THE MAN-MADE MCMURDO ICE WHARF--HISTORY, CONSTRUCTION AND PERFORMANCE

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During the winter months ending DF-73* and commencing DF-74, the winter-over Public Works Department at McMurdo Station constructed a surface-flooded ice structure along the fast-ice shelf in Winter Quarters Bay, Antarctica. Dimensions of the completed appendage included a 460-foot seaward face, a 635-foot backside face, a width of approximately 170 feet and a thickness approaching 29 feet. The giant ice structure served effectively as a wharf during DF-74 resupply operations. It provided both a vertical face

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* The Deep Freeze (DF) year begins in July and ends in June.

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INTRODUCTION

This report documents the construction history and on-site performance of the artificial, man-made ice wharf constructed during the winter months of Deep Freeze-73 in Winter Quarters Bay, near McMurdo Station, Antarctica.

BACKGROUND

Natural Ice Wharf

Since inception of the United States Antarctic research program, surface ships have proven invaluable as a means of providing logistic support. Prior to DF-65, ships which supplied the major U.S. base, McMurdo Station, were forced to unload cargo onto the annual ice at some distance from the base. Thin ice made this operation costly and dangerous. During DF-65, favorable annual ice conditions in the Ross Sea and in the approaches to McMurdo Sound permitted ice breakers to open a channel and clear a turning basin around the shore-fast ice in Winter Quarters Bay. The fast ice which formed the natural ice shelf was believed to be an accumulation of old sea ice [1]. This ice shelf served effectively as a wharf; it consisted of a nearly vertical cliff extending from about 4 feet above sea level to the bottom of the bay, and an almost flat, horizontal top-surface. For the first time in Deep Freeze history, all cargo ships and tankers were able to off-load directly onto Ross Island, discharging cargo onto trucks and trailers in a conventional, efficient fashion. Figure 1 presents an overview of ship traffic along the ice shelf in Winter Quarters Bay.

Damage to the Ice Wharf

The natural ice wharf extended into the bay, providing sufficient cargo handling area and draft depth for simultaneously berthing two large ships [2]. The ice wharf has been used subsequently each year; however, due to erosion of the face, it has been necessary to enlarge the natural quay perimeter by attaching various prosthetic extensions. The following paragraphs describe those measures implemented prior to construction of the man-made ice wharf.

Figure 2 shows the smooth face of the ice shelf during DF-65. Unfortunately, removal of the annual ice around Hut Point was deleterious to wharf survival. The vertical face, no longer protected by a buffer of sea ice, was exposed directly to ablative melting caused by wave action and ship discharge. The result was undercutting. Melted caverns formed at sea level, creating cantilevered lips which would periodically break off unevenly, giving the vertical ice face a jagged and protuberant appearance. Figure 3 shows the effects of ablative melting. In 1969, it was estimated that each year 10,000 square feet of surface area was lost to wave action [3]. Even more serious than the loss of cargo-handling area, however, was the reduced depth of water alongside the wharf. Figure 4 shows how ablation along the seaward face caused the fast ice to recede into the shallower waters near shore.

Remedial Measures

In order to prevent further wave damage, and also maintain a vertical docking surface, the Naval Facilities Engineering Command (NAVFAC) designed a protective dock face. In a 4-year period ending in DF-72, a total of 464 feet of steel and timber facing was installed [4]. Structural beams, placed on the wharf and anchored to piles set in the ice, were used to support a vertical, steel framework with timber panel inserts. This network, which extended from approximately 10 feet above sea level to 20 feet below, prevented wave penetration. A volcanic fill material was packed between the facing and natural ice face to provide additional protection. Figure 5 presents a closeup view along a section of the dock facing. During March 1972, a major portion of the wharf was either destroyed or severely damaged by storm. High tides and pounding ice ripped out many of the steelfaced timber panels, bending the I-beam supports and washing away most of the fill. Unprotected portions of the natural ice face were extensively eroded.

In addition to the problem of a damaged ice dock, submerged debris littered the shipping channel and berthing area. Remedial measures were necessary. A temporary solution was conceived by engineers from NAVFAC who visited McMurdo in December 1972. From their plans, steel workers were able to reconstruct from sections of the original dock structure two piers, 70 and 60 feet long respectively, which extended 5 to 10 feet farther out into Winter Quarters Bay than the previous installation. Two cargo ships (the 18-foot draft *USNS Mirfak* and later the 24-foot draft *USNS Private John R. Towle*), were able to unload from this temporary facility with only minor inconvenience.

