Thermal skin design for extreme cold climate

Joseph Cengia AIA, Kimberly Claucherty AIA, and Joseph Ferraro FAIA
Ferraro Choi and Associates, Ltd.
Honolulu, Hawaii, United States of America, www.ferrarochoi.com

Abstract

Antarctica's pristine, remote location and extreme cold climate make it the perfect laboratory for scientific discovery. These same conditions necessitate diligent design of a building's envelope.

A building's 28 cm skin is the primary system that separates a life-sustaining interior environment from a life-threatening exterior environment.

Presented in this paper is Ferraro Choi's latest envelope design for use in buildings in Antarctica, supported by three of the firm's building case studies within this unique region throughout the last 30 years.

Keywords: Cold, Extreme, Antarctic, Envelope, South Pole, McMurdo

1. Introduction

Sustained Antarctic work on multiple constructed research facilities has provided Ferraro Choi an opportunity to refine building envelope design through an evidence-based process. Since the late 1980s, the firm has incrementally improved the overall performance of building designs as illustrated in the presented case studies that follow in Section 4. The most obvious changes, brought about in the 1990s, resulted from the use of new and innovative materials and thermal barrier systems. Since 2000, the design evolved primarily through refinement of thermal barrier and other envelope details.

Unlike design for temperate climates, failures in this region of the world can be disastrous or, at a minimum, difficult to remedy. Therefore, proven systems and components are more heavily weighted for consideration throughout the design process. Additionally, the design must allow for incremental quality control during the construction process. After installation of each envelope component, rigorous inspection must occur before the next component is installed. Once completed, the entire envelope assembly must be commissioned.

2. Building envelope design considerations

Building envelope design for extreme cold climates continues to evolve within the Ferraro Choi firm's practice. Currently, the components of the building envelope within Antarctica, from interior to exterior, consist of the structural support system, interior finish assembly, vapor barrier, thermal barrier, air barrier, and exterior cladding. Each of these components, or layers, serve a specific purpose (i.e., ultraviolet rays, air, and snow resistance; thermal resistance to extreme cold; and resistance to moisture migration) to protect the interior of the building from the exterior environment.[1] Factors in the selection of these components in order of importance are performance, ease of transportation and construction, aesthetics, and cost.

Ferraro Choi's August 2017 design and upcoming construction of the Information Technology & Communications Primary Operations Facility (IT&C) at McMurdo Station will add to the firm's knowledge base regarding the design of inland stations currently underway. The design team hopes that feedback obtained throughout the IT&C construction phase will identify opportunities for continued improvement as occurred in the following case studies.

3. Environment

"Antarctica is the coldest, driest, windiest, most remote, highest (on average), darkest (for half the year) continent on Earth"[2] according to the 2012 report of the U.S. Antarctic Program Blue Ribbon Panel "More and Better Science in Antarctica Through Increased Logistical Effectiveness."

Design and construction for U.S. permanent stations, Amundsen-Scott South Pole and McMurdo, present numerous challenges that include building envelope resistance to extremes of temperature, wind, and humidity.

3.1 South Pole Station

For the U.S. South Pole Station, the project site is situated at the geographic South Pole (90ºS). The station is located at an elevation of approximately 2800 m above sea level at the summit of a permanent ice cap, approximately 2,700 m thick. The topography is essentially a level plain of snow stretching to the horizon in all directions.

The flight distance to South Pole Station from McMurdo Station is 1,360 km while overland traverse distance is 1,601 km. Transport of personnel, cargo, and fuel has traditionally been provided by ski-equipped Hercules LC-130 aircraft. As of 2018, overland traverse via Challenger C65 tractors with rigid and flexible sledges and fuel bladders supplement air cargo and fuel transport. The annual construction window has been established as 110 days, from November 1 to February 15, with three work shifts within a 24-hour workday.[3]

Environmental and design parameters for the US South Pole Station include the following:

- Wind speed (maximum)	113 kph (31 mps)
- Outside air temperature minimum (heating)	-73°C
- Outside air temperature maximum (cooling)	-17°C
- Inside space design temperature	18°C
- Wind speed (heating)	64 kph (17.7 mps)
- Wind speed (maximum)	112.6 kph (31.2 mps)
- Infiltration	Using -73°C and 37 kph sustained
- Average snow	20 cm per year[4]
- Velocity of ice	10 m per year
- Direction of ice	32.8°W of grid N

