SNOW STUDIES ASSOCIATED WITH THE SIDEWAYS MOVE OF DYE-3

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ABSTRACT

In 1977 DEW Line station DYE-3 on the Greenland Ice Cap was moved sideways 210 ft (64 m) onto a new undistorted foundation. When this life extension concept was proposed, abrupt failure of the supporting snow was a major concern. Snow samples were obtained and strength tested at CRREL to determine the chance of an abrupt failure of the supporting snow. Model studies were also performed to determine the bearing capacity of the snow and predictions were made of foundation settlement during the move. The results indicated that the move could be accomplished safely.

INTRODUCTION

The Distant Early Warning (DEW) Line is a system of self-sufficient USAF communication and surveillance facilities that extends across the North American Arctic. DYE-3 and its sister station DYE-2 are the two most unusual buildings of the DEW Line. They are not founded on soil or rock like most other structures but are built on the snow of the Greenland Ice Cap. Their locations are shown in Figure 1.

In 1977 DYE-3 was moved sideways 210 ft (64 m). Since the DYE-3 composite building weighs over 3,000 tons (2.7x10^6) kg) and is taller than a conventional 10-story building, this was no simple task.

THE DYE-3 STRUCTURE

As shown in Figure 2, DYE-3 is elevated on columns. Periodically the columns are extended and the elevated composite building is raised to account for the 4 ft (1.2 m) of snow that accumulates annually at DYE-3. When built in 1959-60, the footings that support the structure were placed 32 ft (10 m) below the surface where snow with an adequate bearing capacity is located. In 1977 those footings were 100 ft (30.5 m) below the current snow surface. The columns which support the building require lateral support which is provided by subsurface trusses isolated from the adjacent snow by a timber and plywood box called the truss enclosure. The configuration of the origianl trusses is shown in Figure 3a. Truss additions in 1967 and 1972 are shown in Figures 3b and 3c, respectively. The truss enclosure as it looked in 1962 is shown in Figure 4. Its walls are built of studs in much the same way that a conventional framed dwelling is constructed.

SNOW LOADS ON THE TRUSS ENCLOSURE

The truss enclosure was initially designed on the assumption that the lateral snow pressure on it at any depth was 1/3 the overburden pressure at that depth. Pressure cells which Sherwood Reed and I designed and installed on the walls of the truss enclosure in the late 60's (Fig. 5) showed that the lateral pressure increased with depth from a value

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of about 20% the overburden pressure near the surface to nearly full hydrostatic pressure at a depth of 80 ft (24 m) or more. The enclosure was strengthened in an attempt to sustain these increased lateral pressures and except in a few areas such as shown in Figure 6, the strengthening worked rather well.

However, the truss enclosure soon showed that it had an inherent weak link. The adjacent densifying snow gripped it and created heavy vertical compressive stresses on the walls. For the most part, the wall studs themselves were capable of sustaining these stresses but the horizontal plates at the ends of the studs could not sustain them. Where the studs above and below were not aligned, the plates were subjected to heavy shear stresses and they failed. Lacking vertical support except from the adjacent snow, the walls slowly telescoped downward as the adjacent snow densified (Fig. 7). In many areas members of the telescoping truss enclosure interferred with the steel trusses (Fig. 8). Large secondary stresses were generated in the structural frame of the composite building by these interactions.

Additonal secondary stresses accumulated in the structural frame as the result of differential settlement among the eight footings, outward tilt of the footings, and horizontal distortion of the ice cap.

In 1973 CRREL began a program of measuring the level of secondary stresses in the DYE-3 structural frame (Tobiasson, Ueda and Hine, 1974). In some areas stresses greatly exceeded those allowed by the American Institute of Steel Construction. Subsequent measurements indicated that the level of secondary stresses in the frame was increasing at an alarming annual rate of over 10%. Something had to be done.

LIFE EXTENSION ALTERNATIVES

With assistance from CRREL, Metcalf & Eddy Engineers Inc. (M&E) investigated several alternatives for extending the useful life of DYE-3 to 1984. The following three alternatives were evaluated in some detail:

1. Continue with the existing practice of periodically raising the building. This would necessitate major rehabilitation of the truss enclosure and strengthening of the substructure.

