ERDC/CRREL SR-14-2

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Engineering for Polar Operations, Logistics, and Research (EPOLAR)

Elevated Building Lift Systems on Permanent Snowfields

A Report on the Elevated Building Lift Systems in Polar Environments Workshop

Jason Weale, Lynette Barna, Wayne Tobiasson, and Jennifer Mercer

September 2014

Polar Elevated Building Lift Systems Workshop participants.

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Cold Regions Research and Engineering Laboratory (CRREL)
U.S. Army Engineer Research and Development Center
72 Lyme Road
Hanover, NH 03755-1290

Final Report

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EP-ARC 10-15, "Assessment of Elevated Building Lift Systems"

Abstract

The National Science Foundation sponsored this two-day workshop to bring together international experts to discuss the history and state-of-the art of systems used to periodically lift elevated buildings constructed on permanent snowfields. Early structures permanent snowfields were typically built at the surface and became buried over time from accumulating snow. These buildings were prone to short service lives as the accumulating snow increased pressure on the structures, eventually rendering them unsafe. An accepted current practice for constructing most structures on permanent snowfields is to elevate them above the natural terrain. This technique reduces the adverse effects of annual snow accumulation, snow drifting, and snow settlement and prevents thawing of the snow foundation from the heated superstructure. To achieve cost-effective service lives, there is extra incentive to periodically lift the elevated structures and to maintain them above the ever-rising snow surface. This report summarizes lift systems used to maintain the current generation of elevated, permanently occupied polar stations above permanent snowfields.

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Preface

Funding for this work was provided by the National Science Foundation (NSF), Division of Polar Programs (PLR), under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ARC 10-15, "Assessment of Elevated Building Lift Systems." The technical monitor was Patrick Haggerty, Arctic Research Support and Logistics (RSL) Program Manager, NSF-PLR.

This report was prepared by Jason C. Weale, Lynnette A. Barna, Wayne Tobiasson (retired), and Dr. Jennifer L. Mercer (Force Projection and Sustainment Branch, Dr. Edel Cortez, Chief), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Justin Berman was Chief of the Research and Engineering Division. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

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Acronyms and Abbreviations

AWI	Alfred Wegener Institute
BAS	British Antarctic Survey
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
DEW	Distant Early Warning
EPOLAR	Engineering for Polar Operations, Logistics, and Research
ERDC	U.S. Army Engineer Research and Development Center
GISP2	Greenland Ice Sheet Project 2
GRP	Glass Reinforced Panel
IGY	International Geophysical Year
IPEV	Institut Polaire Français Paul Emile Victor
NIPR	National Institute of Polar Research
NSF	National Science Foundation
OSB	Oriented Strand Board
PLR	Division of Polar Programs
PRNA	Programma Nazionale di Ricerche in Antartide (Italian Antarctic Research Program)
RSL	Research Support and Logistics Program
SIP	Structural Insulated Panels
USAP	United States Antarctic Program
USARC	United States Arctic Sciences Program
UK	United Kingdom

Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters
hectares	1.0 E+04	square meters
tons (2000 pounds, mass)	907.1847	kilograms

1 Elevated Building Lift Systems

1.1 Introduction

The National Science Foundation (NSF) sponsored a two-day workshop on 15–16 September 2010 in Rosslyn, VA, to gain technical insight about elevated structures prior to designing new facilities at Summit Station, Greenland. The effort brought together international experts to discuss state-of-the-art systems implemented in elevated building design and construction on permanent snow and ice fields. The primary objectives were to (1) review the history of building on permanent snow and ice fields, (2) introduce design concepts and construction techniques that illustrate new technological and experiential advances developed to withstand the challenges unique to elevated buildings constructed at these locations, (3) briefly discuss the potential for using ice columns as a foundation method for elevated structures, and (4) understand the environmental need to employ systems that reduce the long-term impacts of human presence in both Greenland and Antarctica.

Between 2005 and 2010, Germany, the United Kingdom, France-Italy, and the United States have all erected and commissioned elevated research stations on permanent snow and ice fields in Antarctica (Figure 1). These stations are used to house research and support staff while conducting observations and experiments. Japan also constructed a smaller elevated shelter on a permanent snow and ice field near Syowa Station in 2005–2006. For this workshop, representatives associated with the Antarctic stations Neumayer III (Germany), Halley VI (United Kingdom [UK]), Concordia (France-Italy), and Amundsen-Scott South Pole (United States Antarctic Program [USAP]) and Summit Station in Greenland (Figure 2) (United States Arctic Sciences Program [USARC]) met to exchange technical information and knowledge focused specifically on the mechanical lift systems used for raising the structures to elevate and maintain them above the surfaces of the permanent snowfields.

Major construction in polar environments is not a regular occurrence; and therefore, it is difficult to maintain continuous knowledge in this subject and not to repeat previous mistakes (Mellor 1969). This workshop facilitated an exchange between experts on elevated stations' lift systems and had a focus on recent construction over permanent snowfields. There are sizeable constraints for building in the polar environments, including limitations on transporting materials to the site, extreme working conditions, and short construction seasons. Intense planning, limited resources, and high costs must also be considered.

While this report represents a broad synopsis of the current state of knowledge and of recent experience with elevated structures on permanent snowfields, the bibliography provides additional, in-depth and comprehensive historical sources that discuss structures constructed on the same snowfields as well as the environmental conditions and physical properties at those locations.

Figure 1. Antarctica, showing stations and camps mentioned in this report.

Figure 2. Greenland, showing stations and camps mentioned in this report.

1.2 Workshop goals

The motivation for this workshop was the conceptual design for a new year-round polar research station at Summit, the highest point on the Greenland ice cap. The design under consideration was a rapidly deployable, modular station that used panelized building components as the building envelope. The components were connected with structural metal panels and supported by structural steel columns (integrated with the chosen lift system). The temperature range at Summit Station during the summer is from 0°C to −40°C while the winter temperatures range from

−25°C to −60°C. Annually, Summit receives approximately 70 cm of snowfall. High prevailing winds from the south create drifts as high as 4 m around structures.

The primary mode of transport to Summit Station during the busy summer season is via ski-equipped LC-130 aircraft (approximately 20 annual flights) from Kangerlussuaq (formerly Sondrestrom Air Base). In addition, an overland traverse initiated in 2008 operates between Thule Air Base and Summit Station, carrying fuel and supplies. Overland traverses have been shown to be economically feasible and to reduce both costs and pollution associated with aircraft flights (Dahl 2008). Access during the winter is via four Twin Otter flights from Kangerlussuaq.

The primary goals for the workshop included the following:

- Explore the international history and the state-of-the-art of building on permanent snowfields, focusing on elevated buildings that are periodically lifted to maintain them above the ever-rising snow surface
- Publish a report on this workshop to capture the knowledge and experience gained from past and current operations on permanent snowfields
- Incorporate lessons learned at this workshop into the design of the new research station at Summit, Greenland

2 A Brief History of Building on Permanent Snow Fields

2.1 Beginnings

Early in the 20th century, polar explorers and scientists who travelled on permanent snowfields survived in temporary structures, such as tents, that became drifted over and semi-permanent snow huts excavated into the snow with interconnecting tunnels and storerooms (Mellor 1961; Kadambi 1986). Initially, quite modest facilities were constructed to provide shelter and to sustain personnel. In general, these facilities were considered temporary as they became uninhabitable before long. During the 1940s, ’50s, and ’60s, technologies used during World War II were increasingly adopted for use in the polar regions. Overland traverses using heavy mechanical equipment could haul tons of construction materials, provisions, and fuel where previously only minimal quantities of supplies could be dragged in via sledges (Mellor 1968; Belanger 2006). Air transport also became common.

Polar engineers and researchers gained much knowledge related to snow properties (Mellor 1964), design concepts, and construction techniques. Mellor (1968) summarizes methods of building on permanent snowfields. Tobiasson (1968) describes surface, subsurface, and elevated ice cap facilities and how they respond to environmental factors such as temperature, wind speed and direction, snow accumulation, snow drifting, and ice cap movements. The extreme environment of the polar regions presents enormous living and operations challenges. An inhospitable environment consisting of excessive low temperatures, high winds, and a stark snow-covered landscape presents design and construction challenges to maintain a presence and to operate year-round facilities in support of scientific research efforts.

2.2 Surface stations

Stations constructed on the snow surface typically consisted of prefabricated units supported on timber footings. Snow is limited as a supporting material. It is relatively weak, sensitive to temperature changes, and creeps under load. Continuous snow accumulation and drifting around surface buildings require continuous snow removal with heavy equipment that consumes vast quantities of fuel. This remains an issue today. These structures often had a shortened service life due to snow accumulation and, once buried, could not withstand the increasing snow load unless reinforced. Excavating several feet into the firn layer typically produced snow with a higher density and increased strength properties to support the foundation and provided some protection from winds and drifting snow (Mellor 1961). However, such buildings became buried sooner by accumulating snow. The thermal characteristics of buried building envelopes eventually caused the snow in contact to melt, to leak into the structure, and to erode the structural integrity of the snow.