3.2 McMurdo Station

McMurdo Station is located along the coast of Antarctica (77°47"S 166°40'06"E), 9 m above sea level, at the southern tip of Ross Island, 3886 km south of Christchurch, New Zealand. In contrast to location of the South Pole Station, McMurdo is situated on a volcanic island partially snow-covered in summer and exposed to high southerly winds in winter. Even though maximum temperatures barely exceed freezing during the Austral summer, significant warming from solar radiation melts snow and ice and patches remain year around in sheltered areas that accumulate heavy snowdrifts. Temperatures range from a high of 10.5°C to a low of -51.7°C with an average snowfall of 148 cm. Wind speeds can exceed 185 kph (51 mps) with prevailing winds coming from the east and storm winds from the south.

Environmental and recent* design parameters for McMurdo Station include the following:[5]

- Mean annual temperature	-17° C
- Wind speed (average)	22 kph (6 mps)
- Wind speed (maximum)	in excess of 185 kph (51 mps)
- Precipitation	17.4 cm per year[6]
- Outdoor winter design	-45.5°C[7] (low temp -50°C in winter)
- Outdoor summer design	15°C* (high temp to date has been 9°C in summer)

-	Data Center indoor design	18.5°C, 40–60% RH with a minimum 30% RH threshold
-	Remaining indoor design	20°C, RH of ambient

* It was decided to utilize a summer design temperature of 60°F (15.5°C) in anticipation of future ambient temperatures during the life of the Data Center facility designed in 2017. Climatic news shows that the colder Antarctic region will see a higher temperature change compared to the average anticipated global temperature warming.

McMurdo Station has a deep port available on a seasonal basis for offloading of cargo and fuel. Ice runways make air transport of cargo and personnel by wheeled aircraft possible for a large seasonal window typically from August to April. Weather changes attributed to global warming and navigational improvements have allowed widening of the shoulder seasons for transport of cargo and personnel.

Outdoor construction activity is typically limited to the Austral summer season from October to March with continued interior construction through the Austral winter.

4. Case Studies

4.1 The Albert P. Crary science and engineering center

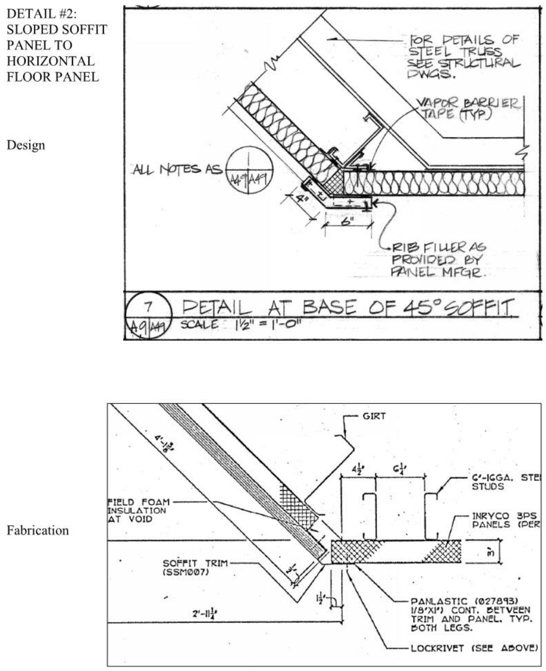
The science facility was designed from 1984–86 as a replacement laboratory for multiple outdated United States National Science Foundation facilities located throughout McMurdo Station. The 4,320 sq m building was developed as four separate building pods for biology, geology, aeronomy, and ocean sciences, respectively, with a fifth pod dedicated to administrative offices, general storage, and a conference center. All pods are connected by a central utility and personnel circulation “spine”. The building was the first elevated structure for the United States Antarctic Program and was designed to preclude snow drifting on and around the building. Its elevated design required the building skin to wrap all surfaces, including the soffit beneath the building.

Ferraro Choi selected a premanufactured composite panel with an R40 rating and overlapping joints. Its construction consisted of a 6.35 cm polyiso core sandwiched within a painted steel skin. The panels were affixed to steel girts attached to the building’s structural steel frame. The panel construction provided the required vapor barrier; however, an adhesive tape was used at all panel joints to ensure a continuous vapor barrier. Silicone and field foam were applied to panel connection voids to preclude air infiltration. Triple pane aluminum windows with a R2.2 rating included integral adjustable shading devices. Freezer type doors were provided as standard at all openings to and from the exterior.