2. Create a giant ice cube out of the bottom 50 ft (15 m) of the truss enclosure by backfilling it with a water spray or a snow-water slurry. Sever the columns above the slurry, realign them and place them on new footings at that elevation, then construct a new truss enclosure from the top of the ice cube to the snow surface.

3. Move the building sideways off the distorted, overstressed substructure onto a new unstressed foundation.

CRREL MEASUREMENTS

The latter two alternatives were conceived and developed at CRREL. Several technical questions concerning snow had to be answered by CRREL before M&E engineers could evaluate either of the CRREL ideas. CRREL engineers evaluated methods of creating an ice backfill both in our cold rooms and at DYE-3. Recommendations on methods of creating a homogeneous backfill, including expected rates of ice production and thermal implications are presented by Hanamoto, Haynes and Mellor (1976).

I was involved in determining the risk associated with the sideways move concept which my brother and I conceived. Stresses in the structural frame were remeasured and with these updated measurements, Mr. Philip Tilton of M&E developed a structural bracing system that could handle the stresses that would be generated when the columns were severed just prior to the move. A prediction of the amount of settlement that would occur along the tracks during the sideways move was needed. Using the CRREL coring auger, 3 in. (7.6 cm) diameter snow samples were taken to depths of 50 ft (15 m) along the track of the move. The density of each sample was determined. Using analytical tools in Properties of Snow (Mellor, 1964) and CRREL temperature measurements made at DYE-3 over the years, the temperature of the supporting snow during the move was estimated. Applying this information to snow settlement test data collected by Reed (1966) it appeared that the footings would settle about 1/2 in. (1.3 cm) if the move took ten days and snow temperatures were somewhat above normal. To account for the proximity of some footings to the wall of the broken truss enclosure and inadvertent warming caused by the construction operation, I recommended that a 1 in. (2.6 cm) settlement be anticipated during the move.

CHANCE OF AN ABRUPT FAILURE

Geometry: The risks discussed above were relatively easy to assess. The final risk, the chance of an abrupt bearing failure of the snow supporting the track in the vicinity of the truss enclosure during the move, was more difficult to determine. Picture a footing 15 ft (4.6 m) below the snow surface only 33 ft (10 m) from the 100 ft (31 m) deep truss enclosure. Assume that the broken truss enclosure cannot be relied on to take any load and the picture simplifies to a footing 33 ft (10 m) from a 100 ft (31 m) high precipice. It is not quite a precipice since the truss enclosure is only 120 ft (37 m) wide in plan view but it is still an unnerving geometry.

Model Tests: To determine the chances of an abrupt and catastrophic bearing failure, tests were conducted at DYE-3 of model footings placed near an excavation. The hydraulic jack in Figure 9 has pushed the model footing into the supporting snow which has failed. The failure load is related to the proximity of the footing to the excavation. Several repetitions of this test were conducted on site.

Unconfined compression tests of the same snow indicated that the snow supporting the model failed at a stress 3-1/2 to 7 times the unconfined compressive strength of that snow. These tests were somewhat primitive and the surface snow was not homogeneous. To better define the model/unconfined stress ratio, additional tests were conducted in the cold rooms of CRREL in Hanover, New Hampshire (Fig. 10). The model/unconfined stress ratio for these tests varied from 4.5 to 5.0. With knowledge of the unconfined compressive strength of the snow that would support the actual footings, the load expected to cause failure of those footings could be estimated.

Unconfined Compression Tests: Core samples taken of that snow were flown to Hanover in refrigerated containers. They were stabilized at 14°F (-10°C) which was somewhat warmer than the snow temperature expected during the sideways move. After careful trimming and end-lapping they were tested in unconfined compression at 14°F (-10°C) in the environmental chamber of a testing machine.

The unconfined stress at failure ranged from 60 to 350 psi (410 to 2400 kPa) except for one sample which failed at 25 psi (170 kPa).

It was obvious that essentially all the snow had an unconfined strength exceeding 25 psi (170 kPa) at 14°F (-10°C) and that the model/unconfined stress ratio certainly exceeded 3. Using these two very conservative values, the foundation failure load would certainly exceed 75 psi (520 kPa) (i.e. 11,000 psf).

