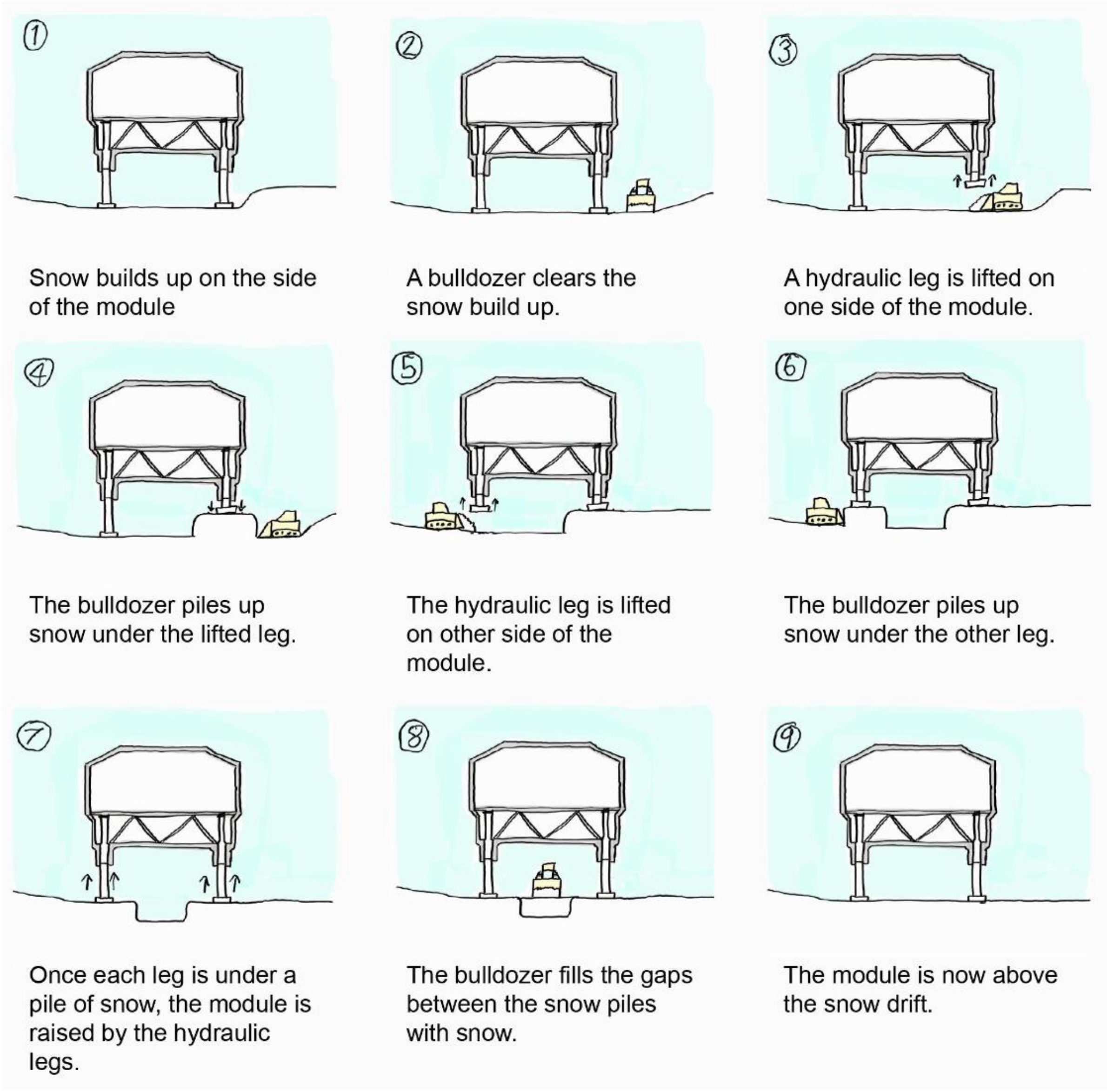
**Stage 7:** Glass-reinforced plastic pre-glazed cladding panels are lifted into position and fixed to the steel frame.

The cladding design maximised the size of the panels to minimise the erection time. The nose cones were made from a series of flat panels bonded together in the factory to create complex geometric forms, which could be bolted into position as fast as possible.

A sequence of sketches demonstrated how Halley VI raises itself each year above the snowdrift to avoid getting buried in snow is illustrated in Figure 13. The hydraulic legs design feature combats one of the main challenges faced when designing for Antarctica's extreme climate conditions, which is avoiding getting buried and crushed by a build-up of snow.

**Figure 13**

*Halley VI snowdrift avoidance strategy sequence sketches*




Note. Authors own, adapted from *AT webinar with VMZINC Designing for Extreme Environments [Video]*, by Architecture Today, 2021, Architecture Today. Copyright by Hugh Broughton Architects.

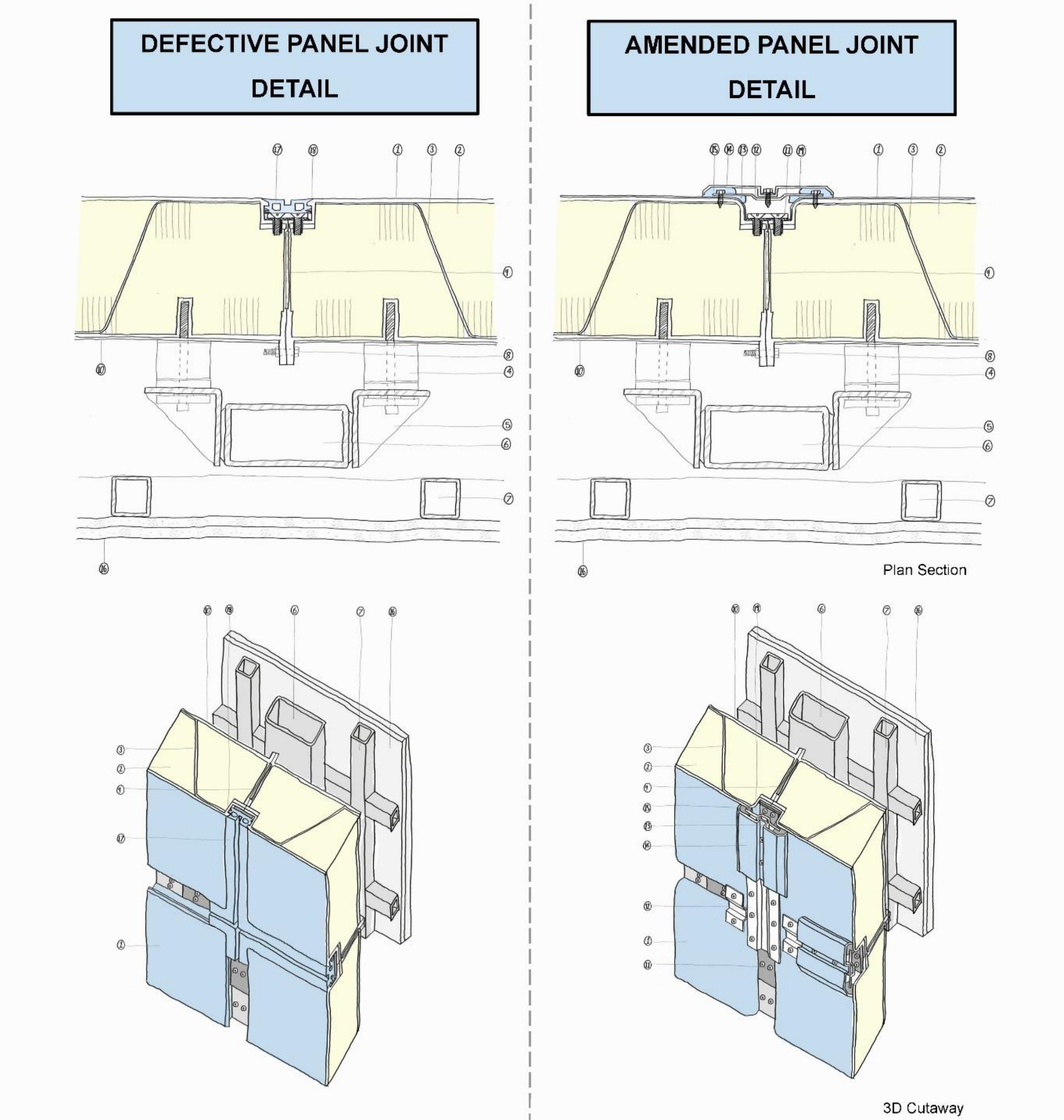
The cladding joint detail between the modular cladding panels was analysed in detail by sketching a plan section (Figure 14) through the junction and demonstrating the construction sequence of this detail (Appendix B and C). The plan section detail showed how two panels were connected and how they are fixed to the primary structure. The detail also shows how the thermal continuity between the two panels is continued by applying compressible neoprene Insulation in between the panels.