Roofs were constructed between these buildings to create corridors that provided safe passages and additional storage space as the snow drifted rapidly and covered the stations completely. As these stations (buildings and corridors) became drifted-in and buried, winter living in the buildings and working in the covered corridors between buildings was, as described by occupants, “somewhat comfortable” as the entrance ramps (to the snow surface) were drifted in and building heat losses were “captured.” When the ramps were opened in the summer, the heat trap was lost, cold outdoor air poured in, and the corridors (tunnels) and buildings were far less comfortable.

The “comfortable” winter living warmed and weakened the snow while the summer “recharge” of cold air helped cool the snow but made for colder living conditions. Additional challenges included difficulty generating and distributing power within buried structures because waste heat from the diesel generators heated the tunnels and caused the surrounding snow to collapse. The limited connectivity with the “outside” world due to a lack of effective communications in high latitudes and underneath the snow was both a safety challenge and contributed to feelings of isolation from home. When the ramps were opened at the end of the long winter, the exposure to sunlight and the freedom to move about was a big moral boost for station inhabitants.

In Antarctica in the 1950s, the U.S. built several camps to support the activities for the 1957–58 International Geophysical Year (IGY). Byrd (1956) describes how the U.S. Navy’s Operation Deep Freeze made an “all-out assault on Antarctica" for the IGY. Four bases, Little America V, Byrd, South Pole, and Ellsworth, were built on permanent snowfields. To accomplish building all four stations expediently and economically for the IGY, all of the stations used similar construction techniques of lightweight, prefabricated buildings grouped together on the surface and were eventually buried by accumulating snow. Interestingly, Mellor (1961) wrote that there was a flawed belief that the height of drift snow would accumulate to the level of the roofline of the buildings and then slow as the profile became stream lined. The primary cause for drift snow to rise rapidly about the roofline (well before the "natural" snow surface rose to that level) was all of the snow control work performed by station personnel to keep the corridors and access ramps open. Mellor and others later understood that almost all of the rapidly accumulating snow was due to an accelerated drift process triggered by the aforementioned snow-control methods. Drift snow was bulldozed away from the access ramps and created large areas of disturbed snow. These undulating, disturbed areas enhanced the snow catchment properties in areas around the facilities and acted as a multiplier for drift accumulation.

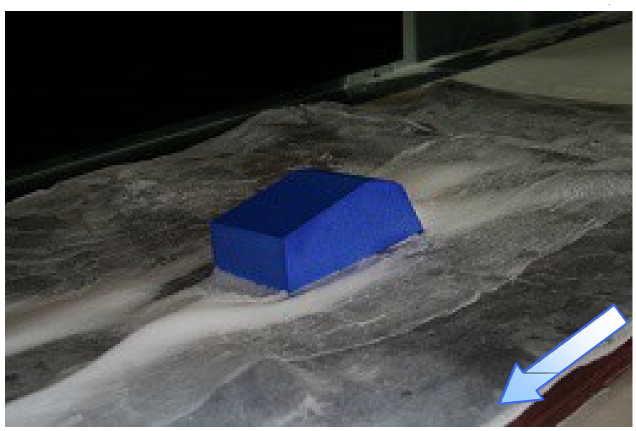
Three of these stations remained in service a few years beyond the duration of the IGY. The original IGY South Pole Station (commonly referred to as "Old Pole") lasted until 1975 (Brooks 1999) when it was replaced by another surface station that consisted of heated buildings, most located within a 50 m diameter aluminum dome and corrugated metal arches.

The British Royal Society established Halley I during the IGY as a surface station. It became buried by accumulating snow and had to be abandoned after 10 years. Replacement facilities consisted of buildings built on the surface, some within metal and then wooden tubes. All became buried and experienced thermal and structural problems.

In addition to the four U.S. stations and Halley I, the IGY was the initial catalyst for several other nations to establish research stations in Antarctica. Approximately 20 years later, the presence had grown to where there were 34 year-round Antarctic research stations maintained by 12 countries. Most of these stations were located on soil or rock along the coastline where conventional cold-climate construction techniques could be implemented (Brooks 1999). They were also subjected to blowing and drifting snow but did not suffer from the snow accumulation and foundation support problems of stations built on permanent snowfields.

At this workshop, Ishizawa (2010) described the new service building designed for Japan's Syowa Station in Antarctica. That coastal site is soil and rock, not snow; but it experiences high winds and significant snow drifting. The Japanese Antarctic Program conducted wind tunnel studies on various building shapes. Of the geometries tested, a combination of a rectangular structure with an up-sloped windward wall and a downsloped-downwind roofline performed best, accumulating the least snow in the wind tunnel (Figure 3).

Figure 3. Shape of Syowa Station Service Building as tested in the wind tunnel. Prevailing wind depicted with the light blue arrow. (Ishizawa 2010).



2.3 Undersnow facilities

Mellor (1964) overviews foundations and subsurface structures constructed in snow. The U.S. Air Force on the Greenland Ice Cap built two large undersnow facilities (Sites 1 and 2) in 1953. They consisted of heated buildings inside a network of corrugate steel tubes. In 1957, the U.S. Army's Camp Fistclench was built nearby Site 2. Its heated buildings were within tunnels cut with Swiss Peter Snow Millers and then covered by timber-trussed roofs. The Corps of Engineers built Camp Century in 1959–60. The tunnels of Camp Century covered an area of approximately 13 hectares. Corrugated steel arches covered with processed snow topped trenches cut with Peter Snow Millers. Heat losses from the buildings in these tunnels caused the snow to deform more rapidly than expected, and considerable effort was required to keep the buildings from being crushed.

Many arches had to be raised, and extensive snow trimming with electric chainsaws was required. Military security interests drove these large-scale projects located on the Greenland Ice Cap.

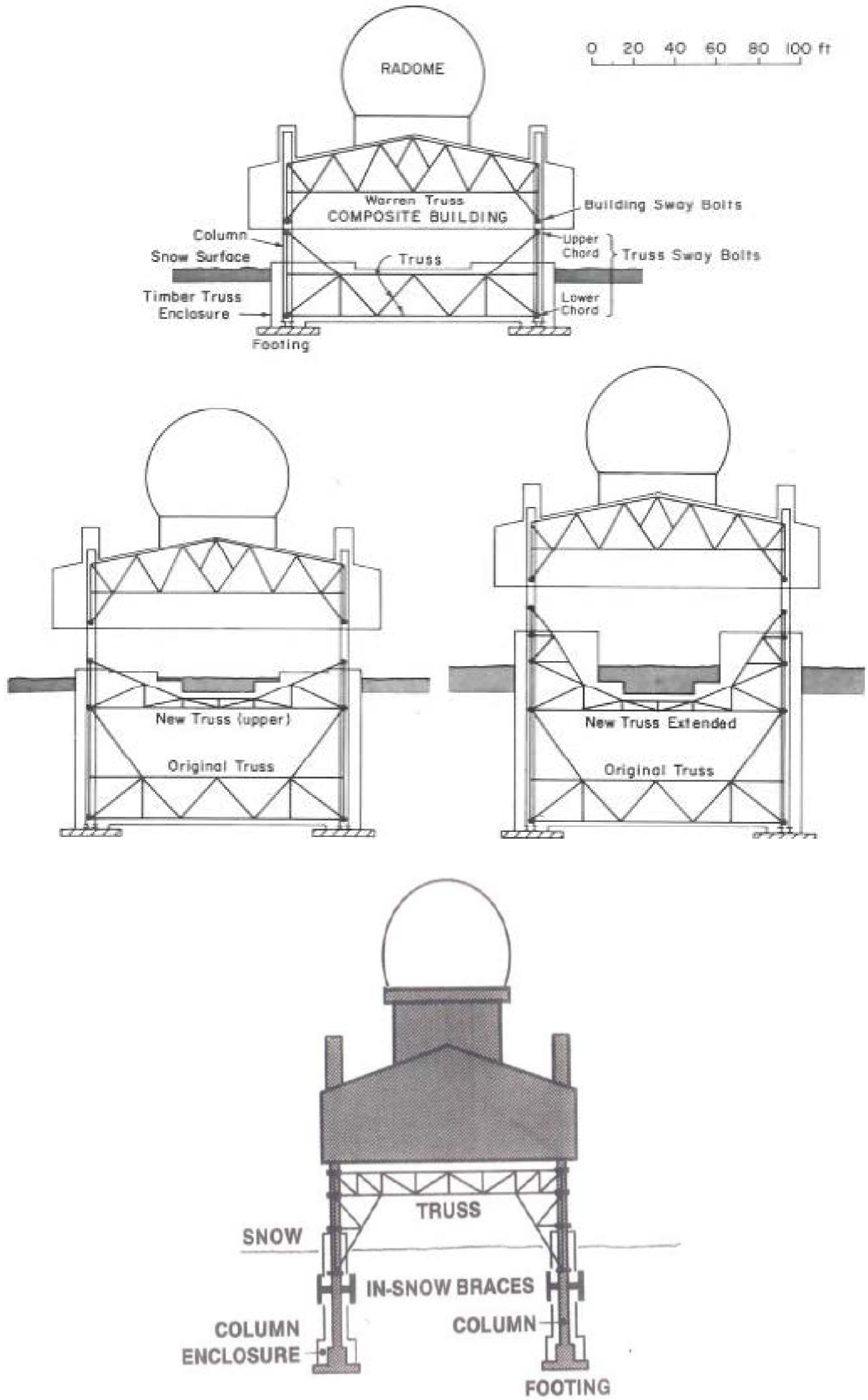
The first Byrd Station in Antarctica was replaced in 1962 with an under-snow station patterned after Camp Century in Greenland. Mellor and Hendrickson (1965) monitored its performance.

