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Advances in Polar Science
doi: 10.13679/j.advps.2017.3.00214
September 2017 Vol. 28 No. 3: 214–227

Design and development of infrastructure of the Dome A Kunlun Station (2005–2015)

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Received 13 Feburary 2017; accepted 17 June 2017

Abstract To enable further advanced study of Antarctica, a new station called Kunlun Station has been built by China in the Dome A region of the inland East Antarctic ice sheet. This paper describes the Antarctic station building design system that was developed with consideration of factors that may affect Kunlun Station, such as environment and climate, construction work and transport, environmental protection and energy conservation, psychological requirements and functional requirements. The design system included site selection, station planning, external building form, construction work, function and indoor environment, energy conservation, environmental protection, and material strategy. We also describe the experience acquired during the transportation and construction phases of Kunlun Station.

Keywords **Antarctica, inland Kunlun Station, Dome A, architectural design strategy**

Citation: Zhang Y, Wang Z J. Design and development of infrastructure of the Dome A Kunlun Station (2005–2015). Adv Polar Sci, 2017, 28(3): 214–227, doi: 10.13679/j.advps.2017.3.00214

1 Introduction

A recent objective of the Chinese Antarctic program has been to establish a new research station supported from the coastal Zhongshan Station for summer operation in the Dome A region of inland Antarctica. Most research stations in the Antarctic have been built on the edge of the continent. Further inland on the ice sheet, the ice thickness generally increases and the temperature gradually drops. It thus becomes increasingly difficult to guarantee transport security and to undertake construction of research stations in such areas. Prior to 2009, there were only five stations, constructed by six countries, at an elevation of over 2000 m in inland Antarctica: Amundsen-Scott Sation (South Pole) built by the United States, Vostok Sation built by Russia, Kohnen Sation built by Germany, Dome F Station built by Japan, and Concordia Sation (Dome C) built as a collaborative project by France and Italy.

China has successfully organized 33 Antarctic expeditions, 15 of which were conducted in inland Antarctica. Thus, China has accumulated considerable experience regarding the organization, management, and logistics of such scientific investigations. The completion of China's capacity building of the Tenth Five-Year Plan (2001–2005) has improved the level of polar exploration infrastructure considerably, which will be of great benefit in further investigations of inland Antarctica. China first successfully conducted ground-based research at Dome A in 2005, and based on those findings, China led an approved scientific research program of the region during the International Polar Year 2007–2008. This marked the first time China had organized a large international partnership in Antarctica, and demonstrated that it had the capability to lead investigation of a region of such scientific importance.

The construction of an Antarctic research station is China's most recent project in the region. The chosen location at Dome A (Dome Argus) is an area of high

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strategic and scientific value because of its unique geographic environment. Dome A is the highest region of the Antarctic ice sheet with a surface elevation of over 4000 m. The new station needed to be capable of supporting perennial long-term scientific investigation and the station system would include:

- Station infrastructure comprising a main building and a relay station covering up to 600 m^2;
- A logistic system including over-snow and airborne transport;
- Scientific observation and investigation systems including deep ice-core drilling at Dome A, drilling into the sub-glacial Gamburtsev Mountains, astronomical observations, remote sensing and ground observations and airborne remote sensing systems, atmospheric environment and meteorological observations, earth–space environment observations, earthquake observations, geophysical observations, and medical and health care monitoring;
- Analysis, testing, research, and emergency command platforms.

Before commencing construction, a Draft Comprehensive Environmental Evaluation (CEE) for the station was prepared and submitted by the Chinese Arctic and Antarctic Administration as a Working Paper to the Committee on Environmental Protection at the XXXI Antarctic Treaty Consultative Meeting (ATCM XXXI–CEP XI) (Chinese Arctic and Antarctic Administration, 2008). Its recognition and formal adoption by the CEP provided important guidelines for establishment of the station, and they are summarized in this paper.

2 Regional topography and site selection

The summit area of Dome A is a plateau, aligned northeast to southwest and approximately 10–15-km wide (east to west) and about 60-km long. During the austral summer of 2007–2008, 17 members of China's 24th Antarctic Scientific Expedition drove 5 snow tractors towing 13 large sleds 1280 km from Zhongshan Station to Dome A. Once there, they undertook comprehensive surveying and mapping within a 30×30 km^2 region centered on 80°25′00″S, 77°06′58″E. This showed that the overall surface is very flat and the extent of the vertical relief is very small (Figure 1). The highest point, of 4092.75 m, is located at 80°22′00″S, 77°21′11″E, at the northern end of the plateau (Tang et al., 2012). The snow surface within the area is soft with a surface snow density of 250 kg·m^{-3} (Bian et al., 2016), and with only a few snow dunes of less than 30 cm height. The snow surface at the edge of this area is harder.

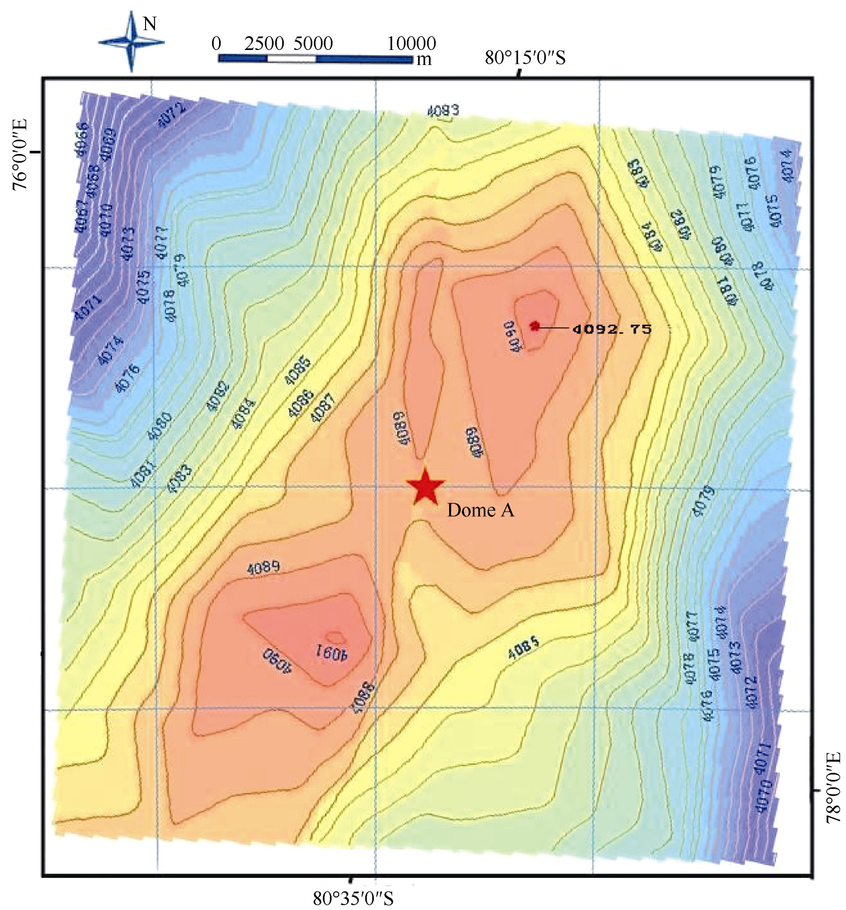

Figure 1 Surface elevation of Dome A summit region (Chinese Arctic and Antarctic Administration, SOA).