The esquisse also investigated how the reported panel defects were caused and how they were amended. This was discussed previously in chapter 2.2.

The comparison between the defective detail and the amended detail can be seen in Figure 14 and 15.

**Figure 14**

Halley VI defective & amended cladding panel joint detail (2D & 3D) sketches




**Legend**

**1** GRP outer skin to panels finished with gel coat and oversprayed with polyurethane acrylic automotive paint to ensure UV stability. Filled polyester resin used to achieve 30 minute fire resistance.

**2** 190mm polyisocyanurate (PIR) closed-cell foam insulation to achieve U-Value of 0.113 Wm²K.

**3** Resin-infused cross-fibres prevent delamination under wind load.

**4** Flexible elastic-silicone cladding mounting screwed into GRP "hardpoints" cast into panels

**5** Steel cladding brackets welded to primary steel superstructure.

**6** Steel superstructure finished in intumescent coating to achieve one-hour fire resistance. Steel grade selected for performance at extremely low temperatures.

**7** Steel structure to prefabricated room pods (bedrooms, bathrooms, offices, etc)

**8** Panels bolted together through GRP flanges using stainless-steel fixings.

**9** Continuous compressible neoprene insulation maintains thermal performance a joints, finished with PTFE to reduce friction during installation.

**10** GRP inner skin to panels finished with intumescent paint to achieve Cs3d2 (Class 0) surface spread of flame characteristics.

**11** Panels jointed with GRP jointing strip fixed with countersunk M0 stainless-steel cap screws through compressed foam neoprene gasket.

**12** Extruded aluminium internal cover mounting strip.

**13** Aluminium mounting strip fixed with coach screws. Foamed EPDM compressed gasket seal between mounting strip and panel.

**14** Extruded aluminium external cover strip finished with polyurethane acrylic automotive paint to match panel finish, fixed to internal aluminium mounting strip with self-drilling stainless-steel fasteners.

**15** Junction cover gasket formed in foamed EPDM.

**16** Pods lined in 2 layers of Fermacell plasterboard selected for rigidity and acoustic performance.

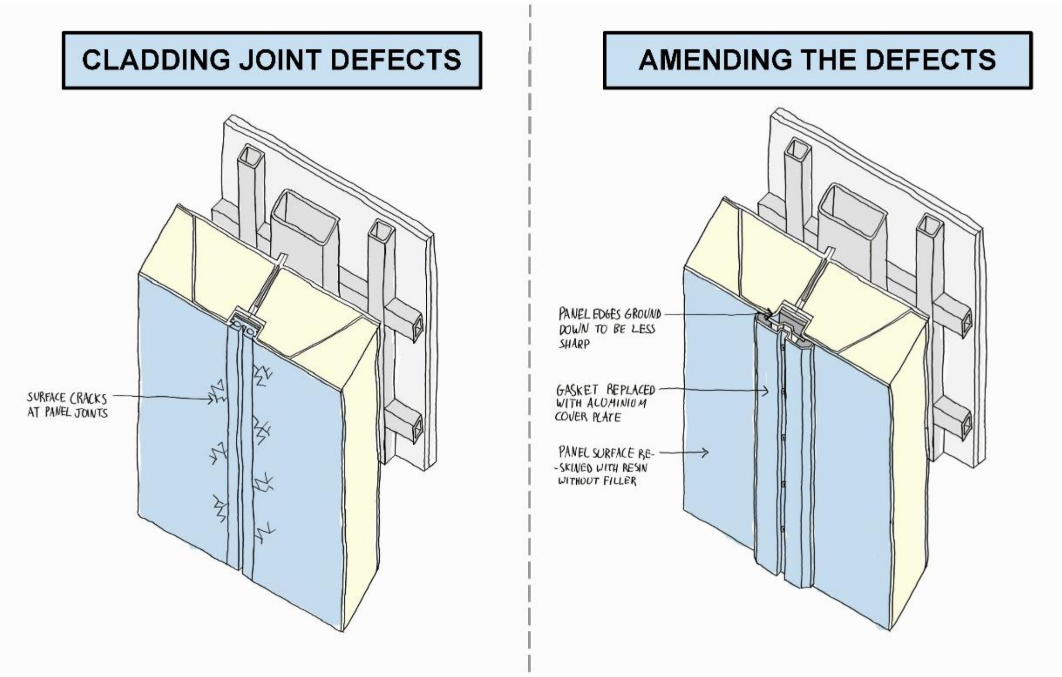
**17** Silicone rubber sealing gasket.

**18** Lip in panel to receive gasket.

**19** Gasket lips machined off to create a smooth corner detail.

**Figure 15**

Halley VI defective vs amended cladding panel joint detail (3D) sketches




This study highlights how building materials can experience defects under extremely cold temperatures and how these issues can be dealt with.

**4.1.3 Case Study: Nk'Mip Desert Cultural Centre, Canada**

For this case study, the esquisse explored how the building envelope was designed to keep occupants cool in the scorching day/summer and warm during the freezing night/winter. A 1:20 section of the building envelope (Appendix D) was analysed through a series of sketches (Figures 16,17 and 19).

Figure 16 demonstrates how during a hot day with plenty of sunshine, the rammed earth wall absorbs the heat, and the thermal insulation slows down the heat transfer from the outside to the inside surface of the wall. Once the outdoor temperatures plummet during the night, the wall slowly releases the absorbed heat keeping the inside of the building warm.

**Figure 16**

*Nk'Mip Desert Cultural Centre building envelope section thermal mass effect sketch*

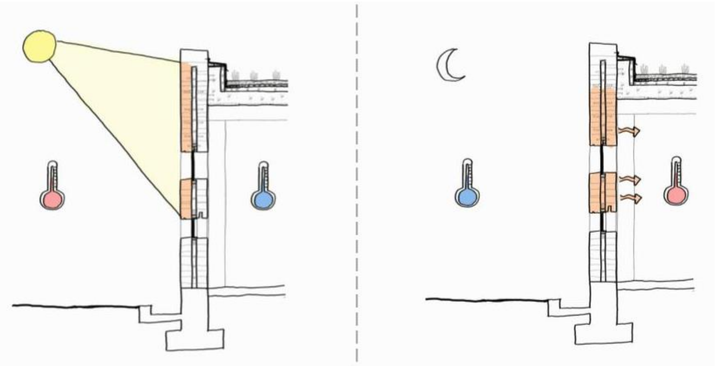


Figure 17 shows how the building keeps cool during a hot day. The narrow height windows centred in the thick wall does not allow for the high summer sun to directly transmit light through the glazing which would cause overheating. The in-slab radiant cooling in both the ceiling and floor slabs have cold running water circulating to keep the inside face of the building envelope cool and thus the inside temperature cool. The pipes are then fed warm water when the building requires heating to radiate heat from the floor and ceiling slabs.