FACTOR OF SAFETY

The original DYE-3 footings were loaded to 2000 psf (96 kPa). This information and other information collected by Reed (1966) at Camp Century in Greenland suggests that 2000 psf (96 kPa) is an appropriate bearing stress for footings founded on dense (30-35 pcf; 480-560 kg/m^3) polar snow. The minimum factor of safety present against an abrupt failure during the sideways move would be 11,000/2000 = 5.5. The actual factor of safety was expected to be somewhat greater since the unconfined compressive strength of the supporting snow exceeded 25 psi (170 kPa); the model/unconfined stress ratio was probably closer to 5 than 3; the snow during the move was expected to be colder than 14°F (-10°C) and the wall of the truss enclosure would probably offer some lateral support.

The model tests and unconfined compression tests convinced the decision makers that the chance of an abrupt failure in the supporting snow during the move was slight.

THE "BIG MOVE"

The sideways move alternative was selected over the ice backfill alternative based on cost estimates by Metcalf & Eddy Engineers Inc. which showed that one million dollars could be saved if the building was moved sideways.

Danish Arctic Contractors (DAC) was awarded the contract to move the building. During the summer of 1977 new footings were built on the snow (Fig. 11), large girders were built on them (Fig. 12) and trusses and girders were installed under the building (Fig. 13). Hydraulic jacks were installed to pull the building along the tracks (Fig. 14). On 2 September 1977 with the columns severed and the weight of the building on rollers, the sideways move began. Four days and 210 ft (64 m) later the building was in its new position (Fig. 15). No particular problems were encountered during the move. The building was occupied and functional the entire time. During the move Bob McLemore of M&E and I measured the settlement of all footings. The total settlement was about 3/8 in. (1 cm) which is in line with the predicted value considering the move took only four days and it was a colder than normal summer.

A great Scandinavian feast was had by all workers once the move was completed. The workmen took the next day off; it was their first day of rest all summer.

In 1978 the building was lifted 26 ft (8 m). Stress measurements taken shortly thereafter indicated that the structural frame was essentially free of secondary stress. In its new position it is expected that the building will be trouble free for many years.

SUMMARY

Snow drawdown forces on the subsurface truss enclosure caused significant subsurface distress at DYE-3. Interfering members, and differential settlement and tilt of foundations generated large secondary stresses in the structural frame. A major effort was needed to avoid a structural failure.

Several alternatives were considered for safely extending the useful life of DYE-3. An ice backfill and a sideways move were evaluated in detail. Core samples were obtained of the supporting snow and its density and unconfined compression strength were determined. Predictions were made of footing settlement during the sideways move. Model studies were performed on-site and in cold rooms to determine the chance of an abrupt failure in the snow supporting the building during the move. Relating these results to the unconfined strength of core samples taken of the supporting snow it was found that the chance of a bearing failure was rather low. All concerned were then convinced that a sideways move could be performed safely. When the engineer's estimate indicated that it would cost a million dollars less than other alternatives, the sideways move was selected.

In 1977 DYE-3 was moved 210 ft (64 m) sideways onto a new undistorted foundation. The actual move took four days and went smoothly.

ACKNOWLEDGEMENTS

My collegues Ronald Bourne, Timothy Dudley, Charles Korhonen, Edward Lobacz, Robert Redfield and Herbert Ueda made major technical contributions to this work. We were greatly assisted by many other CRREL technical and support personnel.

Mr. Philip Tilton of Metcalf & Eddy Inc. designed DYE-3, was directly involved in its construction and has been associated with every life-extension operation since. Over the years he has taught me a great deal about civil engineering.

CRREL programs at the DEW Line Ice Cap Stations since their construction in 1959 have been supported by the USAF Aerospace Defense Command.

REFERENCES

Hanamoto, B., D. Haynes and M. Mellor. Methods of Backfilling Truss Enclosures at DYE-2 and DYE-3. CRREL Internal Report 497, April 1976, Hanover, New Hampshire.

Mellor, M. Properties of Snow. CRREL Monograph III-A1, December 1964, Hanover, New Hampshire.