2.4 Elevated structures

2.4.1 History

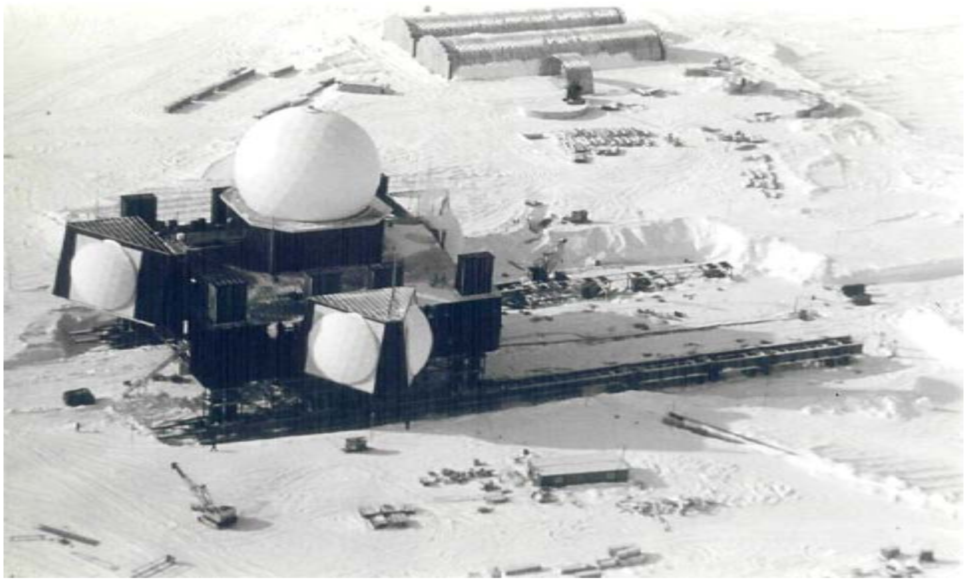
In the late 1950s, the United States constructed two huge, 3270 tonne (3600 ton) structures elevated above the snow surface on the Greenland Ice Sheet. These communication and surveillance sites (DYE-2 and DYE-3, see Figure 2) were part of the Distant Early Warning (DEW) Line (Mellor 1961). They were elevated above the snow surface on steel columns. Each structure was elevated on eight columns, tied together by a subsurface truss system, and supported on footings buried deeply below the snow surface (Tobiasson et al. 1974). The timber enclosure that housed the trusses and columns allowed for access to re-level the trusses due to differential settlement of the footings. To maintain the base of the station at least 4.5 m above the ever-rising snow surface, hydraulic jacks in each building were used to lift it up threaded rods attached to the columns (Tobiasson et al. 1974). The columns were extended to allow the structure to be lifted. As the columns were extended, lateral bracing was added to reinforce against wind and to prevent buckling of the columns (Tobiasson et al. 1974). During their useful lives, DYE-2 and DYE-3 were lifted 32 m and 41 m, respectively. Figure 4 shows changes to the structural support system over the life of these buildings.

Figure 4. Changes to the DYE-2 and DYE-3 structures over the years: as built (top), first truss extended and a new truss added (middle left), new truss extended (middle right), new system after sideways move (bottom).



Regular monitoring of the DYE sites revealed that high secondary stresses developed in the columns, and localized failures occurred within the timber truss enclosure (Tobiasson et al. 1975). In 1977 and 1978, the DYE-3 station was severed from its foundation, moved sideways 64 m onto new spread footings (Figure 5), and lifted 8.2 m to extend its service life (Tobiasson 1979, and Tobiasson and Tilton 1980).

Figure 5. DYE-3 in 1977 just after being moved 64 m sideways onto new footings.



At this workshop, we showed a short time-lapse film of the DYE-3 move. In 1982 and 1983, DYE-2 was also moved and lifted the same amounts. DYE-2 was abandoned in 1988 because it was highly overstressed, and its surveillance and communication functions were no longer essential. DYE-3 was abandoned in 1990–1991. Both are still standing; and Figure 6 shows DYE-3 in 2006, approximately 16 years later. DYE-2 and DYE-3 are instructive with respect to building and lifting elevated stations on permanent snowfields.

There has been a scientific presence near the summit of the Greenland Ice Sheet (Figure 2) since the late 1980s. The Greenland Ice Sheet Project 2 (GISP2) was a deep ice core-drilling project from 1989 to 1993 that interpreted 110,000 years of climate history (Starkweather 2010). The drill camp supported a population of up to 40 people during the summer season. The main administration building (Figure 7) constructed to support daily activities is elevated (Curtis and Tobiasson 1991). Now referred to as

"Summit Station," it has operated as a year-round research camp since 2003.

Figure 6. DYE-3 in 2006, approximately 16 years after it was abandoned.

Figure 7. Summit Station's "Big House" after it was lifted 4.5 m in 2010.

The elevated building, the “Big House,” is currently supported on ten steel columns. Since 1989, it has been lifted four times for a total of 15 m to keep it above the 0.7 m of snow that accumulates annually in the area (Barna et. al. 2011). The most recent lift occurred during the summer of 2010 when the building was lifted approximately 4.5 m. When lifted, steel extensions are added to increase column length during lift operations. Hydraulic jacks (Figure 8) are set on the lower portion of the jack stand and push up on the “center traveler” that is connected to the hanger assembly (Phillips 2010). Two hydraulic cylinders are used to jack each column. Each hydraulic cylinder is connected to the hydraulic pump that raises the structure.

Figure 8. Position of the hydraulic jack used for the “Big House” lift procedure (Barna et. al. 2011).

Elevated scientific facilities have been used in Antarctica for some time. In 1969, Australia’s first Casey Station on the coast was elevated above rock and soil. For the IGY, the United States built the nearby Wilkes station, which the Australians later used. It experienced extensive snow drifting due to the high winds and thus guided the decision to elevate Casey Station. Casey I consisted of a long crosswind line of buildings, most of which were elevated on pipe scaffolding. A continuous passageway interconnected the windward ends of these buildings. In addition to the wind-induced vibration and salt-spray corrosion problems, which deteriorated these buildings, moral within them was quite low. Work started in 1979 on an at-grade station a short distance away. The Australians anticipated snow drifting, and each building was sited to minimize problems created by drifted snow. The station was created such that personnel had to go out into the weather to commute between buildings. As expected, this greatly improved moral. Getting people outside continues to be an important design consideration for all polar facilities.

Most other stations built on soil or rock around the coast of Antarctica have many of their buildings elevated from 0.5 to 2 m above grade to reduce snow drifting problems. Because that snow completely melts away during the summer in almost all of these places, these stations do not have to contend with continuous snow accumulation year after year as buildings on permanent snowfields do.

The first elevated station built on a permanent snowfield in Antarctica was Germany's Filchner Station. The British incorporated a similar concept into Halley V, the first elevated station on the Brunt Ice Shelf. Construction of Halley V began in 1988.

2.4.2 Aerodynamics

Numerous studies on snow drifting have been completed (Sherwood 1967, Kim et al. 1990a, 1990b, 1990c, Beyers et al. 2004). Scale models of elevated buildings have been tested in wind tunnels to assess building geometry and elevation above the surface. Snow drifting was diminished by reducing the number of 90° corners on a building (Sherwood 1967). Further, compared to a rectangular-shaped building, chamfered or rounded corners considerably reduced wind-induced loading (Kim et al. 1990a). Elevating a building designed with chamfered corners as high as practical to take advantage of the scour created by wind blowing under the structure reduced both the wind-induced loading and the height of the snow drift (Kim et al. 1990b), extending its service life. Even so, these design changes add complexity and cost to design and construction of elevated facilities, and a compromise is required to balance cost limitations with optimal design. These changes certainly do not eliminate snowdrifting completely

(Waechter and Williams 1999), and new projects will always need a snow management program.

2.4.3 Lift system issues

Having to lift a building increases its cost and complexity. Hydraulic jacks have been used to lift almost all buildings built on permanent snowfields. One exception is the small elevated building at Japan's nearby skiway. It is lifted manually with a lever hand winch.