**Figure 17**

*Nk'Mip Desert Cultural Centre heating & cooling strategy sketch*

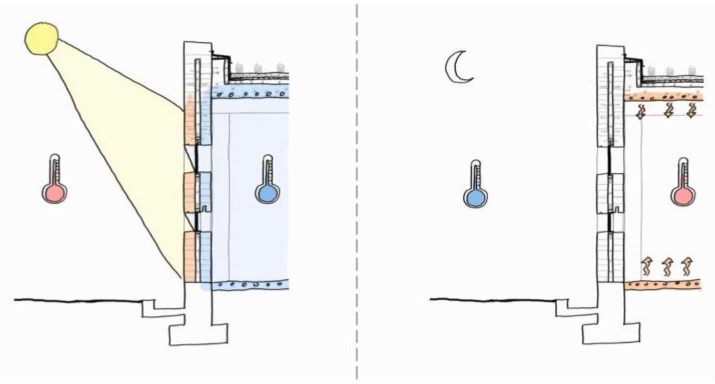


Figure 18 identifies the benefits of the green roof on top of the Nk'Mip Desert Cultural Centre. The green roof provides extra insulation and dissipates heat rather than absorbing heat which would cause overheating in a building with a typical concrete flat roof slab.

**Figure 18**

*Nk'Mip Desert Cultural Centre green roof sketch*

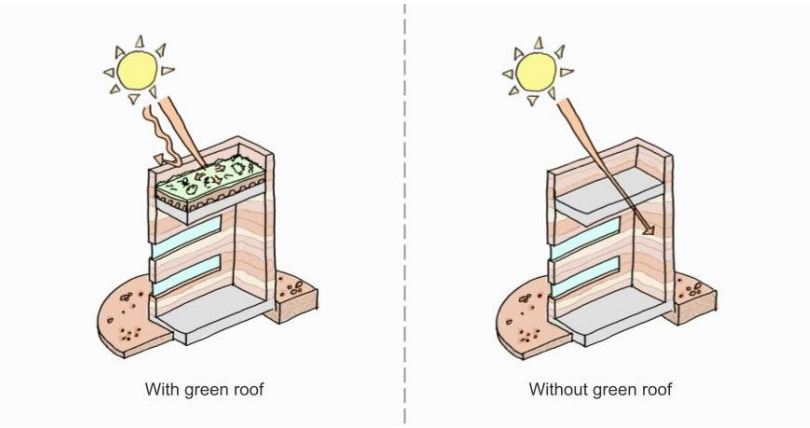
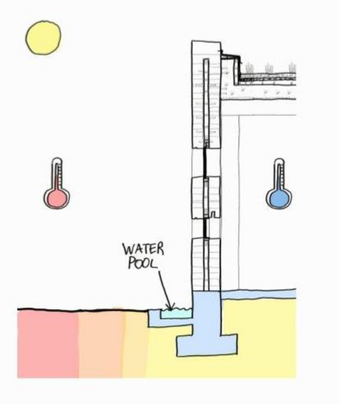



Figure 19 highlights the narrow stream of water designed into the foundation of the building. This acts as an evaporative cooling device to keep people cool whilst walking around the building to enter or exit. This also keeps the concrete foundation cooler than the surrounding soil which also prevents the grounds absorbed heat from entering the building through the floor.

**Figure 19**

*Nk'Mip Desert Cultural Centre water cooling device sketch*



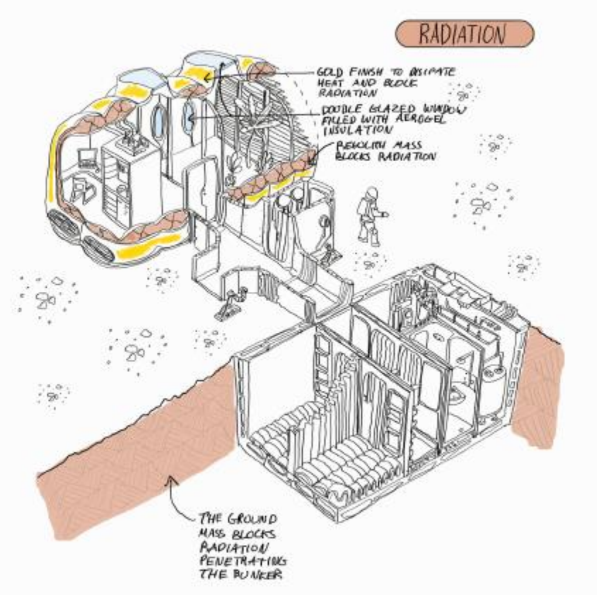

**4.1.4 Case Study: Martian House, Mars**

Hugh Broughton's concept sketch was looked at through several analytical filters.

Figure 20 indicates how the building protects occupants from harmful exposure to solar radiation. The mass of the regolith wall infill blocks the radiation. The gold coated membrane formwork is designed to dissipate the heat on the outside of the building.

**Figure 20**

*Martian House radiation protection sketch*

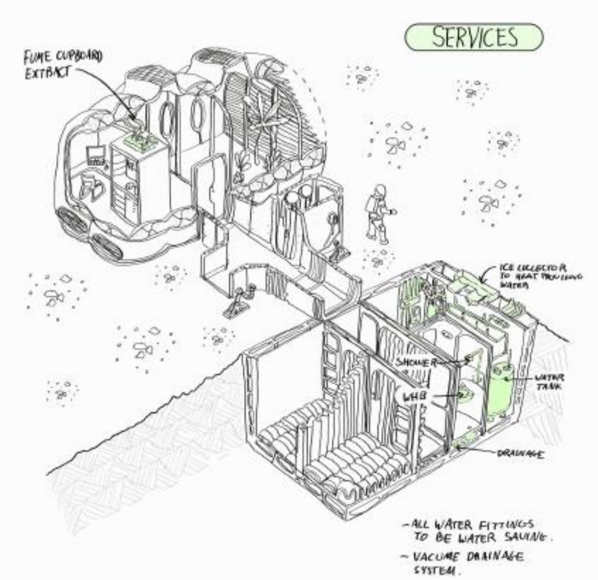



*Note.* Authors own, adapted from *Hugh Broughton's Bristol 'Martian House' has lift-off*, by G. Pitcher, 2020, Architects Journal. Copyright by Hugh Broughton Architects.

Figure 21 shows all the services that will be integrated into the building. The services include a fume cupboard extract, shower, WHB (Wash Hand Basin) and water tank.

**Figure 21**

*Martian House services sketch*

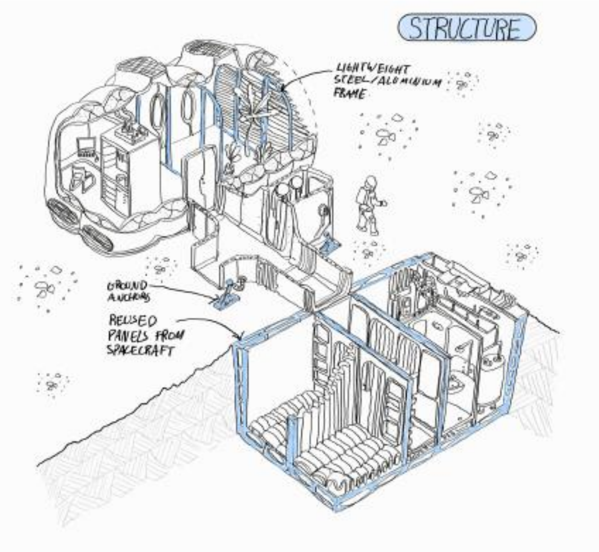



*Note.* Authors own, adapted from *Hugh Broughton's Bristol 'Martian House' has lift-off*, by G. Pitcher, 2020, Architects Journal. Copyright by Hugh Broughton Architects.