Temporary Man-made Ice Shelf

The tanker *USNS Maumee* was also accommodated along the ice shelf; however, because of its 30-foot draft, a fender between ship and shore was necessary. Such a fender was realized in the shape of a large piece of man-made ice, the so-called experimental ''ice cube'' built by the DF-72 winter-over crew. This test section was constructed by periodically flooding and freezing an enclosed 25-foot-wide by 50-foot-long section of annual ice along the natural ice shelf between the two reconstructed pier sections. The original concept was to create a large 15-foot thick free-floating ice floe. Later an attempt was made to freeze the ''ice cube'' to the natural ice shelf, but this attempt failed because the ''ice cube'' could not be freed from the surrounding sea ice. Besides, the success of the pier reclamation effort obviated the necessity for affixing the ''ice cube'' to the wharf. The *Towle* and *Mirfak* were serviced adequately by the two reconstructed piers. The free-floating ice fender was removed during cargo handling with these two ships, and floated back to assist the *Maumee*.

Construction Technique. The DF-72 ''ice cube'' was actually preliminary to a much more comprehensive DF-73 program. It was designed to establish the feasibility of constructing and then maintaining a large ice structure. Flooding techniques and winter construction methods were tested. A framework of 1-inch-thick lumber, supported by 2- by 4-inch posts placed in the annual ice, was built to enclose the 25- by 50-foot test area which was located between the two reconstructed dock sections. During the first month of flooding operations, from 17 June until 10 July, freshwater was pumped in 3- to 4-inch lifts. Water was fed into a truck at 80°F, allowed to cool, and then pumped at about 38°F. This process was tedious, time-consuming, and full of problems. On advice from NCEL*, seawater was used after 10 July until the final pour in October. This substitution accelerated construction time and decreased freeze-up problems. The use of seawater at the freezing point temperature minimized distortion to the structure during flooding.

Problems. Problems were encountered. The inability to free the cube from the surrounding annual ice has previously been mentioned. Although this was not a handicap during shipping operations, it was a nuisance during construction. The forces of tidal action and drifting snow combined to downwarp, often unevenly, portions of the annual ice sheet. The result was unwanted flooding which distorted the form walls and caused additional uneven settlement. All in all, however, the general feeling resulting from this project was one of success and optimism. It set a precedent for future ice construction.

Summary. In summary, shipping operations during DF-73 were completed under less than optimum conditions. The reconstructed dock sections and the ''ice cube'' provided only temporary relief; a more comprehensive, long-term engineering solution was required. Such a solution was envisioned in the form of a very large, man-made ice wharf over 600-feet long, extending 200 feet out into Winter Quarters Bay.

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* The Naval Civil Engineering Laboratory which was redesignated the Civil Engineering Laboratory (CEL), Naval Construction Battalion Center, Port Hueneme, CA, on 1 January, 1974.

ARTIFICIAL ICE WHARF

Construction Plan

During the winter months ending DF-73 and commencing DF-74, the winter-over Public Works Department at McMurdo Station constructed an artificial ice wharf. The completed structure was located between the two reconstructed pier sections. The dimensions included a 460-foot seaward face, a 635-foot backside face, and a width of approximately 170 feet. The final thickness was 29 feet at the center and somewhat less along the seaward face.

No attempt was made during construction to mechanically cut free or artificially support the giant ice structure. The wharf was allowed to welter with the surrounding annual ice. Therefore, the tidal crack between the backside of the flood zone and the natural ice shelf was simply isolated and allowed to work (later in the season the crack was packed with snow and flooded for added thickness). Initially, it was anticipated that increased weight from the layered buildup of flood ice would precipitate a crack along the annual-ice/ice-wharf interface, and that additional weight would sink the appendage, grounding it to the ocean bottom and thereby preventing further welter. It was then expected that the tidal crack would freeze, making the wharf a natural extension to the fast ice shelf. Though in practice this separation did not occur naturally; the structure was used successfully to dock the cargo ship *Towle* and tanker *Maumee* during DF-74 shipping operations. The following sections summarize the construction history of this unique wharf as well as its performance during offloading.

Construction History

Ideally, construction was to be accomplished according to the following schedule: (1) enclosing the selected area of annual ice, (2) flooding the enclosed area with 3 to 4 inches of seawater, (3) allowing the water a few days to completely freeze, and (4) repeating the process until a thickness of 30 feet was realized. Under recommendation from CEL, collapsible 8-inch-diameter polyethylene tubing was used to enclose the construction area. The procedure planned was simple: (1) placement of the collapsible tubing; (2) filling the tubing with seawater; and (3) allowing the water time to freeze (resulting in a rigid 8-inch wall, high enough for two or three pours of seawater for each lift); (4) to stack the next run of tubing on the first and (5) to repeat the procedure until completion.

Initially, two pumphouses were installed on the annual ice, each positioned about 40 feet off the centerline of the ice wharf on the seaward side. Open-ended 55-gallon drums were placed in the ice sheet and heated in order to maintain open access to seawater. The original plan required the installation of deadmen and connecting cables in the flood zone at a selected period during construction. This network was designed to lash the structure against shore during periods of open water.

In practice, flooding did not progress as smoothly as anticipated. The first pour was made on 27 April, the day after the polyethylene enclosure was placed and filled.* The close spacing of the two pump houses near the center did not provide an even distribution of water over the entire enclosure. As a result, the weight of the flood water depressed the center area, an effect which in turn attracted additional water. Uneven flooding also caused the south end to downwarp, further adding to the unequal distribution of water. The annual ice did not maintain the wharf area in a level position, but rather behaved as a moving base, changing elevation according to tidal fluctuations and the distribution of flood water.