The Crary Science and Engineering Center building envelope has performed relatively well over its 25+ years of life. However, issues have occurred that have required substantial modification to the original design and operation.

The entire building was designed so as to maintain a 30% relative humidity within occupied space by the use of a steam generation system. Due to the site’s extreme dry Antarctic location, vapor pressure due to humidity in the building caused icing at envelope openings including windows, doors, exhaust apertures, and any voids in the building skin. The steam generation system was dismantled, and the facility now operates at ambient relative humidity.

In July of 2015, a major storm with high winds and below-normal temperatures caused snow infiltration and freezing conditions within the soffit space beneath the floor of the building. A 2015 inspection[8] report by Lockheed Martin, the Antarctic Support Contractor, indicated that poor building envelope construction and misapplication of field foam at exterior panel joints existed as the cause for the freezing conditions within the floor plenum space, which, then, resulted in the freezing of the plumbing pipes.



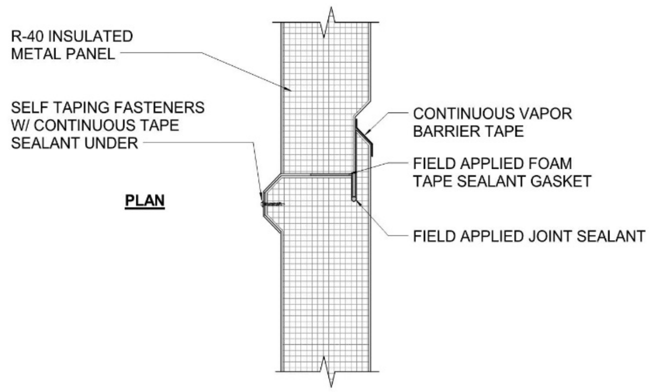


Figure 1: Details from report showing a design detail and fabrication detail	*Figure 2: The Albert P. Crary Science and Engineering Center envelope assembly*

The integrated shading devices successfully limited heat gain, but they did not stand the test of use and abuse and were ultimately removed from the window units.

4.2 The South Pole Elevated Station[9]

The Amundsen-Scott South Pole Station, located at the geographic South Pole (90°S), was designed in 1998 and completed in 2009, after eleven stages of construction, as a replacement facility for multiple outdated United States National Science Foundation facilities. Temperatures at this extreme remote environment range from a high of -13.8°C to a low of -78.9°C with an average snow accumulation of 20.3 cm. Wind speeds are generally light with the highest recorded speed set at 93 kph (25.9 mps). The station sits atop a slowly moving (11 m per year) glacier of ice approximately 2,700 m thick.

The station is divided into two distinct building types with infrastructure (i.e., fuel storage, garage, power plant, and storage) located in insulated buildings within steel arch structures below the snow surface and elevated buildings built above the snow surface. The main 7,432 sq m above surface building houses dormitories, science labs, offices, a healthcare clinic, a food growth chamber, and a recreational facility. The building was developed as two separate pods with piano key like extensions, elevated 3 m above the surface, with a vertical stair and lift connection to the below surface arches. Since there is no snow-melting period at the pole, the building's cross-sectional shape was designed to induce higher wind speeds beneath the structure to clear snow and deposit it behind, and clear of, the structure.

The building's steel structural frame sits upon steel grade beams atop a wood timber mat footing. Structural insulated panels (SIPs) attached to steel girts form the building's roof, walls and soffit envelope. Wall panels rated R50 are 25.4 cm thick, and soffit and roof panels rated R70 are 38 cm thick.

Due to transport, storage, and construction conditions at the site, the envelope was designed to be constructed in two distinct phases. The first phase provided closure of the building. SIPS, with a factory applied interior vapor barrier, were initially connected onto the building frame. Panel-to-panel connection joints were designed with an interior spline running the length of the panel joint with a peel-and-stick vapor barrier tape applied at each interior joint location. The entire exterior envelope was wrapped in Tyvek building paper to inhibit air infiltration. The second envelope construction phase added a pre-painted metal composite skin with metal battens at each joint that were offset from the SIP joints.

The windows selected were high performance aluminum framed with triple panes of glass to provide an R6.66 rating. Removable SIP panels were installed in the interior wall opening of each window during the continuous darkness of the Austral winter to provide additional insulation and to block the building's light from interfering with ongoing science activities. Exterior doors chosen were those of the freezer type with an R50 rating.