Figure 22 highlights the structure of the building. This thin lightweight structure is designed to be easily transported from Earth to Mars and be strong enough to hold up the building envelope. The structure will have much lower structural loads than that on Earth because there is 62% less gravity on Mars (NASA, n.d.) which explains the design of the thin portal frames. The basement structure is shown as a system of connected panels design will be reused from the spacecraft's components that will transport astronauts to Mars.

**Figure 22**

*Martian House structure sketch*

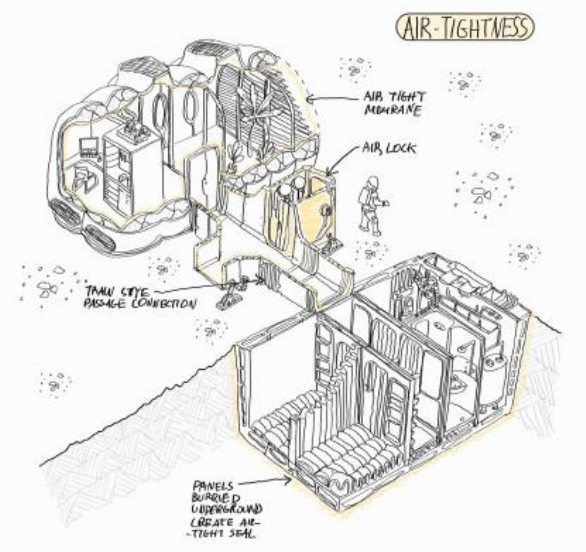



*Note.* Authors own, adapted from *Hugh Broughton's Bristol 'Martian House' has lift-off*, by G. Pitcher, 2020, Architects Journal. Copyright by Hugh Broughton Architects.

Figure 23 shows how airtightness is dealt with in the design. This is a vital aspect of the building because there is no breathable oxygen on Mars. The building will have to be pressurized on the inside with its own oxygen generator. The building envelopes inflatable formwork will provide an airtight seal. An airlock lobby will prevent the generated oxygen from escaping the building into the atmosphere when the astronauts have to leave the building.

**Figure 23**

*Martian House airtightness sketch*




*Note.* Authors own, adapted from *Hugh Broughton's Bristol 'Martian House' has lift-off*, by G. Pitcher, 2020, Architects Journal. Copyright by Hugh Broughton Architects.

**4.2 Interviews**

A series of webinars organised by Shackleton named "Antarctica Now" were available to access via a zoom link from 25-31 January 2021. Each day a professional who has worked in Antarctica presented on the webinar for an hour. On the 30th, architect, Hugh Broughton presented his work on the Halley VI project explaining the design and construction process behind the British Antarctic Research Station. He also discussed the work he is currently doing on other research stations for Australia and New Zealand in Antarctica.

During the Q&A section, the researcher asked the question, "What have you learnt from building in the Antarctic that you've applied to your construction for Mars?". Hugh Broughton answered the question by stating; "There are things like water usage which we have learned how to drive down and how to make the best use of recycled water. I think that is going to be important on Mars where water could be quite scarce."

“We look very carefully at the ergonomics of the social spaces to make sure that you could still provide space that people could be as a community but also on their own and very importantly on those missions where you are in very low gravity that you would be able to have lots of exercises to keep your muscles in shape.”

“I think it is things like water usage, reusing heat and well-insulated envelopes, those are all going to be important on Mars but also the sort of psychological and social aspects of preserving people through combinations of private and communal spaces. Those we've also learnt about in the Antarctic and will apply to the design of our Mars house” (Shackleton, 2021).

This answer was very informative as Hugh Broughton described what Halley VI design features will also translate to his Martian House design. These features are low water/heat usage, social/private spaces, exercise equipment and well-insulated building envelopes. This entails that the Martian House will have to have a similar water usage strategy to the Halley VI project which used a vacuum drainage system which resulted in occupants only using 20 litres of water a day. The Martian house may have to be in an interconnected community to allow for the private house space to have access to a bigger central community building. The design will have to incorporate exercise equipment to combat muscle deterioration in low gravity, possibly like that on the ISS (International Space Station). The building envelope will have to achieve a low enough U-value to allow the sustainable heating system to maintain a comfortable indoor temperature in the extremely cold environment.

The full transcript of the interview can be read in Appendix A.

## 4.3 Digital Simulation Software

### 4.3.1 Thermal Analysis

A thermal analysis of a 1:20 section for each case study revealed how the building envelope performed under the most extreme temperature of the climate taken from the temperature graph shown in Figure 10. Each 1:20 section revealed the thermal continuity of the thermal envelope as well as outputting the U-value, Phi value, temperature difference and fRsi values shown in Figures 24-26.

**Figure 24**

*Halley VI building envelope section thermal analysis drawing*

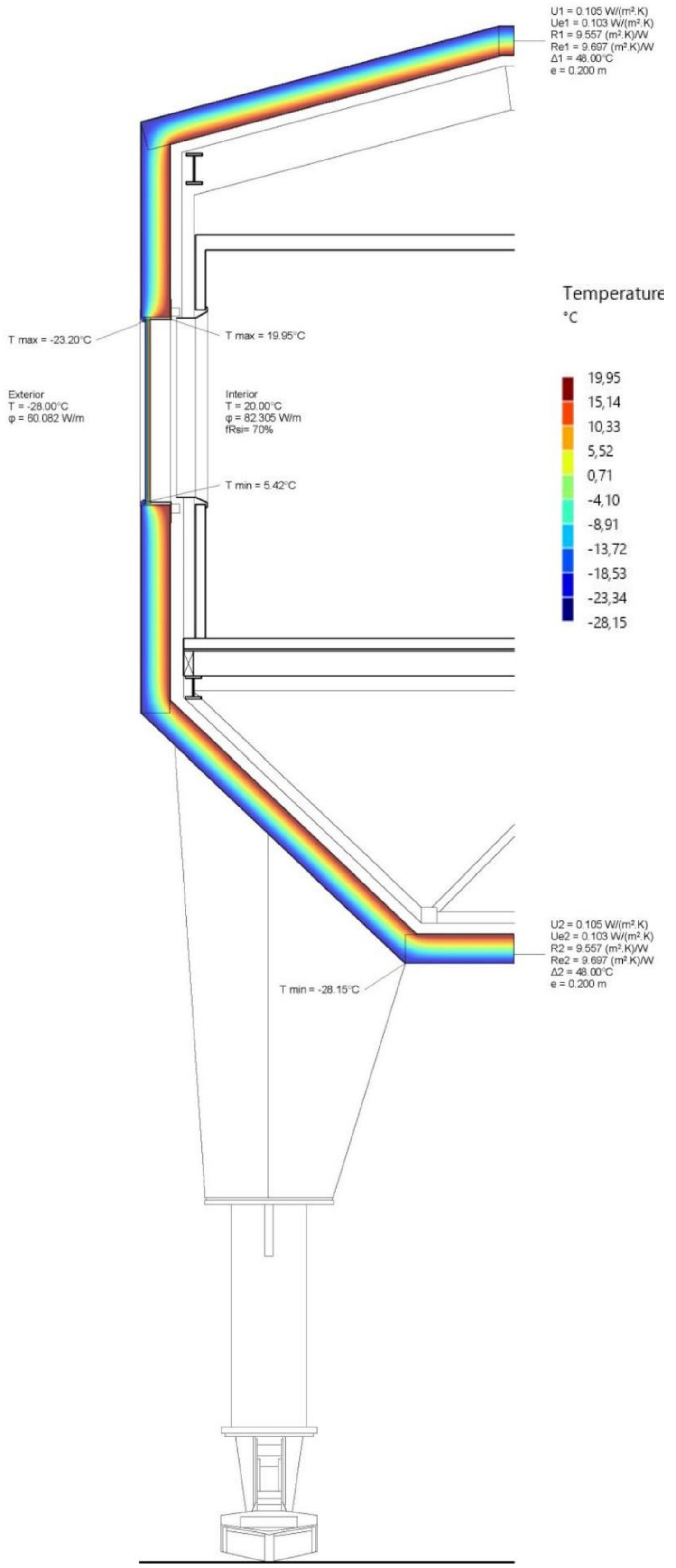


**Figure 25**

*Nk'Mip Desert Cultural Centre building envelope section thermal analysis drawing*