The CHINARE-24 team also made a comprehensive mapping of the Dome A ice thickness and sub-glacial terrain using an advanced multi-polarization modulation pulse radar system. This showed that the average ice thickness in the Dome A area is 1680 m but with significant variation (Cui et al., 2010). At the central position, the ice thickness is up to 3132 m, which is much thicker than previously speculated (Tang et al., 2012). The deep ice distribution is continuous, showing no evidence of melting at the base of the ice sheet nor the existence of a sub-glacial lake. These, together with measurements showing ice movement in the Dome A region is small and vertical deformation is the principal dynamic process, suggest that the Dome A area is ideal for undertaking deep ice core drilling. It is possible that a deep ice core could be acquired covering a period of more than one million years.

Following these analyses, it was recommended that the main building of China's inland Antarctic station be located at 80°25′01″S, 77°06′58″E. This is at an elevation of 4087 m, 7.3 km southwest of the Dome A summit. The site selected can satisfy the requirements of climate background monitoring, observation of the solar–terrestrial system, and other astronomical and geophysical observations, as well as meeting the requirements of major projects of deep ice-core drilling and geological drilling beneath the ice.

3 Meteorological conditions

The temperature measured at 10 m depth in the firn at the highest point of Dome A in 2005, which approximates the annual average surface air temperature, was −58.3°C (Chen et al., 2010a). Observations from an Automatic Weather Station (AWS) deployed at the site in January 2005 confirm that it has one of the lowest temperatures on the surface of the earth. The 2005 average air temperature (2 m above the surface) was −58.4 and the lowest was −82.3°C (on 23 July 2005).

Figure 2 shows that in 2005 the maximum daily average temperature recorded by the Dome A AWS was −27.3°C (8 Dec) and the minimum daily average temperature was −71.7°C (1 Sep). The average temperature over the summer half of the year (Oct–Mar) was −43.2°C. Over the peak of summer (Dec–Feb) the daily average temperature varied from −27°C to −50.5°C, with an average of −36.7°C (Figure 3).

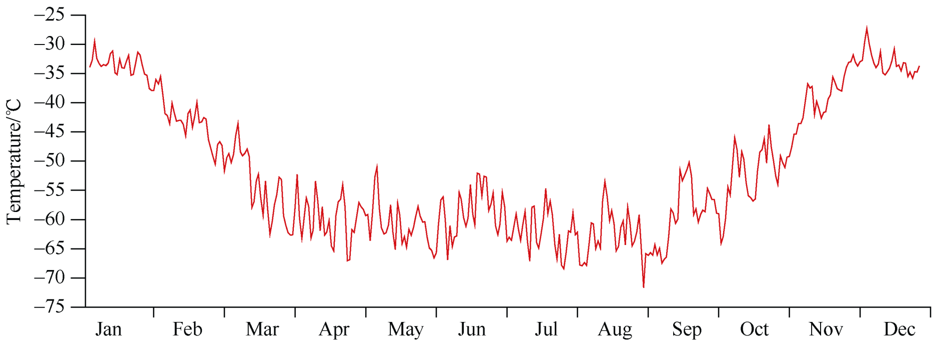

Figure 2 Daily mean air temperature (Jan 2005–Dec 2005)(Chen et al., 2010a).

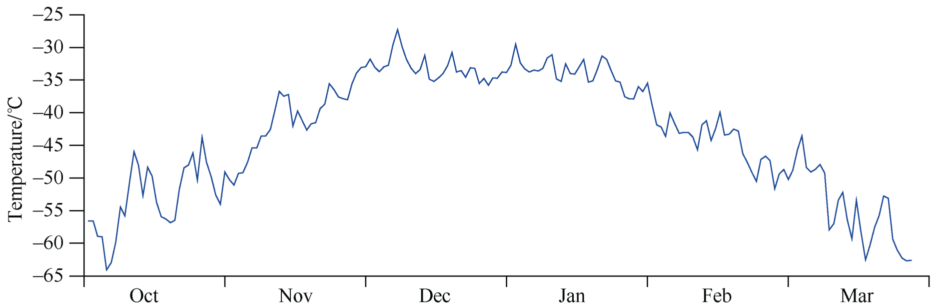

Figure 3 Daily mean air temperature (Oct 2005–Mar 2006)(Chen et al., 2010a).

The average annual firn temperatures recorded at depths of 0.1, 1, 3, and 10 m at Dome A in 2005 were −56.5°C, −57.2°C, −57.8°C, and −58.2°C, respectively (Figure 4; Chen et al., 2010b).

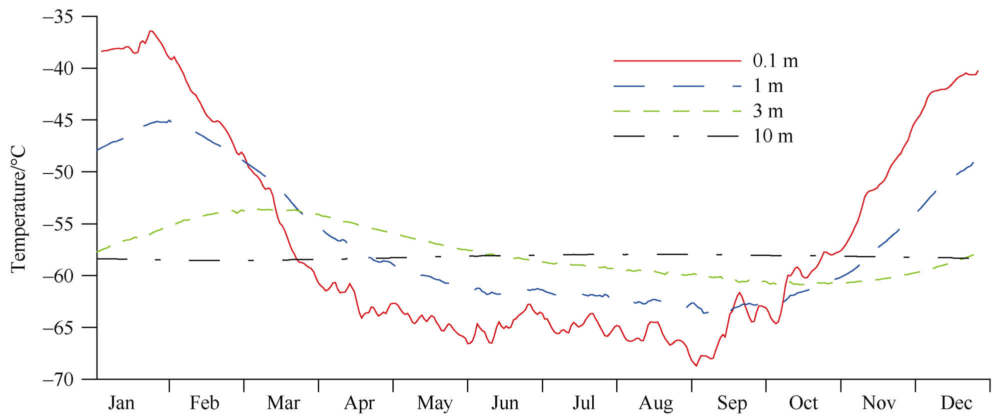

Figure 4 Daily mean firn temperature (Jan 2005–Dec 2005).