At DYE-2 and DYE-3 in Greenland, the systems of hydraulic jacks and threaded rods with motorized follower nuts were built into the structure and were located within the building envelope, which proved advantageous because the system was protected from the cold climate and extreme weather conditions found on the Greenland Ice Sheet. Most other lifts have been accomplished out in the weather, thus exposing the lift system and construction personnel to the extreme cold. For some buildings, lifting hardware remains in place; but for others, it is brought to the site only when needed.

As differential settlement, column tilt, and ice sheet movements distort the structural frame and cause secondary stresses to accumulate in it, lifting and leveling become much more difficult. DYE-2 and DYE-3 were designed to be lifted and leveled annually, but the first 0.9 m lift of DYE-3 in 1959 was more difficult and time consuming than expected. Therefore, all subsequent lifts were several years apart with skilled teams brought on-site to do that specialized work.

Lifting elevated buildings also requires extending utility systems (waste, water, and power) as well as egress systems.

2.5 Moveable structures

Because of size limitations and the utility (water, waste, and power) connections, arctic engineers once thought that buildings created to be periodically repositioned to battle accumulation and structural problems were limited to only small-sized camps (Mellor 1961). The 1977 sideways move of DYE-3 (Figure 5) and the 1982 sideways move of DYE-2 expanded such limitations dramatically. Had these stations remained open a few years longer, their new fuel storage systems would have been tanks within elevated buildings moved every few years to higher ground by using crawler-transporters.

Buildings such as garages have been supported on skis, skids, and pontoons so they could be moved about. The garage for Halley V (Blake 1997) is a good example. A robust base was needed to withstand the horizontal forces while being towed by heavy equipment. Inflatable air bags were used to overcome the bonds between the skis and the snow. At Halley, temperatures below −10°C were needed to ensure adequate snow strength during moves. The success of the moveable Halley garage prompted the design of a moveable 30-person living module. It was put into service at Halley during the 1994–95 season.

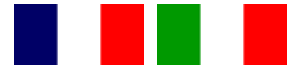
3 New Elevated Building Lift Systems and Concept

This section describes new lifting systems used in Antarctica since 2005. It also presents a new lift system concept presented at this workshop. Figure 1 shows the location of Neumayer III, Halley VI, Concordia, and Amundsen-Scott South Pole stations. Table 1 provides a summary of their key features.

3.1 Neumayer III Station, Antarctica

Germany's Alfred Wegener Institute (AWI) for Polar and Marine Research, Helmholtz Foundation, has operated year-round facilities on the Ekström Ice Shelf, in the northern portion of Queen Maud Land, for nearly 30 years. The first permanent German station was Georg von Neumayer I, commissioned in 1981. It and Neumayer II were not elevated. In 1981–82, AWI built a "summer" station on the Filchener-Ronne Ice Shelf. It consisted of buildings on a guyed, jackable platform supported on steel legs, each with a steel and timber spread footing at its base. The designers of this facility (Christiani & Nielsen) designed and built at least one of the two Neumayer early stations and some years later designed Halley V for the British Antarctic Survey (BAS). The newest AWI station, Georg von Neumayer III, was constructed over two austral summer seasons and was commissioned in February 2009 (Figure 9). The design used for Neumayer III differed from the previous two stations in that it is, in large part, an elevated structure maintained above the snow surface on steel columns.

Table 1. Information for four new elevated stations in Antarctica (D. Terry, 2010, pers. comm).

				
Station Name	**Halley VI**	**Amundsen-Scott**	**Neumayer III**	**Concordia**
Nation/ Organization	UK/BAS[*]	USA/USAP	Germany/AWI[†]	France/IPEV[‡] Italy/PRNA[§]
Latitude/ Longitude	75°35' S, 26°34' W	90°S	70°40' S, 8°16' W	75°06' S, 123°23' E
Geographic Location	Brunt Ice Shelf, Weddell Sea, Antarctica	South Pole, Antarctic Plateau	Ekström Ice Shelf, Atka Bay, Weddell Sea, Antarctica	Dome C, Antarctic Plateau
Altitude	30 m	2830 m	43 m	3233 m
Topography	Coastal ice shelf	Polar plateau ice sheet	Coastal ice shelf	Polar plateau ice sheet
Annual Snowfall	1.2 m	0.2 m	0.8–1 m	0.02–0.10 m
Temperature Range	High: −0°C Mean Annual: −18.5°C Low: −55°C	High: −13.6°C Mean Annual: −49°C Low: −82.8°C	High: +5°C Mean Annual: −16°C Low: −45°C	High: −25°C Mean Annual: −54.5°C Low: −83.9°C
Wind Speed (Monthly Average) Prevailing wind	<5 m/s (18 km/h) S[**] Annual average = 6.8 m/s (24.6 km/h)	5.5 m/s (20 km/h) NNE	9 m/s (32 km/hr) E	2.6 m/s (9 km/h) SSW
Distance from Nearest Logistical/Supply Hub	30 km from ship offload point (Creek 2)	1500 km from ship offload point (McMurdo)	10 km from ship offload point (ice shelf edge)	1100 km from Dumont D'Urville, 1200 km from Terra Nova Bay
Station Access	Sea-ice traverse or via ski-equipped aircraft	Ground traverse or via ski-equipped aircraft	Sea-ice traverse or via ski-equipped aircraft	Ground traverse or via ski-equipped aircraft

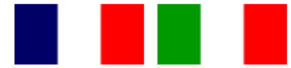
* British Antarctic Survey

† Alfred Wegener Institute

‡ Institut Polaire Français Paul Emile Victor

§ Programma Nazionale di Ricerche in Antartide (Italian Antarctic Research Program)

** King (1989)

				
Station Name	**Halley VI**	**Amundsen-Scott**	**Neumayer III**	**Concordia**
Station Size	Habitat: 1363 m^2 Science/Refuge: 961 m^2 Shop/Garage/Lab: 730 m^2 Total: 3054 m^2	Main Bldg. (elevated): 6040 m^2 Garage (buried): 835 m^2 Cargo Arch (buried) : 1640 m^2 Power Plant (buried) : 600 m^2 Fuel Arch (buried) : 1325 m^2	Habitat: 1640 m^2 Laboratory: 210 m^2 Garage: 2623 m^2 Total: 4473 m^2	Main Bldgs.: 1612 m^2 Power plant: 188 m^2
Population	Summer: 52 Winter: 16	Summer (3 mo.): 150 Winter (9 mo.): 50	Summer (3 mo.): 40 Winter (9 mo.): 9–10	Summer (3 mo.): 45 Winter (9 mo.): 16
Design Life	20 Years (min.)	25 Years[*]	25–30 Years	25 Years[†]
Foundation System	Elevated, jackable, and moveable for initial transport to site and periodic relocation	Elevated, jackable, on 36 extendable columns with footings on compacted snow pad with its base at the snow surface	Elevated, jackable, on 16 "bi-pod" columns and footings lifted one at a time. A garage is located below the facility	Elevated, jackable, on 12 columns and footings on a 6 m high compacted snow pad with its base 3 m below the surface
Initial Station Field Commission Date (Full Operation Date)	2009 (February 2010)	2008 (March 2010)	2009	2005 (November 2006)
Number of times lifted	Has not been lifted.	First lift scheduled 14 years after commissioning. North side lifted due to differential settlement of support columns caused by massive snow ramps built in that area to facilitate Station construction.	3 lifts beginning in November 2009 (total lift height is unclear). Experiencing more accumulation than expected.	Has not been lifted.

[*] Brooks (1999)

[†] P. Godon, June 2012, pers. comm.

Figure 9. The commissioned Neumayer III Station. Note the raised roof of the ramp in the left of the photo, which leads down to the subsurface garage and storage area directly below the elevated building. The roof is lowered during storms (Gernandt et al. 2010).