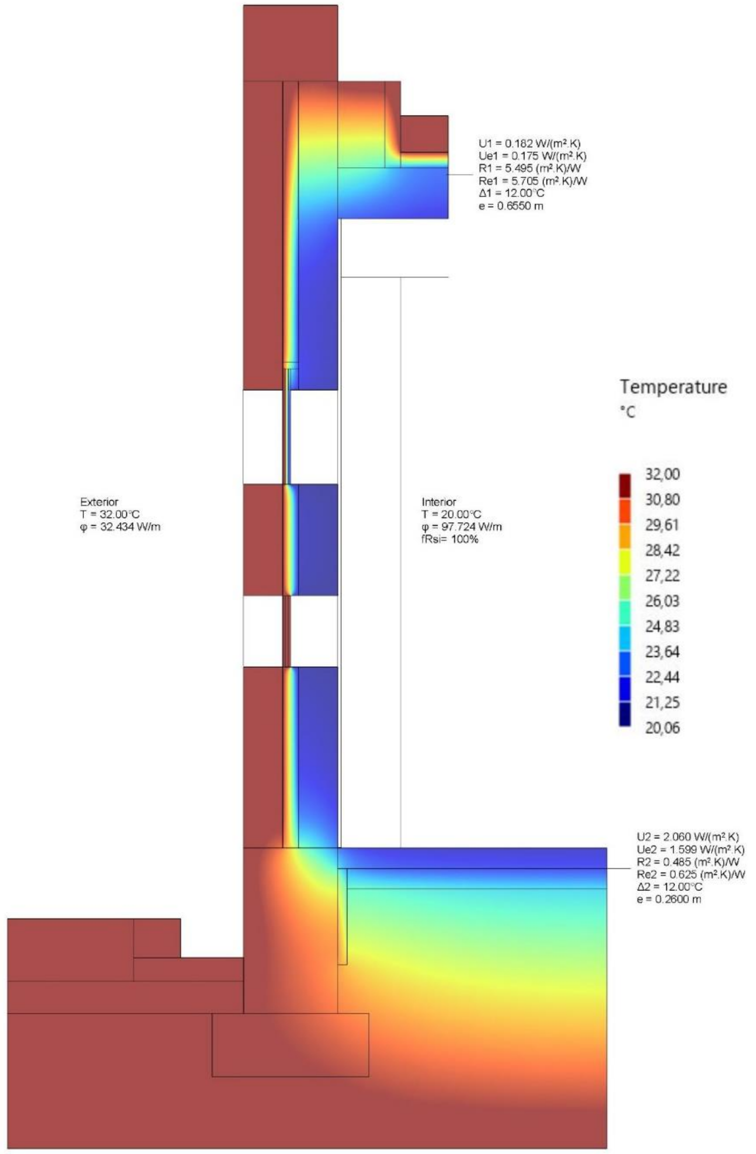
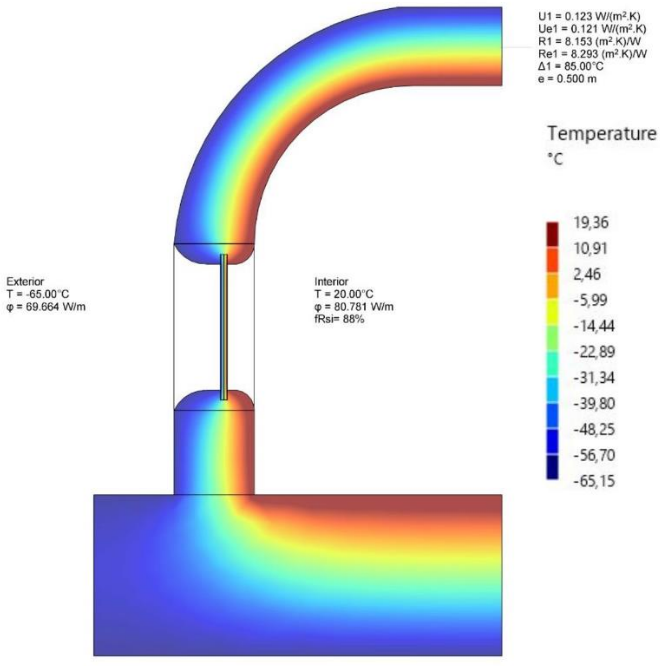


**Figure 26**

*Martian House building envelope section thermal analysis drawing*

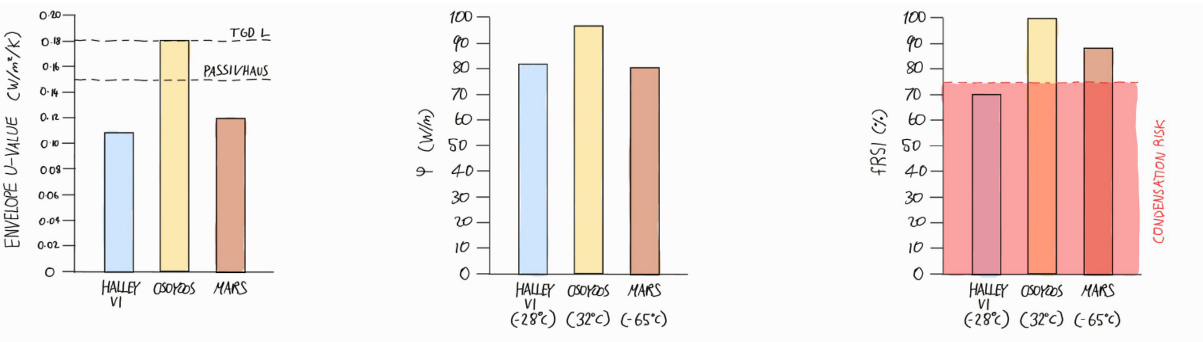



Each section shows little cause for concern for thermal bridging. However, the form of Halley VI and the Martian House have more linear isolines compared to the Nk'Mip Desert Cultural Centre building envelope. The wall-floor and wall-roof connection points isolines slightly deviate at these junctions.

To compare all the results obtained from the thermal analysis, U-values, Phi values and fRsi values were input into three graphs shown in Figure 27.

**Figure 27**

*Case studies thermal analysis results graphs*



The U-value graph shows that all three building envelopes meet the minimum TGD (Technical Guidance Document) L wall U-value of 0.18 $Wm^2K$. However, only Halley VI and the Martian house meet the Passive house standard of 0.15 $Wm^2K$.

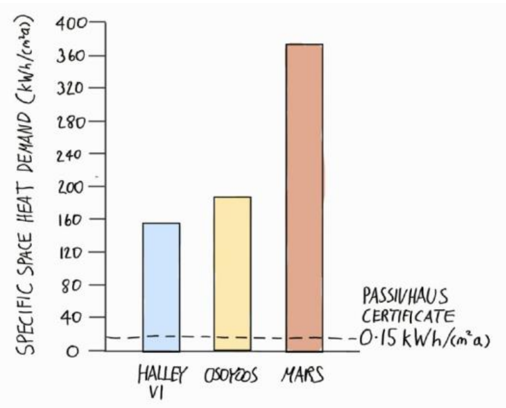
The fRsi graph indicates that there is a concern for the Halley VI building envelope when temperatures reach -28°C in Antarctica. TGD L indicates that fRsi figures under 75% are at risk of condensation and mould growth.