The wind speed in the Dome A region is generally low, with an annual average of 1.8 $m \cdot s^{-1}$ (Yang et al., 2007). The wind is calm most of the time. The maximum wind speed at 2-m height in 2005 of 13.9 $m \cdot s^{-1}$ was recorded on 17 September (Yang et al., 2007). There is no obvious prevailing wind direction in the Dome A region.

The 2005 annual average atmospheric pressure at Dome A was 574.2 hPa, and the average pressure in summer (Dec–Feb) was 581.7 hPa (Ma et al., 2010). The Dome A AWS has now operated for over a decade and the longer-term climate record at the site has been reported by Bian et al. (2016). The average snow accumulation rate from the AWS over this period was 150 $mm \cdot a^{-1}$ [equivalent to only 37 $kg \cdot m^{-2} \cdot a^{-1}$] (Bian et al., 2016). For the individual years 2005, 2006 and 2007 the snow accumulation was 110, 50 and 190 mm, respectively (Ma et al., 2010).

4 Logistic and construction facilities and difficulties

4.1 Available facilities

The capacity of Zhongshan Station in the Larsemann Hills, East Antarctica was expanded as part of the logistics system and functioned as the base for the Dome A construction project. The R/V *Xuelong* was used to transport necessary supplies and personnel from China to Zhongshan Station. The season available for inland station construction was limited to between late December and January, i.e., about 30–40 d. Ground transportation used snow tractors pulling sleds for moving all materials required for building the inland station. The largest unit that could be transported by sled was a 6-m container, and the total weight of construction materials was within the capacity of the traverse facilities. The total weight of the supplies was 570 t using 44 sleds, pulled by Caterpillar Challenger and Kässbohrer PB-240 and PB-300 tractors.

Relay stations were located at distances of 500 and 800 km from Zhongshan Station. These were constructed from two fiberglass-reinforced plastic containers that can satisfy the demands of living, storage, and other activities. The relay station at 800 km has a sled-connected oil tank system, whereas the relay station located at 500 km stores oil in drums.

Construction facilities included power supplied from 50–80 kW air-cooled generators in containers, heating from a combination of emergency electrical power generation and solar heating, and two tractors with an 8-m-long and 7-m-high jib. Water was obtained by melting snow, and portable toilets were used with all waste collected and removed from the site Zhongshan Station is equipped with satellite, shortwave, and longwave telecommunication equipment and the construction team could contact Zhongshan Station using the communication equipment supplied for the traverse.

4.2 Main difficulties of inland station construction

Constructing the new station involved transportation difficulties due to large distances, severe in-situ environmental conditions and a requirement for strict environmental protection measures.

The distance between Shanghai and the inland research station is about 15000 km, which presented many logistical challenges for both shipping and the inland traverse. The fully laden snow tractors were unable to ascend the steep coastal slopes at Zhongshan Station, so helicopters were used to lift the tractors, limiting their weight to no more than 4 t. The linear distance between Zhongshan Station and Dome A is 1228 km, although the actual traverse distance is 1280 km. Because of the high elevation, low temperature, and oxygen-deprived environment, the transportation of material and personnel was time consuming and required establishment of the relay stations.

The extreme minimum temperature at Dome A of −82.3°C (Section 3) contrasts with the lowest temperatures recorded at Great Wall Station of −27.7°C, and at Zhongshan Station of −40.4°C. In order to withstand the challenges posed by such extreme low temperatures over a long period, the design of the construction materials and equipment used in building the inland station had to be extraordinary.

The peak elevation of Dome A is about 4093 m, and the surface atmospheric pressure is therefore very low, ranging from about 545 to 600 hPa (Ma et al., 2010). The low oxygen content is equivalent to that at an elevation of 5000 m on the Qinghai–Tibetan Plateau in China. Nevertheless, after a few days adaptation, four people are able to carry a 50-kg ice-core sample box and three people are able to move 200-kg drums on the surface. Also, under these conditions, the power of the Kässbohrer PB-240 snow tractors used is significantly reduced because of inefficient combustion. Thus, the tractors were capable only of pulling a two-sled load of about 15 t, which complicated the construction process.

The average wind speed in the Dome A region is <5 $m \cdot s^{-1}$, and commonly it is only 2–4 $m \cdot s^{-1}$, which means that exhaust waste gases are not dispersed easily from the station area. Another difficulty is that foundations need to be built on low-density snow, which is unfavorable for ground-based buildings.

Protection of the Antarctic is of considerable importance, not only to the Antarctic environment itself but also to the rest of the planet. Therefore, construction of an inland Antarctic station must, as far as possible, guarantee the preservation of the Antarctic environment and minimize the detrimental effects of human activities.

5 Design and construction strategy

The construction scale of the Dome A research station was based on the scope of the research, number of expedition members, and transport capacity of the inland traverse. It must meet the needs of 20–24 people over summer, with a main building comprising separate areas for accommodation, scientific research, and logistical support. Other buildings should include an emergency safeguard system and an assembly garage.

The expected service live of most inland stations is around 20 years. As they are built on the snow, burial and subsequent subsidence of the buildings can shorten their service life. To prolong their serviceable use, some Antarctic inland stations have been built on elevated positions whereas others have been built on stilts, e.g., the new buildings of the South Pole Station built by the United States, Dome C Station built by France and Italy, and Kohnen Station built by Germany. However, the average snow accumulation in the Dome A region is only about 150 $mm \cdot a^{-1}$ and over a 25-year service life, the maximum depth of snow accumulation would be less than 3.75 m (after firnification). Consequently, the main building of the Dome A station was designed and built on a precast steel base placed on compacted snow, with an overhead form on pillars and an aerial platform. The system had a range of adjustability to adapt to uneven settlement. To ensure a service life of at least 20 years, the platform was intended to be about 3 m above the snow surface. Additionally, snow could be moved as required to accommodate the placement of separate container-style units or the units could be moved to avoid burial. Tracks could be excavated to maintain access to the garage.

To achieve a balance between practical use and ease of transportation and construction, two construction methods were considered. Scheme 1 used packaged prefabricated units for the entire building and Scheme 2 combined internal precast modules with field assembly.

5.1 Scheme 1

Scheme 1 (Figure 5) adopts a building design based on modular units. Both greater functional space and convenience of transportation can be achieved by improving the profile form of the unit modules. Building cladding is made of fiberglass-reinforced plastic and insulation materials with high strength, refractory, and insulation features that can absorb transport vibrations.