Contractor modifications to the design substituted a simple butt joint at the panel seams. Infrared (IR) camera inspection prior to installation of the finished skin revealed heat leakage in the envelope. It was determined from IR inspection results that the contractor had eliminated the vapor barrier tape at some panel joints. The contractor repaired these locations, and the envelope has performed well to date with no significant issues.

During construction, the architect's review of shop drawings, close monitoring of critical envelope details, and IR camera or similar inspection are critical strategies so as to achieve the desired envelope performance.

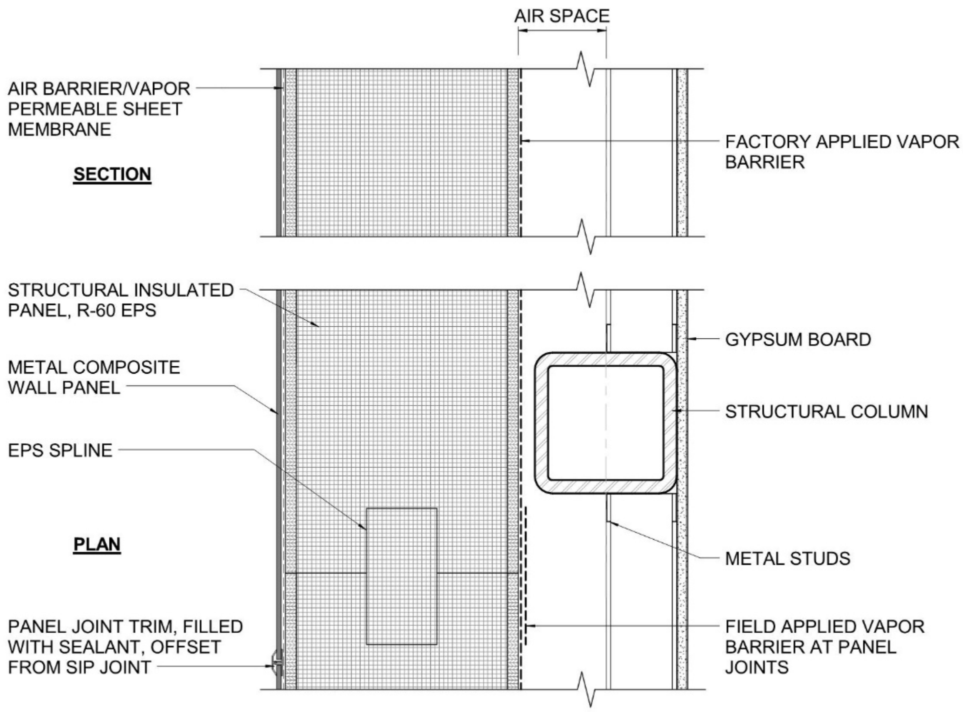


Figure 3: South Pole Elevated Station Envelope Assembly

4.3 Balloon Inflation Facility (BIF)[10]

Located at the Amundsen Scott South Pole Station, the BIF is a 270 sq m building that serves as a laboratory for aeronomy science launches of high altitude weather balloons and balloons that carry instruments for science experiments. In 2016, the former Cryogen building, built in 2006, was relocated a short distance from its original location after being buried in snowdrifts. It was renovated to include a 6 m high bay to accommodate balloon preparation and a 5 m x 6 m double-swing refrigerator-type door for balloon launches.

Unlike the main station, the BIF has no structural steel skeletal structure and is constructed entirely of SIPS with a secondary metal skin similar to the main elevated station's skin. The building is constructed on a steel chassis equipped with skis, which allow the building to be towed to higher elevations as the snow surface increases in height.

The SIPS provide R-50 (30.5 cm) at walls and R-70 (40.6 cm) at roof and soffit and are constructed of oriented strand board (OSB) or plywood. The OSB sandwiches a polystyrene core framed in sawn or laminated lumber and glued together under pressure. SIP joints are constructed of lumber splines perpendicular to the panel face and are concealed by an overlapping exterior metal skin. Factory applied vapor barrier, with field applied vapor barrier joints, is finished with gypsum board or FRP on the building envelope interior.

Construction of the BIF is relatively simple compared to that for the primary, elevated station. The BIF is at grade level and required no structural steel erection. Joint details were modified based on manufacturer's recommendation for constructability and structural integrity.