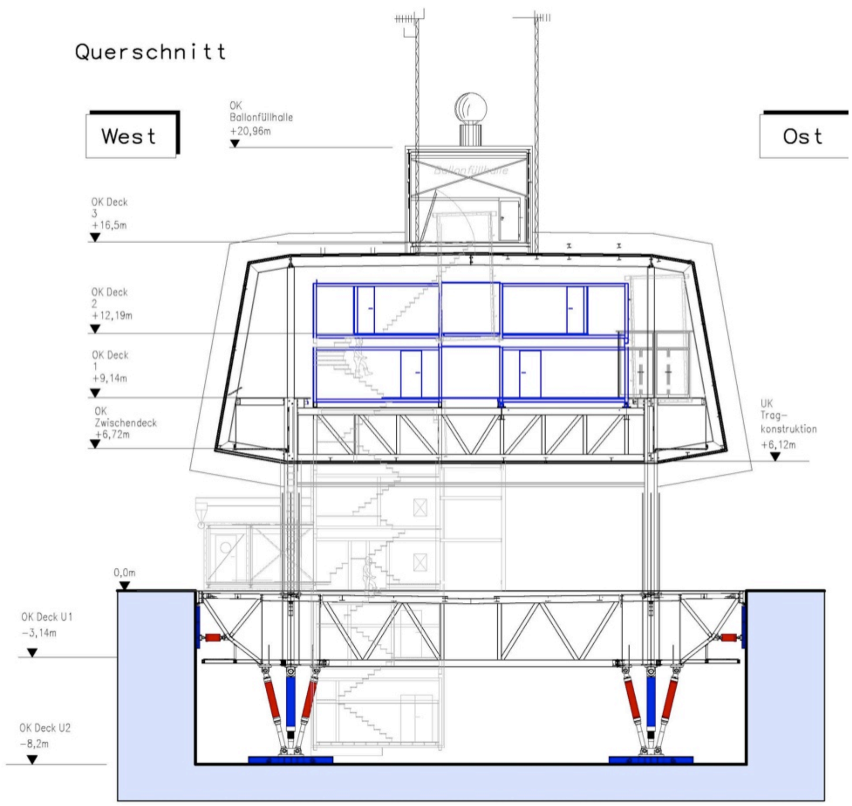
The environmental conditions Neumayer faces on the Ekström Ice Shelf (Figure 1) consist of a 280 m thick ice shelf moving at an annual rate of approximately 150 m. Snow accumulates annually at 80–100 cm and is the most significant design challenge. The combined service period for both of the previous Neumayer stations was 28 years (Gernandt et al. 2007). In an effort to extend the station service life, to reduce overall maintenance costs, and to minimize the impact on the Antarctic environment, Neumayer III employed an all-inclusive design that combines an elevated station (containing areas for living and berthing, science, and mechanical systems) with a subsurface facility that houses additional science, storage, and garage space (Gernandt et al. 2007). The design life of Neumayer III is 25 to 30 years where, in the span of this time frame, it is expected to move roughly 4.5 km with the flow of the ice shelf.

To maintain the station above the ever-rising snow surface, Neumayer III is lifted, spread footings and all, thereby eliminating both the need to extend the 16 columns that raise it above the snow surface and the logistical and financial costs associated with transporting additional steel.

The two-story elevated structure is 68 m long × 24 m wide × 15 m high and encloses 2100 m^2 of heated floor space. The structure is 6 m above the surface of the snow on bipod support columns. A 76 m long × 26 m wide × 8 m deep subsurface trench accessible via a ramp is used primarily as a garage to store vehicles and equipment below the building.

The total vertical load of the building (2600 tons) is transferred to the snow via 16 hydraulically operated bipods located between the roof and floor of the trench (Figure 10). Each bipod is equipped with two hydraulic cylinders that form a V-shape, a vertical support rod, and footing plate connected via a specialized hinge point. The vertical strut is adjustable and serves as a backup in the event of a hydraulic system failure (Rotthäuser and Jagolski 2010). The total area of all of the bipod pads is 208 m^2 that transfer the mass of the structure to the snow foundation. For the foundation pads, the permanent pressure exerted on the snow is approximately 125 kNm^{-2} (Gernandt et al. 2007).

Figure 10. Section view of Neumeyer III illustrating the main structural components of the station: main facility (above grade), steel roof (at grade), and garage (below grade). The vertical and horizontal hydraulic jacks are visible in red (Gernandt et al. 2010).



Neumayer III has a below-grade portion with an at-grade roof attached to all the columns. The walls and floor of the below-grade portion are snow. The roof is a steel truss, which has a vertical "apron" around its perimeter. Numerous hydraulic jacks allow that apron to engage the snow alongside, thereby distributing horizontal wind loads on the elevated building into that snow (Figure 11). When the building and steel truss roof are lifted by the dual hydraulic jacks at the base of each column, the aprons are moved back away from the snow. Once a lift is completed, they are returned. Every couple of weeks, the aprons are relaxed, the building is re-leveled and the aprons are re-engaged. Information from the hydraulic control and monitoring system is continuously monitored on-site and in Germany. It can be set to make adjustments either manually or automatically.

Figure 11. Numerous hydraulic jacks (blue and black color at upper left of photo) allow the apron to engage the snow alongside, thereby distributing horizontal wind loads on the elevated building into that snow. Note the vertical bipods are visible at the lower right of this image (Gernandt et al. 2010).

Based on the rate of snow accumulation, an annual lift is planned to maintain the station above the snow surface. This is achieved by lifting one bipod at a time, backfilling clean snow under its foundation pad and setting the bipod back down. The load on the bipod is slowly brought up to its full level while it compacts the newly added snow layer. The lifting sequence is shown in Figure 12 (Rotthäuser and Jagolski 2010). A single (1.5 m) lift of all 16 bipods was originally estimated to take 8 to 10 days to complete.

Once all footings have been lifted, backfilled, and reloaded, 2500 m^3 of snow is brought into the subsurface area to raise the entire floor to the new level.

During the first year of occupancy (2009–10) snow drifting was greater than expected, and it was necessary to lift the station three times (Rotthäuser and Jagolski 2010). Because the procedure for back-filling snow under each foundation pad was found to be slow and labor intensive (Figure 13), the lift process took much longer than noted above in the original estimate.

Figure 12. Sketch of the lifting sequence for Neumayer III Station (Rotthäuser and Jagolski 2010).

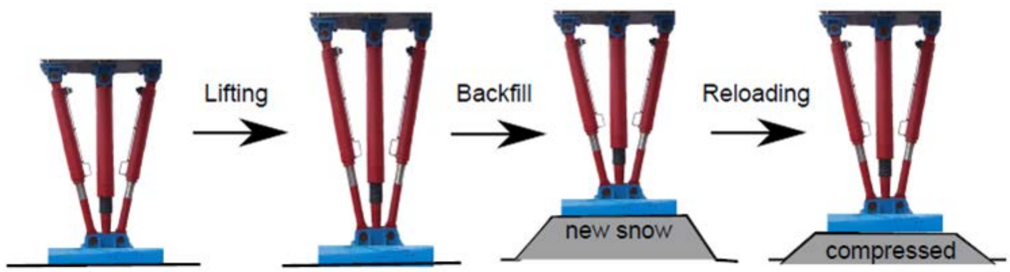


Figure 13. Back-filling snow under a raised footpad (Rotthäuser and Jagolski 2010).

3.2 Halley VI Station, Antarctica

Located on the Brunt Ice Shelf, Halley serves as the year-round station supporting the Antarctic scientific work of BAS. The Brunt Ice Shelf typically receives 1.2 m of snow accumulation annually. Temperatures may reach lows of −55°C. The primary wind direction is from the east, and wind speeds may reach 160 km/hr. The Brunt Ice Shelf is approximately

150 m thick and moves toward the Weddell Sea at an annual rate of 400 m. The station supports a population of 18 during the winter and up to 60 in the summer. Halley is an isolated location owing to challenging access and logistical issues.

The first buildings (Halley I) were erected in 1956. They were heavy timbered structures placed on the surface. By 1966 they had become buried under as much as 17 m of snow and were being crushed. In their vicinity, the natural snow accumulation had increased by about 50%. In 1967, the buildings were replaced by steel-framed timber buildings of Halley II (except for fuel tank storage, which was located within a horizontal corrugated metal tube) and built on the surface. Halley II drifted over rapidly, was damaged by accumulating snow, and was abandoned in 1973. Almost all the single-story buildings of Halley III (built in 1973) were contained within 6 m diameter corrugated metal tubes placed on the surface. They quickly drifted over, also, and heat losses from the heated buildings caused warmed snow to rapidly distort the tubes. The buildings were damaged, and the station was abandoned in 1983–84. Halley IV (built in 1983) consisted of insulated wood and plywood tubes 9 m in diameter, housing two-story, well-insulated buildings. These tubes began failing within 4 years under the weight of accumulating snow. Halley IV was abandoned in 1988–89.

A different approach was used for Halley V, which was first occupied during the austral winter of 1992. Halley V was an elevated station consisting of three jackable platforms 4.4 to 5 m above the snow surface. These platforms were supported by guyed, extendable columns, each having a steel and timber spread footing at its base, which was set 1.5 m below the surface (Blake 1997). The platforms were jacked many times. The foundation is now buried approximately 30 m below the snow surface. The process of lifting the structure became enormously burdensome, labor intensive, and difficult to maintain. Due to the rapid movement of the ice shelf, the columns supporting Halley V continued to twist out of alignment, causing stresses to buildup. In later years, some of the legs had to be cut and offset every year.

Halley V was located approximately 15 km from the coast. The ice shelf at that location is unstable, and glaciologists familiar with the site anticipate that a sizeable section of the ice shelf will break away within the next 3 or 4 years. Since it was not possible to relocate Halley V, a new station, Halley

VI, was recently constructed further inland (Table 1). It is a moveable, sustainable facility capable of being completely removed at the end of its service life with minimal impact to the Antarctic environment. Experience gained from operating the Halley V station was instrumental in the design for Halley VI.