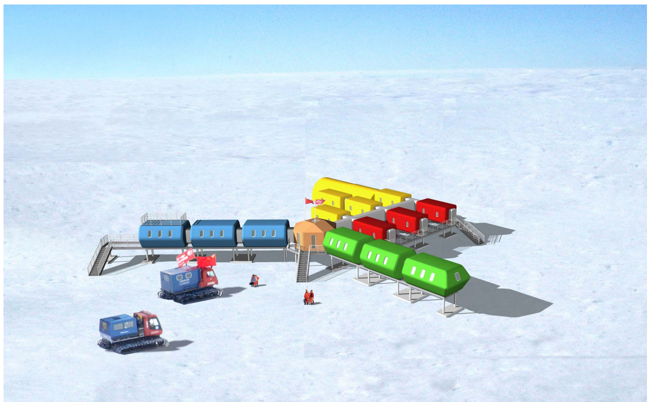

Figure 5 Aerial perspective of Scheme 1.

The profiles of the prefabricated containers adopt two forms to meet the needs of different internal functions. One form comprises a widened standard container, mainly used for power generation, water treatment, and warehouse logistics. For portability by sled, a switch base is mounted at the bottom. The second form comprises a heteromorphic section (Figure 6). The width of the bottom of the unit can be adapted to the width of a sled. An interlayer is set within the floor and internal pipework is laid in advance. The upper room is designed for activities such as scientific research or as a dormitory, and there are connecting openings at the ends of the container.

The on-site installation steps constitute field processing, snow compaction, installation of precast box foundations, aerial platform construction, positioning of container unit, and connection with previously assembled buildings. The advantages of Scheme 1 are its convenience and efficient construction process.

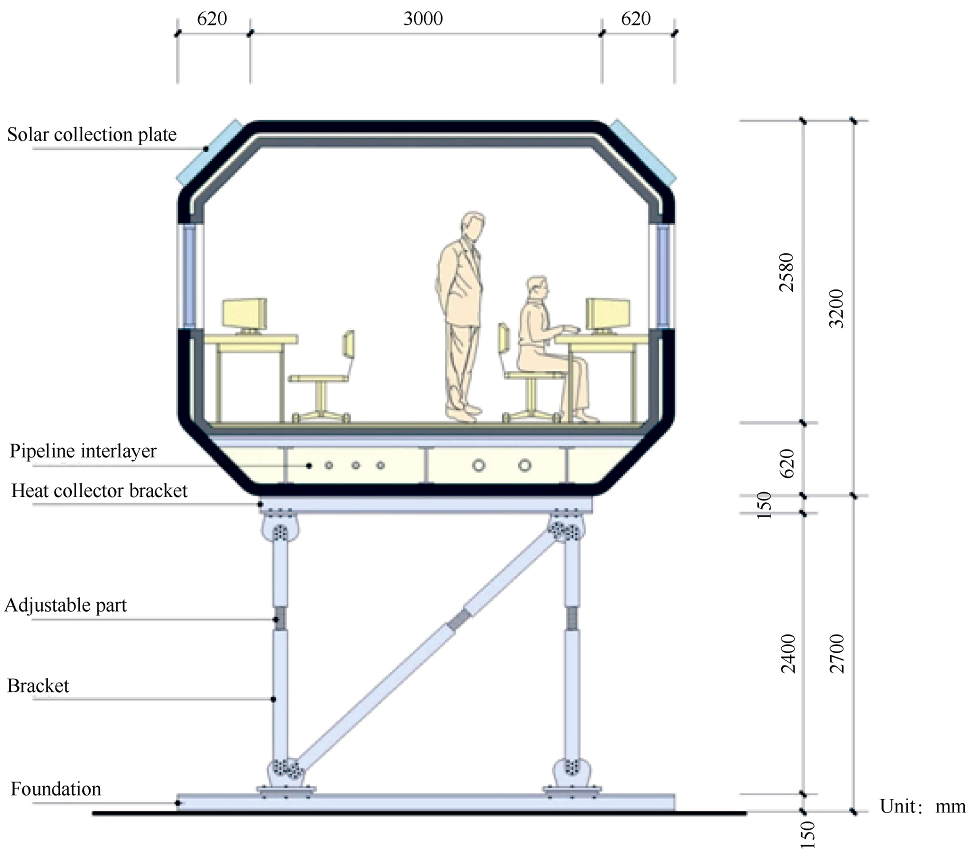

Figure 6 Unit profile of Scheme 1.

5.2 Scheme 2

Scheme 2 adopts the method of combining prefabricated container modules with field assembly (Figures 7–9). On-site installation of an external palisade layer ensures the insulation performance. In order to reduce the workload, the internal form is based on container-type modules. The on-site installation steps constitute snow compaction, installation of precast box foundations, construction of aerial platform, positioning of container, and installation of the building envelope.

Figure 7 Profile perspective of Scheme 2 complex.

Figure 8 Aerial perspective of Scheme 2 main building.

5.3 Comparison of the two schemes

Table 1 presents a comparison of the two schemes. It is evident that Scheme 2 has advantages regarding transportation and hoisting, space, energy conservation, and cost, whereas it has disadvantages in terms of on-site construction difficulties and the length of the construction period. Considering the transportability, functionality, and process and period of construction, Scheme 2 was chosen.

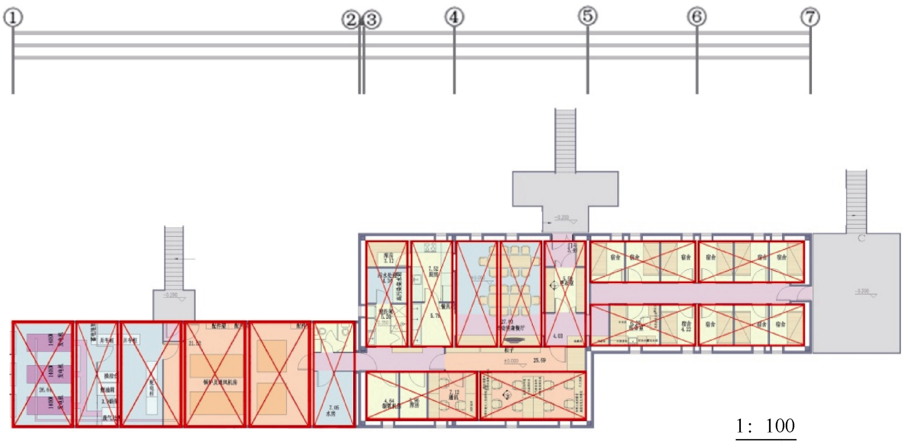

Figure 9 Layout of Scheme 2 internal containers (the numbers at the top of the Figure are building axes).