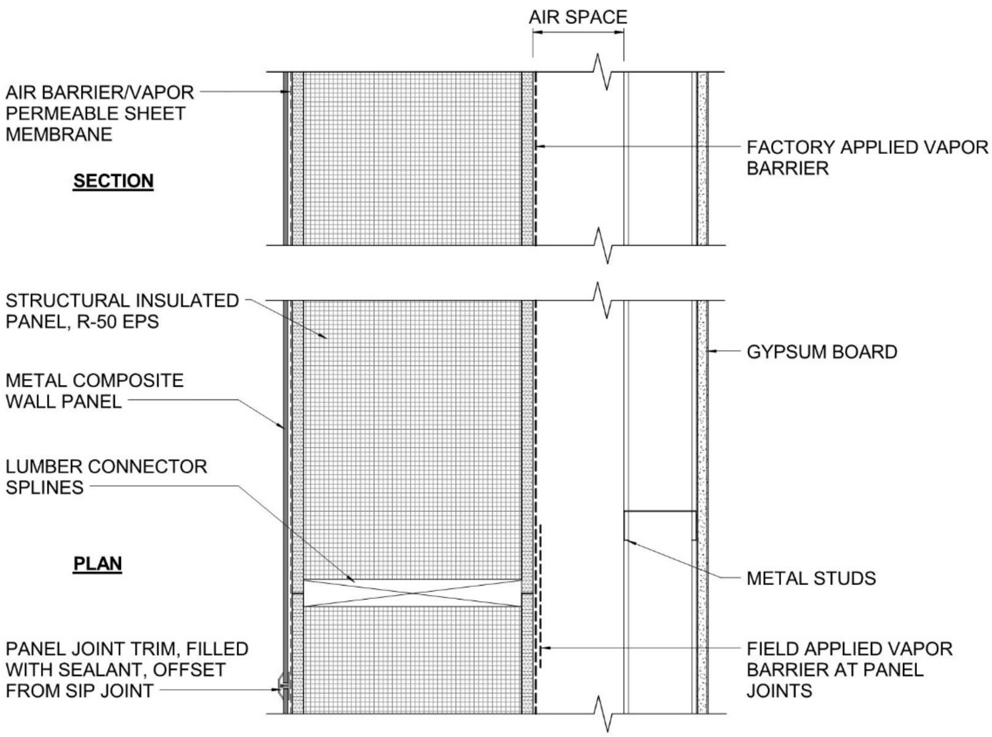


Figure 4: Balloon Inflation Facility (BIF) Envelope Assembly

5 Latest Envelope Design 2017

5.1 McMurdo Information Technology & Communications Primary Operations Facility (IT&C)[11]

Designed in 2017, the new IT&C Primary Ops Facility is a 3,716 sq m, two-story building including a 1,115 sq m Data Center addition. It will serve as the primary Data Center at McMurdo Station and "will house critical back-up emergency operations and communication functions."[12] The site orientation and building configuration of the new Data Center wing is designed to optimize snow scouring around and under the building[13].

An ongoing tenet regarding Antarctic building design is for all systems, including the envelope, to be simple to construct and maintain. Due to the remote location and extreme environment, it is essential that the envelope be easy to construct, maintain, and repair.

The envelope assembly is composed of the following:

- Structure: steel support from superstructure w/fiberglass-reinforced laminated composite thermal breaks
- Interior finish assembly: light gauge metal framing w/gypsum board
- Vapor barrier–factory applied self-adhered vapor barrier, vapor barrier tape at seams
- Thermal barrier–structural insulated panels (GPS insulation) w/block splines

- Air barrier–mechanically fastened air barrier
- Exterior cladding–aluminum/phenolic composite panel
- Doors & windows–insulated metal doors w/thermally broken frames and thresholds, triple pane high performance aluminum windows