### 4.3.2 PHPP

To find out how what the space heat demand for each study was, the climate, U-value, area and volume data were input into the PHPP (Passive House Planning Package) excel spreadsheet calculator. The results can be found in Figure 28 where each case studies results are compared.

**Figure 28**

*Case studies PHPP results graph*




The calculation shows the impact of the boundary conditions on the space heating demand. Interestingly, Antarctica has a much colder climate than Osoyoos and yet Halley VI has a lower space heating demand. This shows the impact of a better U-value of the building envelope has on the space heating demand. For the situation on Mars, the U-Value of the thermal envelope may need to be increased by increasing the wall thickness or by adding insulation to lower the space heating demand.

The results also show that none of the case studies could achieve the Passive house standard of 0.15 $kWh(m^2a)$. This shows the huge impact the extreme annual temperatures have on the space heating demand even with a high standard building envelope U-value.

### 4.4 Energy Loss Calculation

Similar to the PHPP calculation, a typical Halley VI cladding panel was taken and input into the formula: Area (m2) x U-Value (Wm2K) x Temperature Difference (°C) = Heat Loss (Wm2h). The same area of wall fabric was taken from the Nk'Mip Desert Cultural Centre and Martian House case studies to compare the results.

**Figure 29**

*Halley VI panel inputs and calculation*

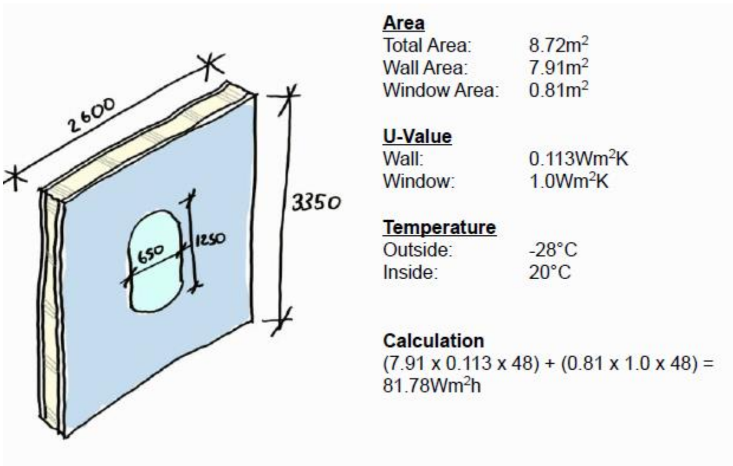



**Figure 30**

*Nk'Mip Desert Cultural Centre wall inputs and calculation*

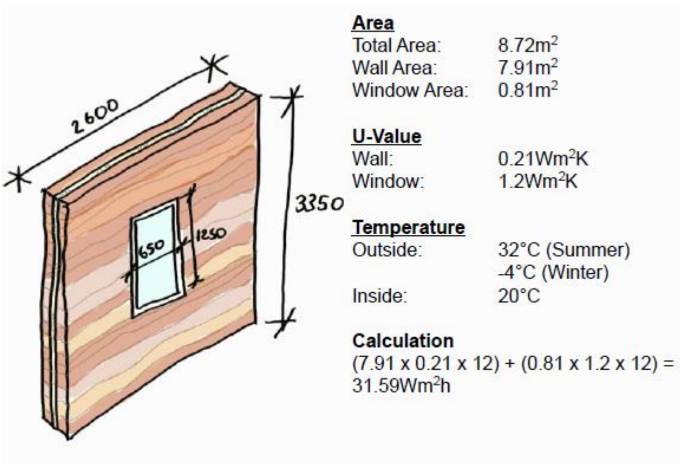
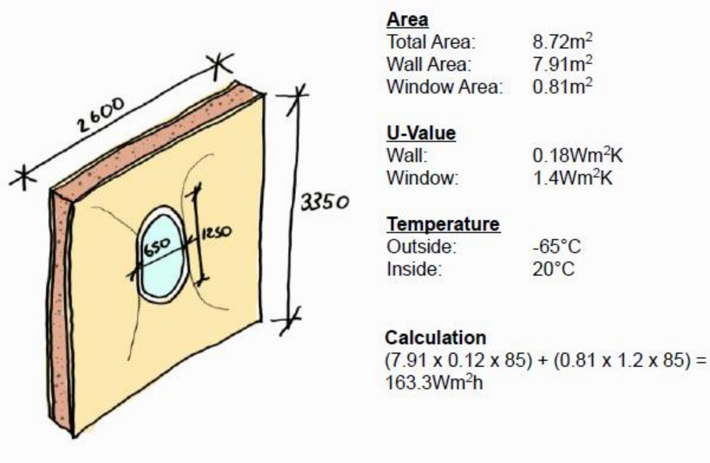


**Figure 31**

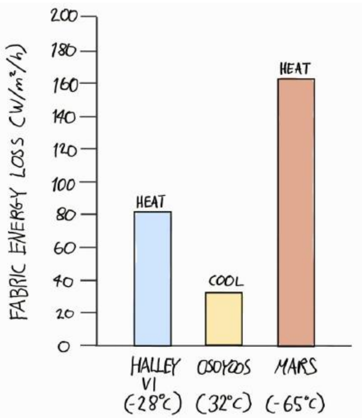
*Martian House wall inputs and calculation*




The results are compared to each other in a graph shown in Figure 32.

**Figure 32**

*Energy loss calculation results graph*




The graph shows that the energy lost through the wall fabric is greatest for the Martian House than the other two case studies. For the Nk’Mip Desert Cultural Centre, the energy lost through the wall is from cooling whereas the other two case studies are heating energy losses.

# 5.0 Conclusions

## 5.1 Implications of Findings

The research found that the design choices made for the building envelope construction type, U-Value, form and material specification were all impacted by the extreme climate conditions.

The Halley VI case studies construction type was impacted by the fact that components could only have a maximum weight during transportation over thin ice and because construction time on-site was limited to a 12-week summertime slot each year due to the harsh winter working conditions in Antarctica. The U-value of the thermal envelope was impacted by the space heating demand the sustainable building must achieve to maintain a comfortable indoor temperature of 20°C. The cladding design was greatly impacted by the cracking GRP found when the cladding panels arrived in Antarctica. This led to the panels having to have more rounded corners and an aluminium cover plate instead of a rubber gasket.

The Nk'Mip Desert Cultural Centres building envelope design was impacted by the climates hot summer and cold winter temperatures. The building envelope had to have thermal mass properties to absorb the heat in the day/summer and dissipate it during the night/winter. The sustainable design approach meant that using rammed earth instead of concrete to achieve this was selected.

The Martian House design concept was impacted by the extreme environment on Mars that has extremely low temperatures and dangerously high levels of radiation. This led to the building envelope having to have a high mass to block the radiation and to achieve a U-value low enough to reduce the heat loss through the building envelopes great temperature difference. Also, the choice to transport lightweight minimal construction materials to Mars was influenced by the fact that a rocket's cargo will have limited space.

### 5.2 Achieved Objectives

All the objectives were achieved however, a full interview discussing the building envelope of Halley VI with Hugh Broughton or Coleman Billings could not be organised due to their busy schedules.