Reed, S.C. Spread Footing Foundations on Snow. CRREL Technical Report 175, April 1966, Hanover, New Hampshire.

Tobiasson, W., H. Ueda and G. Hine. Measurement of Forces Within the Structural Frame of DEW Line Ice Cap Stations DYE-2 and DYE-3. CRREL Special Report 205, April 1974, Hanover, New Hampshire.

Figure 1. Map of Greenland, showing locations of DYE-2 and DYE-3.

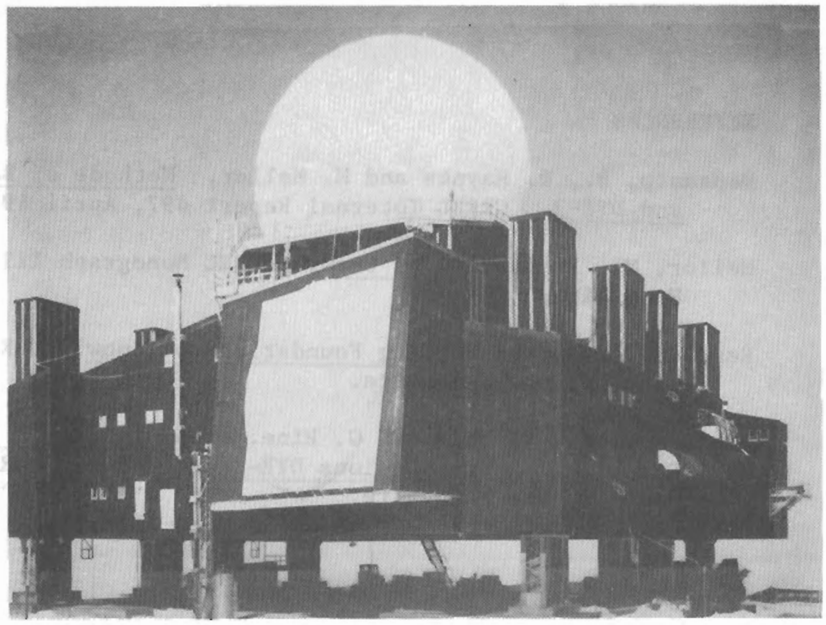
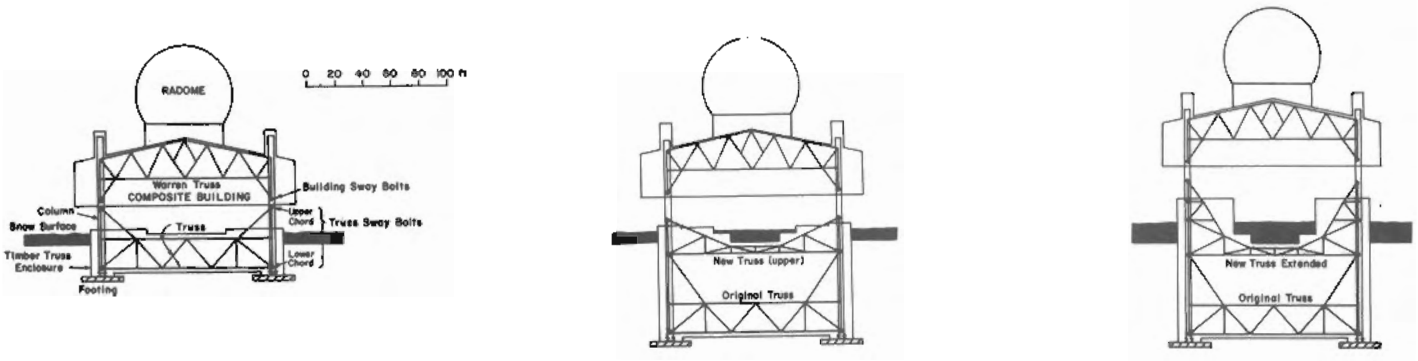


Figure 2. DYE-3 from the surface. Note the bulldozers for scale.



a. As built in 1959-60 b. New truss installed in 1967 c. New truss extended in 1972

Figure 3. Cross-sections of the DYE-3 structural frame.