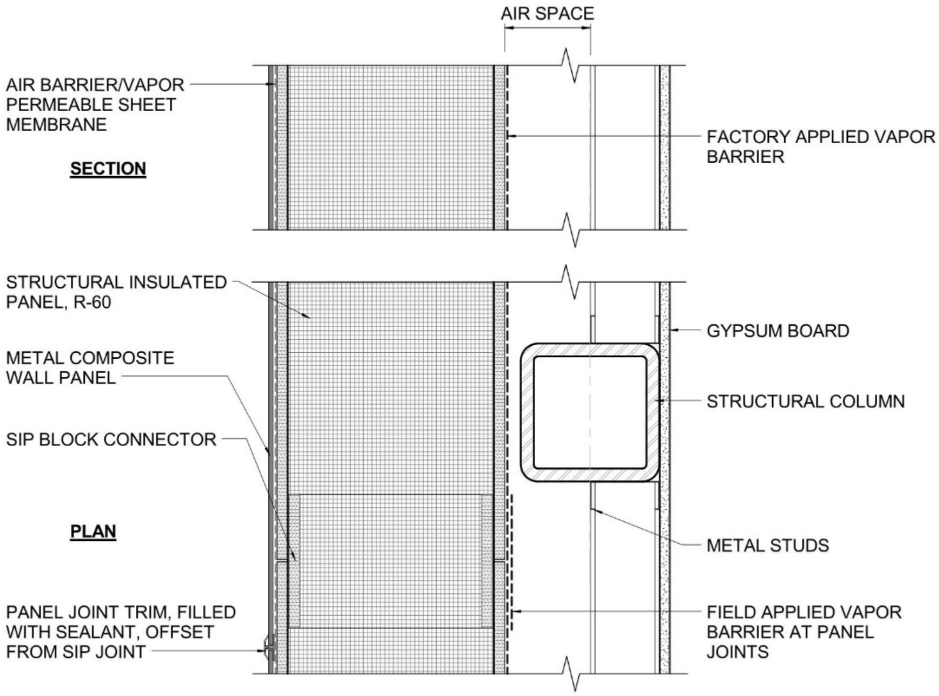


Figure 5: IT&C Primary Operations Facility Envelope Assembly

5.1.1 Structure

The structural system provides the support required for the envelope. The building's superstructure can double as the support for the envelope, the envelope can have a separate support system from the superstructure, or the envelope can itself be self-supporting.

Since structural steel is relatively easy to erect, transport, store, and is non-combustible, it has become the preferred structural system on the Antarctic continent. As such, the IT&C utilizes a steel superstructure that is also used as support for the exterior building envelope. Challenges to this approach occur wherever the superstructure penetrates the envelope. Examples of these penetrations include exterior exposed steel columns that elevate the building and structural roof equipment platform supports. Fiberglass-reinforced laminated composite thermal breaks in the structure are provided at such locations.

Thermal bridging requires considerable attention to detail to prevent any pathways for heat to escape from the building's interior. One such area exists within the steel structure as it penetrates the building soffit where the building is raised to allow for snow scouring. These penetrations are limited as much as possible. Thermal Insulating Materials (TIMs) manufactured from fiberglass-reinforced laminated composites have been used to provide the thermal breaks in steel structures in areas where the respective structure penetrates the envelope. Stainless steel bolts and other types of fasteners are also used since they have a lower conductivity than carbon steel.

5.1.2 Interior finish assembly

The interior finish assembly allows for fastening of equipment (e.g., cabinets and shelving) and provides locations for vertical shafts without damage to the interior vapor barrier and envelope. Light gauge metal framing fastened to the floor and ceiling structure provides easy installation and precludes damage to the exterior wall.

5.1.3 Vapor barrier

A vapor barrier is essential for preventing moisture migration, known as vapor drive, through the exterior envelope. Vapor barriers are located on the warm, humid side of the envelope. In Antarctica, warmth and humidity are on the inside of the building. Moisture travels from the warm, humid side (interior) to the cold dry side (exterior). Due to the extreme temperature and humidity differentials, vapor drive is one of the biggest concerns and challenges when designing within Antarctica.

Due to the firm's past Antarctic design experience, added humidity is avoided except at critical locations such as the Data Center designed in 2017, where 30% RH was required to limit production of static electricity and resulting damage to electronics. Direct openings such as doors and windows to the exterior of the building are also eliminated, if possible, within locations requiring humidification. If moisture passes the vapor barrier and enters the exterior wall, it will freeze, which will result in damage to the exterior envelope. Significant problems result from small amounts of moisture that penetrate the vapor barrier. Therefore, a Class 1 impermeable vapor barrier (0.1 perm or less) is required to limit vapor transfer. Options to achieve a Class 1 vapor barrier are either self-adhered or fluid-applied vapor barriers.

The IT&C vapor barrier includes a self-adhered membrane factory applied to the SIPs and a field applied vapor barrier tape at the joints. This approach allows for greater quality control of the application off site. Installation of the vapor barrier tape at the joints is critical. Construction details at joints are critical especially at structural connections where application of the field applied vapor barrier tape is difficult. One solution is to wrap the wood nailers on the steel structure with the vapor barrier tape to form a seal when the SIPs are installed.