Table 1 Comparison of Schemes 1 and 2

	Heteromorphic container (Scheme 1)	The combination of prefabrication and assembling (Scheme 2)
Transportation	Large volume, unsteady gravity center, danger of overturning. The total weight is small, but needs more sleds.	Internal precast engineering position is the standard container size, easy to transport. The material is used for internal space, protection against the outside climate is not strong. The total weight is large, but easy to load and unload. The number of sleds needed is less.
Unit weight	5–6 t	3–4 t
Site construction	Very convenient，the major task of the construction is the foundation platform. The upper buildings can be directly hoisted in place, then connected.	Convenient, 60% of the construction has been prefabricated in advance. The major tasks of the construction are the foundation platform and envelope. The inner container of the main building can be directly hoisted in place, but the pillar on the second floor has a slight impact on hoisting.
Construction machinery	Small crane, but with a high elevating capacity	Small crane
The structural system	Single layer, simple construction	Double layers，high workload
Construction period (first phase)	15–20 d	30–40 d
Functional use	Small space	Large space
Energy saving shape	Outer surface area is large.	Outer surface area is smaller, favorable for energy saving.
Investment	Larger surface, higher cost	Smaller surface, save 30%

As constructed, the total building area is 558 m^2, with a main building of 349 m^2. Other buildings include an emergency safeguard system that consists of an assembly garage (60 m^2) and five prefabricated fiberglass insulated containers. These also serve as part of the space assigned to the ice-core drilling project.

6 Site plan

In general layout, the station buildings and facilities are arranged around a square at the front of the station (Zhang, 2009). The main building and the garage are located in the center. The ice-core drilling area and the emergency container are located on the eastern side, and material storage and the snowmobile parking area are located on the western side. The scientific observation area is located to the southeast of the main building (Figure 10).The construction site is a flat platform of compacted snow 0.5–0.8-m high. The areas of the ice-core drilling site and the ice-core storage space, located partially or fully underground, are formed by excavation of the snow. An aircraft ski-way is located 2 km north of the station, and the highest point of Dome A is 7.3 km to the NNE.

Traffic is kept mainly to the north of the station to avoid it passing through the scientific observation area and the ice-core drilling area. The external pipework, which includes cables, and drainage and oil pipelines, is located to the south of the complex to avoid crossing the vehicle access tracks.

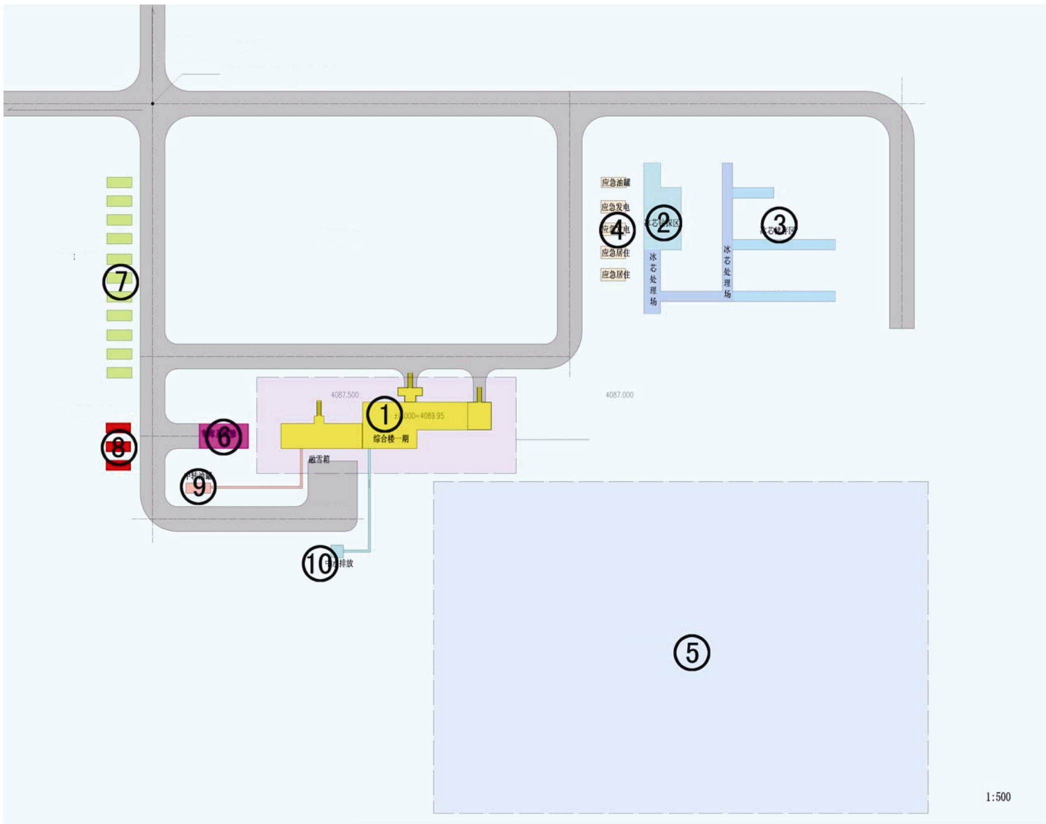

Figure 10 Plan of the station area: (1) main building, (2) ice-core drilling site, (3) ice-core storage, (4) emergency container, (5) scientific observation area, (6) garage and maintenance area, (7) vehicle parking, (8) storage area, (9) oil tank, and (10) drainage pit.

7 Architectural design

In overview, the architectural features are a steel structure or container-type construction with a useful life of 25 years. The station has a fire rating of level 2, but no seismic fortification.

7.1 Layout and functional partitioning

The main building includes a sleeping area, living area, workspace, and technical support area (i.e., power generation, boiler, and wastewater treatment). Heated rooms are located centrally, which is helpful for energy conservation. Moreover, dividing the limited available space into separate partitions makes it easier for personnel to interact and it reduces interference between units. After passing through the foyer and entering the dressing rooms, there is a space for the storage of protective clothing and snow boots. The dormitory area (for 10 people) and a medical clinic are located at the end of the building, which is relatively quiet. An area of about 50 m^2 is available for scientific research, observations, and communication. The activity area is positioned at the center of the building close to the kitchen, providing space for dining and other daily activities. The laundry room and wastewater treatment are relatively independent. In order to avoid interference with other spaces, the bathroom is combined with a corridor that serves as the transition zone between the equipment room and the activity space.

Except for the equipment used for wastewater and sewage treatment, located near the kitchen and the bathroom, other major equipment, including the power generation system, ventilation system, boiler, and power distribution and water supply systems, is located in the facilities area to avoid heat loss and frost damage (Figure 11).