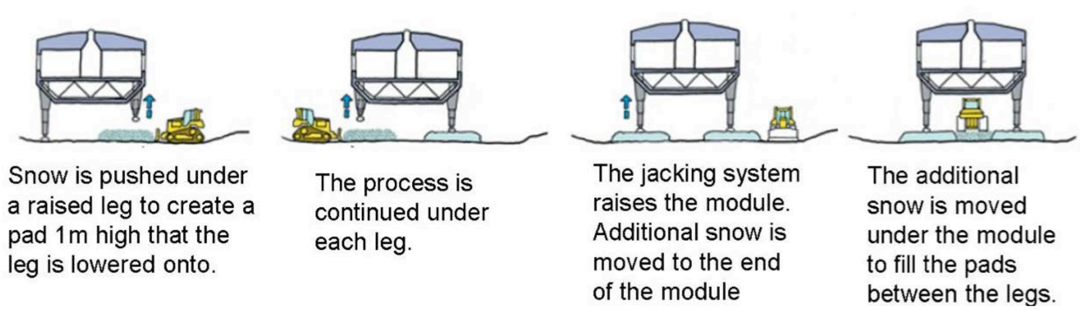
The design concept for Halley VI desired a method to “self-manage” snow drifting by using a facility oriented to minimize snow capture. Through the use of aerodynamic shaped columns and chamfered corners, the snow surface under the station was designed to decrease the impact of snow drifting. The distance between the bottom of the station and the snow surface was large enough to accommodate heavy equipment operating on the snow surface underneath the structure. Creating modular units that could be detached and moved provided great flexibility and increased service life (Figure 14). A ski affixed to the bottom of each support column allows an individual module to be towed into position using standard heavy equipment (Figure 15).

Figure 14. Construction of Halley VI’s central living module (Broughton 2010).

An electronically controlled hydraulic lift system was designed to reduce the challenging impacts of complex exterior mechanical systems, the harsh environment, and safety concerns of conventional manual lift systems. The Halley VI design incorporates proven technologies, such as hydraulic systems, from the aircraft and other industries. The design of the integrated lift-move concept seeks to overcome the intense labor demands of the current system employed at Halley V (Figure 16). However, this new method does require a significant temporary steel support system that is not illustrated in Figure 16 that must be placed under each module when its legs are raised one at a time.

Figure 15. Towing a standard module for Halley VI (Broughton 2010).

Figure 16. Lifting and snow management concept for Halley VI (Maunsell et al., n.d.).



Halley VI uses a smaller footprint and geometry compared to either the Neumayer III or Concordia stations. The pressure applied to the snow is 60 kNm^{-2} (Broughton 2010). Because the module must be able to move, this pressure is low. A module may be lifted while it is in operation; however, the limiting factor is the under-floor service connection that is restricted to differential movement of 100–200 mm.

3.3 Concordia Station (Dome C), Antarctica

In 1993, the French and Italian research programs entered into a partnership to build and operate a permanent research station on the East Antarctic Plateau (IPEV-PNRA 2005). The station, commissioned in 2005, consists of three primary buildings: two elevated buildings and a power and mechanical module. The layout of the elevated buildings was based on the types of activities they would accommodate. One module houses the "noisy" activities (such as galley, lounge, and working areas) while "quiet" activities (such as berthing and medical) take place in the other module. The building housing the power plant and mechanical systems is non-elevated and is equipped with skis for mobility (Figure 17). An elevated walkway links the modules. The elevated station supports a population of 16 during the winter (9 scientists and 7 support staff). There is also a separate summer camp that serves as an emergency backup station.

Figure 17. Completed Concordia Station, April 2005. The three buildings from left to right are the power plant and mechanical systems, the "Noisy" building, and the "Quiet" building (courtesy of P. Godon).

Concordia Station is very isolated, located 950 km inland from the Banzare coast (IPEV-PNRA 2005). The nearest neighboring station is the Russian station, Vostok, 560 km away. Light aircraft are the primary means of transporting cargo and passengers to the station, and overland traverses haul heavy cargo. The aircraft transport and traverse operations originate from Dumont d'Uville on the Antarctic coast. Average monthly temperatures at Dome C range from −30°C during the summer to −60°C during the winter. The minimum recorded temperature of −83.9 °C at Concordia occurred on 4 July 2010 (IPEV, n.d.). The annual snow accumulation ranges from 2 to 10 cm with average wind speeds of 2.8 m/sec.

All of the structures at Concordia, including the summer camp, sit on a 6 m thick, compacted snow foundation. The foundation was constructed by excavating down 3 m below the snow surface, back-filling, and compacting in 0.5 m lifts until the pad was 3 m above the snow surface. Following compaction, the snow sintered for approximately 24 hours to gain strength before the next lift was added.

Each of the elevated buildings is supported on six columns. At the base of each column is a large "footing" pad (hereafter referred to as "footing"). The footing is approximately 6 m in diameter and 0.5 m thick and spreads the load of the structure over the snow surface with a pressure of 20 kN/m^2. Unlike a conventional foundation that gradually becomes deeper as snow accumulates on the surface, each footing was designed to be lifted with the column it supports. Thus, the entire steel superstructure remains elevated; and the column footings were designed to remain on the snow surface without the need to add column extensions (IPEV-PNRA 2005).

The structure is composed primarily of steel. There are a total of three levels (Figure 18) with the bottom of the station 4 m above the snow surface. The columns are joined to the main structure at the second level. To level the station, each column has two hydraulic jacks within the building (Figure 19) that are designed to raise and lower the column. In the future, when a column and its footing are raised, the design calls for snow to be pushed under the footing; and then the column will be set back down. The jacks are designed to raise the station a maximum of 35 cm at a time. Once the height of the station is set, a screw and nut configuration will remove the load from the hydraulic jacks. An optical level system will be used when raising the building. It compares the height difference from the central axis to leveling poles located outside the frame (IPEV-PNRA 2005).

Figure 18. Construction of the steel framed elevated structures on site (courtesy of P. Godon 2010).

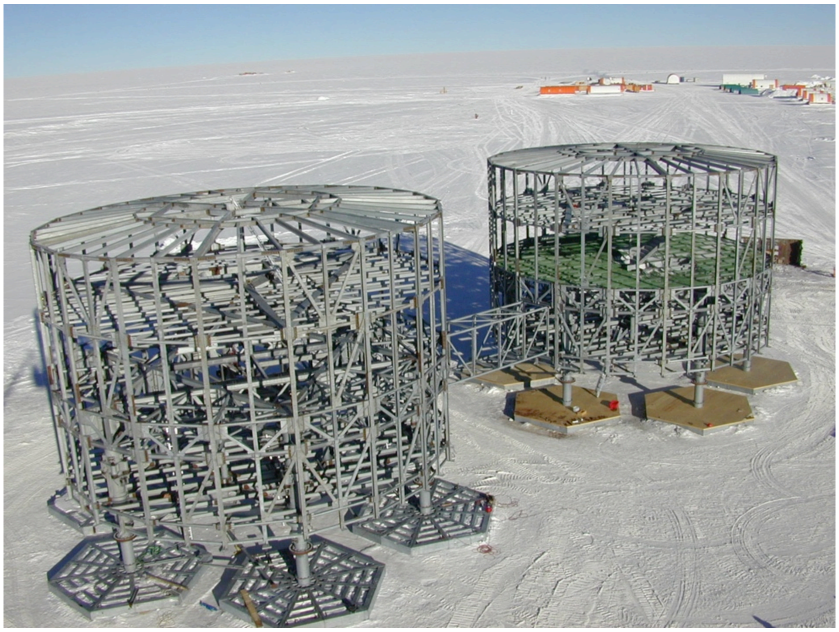


Figure 19. Constructing the lifting columns on site (courtesy of P. Godon 2010).

Concordia will be lifted from inside the structure with the jacks fixed directly to the structure's frame. The large hexagonal footings were designed to minimize the amount of heat transferred to the snow. Retractable footings reduce the buildup of horizontal stresses in the structure. Once new snow is back-filled and compacted under the footing, loading will occur slowly. Additional experience will be gained in the future as this station has yet to be lifted.

3.4 Amundsen-Scott South Pole, Antarctica

Located at the geographic South Pole, the primary research facility for USAP is the Amundsen-Scott Station. The previous two stations at South Pole were constructed on the snow surface. In 1956, the first South Pole station was constructed on the snow surface and continued to operate as it became buried by accumulating snow. The second South Pole station was maintained on the surface, requiring significant maintenance for the snow accumulation. The newest station was fully commissioned in March 2010 and is elevated above the snow surface. Access to the station is primarily via LC-130 flights as it has a maintained skiway. An overland traverse supplies fuel for station operation. During construction, all of the materials needed to construct the new station were brought in via ski-equipped LC-130, accounting for over 2 million pounds of cargo.

The South Pole station is located on the slow moving polar plateau at an elevation of 2850 m. The thickness of the ice is approximately 3200 m. The ice sheet moves at an annual rate of 10 m. At this rate of movement, horizontal distortion is not a significant concern (Berry and Braun 1999), unlike at Halley and Neumayer stations. Temperatures during the winter may be as low as −80°C and during the summer −20°C. While the rate of snow accumulation at South Pole is approximately 20 cm per year, significant drifting, up to 2 m, occurs from blowing snow. Wind speeds up to 120 km/hr were accounted for in the design of the station.