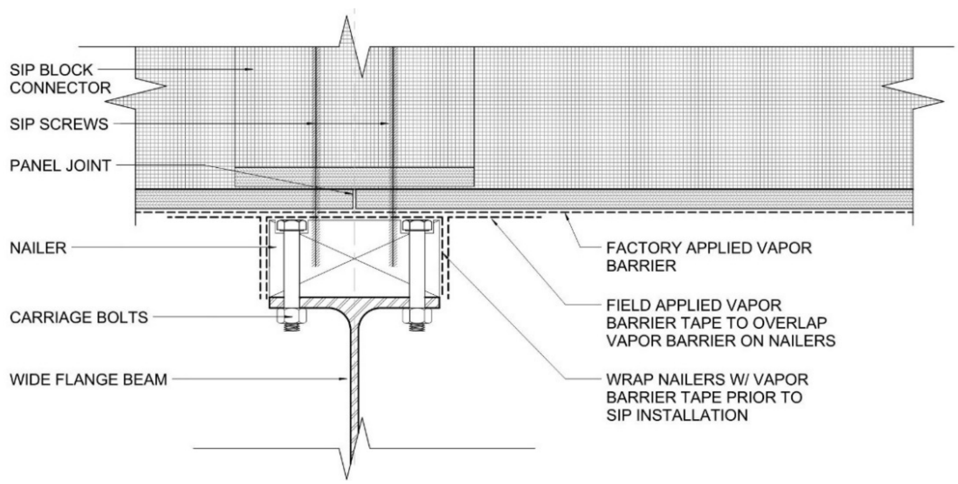


Figure 6: IT&C Primary Operations Facility vapor barrier detail at SIP joint

Locations where the steel structure penetrates the envelope are also a challenge and have been dealt with similarly. Any gaps are filled with spray foam and sealed with the vapor barrier field-applied tape.

5.1.4 Thermal barrier

The thermal barrier's function is to insulate the respective building. The performance of a thermal barrier is measured by its resistance to heat transfer, designated as R-value.

Typical materials used include open-cell (e.g., cellulose, fiber glass batts, and mineral wool) and closed-cell rigid foams (e.g., EPS, XPS, PIR, and GPS). Rigid foams can be manufactured into SIPs. SIPs provide structural stability and resist windblown projectiles due to their flexural strength and are easy to transport, erect, and repair.

The IT&C Facility is designed with Graphite Polystyrene Insulation (GPI), R-60 SIP panels (30 cm thick), similar to Expanded Polystyrene Insulation (EPS) with graphite particles infused into the foam's cell structure. This addition achieves a higher R-value than standard EPS. Experience indicates high R-value insulation is not as important as well-designed joint, barrier, and cladding details (see Crary Lab case study in Section 4.1).

Design of the panel edge connections has evolved since initial use in the elevated station building envelope. The latest iteration is Mini-SIP block splines, continuous solid wood blockings, that fit within the OSB skin at panel seams. This panel edge connection provides increased protection from air infiltration than previously used connections such as thin splines or dimensional lumber splines.

5.1.6 Air barrier

An air barrier prevents air and water infiltration into the building. A vapor-permeable air barrier allows release of any moisture trapped inside the envelope into the exterior. Vapor barrier options include mechanically fastened, liquid applied, sprayed, and self-adhered air barriers.

A mechanically fastened vapor-permeable air barrier was used at the South Pole Station and specified for McMurdo Station IT&C Facility in 2017. The on-site liquid applied, sprayed and self-adhered barrier options are difficult to install by the contractor within the Antarctic environment due to extreme cold temperatures.

5.1.5 Exterior cladding

Exterior cladding exists as a protective finish building skin to resist ultraviolet rays, air, snow, fire, wind, corrosion, abrasion, water, and to be aesthetically consistent with the owner's image. The cladding must be thermally stable and easily installed within the harsh Antarctic environment. Options include metal, metal composite, and fiber reinforced plastic (FRP) claddings. Exterior cladding is also the first line of defense against moisture penetration into the envelope. Therefore, the cladding's joints must be designed to maintain extreme weather tightness.

Aluminum composite panels with a phenolic resin core are the preferred choice for exterior cladding. These panels provide the desired aesthetic, impact resistance, and thermal stability, and they are highly corrosion resistant and easy to install, maintain, and repair.

5.1.7 Doors and windows

The main performance criteria for doors and windows are the overall system's R value and weatherproofing.

Two types of doors are typically required—passage doors and loading dock or garage type doors.