Figure 4. Within the truss enclosure in 1962 (CRREL photo by S. Reed).

Figure 5. Lateral pressure cell installed on the wall of the truss enclosure.

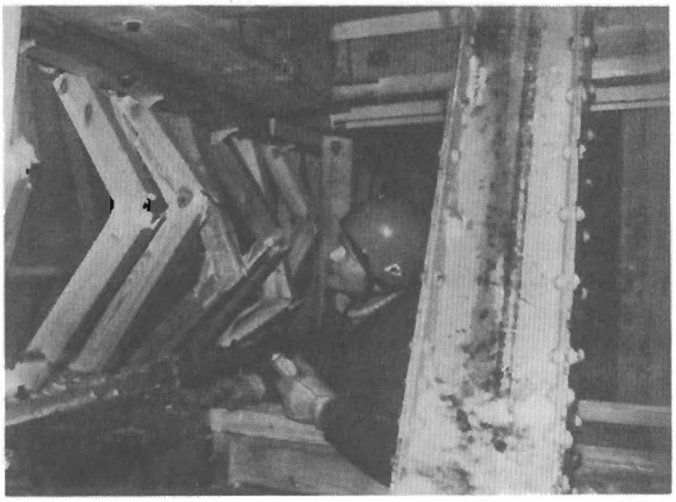


Figure 6. Failed wall studs of the truss enclosure (photo by E. Hodgkins, ADC).

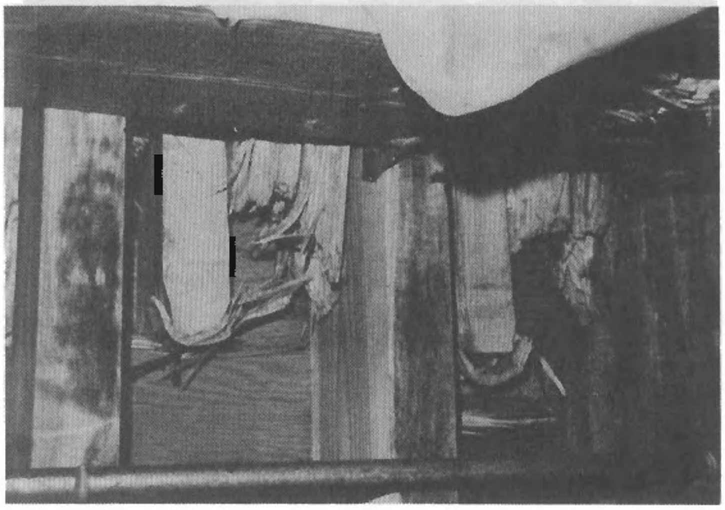


Figure 7. Failed wall plates and telescoping wall studs.

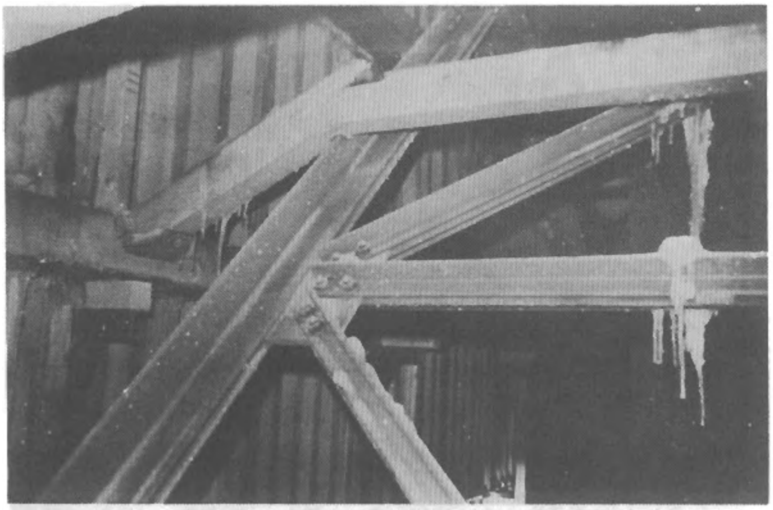


Figure 8. Interference between the timber truss enclosure and the subsurface trusses.