Built on a permanent deep snowpack, the South Pole station consists of two C-shaped pods with a 12 m connecting link between (Figure 20). The station is supported above the snow surface by thirty-six cylindrical columns located on the outside of the structure. During its 25-year design life, the station is to accommodate two lifts of 3.7 m each (Berry and Braun 1999). As shown in Figure 20, the columns support building truss extensions outside the heated, occupied space. Jacking is done out in the weather. The columns sit on grade beams supported on timber footings that spread the vertical load to the compacted snow pad. The dimensions of the snow pad are 45.7 × 137 m, and it was constructed 1.8 m above the snow surface to a minimum density of 0.5 g/cc (Blaisdell and Weale 2005). The snow below the pad was not compacted.

Figure 20. The Amundsen-Scott South Pole Station supports the U.S. Antarctic Program.

The South Pole station has not yet been lifted. Shimming the grade beams when the differential settlement exceeded the maximum allowable 50 mm leveled the structure during construction. This method of shimming retained all of the leveling capacity in the screw jacks to respond to future differential settlement. Hydraulic jacks used for leveling were specified to operate under low temperature conditions between −20°C and −50°C (Berry and Braun 2000). Differential settlement measurements are collected on both the elevated station and the connecting vertical tower twice during each Austral summer. When needed, the same type of jacks may be used to lift the station. The lifting procedure designed for the station may either lift the station in its entirety or lift each pod separately in increments of 254 mm (Berry and Braun 2000).

3.5 Syowa Station, Antarctica

Syowa, the primary Japanese Antarctic station, was originally established in 1957 and is located on rock and soil near the coast at the Lützow-Holm bay on Ongul Island (StratoCat 2014). In 2005 and 2006, Japan's National Institute of Polar Research (NIPR) constructed a small jackable building on the permanent snowfield where the skiway that serves Syowa Station is located. The jackable building consists of pre-fabricated panels that were assembled in approximately half a day (Figure 21). Steel and timber footings and steel columns support the guyed structure above its graded snow pad foundation. The lifting mechanism consists of a hand winch (Figure 22). The building is lifted prior to winter to minimize snow drifting and lowered during the summer for the convenience of its users. The columns can be extended upward when snow accumulation necessitates.

Figure 21. Jackable shelter near Syowa Station, Antarctica (courtesy of K. Ishizawa, Japan NIPR).

Figure 22. Lever hand winch is the lifting mechanism to raise the structure (courtesy of K. Ishizawa, Japan NIPR).

3.6 A jackable station concept using ice columns

The concept of a relatively rapidly deployable, mobile, jackable station was presented during the workshop. The concept consists of deployable units supported structurally on columns of ice cast by a slip form that also lifts the structure. The modular design consists of containers (similar to a Milvan or ISO shipping container approximately 6 m in length) transportable either by LC-130 or towed overland with heavy equipment via traverse. All of the station components fit within the shipping containers, which are sized to move into position with a forklift-equipped front-end loader.

The station's main structural framework consists of cargo containers bolted together. A platform above the framework supports the main structure. The building envelope is constructed with light, panelized components: a foam core with high insulation characteristics (typically urethane) sandwiched between metal structural panels. These are similar to common structural insulated panels (SIP) found in the construction industry.

The feet of the support columns rest on ice cast with "slip-form" footers. The support columns are outfitted with cylindrically-shaped footers on the bottom that are lifted when it is time to extend the support column. The footer is raised, and an ice and snow slurry is pumped into the unfilled space and allowed to freeze, lengthening the column. Load is slowly returned to the leg and the extension procedure continues for the other support legs (Figure 23). Once the columns have been extended, the station is then elevated to a new height. As with Neumayer III and Concordia, this concept addresses the desire to remove the need for steel extensions and for not leaving any foundation components buried within the snowpack.

U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) tested this concept and revealed several technical challenges that must be addressed to assess whether or not the use of ice columns is feasible (Burzynski et al. 2013).

Figure 23. Model of modular mobile design showing lifting concept using ice columns formed using “slip-form” footers (courtesy of P. Sadler).

4 Drivers for Considering Elevated Structures at Summit in Greenland

History has demonstrated and the summary discussion in this document illustrates the evolution of polar construction from at-grade buildings to buried structures to elevated facilities. This evolution is due to a collection of unique polar-drivers coupled with the development of materials and construction technologies that perform better in these extreme environs. Four main drivers have led to the significant number of recently constructed elevated and mobile facilities: science, sustainability, temporary impact, and construction materials and processes. These primary drivers are not limited just to Greenland, however; they are currently relevant to Summit as a new Station concept is formulated.

4.1 Science

Scientific interest, particularly in relation to the dynamics of environmental change, has supplanted defense needs as the primary reason for our presence in polar environments. Though long-term measurements are important and are being collected, the current model for scientific study is focused on the ability to be flexible, adaptable, and mobile. These needs drive similar requirements for supporting facilities, logistics, and transport systems. Permanent underground and at-grade facilities do not meet these requirements as well as elevated facilities do. Elevated and mobile structures can be designed for efficient transport; relatively rapid deployment; and, in some cases, over snow mobility by use of tractors.

4.2 Sustainability

Conservation of environmental and economic resources is driving the need for sustainable facility designs. New structures are required to operate as efficiently as technically possible to protect the environment; to maintain the integrity of scientific measurements (e.g., clean air and clean snow); and to reduce capital, logistical, operations, and maintenance costs. Highly efficient systems using clean energy sources help meet these needs. It is expected that elevated structures will last longer, require less energy and maintenance, have lower emissions (e.g., through fewer snow-management needs), and use wind and solar energy sources (available at the surface) to produce environmentally and economically sustainable operations throughout their design lives. Highly efficient (well insulated, properly constructed, etc.) facilities will consume a minimum of petroleum-based resources to deliver raw energy to stations and thus reduce emissions.

Significant attention is being paid by designers to the make indoor environments more habitable and aesthetically pleasing. Living in remote locations can be isolating, and the need exists to include space for recreation activities. This is especially true during the winter when the sun does not appear for several months. Some approaches include the use of windows to permit more natural light, which reduces electricity demand during summer months; single rooms for privacy and quiet; sufficient space for recreation (exercise is a fundamental component to living and working in remote locations) and group activities; color to break the visual monotony; improved connectivity for keeping in touch; and near real-time data transfer with the “outside world.” Building a sense of community is imperative to the people living and working at these stations.

Diesel-powered generators currently produce all electrical power at polar research stations. Waste heat given off by the generators is used to melt snow for potable water and, in some cases, in hydronic heating systems. Hydronic heating systems, snow melting, and the use of water as a “thermal storage battery” are great uses for dump (excess) loads created by renewable power systems when their production outpaces station needs.

Reducing the use of fossil-based fuel is an ambitious goal. Polar stations have successfully used renewable energy sources for scientific data collection. Photovoltaic and wind systems show promise. Smaller 6 kW wind turbines have successfully been used to produce power. However, to date, renewable technology is only able to meet a small percentage of energy demand. Technical challenges, such as foundation design to support larger wind turbines, remain. Solutions to these issues require further investigation.

4.3 Temporary impact

Though a facility may have a design life of 25 or even 50 years, these time periods are very small when compared to the time spans required to naturally create and change polar environments. Human impacts must be considered temporary, and thus we must create as small an environmental footprint as possible. Currently, all entities constructing and operating structures in polar environments are exploring recycling or retrograde of entire waste streams—including the facilities themselves once they are no longer required or reach the end of their design life. Elevated structures meet this requirement. The entire facility, except perhaps footings and buried portions of columns can be removed and reused or recycled.

Ultimately, when use of the structure is complete, materials from the building may be repurposed. We note that removing the built materials from a remote site is very expensive whether or not the footings and steel column extensions are excavated from deep below the surface. Coupling the main facility to a structural foundation placed high on top of an elevated compacted snow pad has significant benefits because it can be designed to last a long time before the facility must be moved, lifted, or abandoned. Environmentally, it reduces the material left behind and either reduces or eliminates any additional steel needed to extend support columns founded below grade. This approach seeks to maximize the utility of the in situ foundation material (snow).

4.4 Construction materials and processes

Building-envelope materials are constantly being improved. SIP systems with oriented strand board (OSB) and high insulation values have been used successfully to create energy efficient, comfortable living environments. They do require exterior cladding, which is often metal. Glass reinforced panel (GRP) systems, such as those used at Halley VI and Concordia, are another structural skin option. They are performing well across varying environmental conditions in Antarctica, and they do not require exterior cladding. Some initial challenges, such as cracks at joints, appear to have been resolved.