For acoustic division, the main building is divided into three parts: a quiet zone, noise zone, and buffer zone. The quiet zone includes the dormitory and clinic. The noise zone contains the generator room, ventilation equipment room, boiler room, and transformer room. These are at opposite ends of the building, separated by the buffer zone which includes the activity room, scientific research room, kitchen, water treatment, warehouse, and toilet. The noise zone incorporates sound-absorption and noise-reducing measures, and in conjunction with the multiple sound insulation features of the buffer zone, the level of sound that reaches the quiet zone is very low. Structural fractures at the junction between the noise zone and the buffer zone prevent the transmission of vibrations.

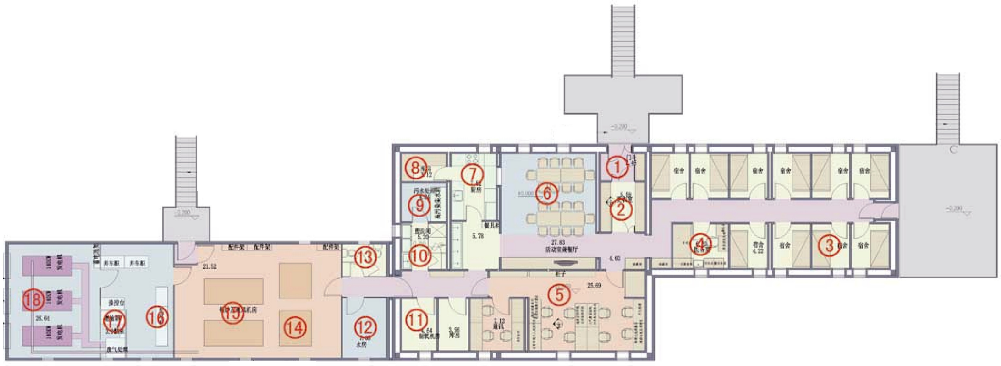

Figure 11 Plan of the main building: (1) foyer, (2)changing room, (3) sleeping area, (4) clinic, (5) scientific research room, (6) activity room, (7) kitchen, (8) warehouse, (9) sewage treatment, (10) bathroom and laundry, (11) oxygen equipment, (12) water supply, (13) bathroom, (14) ventilation equipment room, (15) boiler room, (16) distribution and control room, (17) temporary storage, and (18) generator room.

To minimize the possibility of heat loss and frost damage, all the heating and water supply pipelines are installed internally. Only some of the electrical cabling, and the oil and drainage pipelines, equipped with heating and ventilation systems, are installed externally, and the lengths of external pipework are as short as possible. The kitchen, bathroom, sewage treatment, and other units that use water are all located within two adjacent prefabricated containers, forming the most convenient and efficient discharge, recycling, and reuse circulation system.

7.2 Profile and facade

The main complex, garage, and all emergency rooms are single-story buildings. The height of the 03–07 axis containers in the main complex is 2.89 m (see Figure 9). The building envelope is 4.054 m; the difference between the internal and external height is 2.45 m; and the overall height of the building is 6.504 m. The height of the 01–02 axis containers is 3.29 m (see Figure 9), and the difference between the internal and external height is 2.45 m. The overall height of the building is 5.54 m.

The overall height of the garage is 6.3 m, and the difference between its internal and external height is 0.2 m.

Figure 12 Photo of the façade.

The No. 1 and 2 emergency accommodations at Kunlun Station, the Kunlun emergency habitat, relay station emergency habitats, and the emergency power station are all 2.59-m high.

The elevation of the main complex is faced with metal sandwich board in the colors of the Chinese flag. The facade is simple in design but styled with Chinese characters (Figure 14).

8 Energy-conservation strategy

The energy-conservation strategy for the inland station gives full consideration to the special environmental climate, logistics, construction capability, and technology level, and adopts an optimum balance between practicability, economy, feasibility, and innovation.

8.1 Heat generation and retention

The dual-energy boiler, using fuel and flue gas as a heating resource, makes full use of the waste heat of the flue gas from the generator. The fuel is only used as a supplement and for standby power, which greatly improves energy saving.

Improving the insulation performance of the retaining structure is one of the most important methods for reducing energy consumption. Heat retention and sealing of the palisade structure are very high. The exterior walls, roof, and floor of the living area in the complex have a double-insulation structure. The outer layer is 150-mm- thick polyurethane metal sandwich board, while the internal walls of the prefabricated containers are 100-mm-thick rock wool with calcium silicate board and a decorative wooden composite structure. The width of the air layer between the two skins is 300 mm. The heat transfer coefficient of the palisade structure is 0.173 $W\cdot m^{-2}\cdot(°C)^{-1}$.

The external windows comprise double fiberglass-reinforced plastic window frames with triple glazing. The outside of the inner glass is coated with LOW-E film. The heat transfer coefficient is <1.5 $W \cdot m^{-2} \cdot (°C)^{-1}$.

There are two ways to improve indoor air quality. The first is via natural ventilation and the other is through mechanical ventilation. Infiltration is the main factor affecting heat loss for the entire building. A mechanical ventilation heat recovery device can achieve heat transfer by convection. This device can heat inlet air through an exchanger to recycle exhaust heat. The average recovery efficiency can reach 75%. For example, for an external temperature of −20°C and an internal temperature of +22°C, the temperature of fresh air supplied to the room can be elevated to +11°C, improving indoor air quality without additional energy consumption. The adoption of mechanical ventilation means that all window units can be fixed, and these are both cheaper and better at retaining heat.

8.2 Generation of renewable energy

The wind speed in the Dome A region is generally <3 $m \cdot s^{-1}$; therefore, solar energy is the main renewable energy resource. Use of solar energy is made both for electricity and heat. After an initial trial period, the intention is to increase the proportion of solar energy usage. The ultimate goal is to meet the electricity consumption needs of the station during the summer, retaining the generator for use as a backup supply.

The solar heating system consists of collectors, a heat exchanger, heat preservation water tank, refrigerator, air pipe, water pump, and fan. The radiation intensity of the sun at Dome A is almost the same as elsewhere, and the amount of heat obtained by the collector depends on the amount of radiation, rather than the ambient temperature. In Antarctica, the key consideration is reliability of the collector. Once heat is generated by the collector, heated air is supplied via draught fans through air ducts to introduce fresh air into the internal spaces and to increase the indoor temperature. Heat from the air can be transferred into the water tank through heat exchangers, while excess heat can be used to melt ice.

There is no water in the external components of this system and therefore no concerns regarding freezing. Without changing the overall structure of the units, this system can be installed by attaching the collector on an external wall, and determining appropriate positions for the inlet and outlet of the air duct, water tank, ice-melting device, and heating ducts. Domestic experiments have proven the feasibility of such schemes.

This solar power system uses domestic prefabricated solar panels that are fitted during field assembly of the units. Considering the severe weather conditions at the site, the designs of the components and interconnections are designed for easy installation.