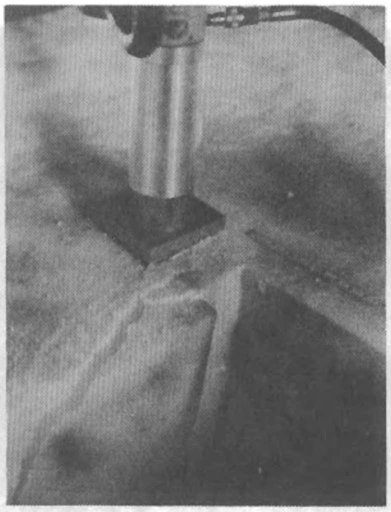


Figure 9. Model footing test conducted at DYE-3 under a crane which provided reaction for the hydraulic jack shown.

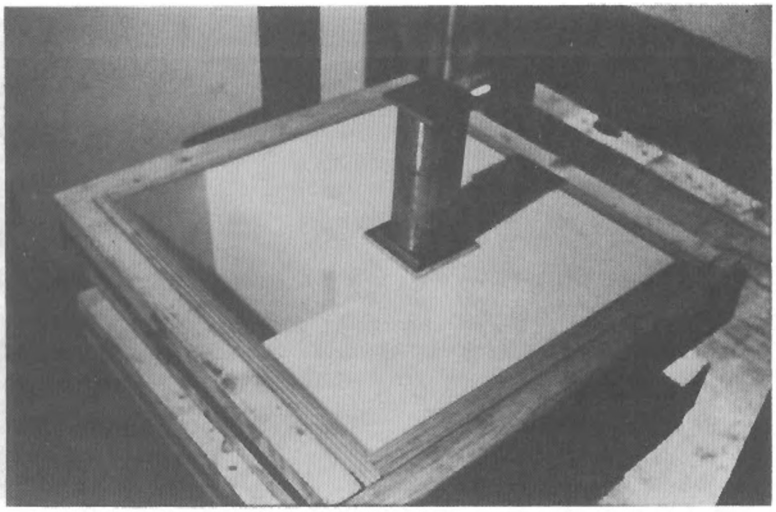


Figure 10. Model footing test conducted on a testing machine in a CRREL cold room.

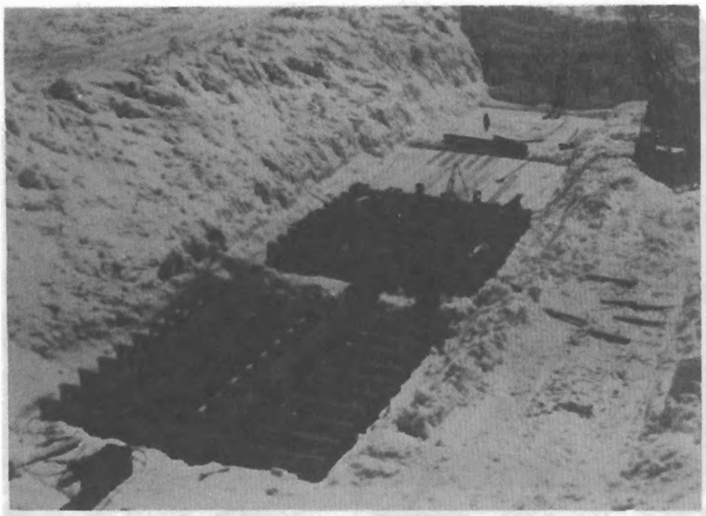


Figure 11. New footings (photo by R. McLemore, Metcalf & Eddy Inc.).

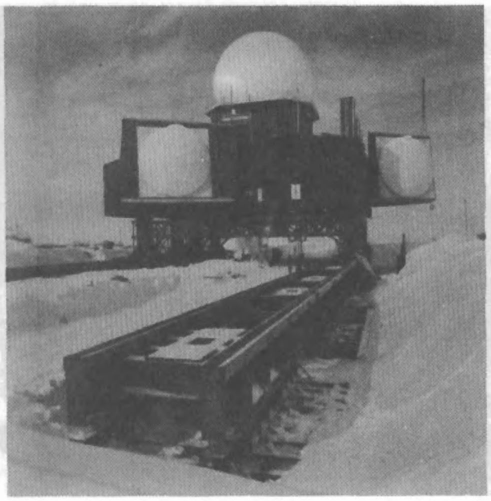


Figure 12. Girders over which DYE-3 was moved sideways.