Overcoming challenging construction logistics due to the short construction season is critical to successful long-term performance of facilities fabricated in polar regions. It is important to design for simple assembly of the parts and to maintain safety while working in bulky, extreme-cold-weather clothing in harsh weather conditions. Experience has demonstrated that prefabricated units are preferable over systems constructed from smaller pieces in the field. It is now standard practice to first test-fabricate facilities under more ideal environmental conditions prior to shipping components to the field. This practice confirms (or not) the ease of constructability and allows for modifications to be made prior to deployment to remote and extreme sites. All necessary (and extra and spare) parts must be available on site as missing or broken parts may not be readily replaced in these remote locations. Further, transport modes (airlift, cargoship, and overland traverses) limit the quantities, sizes, and weight of components that can be shipped. All of these factors play important roles in determining how polar structures are designed, constructed, and maintained.

5 Conclusions

The ability to provide safe, comfortable, modern facilities located in isolated locations surrounded by an extreme environment have greatly improved in the past few decades. This workshop provided an opportunity to collaborate and to establish a dialogue with international experts familiar with the design challenges for facilities that must withstand the punishment of the harsh polar environment. These “newest generation” permanent structures constructed on permanent snowfields have incorporated several promising features that should be considered as the design proceeds for new facilities at Summit Station, Greenland:

- Environmental conditions continue to be an important design factor. Long-term monitoring programs and historical climate records collected at the site provide the best understanding of the site conditions from which to design future facilities.

- More information on the engineering properties of the snow at Summit would allow a tighter (i.e., less expensive) design to be developed.

- The most notable technical development identified during this workshop was the refinement of hydraulic lift systems. Improvements in hydraulic systems have added great capability to modern building lift systems. An extreme environment requires reliability of hydraulic system performance to enable the structure to operate as intended. The backup screw-jack system remains a dependable system, albeit more labor intensive. Another limiting factor is the number of support columns that must be raised. Each additional column adds to the complexity of the entire system.

    - The Neumayer III station has been lifted three times, instead of once, since being commissioned. This ability to lift and adjust in many places in response to changing snow conditions has merit in light of “the bewildering and very complex behavior of the snow” as stated by the late Dr. Malcolm Mellor of CRREL.

  - At Summit Station, we do not anticipate rapidly changing snow conditions, and the rate of movement of the ice sheet is not nearly as fast as that of Neumayer III or Halley VI.

  - The number of support legs for DYE-2 and DYE-3 (8 each), Concordia (6 for each of 2 modules), Neumayer III (16), and Halley VI (6 for the big central module, 4 for all others) is instructive for Summit Station. To date, of these, only DYE-2, DYE-3 and Neumeyer III have been lifted.

- The ability to adjust the station to relieve the buildup of secondary stresses in its structural frame is quite beneficial. Over time, this reduces the adverse effects of differential settlement and foundation tilt.

- Back-filling and compacting the snow under the support legs remains a rather labor-intensive procedure. Methods of improving this deserve attention.

- Monitoring of the foundation and the supporting columns was important at DYE-2 and DYE-3 and is essential at Neumayer III.

- Snow with uniform and consistent mechanical properties is critical for use as back-fill beneath footings to reduce differential settlement among supports.

- Remote monitoring of structures supported on snow, as demonstrated by Neumayer III, may have value and applicability for Summit Station.

- The potential savings from not needing to transport additional steel to the site for column extensions and such is a very appealing feature of Neumayer III, Halley VI, and Concordia stations.

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Appendix A: Workshop Agenda

15–16 September 2010

Elevated Building Lift System in Polar Environments Workshop

National Science Foundation, Office of Polar Programs

Agenda: Day 1

Location/Room: Holiday Inn Rosslyn, Georgetown Room

0845–0915	Welcome and Introductions (P. Haggerty)
0915–0930	Review Workshop Goals (P. Haggerty, J. Mercer, J. Burnside, and G. Blaisdell)
0930–1000	Overview of Summit Station, Existing and Future (S. Starkweather)
1000–1015	Break
1015–1111	System and Lift Procedure at Dome Concordia—30 min. presentation/30 min. discussion (P. Godon)
1115–1215	System and Lift Procedure at Neumayer III—30 min. presentation/30 min. discussion (H. Gernandt)
1215–1315	Lunch

1315–1415	System and Lift Procedure at Halley VI—30 min. presentation/30 min. discussion (M. Wright or representative)
1415–1530	Systems and Lift Procedures at A-S South Pole Station and Summit Station—45 min. presentation/30 min. discussion (D. Berry)
1530–1545	Break
1545–1630	Ice Foundation and Lift System Concept (P. Sadler)
1630–1730	Day 1 Discussion and Wrap-up (P. Haggerty and J. Mercer)

Agenda: Day 2

Location/Room: Holiday Inn Rosslyn, Georgetown Room

0845–0900	Day 2 Opening Remarks (P. Haggerty, J. Mercer, J. Burnside, and G. Blaisdell)
0900–0930	Summit Model 5 Concept Design (A. Marugame)
0930–1100	Discussion: Successes, Challenges, and Feedback—input and items to consider for Summit Model 5 from what was learned in constructing and operating the other stations (All Participants—facilitated by CRREL)
1100–1115	Closing Remarks for Lift System Workshop (P. Haggerty and G. Blaisdell)
1115–1215	Lunch

Afternoon schedule to include more general presentations:

1215–1315	Overview of Halley VI (H. Broughton)
1315–1415	Overview of Japan’s polar operations (K. Ishizawa)
1415–1500	Determine next steps for Model 5 Lift System (NSF/PFS-CPS/CRREL Only)

- NSF input and feedback on what they saw from the international stations and what they would like considered and/or incorporated into the Model 5 lift concept
- CPS input/remarks
- CRREL input/remarks
- Design Charrette
- Actions and conclusions

Appendix B: Polar Elevated Building Lift Systems Workshop Attendance List

Invitee	Represents	Position
Patrick Haggerty	NSF	OPP Arctic RSL Program Manager
George Blaisdell	NSF	OPP-AIL Operations Manager
Renee Crain	NSF	OPP Arctic RSL Program Manager
Randy Olsen	NSF	OPP Arctic RSL Project Manager
Dane Terry	NSF	
Monte Ingram	NSF	
Sandy Singer	NSF	
Brian Stone	NSF	OPP-AIL Deputy Division Director
Simon Stephenson, Dr.	NSF	OPP-Arctic Sciences Division Director
Will Colston	NSF	OPP-AIL Division Director
Jennifer Mercer, Dr.	CRREL	Program Manager for CRREL EPOLAR
Jim Buska	CRREL	Branch Chief and CE-CRREL Force Projection and Sustainment Branch
Jason Weale	CRREL	Program Manager and CE-CRREL EPOLAR
Maggie Knuth	CRREL	Civil Engineer
Renee Melendy	CRREL	Program Specialist for CRREL EPOLAR
Lynette Barna	CRREL	Civil Engineer
Bob Haehnel	CRREL	Mechanical Engineer
Sandy Starkweather	PFS/CPS	Greenland Science Support Manager
Jay Burnside	PFS/CPS	Construction Manager
Russ Howes	CPS	
Geoff Phillips	CPS	
Tracy Dahl	CPS	
Larry Levin	CPS	
Mike Mckibben	CPS	
Jill Ferris	PFS/CPS	
Dennis Berry	NPX/Summit/BBFM	
Wayne Tobiasson	NPX	CRREL Research Civil Engineer (retired)
John Rand	NPX	CRREL Expert
Stephen Fujino	NPX/NAVFAC PAC	
Jim Masek	Summit	
Alan Marugame	Summit/Kumin	
Hartwig Gernandt, Dr.	Neumayer III	Operations
Hans-Juergen Meyer, Dr.	Neumayer III	Engineering

Invitee	Represents	Position
Siegfried Rotthauser, Dr.	Neumayer III	Control Systems Operations (hardware and software)
Dietrich Enss	Neumayer III	Engineering design, manufacturing, and construction consultant
Michael Wright	Halley VI/AECom	Lead Engineer
Hugh Broughton	Halley VI/HB Architects	Lead Architect
David Blake	Halley VI/BAS	
Patrice Godon	Concordia	IPEV Head of Polar Logistics
Dick Armstrong	RSA	
Kenji Ishizawa	Japan National Institute of Polar Research	Logistics Manager
Martin Lewis	South Pole/RPSC	
Jack Corbin	South Pole/RPSC	
Phil Sadler	Sadler Machine	President

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14. ABSTRACT
The National Science Foundation sponsored this two-day workshop to bring together international experts to discuss the history and state-of-the art of systems used to periodically lift elevated buildings constructed on permanent snowfields. Early structures permanent snowfields were typically built at the surface and became buried over time from accumulating snow. These buildings were prone to short service lives as the accumulating snow increased pressure on the structures, eventually rendering them unsafe. An accepted current practice for constructing most structures on permanent snowfields is to elevate them above the natural terrain. This technique reduces the adverse effects of annual snow accumulation, snow drifting, and snow settlement and prevents thawing of the snow foundation from the heated superstructure. To achieve cost-effective service lives, there is extra incentive to periodically lift the elevated structures and to maintain them above the ever-rising snow surface. This report summarizes lift systems used to maintain the current generation of elevated, permanently occupied polar stations above permanent snowfields.

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