Solar photovoltaic panels use solar cell arrays to convert solar energy into direct current (DC). The DC generated from solar energy is then converted into alternating current (AC) through a DC/AC grid inverter. Solar photovoltaic panels and a 140-kW diesel generator supply the power requirements of the Antarctic inland station. Surplus electricity can be stored in batteries.

Maintenance of the solar power system is simple. After initial installation, electricity generation is managed automatically by controlling software, i.e., the system does not require professional maintenance or special operation.

9 Environmental protection

9.1 Environmental impact of Antarctic research station construction and operation

The construction program included the development of the inland station and the expansion of Zhongshan Station. Site construction at Dome A had a phased implementation. The date set for the completion of the initial phase of the station construction was during the period of the 11th Five-Year plan (2006–2010). The intention is then to expand the station gradually to its full operational size. The construction will inevitably produce construction waste, which could cause serious pollution at the station site and the surrounding environment if the processing procedures are ineffective.

The station operational impacts on the environment are:

(1) Impact on the water environment. The water used for drinking and cooking at the inland station is derived from melting snow, while other water is recycled. The drinking and domestic water of Zhongshan Station is obtained from a nearby lake. Both stations have sewage discharge and if emission standards are not met and emissions are uncontrolled, the water and the environment will become polluted.

(2) Impact on the air environment. The environmental impact of this project is largely due to the fuel system. The main pollutants are SO_2, NO_2, soot, and dioxins caused by the burning of waste.

(3) Impact of noise. The main source of noise is the operation of the generator set, which is usually at a level of about 70–90 db (A).

(4) Impact of solid waste. Solid waste produced by the operation of the station includes garbage from daily life and other solid waste related to experimental research. The residues of solid waste incineration should be collected and transported off the continent rather than be discharged into the environment.

(5) Other effects. The inland station is located on the ice sheet, where there is no vegetation and no animals. Therefore, the construction of the research station has no impact on local biodiversity or the ecological environment.

9.2 Environmental protection measures

Some environmental protection measures and emergency plans regarding major environmental impacts were established for the transportation, construction, and operational modes of the program. These measures, shown in Table 2 (Tsinghua University, 2008), reduce detrimental effects of the inland station on the Antarctic environment.

To minimize site installation work, lightweight materials were widely used to reduce the overall weight of the project material and container-type buildings were used to form the actual research station. Therefore, the influence on the surrounding environment is mainly related to the process of snow leveling. A storage site was established specially to store building materials and construction waste. Construction management was strengthened to prevent environmental pollution caused by construction waste.

Table 2 Environmental protection measures

Environmental elements	Impact description	Anti-pollution measures
Atmosphere	The emissions produced by fuel system in the process of combustion will directly or indirectly contribute to the greenhouse effect. The settlement of soot and other pollutants affect the quality of the ice and may cause changes to some physical environmental properties such as ice albedo.	Use clean energy to improve the efficiency. Take energy saving and waste gas treatment measures.
Water environment	Any fuel leak will likely cause pollution of the water system. In addition, the water storage appliances, if not regularly replaced, may also cause to pollution of the water system. Microorganisms may be affected by pollutants from wastewater and leaked fuel. Because the fuel is difficult to degrade, it will affect the growth environment of the species to some extent.	Strengthen the management of the fuel storage system and set up oil spill prevention facilities. Build reliable drainage pipelines to reduce leakage and formulate emergency measures. Strengthen the management of the storage system. Improve the level of wastewater treatment to minimize the concentration of waste water emission. Collect and transport all faeces from Kunlun Station back to China. Use clean energy.
Sound environment	Due to the operation of the power generation system, living conditions of research staff will be affected.	Adopt acoustic noise reduction measures.
Solid waste	Daily garbage and solid waste produced in the operation of the station may adversely affect the local environment.	Adopt garbage classification. Procurement of materials should comply with Antarctic packaging standards. Reduce the waste.

To minimize the influence on the water environment, all faeces produced at the Antarctic inland station are collected and transported off the continent for domestic processing in China. The wastewater from bathing and the kitchen comprises slightly polluted water and is handled according to requirements. Part of the recycled wastewater is used for washing clothes after advanced treatment. Coagulation and Rautenbach filtration were selected as the main treatment processes to deal with sewage discharge.

According to the Protocol on Environmental Protection to the Antarctic Treaty, wastewater produced at stations located on an ice sheet or located on an inland ice shelf, which cannot be moved out of the Antarctic treaty area, can be disposed of in deep trenches. When choosing disposal sites, areas without ice or with melting ice should be avoided.

Clean energy and increasing energy efficiency are used to save energy minimize the influence on the air environment. Exhaust gas treatment measures are taken, and a Lampblack purifier is installed in smoke vents to ensure that flue gas emissions remain in accordance with national health standards.

Low-noise equipment was chosen in the project design and installation. Control measures such as damping, sound insulation, and noise elimination are taken. In order to minimize noise levels, the pump room has sound-absorption features. In the completed station, the locations of all sources of noise should be reasonably arranged. The containers used for accommodation are located away from sources of noise for the comfort of the research personnel.

The solid waste produced in the operation of the station includes daily garbage and other solid waste related to experimental research. Radioactive materials, batteries, liquids, solid fuels, waste containing harmful heavy metals or poisonous or harmful persistent compounds, polyvinyl chloride, poly helium foam, polystyrene foam, rubber oil and lubricating oil, processed timber, additives producing noxious emissions on incineration, fuel barrels, and other nonflammable solid waste are removed from the Antarctic treaty area. Other waste such as microorganisms and plant pathogens are incinerated to minimize their influence on the Antarctic environment after the cessation of the operation of the research station.

10 Special security measures

Security measures adopted for the inland station include emergency rescue, emergency storage, and a fire control system, although the main measure is an oxygen-generation system. Because of very low air pressure at Dome A, an oxygen-generating system is used to supply oxygen to each room in the main complex to meet the basic physiological needs of the personnel.

The oxygen-generation system uses the molecular sieve method. When environmental air flows through a molecular sieve, the non-oxygen components are absorbed by the molecular sieve and the oxygen becomes enriched. The equipment continuously and evenly extracts oxygen from an environmental air supply without additional raw materials. It is a safe, reliable, low-energy system (4 kW) and it is especially beneficial in terms of environmental protection.

The oxygen-generation system consists of a compressed air source, molecular sieve, valves, pressure reducing valve, and a control device. In order to reduce the load of oxygen production, the oxygen is not sent directly into the ventilation system. Instead, oxygen is provided through a dedicated pipeline (deoxidized copper pipe) that uses an oxygen plug to distribute the oxygen. The output of the oxygen-generation equipment is 1.2 $m^3 \cdot h^{-1}$, which can meet the needs of 6–7 people (individual requirement of approx. 0.18 $m^3 \cdot h^{-1}$). Furthermore, compressing 12 m^3 of oxygen into a 2-m^3 tank can meet with the peak oxygen demands of 20 people over 3 h.