Insulated metal swing doors were used for the IT&C Facility, and a vestibule was provided at every exterior door. These doors have polyurethane core with an R value of approximately 3. Thermally broken metal frames and thresholds were also utilized with neoprene gaskets for weatherproofing. Overhead sectional doors were used at loading docks and have an R value of 18.3.

High performance triple pane aluminum windows with an R value of 7.6 were specified at the IT&C Facility. These windows have frames with a continuous thermal break as well as foam insulation inserted within the aluminum extrusions to limit heat transference. Spacers between panes of glass are nonconductive to prevent thermal bridging. High performance fiberglass windows, which can achieve a higher R value of about 10, are also an option. However, aluminum windows are a tried and true solution at McMurdo Station.

6. Challenges/Limitations Facing Current Envelope Assembly Practice

The preferred use of standard SIPs limits the capability to design and construct aerodynamically shaped buildings that inhibit snow deposition on and around the structure. Other design options, such as the use of custom FRP panels, have greater potential for aerodynamic design. However, custom FRP panels are costly, require long lead time, are difficult to install, and are difficult to repair if damaged. Therefore, standard SIPs have remained the preferred system.

Joints that are would typically be easily constructed in a temperate climate present a challenge to envelope design within the Antarctic environment. Construction workers must operate in extreme cold temperatures and typically wear heavy and bulky protective clothing, which inhibits dexterity and mobility. These inherent conditions impede precise craftsmanship.

A recurring problem is that construction contractors often do not follow the intended design. Standard manufacturer's details for connections, joints, etc. are typically not specified by the designer for Antarctic projects due to the environment's unique climatic conditions. However, manufacturers have historically reverted to their standard details and fabrication techniques. Changes from project specific details to standard manufacturer's details negatively impacts building envelope performance.

7. Conclusion

Antarctica's pristine, remote location and extreme cold climate make it a perfect laboratory for discovery in not only the natural sciences but also building science. Ferraro Choi's 30 years of design and engineering work with United States National Science Foundation's (NSF) Office of Polar Programs and its Antarctic Support Contractor, Leidos Innovations, continues at McMurdo and South Pole Stations. The firm's building envelope design for extreme cold climates continues to evolve and mature with the latest design and the upcoming construction of the IT&C Primary Operations Facility at McMurdo Station. Feedback through the IT&C construction phase may identify new opportunities for continued improvement, as traditionally occurred in the presented case studies. Further research and testing of new materials for current NSF projects and for other inland stations will continue to add to the firm's knowledge base for future work in extreme environments.

8. References

[1] *OZ Architecture*, "McMurdo Station Modernization Study, Building Shell & Fenestration Study," April 29, 2016, p. 54.

[2] *U.S. Antarctic Program Blue Ribbon Panel*, "More and Better Science in Antarctica Through Increased Logistical Effectiveness," 2012, p.13.

[3] J. W. Marty, "Construction of the New South Pole Station," *Cold Regions Engineering: Putting Research into Practice,* 1999, pp. 45–56.

[4] J. J. Ferraro, "Master Plan for the South Pole Redevelopment Project," *Cold Regions Engineering: Putting Research into Practice,* 1999, p. 15.

[5] Ferraro Choi & Associates, Metcalf & Eddy, Inc., and RWDI Inc., "Amundsen-Scott South Pole Station Conceptual Design and Programming Study," March 1994, p. A-3.

[6] CJS Group Architects, Ltd., "National Science Foundation Replacement Science Facility, Basis of Design," Rev. 1987, p. 11.

[7] "McMurdo Station BL010–IT&C Primary Operations Facility, Basis of Design," August 3, 2017, p. 29.

[8] F. Arduini, "Review and Inspection of CSEC Building Envelope After 7/9/15 Storm Event," July 2015, p. 10.

[9] J. J. Ferraro, "Master Plan for the South Pole Redevelopment Project," *Cold Regions Engineering: Putting Research into Practice,* 1999, pp. 11–22.

[10] Enercept, Inc. Superinsulated Building Systems, "Cryogen/Balloon Inflation Fac. SIP Shop Drawings," 2002, p. 4.

[11] "McMurdo Station BL010–IT&C Primary Operations Facility, Basis of Design," August 3, 2017, p. 1–69.

[12] "McMurdo Station BL010–IT&C Primary Operations Facility, Basis of Design," August 3, 2017, p. 1.

[13] Cermak Peterka Petersen, "McMurdo Station Snow Scouring and Deposition Modeling Study: Preliminary Results," September 19, 2016.