### 5.3 Reflection and future work

There is an opportunity to further develop this research by investigating how typical construction materials react to the extreme temperatures on Mars. Testing of these materials should be undertaken in laboratories that could not be accessed during the time of this research due to the COVID-19 pandemic. It would also uncover what construction materials will not be able to withstand the extreme temperatures on Mars and what materials could be specified.

Further development of the Martian House building envelope could be explored further by constructing physical scale models to demonstrate how an inflatable formwork filled with soil could be accomplished.

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## Appendices

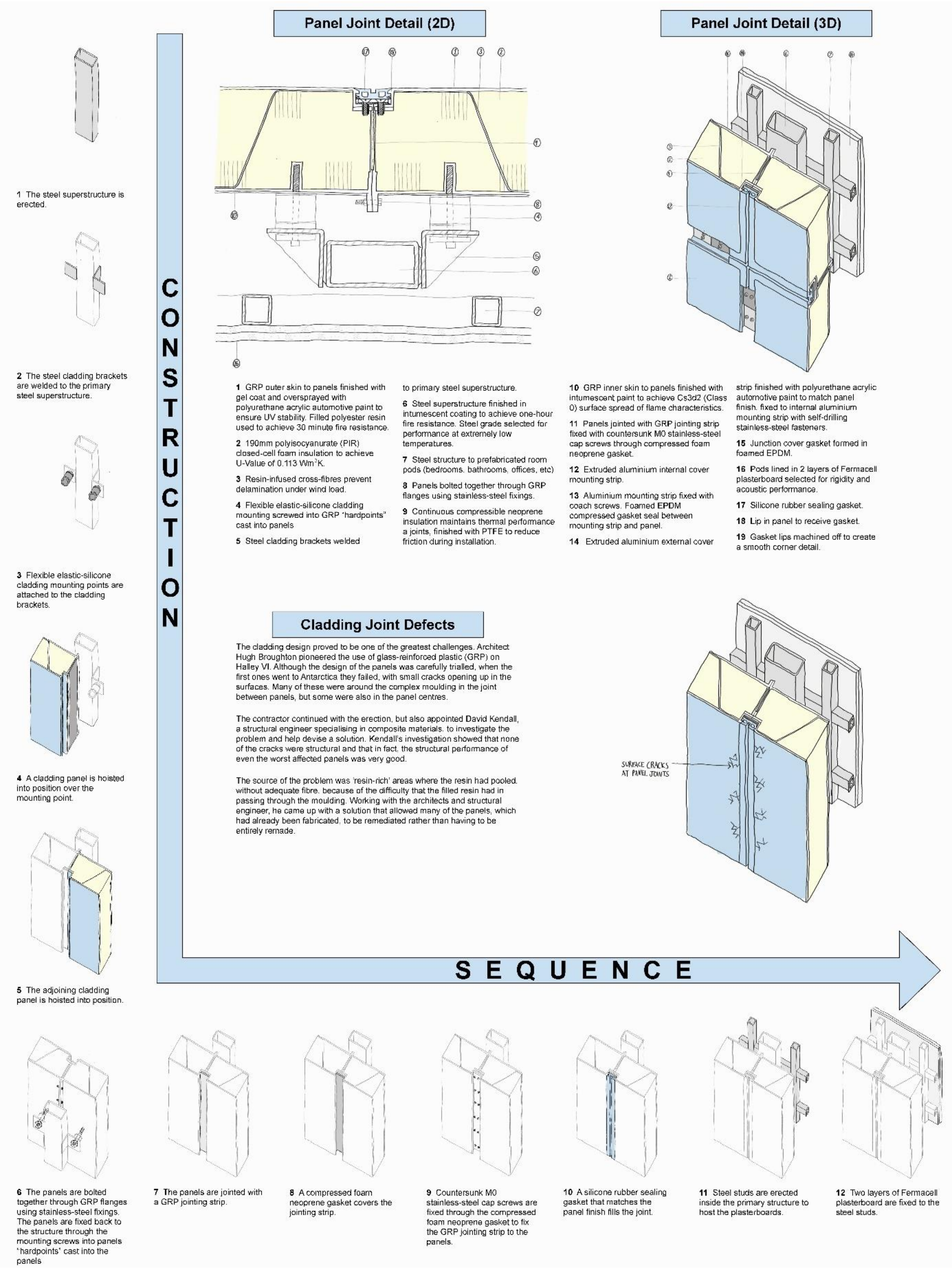
**Appendix A:** Hugh Broughton full interview transcript.

| | |
|---|---|
| Researcher: | What have you learnt from building in the Antarctic that you have applied to your construction for Mars? |
| Hugh Broughton: | That's an interesting question and I think it is on several levels. There are things like water usage which we have learned how to drive down and how to make the best use of recycled water. I think that is going to be important on Mars where water could be quite scarce.<br>I was part of a NASA working committee looking at the design of long-duration space missions and how people might survive on a year and a half trip to Mars. We look very carefully at the ergonomics of the social spaces to make sure that you could still provide space that people could be as a community but also on their own and very importantly on those missions where you are on very low gravity that you would be able to have lots of exercises to keep your muscles in shape.<br>So, I think it is things like water usage, reusing heat and well-insulated envelopes, those are all going to be important on Mars but also the sort of psychological and social aspects of preserving people through combinations of private and communal spaces. Those we've also learnt about in the Antarctic and will apply to the design of our Mars house.<br>This answer was very informative as Hugh Broughton described what Halley VI design features will also translate to his Martian house design. These features are low water/heat usage, social/private spaces, exercise equipment and well-insulated building envelopes. |
| Researcher: | What changes would you make to a potential future Halley VII? |

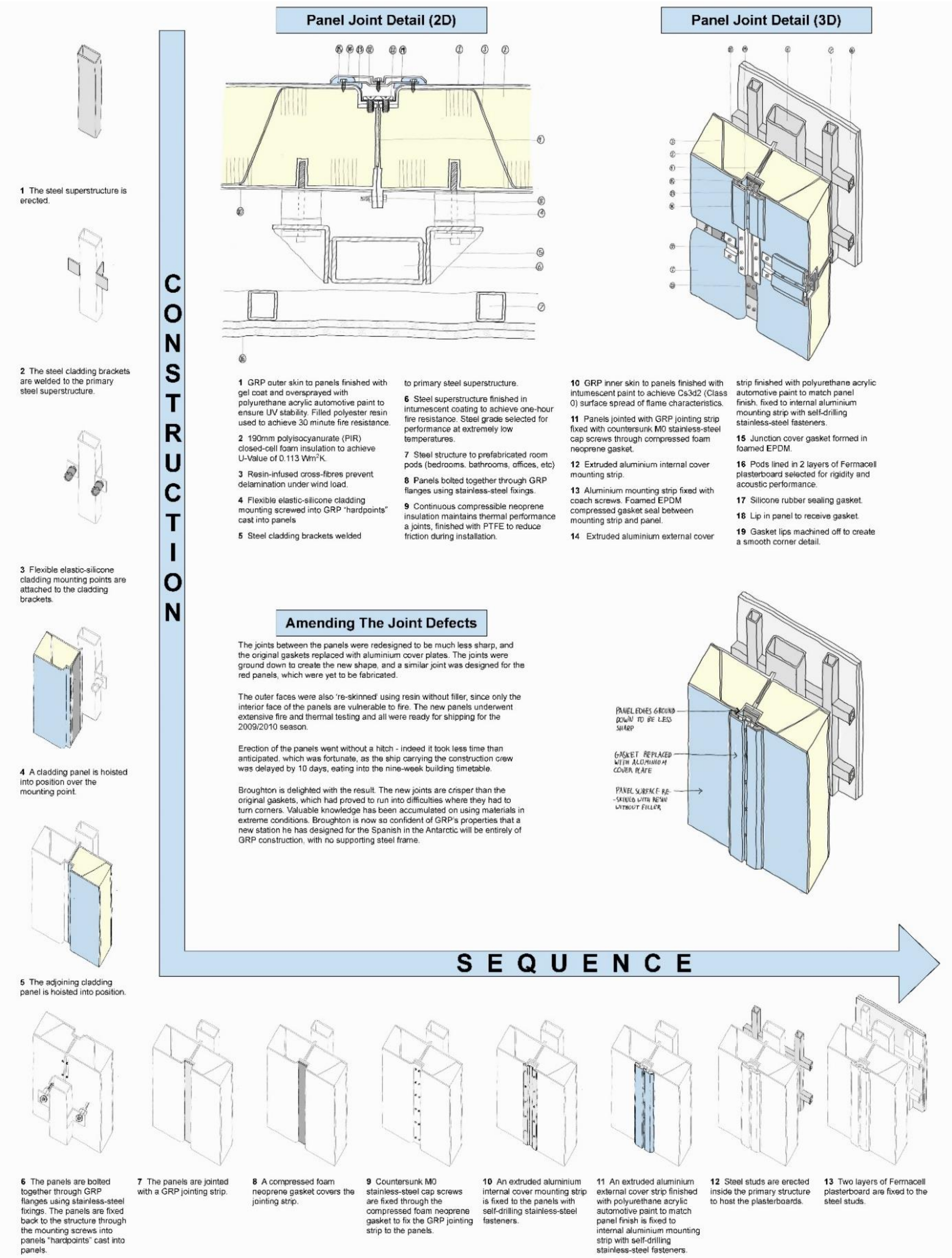
Hugh Broughton: That's an interesting question because right now Halley VI is facing some significant challenges. After it was completed, quite soon afterwards, an expected crack appeared in the Brunt ice shelf and as a result, the British Antarctic Survey relocated the base another 15km inland. Having relocated inland they found yet another crack in the Brunt ice shelf running perpendicular to the main crack and that was seen to create such a dynamic environment that they decided to remove everybody from the station during the winter months. At the moment Halley is only operating as a summer base and in fact, the British Antarctic Survey is evaluating whether they ever will be able to have people operating there in the winter.