11 Station construction

Implementation of Kunlun Station was divided into three stages: domestic manufacture and assembly, transportation, and field construction.

11.1 Domestic manufacture and assembly stage

Many workers were involved in the precast work in the plant in Shanghai and the prefabrication was completed on schedule. The purpose of the assembly stage was to develop familiarization with the process and to identify installation problems. After training, the speed of the hoisting work was improved and some initial installation problems were found and remedied.

11.2 Transportation stage

Because of unusual sea ice conditions near Zhongshan Station in the 2008/2009 season, the sea ice had not completely melted, which prevented the barges from accessing the unloading point at the first attempt. However, the sea ice was not sufficiently strong to ensure safe transportation across the ice. Thanks to the preliminary planning for worst-case scenarios, the weights of individual prefabricated containers and the main components of the station were not more than 3.5 t, which meant they could be transported successfully by helicopter. After hundreds of sorties, all supplies were transported to the point of traverse departure.

11.3 Field construction stage

The first step involved preparing the compressed snow base. The temperature is at its lowest after midnight, which is the optimum time for Caterpillar tractors to compress the low-density snow. Repeated rolling in a crisscross pattern leveled and hardened the snow. Then, the Kässbohrer tractors were used to roll across the snow surface to achieve the optimum density.

After rolling the snow, wooden planks were placed where the base plates of the steel platform structure were to be located. Strong bamboo plywood was used as bedding upon which the steel base plates were lowered. The steel structure was then adjusted for height using a precision optical instrument. The installation was divided into two parts: the upper part and the lower part. Two F150AC 22 crane booms were then used in the double-derrick crane method for the installation of the engineering cabin (Figure 13).

Figure 13 Hoisting the engineering cabin (Source: Chinese Arctic and Antarctic Administration, SOA).

In February 2009, the construction of Kunlun Station at Dome A was successfully completed after one month of effort (Figure 14).

Figure 14 Kunlun Station (Source: Chinese Arctic and Antarctic Administration, SOA).

12 Taishan Station

A new relay station, Taishan Station, has been constructed to provide transportation support and emergency protection for Kunlun Station, the Grove Mountains and Prince Charles Mountains, and is now playing a pivotal role. Taishan Station is located at 73°51′S, 76°58′E, at an elevation of 2621 m. It is 522 km from Zhongshan Station, and 715 km from Kunlun Station. The surface terrain and the terrain under the ice at this site are both flat. The thickness of the ice sheet is about 1900 m and there is no melting at the bottom of the ice sheet (Tang et al., 2016). The horizontal flow of the ice is less than 20 $m \cdot a^{-1}$ (Zhang et al., 2008) and the snow density on the surface is 362 $kg \cdot m^{-3}$ (Ding et al., 2011). The 10 m firm temperature is −35.8°C (Ding et al., 2011). The average wind direction is 55 degrees and the prevailing wind is easterly. The snow accumulation rate of this location is stable and low. The average accumulation rate is 67 $kg \cdot m^{-2} \cdot a^{-1}$ (Ding et al., 2011), which is an ideal site for the construction.

The main building at Taishan Station, with an area of 410 m^2, is assembled from light-weight modular metal building materials. It is about 11 m above the snow surface, and its bottom is built on 2-m high stilts. It can meet the requirements of scientific research, observation, living, logistic support, waste disposal, etc. The auxiliary building area of 300 m^2 uses a modular and mobile sled structure. It is used for scientific research, electricity generation, boilers, waste disposal and snowmelt facilities. It connects to the main building by a pipe rack under snow.

All materials are designed to withstand −64°C and to resist a maximum wind speed of 60 $m \cdot s^{-1}$. The first phase of the station was completed on 8 February 2014 (Figure 15), and preparations for a second phase of the project are under way.

Figure 15 Taishan Station.

Now that it is the main relay station between Zhongshan and Kunlun stations, Taishan Station will effectively support scientific investigation, environmental monitoring and other research projects. It is also an important base for inland investigation, expedition staff rest, and equipment supply.

13 Concluding comments

Considering the extreme conditions of the site, the design and construction of Kunlun Station has focused on the following issues: long distance transport over snow, fast construction and operation at very high altitude and very low temperature, and seasonal closing and restarting of the station at low temperature.

With limited transportation capacity and field construction capacity, the construction and transportation of construction materials for Kunlun Station have been completed. A small amount of interior decoration was damaged during long distance transportation and should be avoided in future design.

Each inland expedition took about 60 d and involved 25–30 people. They were all inland expedition team members, including support and scientific expedition personnel. Some members need to work as drivers. From Zhongshan Station to Kunlun Station, the one-way trip took 15 d and the team members needed take into account the expedition projects, also undertook scientific projects along the way.

Table 3 Timeline

Time	Work
2008–2009 (The CHINARE-25 team)	The first phase of the projec was completed
2011–2012 (The CHINARE-28 team)	The construction of equipment building was completed
2014–2015 (The CHINARE-31 team)	The whole project was completed

In summer (minimum temperature of −40°C), the operation of Kunlun Station is basically as planned. The generators and boilers are effective in the rarefied high-altitudeair. One of the most important challenges has been securing the station for winter. All equipment needs to withstand low temperature below −80°C. The closing of the station must comply with strict procedures: all oil and water in equipment should be emptied and blown dry using a powerful air-dryer and the critical equipment control panel should be brought back to Zhongshan Station. The starting of the station in the following summer has been conducted smoothly after equipment preheating and other measures. Only a small amount of sealing gasket has been needed to be replaced.

The planned objectives of Kunlun Station have been achieved, except for operation during winter. As a summer-only station, the system and the equipment requirements are greatly simplified, although the round trip on ice sheet of nearly 1300 km, the work time of no more than a month at Kunlun Station, and the requirement that all equipment should be preheated and then turned off and winterized again after only a few weeks still make the workload large and challenging. While Kunlun Station has not been operated at the extreme cold of a Dome A winter, equipment and systems are also in place for the possible future expansion to winter operation.

Acknowledgments Firstly, we are grateful to the Architectural Design and Research Institute of Tsinghua University that supported and encouraged us throughout this project. Secondly, we would like to express our sincere gratitude to the Chinese Arctic and Antarctic Administration, the Polar Research Institute of China and Baosteel Construction System International Co. Ltd., whose valuable data helped us produce this paper. We also thank Prof. Ian Allion for his review and sugguestion to improve this paper.

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