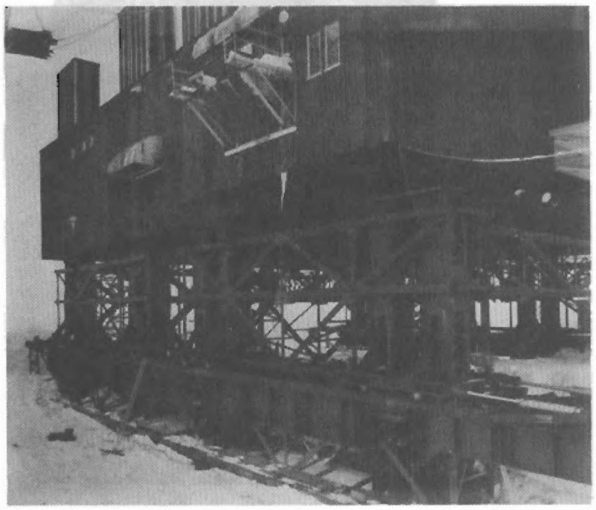


Figure 13. Trusses and girders installed under the building.

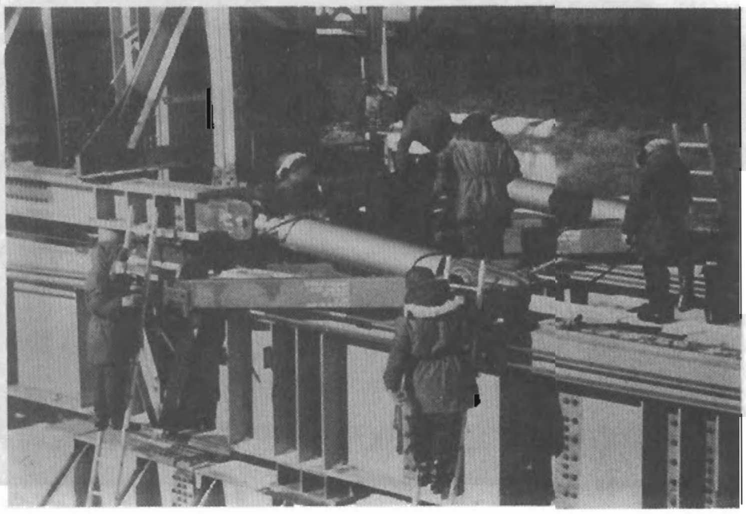


Figure 14. Hydraulic jacks used to pull the building along the girders.

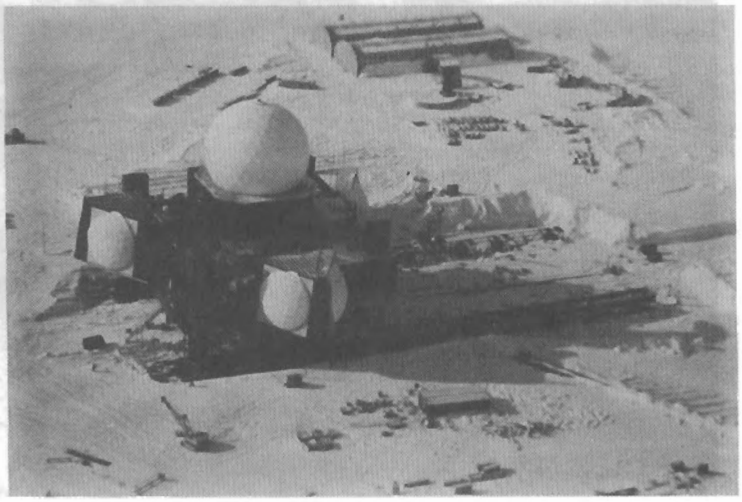


Figure 15. Air photo of DYE-3 shortly after the 210 ft (64 m) sideways move.