So, I think the changes that might be made may be quite fundamental in terms of the actual location more than design, but I think that there were things that we had in mind for Halley that we didn't install in the long term, probably for cost-cutting reasons and maybe mistakes that we made. One of them is that I would have liked to have seen that hydroponics installation installed at Halley. It was cut out of the main living module because hydroponics can have a bit of a smell at the time when everything has been harvested and you are replacing some of the nutrients in the water, so people were anxious about having it in their main living space and thinking it could be a bit stinky. I think that I have learnt from that that it would have been much better to have proposed it on one of the fringe modules rather than in the main social module. I think there are real benefits from hydroponics. Not only do you get fresh fruit and veg, but it is also a source of humidity and Antarctica is very dry so that humidity could be very welcome and also, the very bright light. At the south pole station, they have a hydroponics installation and they have to have a booking system because it's so popular. People book out half an hour slots in the winter to just go and quietly sit there and read their book in a bright and humid environment. So probably that is the one thing I'd like to have kept in the scheme put in that way.

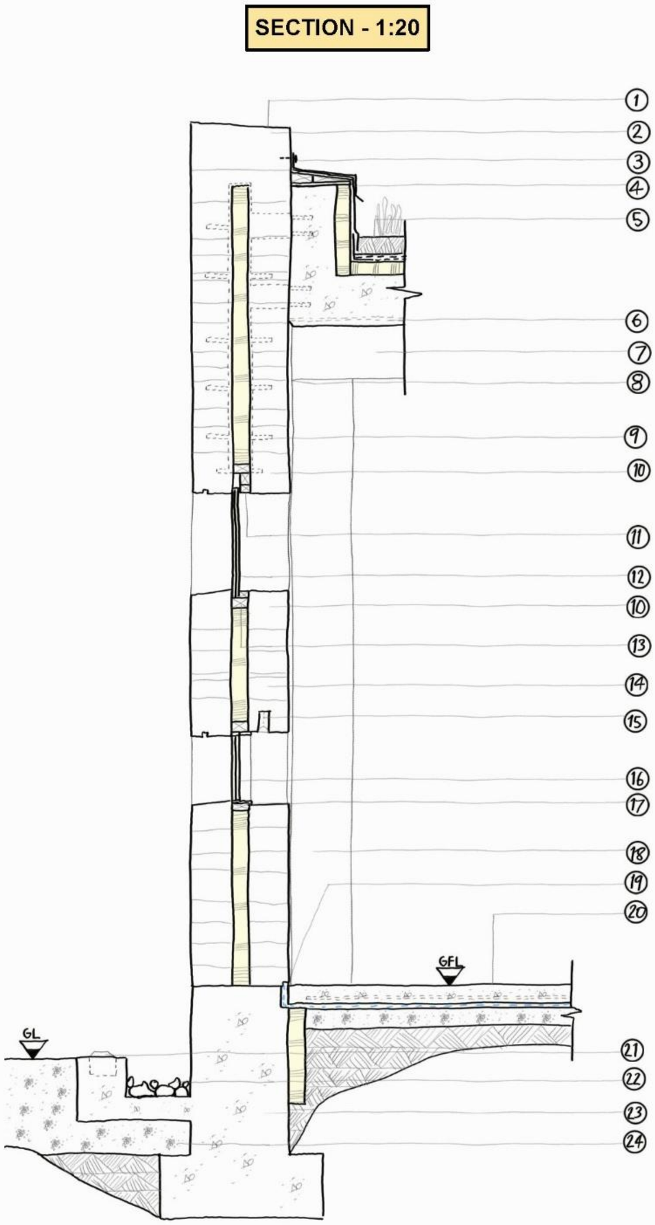
**Appendix B:** Halley VI defective panel joint detail.



**Appendix C:** Halley VI amended panel joint detail.



**Appendix D:** Nk'Mip Desert Cultural Centre building envelope section and specification.




**Legend**

**1** Topcoat - cementitious water stop seal to top of the parapet.

**2** Puddled earth top lift

**3** Saw kerf reglet for continuous membrane flashing and pressure bar - caulk.

**4** Prefinished metal flashing.

**5** Green roof construction (inverted torch on 2 ply SBS membrane):

- Native plants on
- 230 native soil growing medium on
- Root resistant membrane on
- Drainage panel & filter fabric on
- 100mm rigid insulation (RSI 3.5) on
- Cap sheet on
- Base sheet on
- Primer on
- Sloping suspended concrete with radiant pipes cast in the slab.

**6** Radiant piping in the slab.

**7** Concrete slab band (sloping)

**8** Reveal.

**9** HSS frame inn wall

**10** Puddled earth

**11** Continuous clear finish ash wood window stop and trim (at window head and cill)

**12** Continuous double glazed sealed frameless window - silicone in place.

**13** Continuous timber stud (at window head and cill)

**14** Wall construction:

- 250mm rammed earth wall - reinforced on
- 100mm PIR insulation on
- 250mm rammed earth wall - reinforced.

Note: Lift heights vary from 125mm to 170mm.

**15** Recessed halogen light centred in 76mm dia opening.

**16** 400 x 400mm double glazed frameless window - silicone in place.

**17** Solid ash window stop and trim.

**18** Concrete column.

**19** Caulk.

**20** Floor construction:

- Concrete slab on
- Grade cast with radiant slab heating/cooling pipes on
- Vapour barrier on
- 50 x 610mm rigid insulation around the outside perimeter of
- Gravel base on
- Native soil.

**21** Recessed in-slab light @ 3200mm centers.

**22** Sloping continuous water trough.

**23** Concrete strip foundation.

**24** Gravel base.

**Appendix E:** Mars vs Earth facts infographics.