In order to correct the problem of uneven flood distribution, the pumphouses were relocated. One was positioned at the center, and an additional station was placed at each end. The second lift was started on 9 May and completed on 17 May. The major problems in this portion of the operation were associated with placement of the polyethylene tubing. After the first lift, the flood zone contained high and low spots and, as a result, did not provide an even surface for stacking the tubing. Also, it was not possible to stack the second run of tubing directly over the first. Further, winds caused the water-filled tubing to slide over the ice. These problems were serious since one of the prime requisites was a vertical face. After 900 man-hours of labor, at the end of May, only 1-1/2 feet of ice had been added to the thickness.

From this dilemma the concept of the snow wall was conceived. This concept involved a segmental construction of the seaward wall by means of packing a snow-water mixture into plywood forms of various lengths. These forms, 1 foot wide by 4 feet tall, were positioned and repositioned along the entire length of the seaward face. The overall product, after a short freeze-up period, was a rigid and continuous wall able to withstand winds and prevent serious water leakage. Since the wall was constructed in segments, it was easy to accommodate irregularities in surface elevation. The first snow wall along the ship berthing side of the wharf was completed on 14 June after a concentrated effort. The remainder of the wharf perimeter did not require a nearly vertical face; therefore, snow was simply piled into mounds using a low ground pressure D-4 bulldozer.

The first snow wall provided sufficient height for 3 weeks of flooding. The objective during this period, and for that matter until the end of construction, was to make as many pours in as short a time as possible in the hope that later cold temperatures would completely freeze the seawater layers. As a result, distorted areas of the wharf flooded to depths of several feet in partially frozen layers. This procedure was not an application of good flooding techniques. Surface

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* The backside boundary was offset 50 feet from the steel pier in order to isolate the tidal crack. Later this area was flooded to form a thickened causeway.

flooding is usually done in 3- to 4-inch layers in order to insure complete freezing between pours. Subsequent follow-up coring indicated that indeed most of the ice was soft and just barely frozen, while below the surface crust there was slush. However, in November a core taken through the entire thickness of the completed wharf indicated that the flood ice was solid and typical of ice formed by surface flooding. It appeared as if the necessity for rapid thickening did justify the deviation from standard procedure. At any rate, during this 3-week period 5 additional feet were added to the thickness.

The second snow wall was constructed on 9 July in 7-1/2 hours in spite of 25-knot winds and blowing snow. At that time it was decided to thicken the area of ice around the tidal crack - that is, between the backside snow mound and steel pier. The necessity for crack strengthening became even more apparent a few days later when an ''artificial'' crack developed in the wharf itself, a 175-foot-long crack in the southwest corner which ran 5 feet inside of the snow mound. Additional flooding was prohibitive because of seepage through the crack. Therefore, operations were halted until 1 August when a third snow wall was built. It was believed that the delay would give the crack time to refreeze.

It was also decided not to install deadmen in the wharf. Cables in the area around the tidal crack would have reduced the maneuverability of construction equipment. An alternate plan was adopted which required the installation of bollards at the end of construction in October or November. This plan had several advantages: (1) construction would not be obstructed; (2) cables need be secured to shore just prior to docking when the structure was cut free; and (3) the bollards could also be used to moor the ships.

The fourth and final snow wall was completed on 11 September, when the thickness at wharf center was 21-1/2 feet. Pumping operations on a 12-hour pump rotation continued until the final pour on 7 October. The final thickness of the wharf near the center was 29 feet.

Ice Core Sampling

On 25 November, CEL personnel extracted a 3-inch-diameter ice core from near the center of the surface-flooded ice wharf for its full thickness of 29 feet. The ice core was examined as it was recovered and ice samples collected from each foot of depth for determination of salinity. Examination of the 29-foot long core showed the following:

1. The snow depth on the ice surface was 22 inches; the snow was hard and wind packed.

2. The flood ice extended from beneath the snow cover to a depth of about 25 feet and was solid and typical of ice formed by surface flooding. Layered bands were prominent in the upper 10 to 12 feet, and no pockets of unsaturated snow were found.

3. Between 12 and 25 feet the layers were not visible. The ice crystals were larger and brine passages were more prominent; but the ice was sound, and no pockets of slush or distinct poor ice were observed.

4. At the 25-foot depth, the appearance of the ice changed markedly and contained a smaller crystal structure with fewer, less distinct brine passages and pockets. This condition was observed in the remaining 3 feet of core recovered and can be defined as the natural ice on which flooding began. The last section of core, estimated to be about 1 foot long, was lost; and no examination of the ice structure at the water interface was possible.

5. The drilling rate during the coring operation was much greater than in natural sea ice, and water was present in the hole from a depth of approximately 10 feet to the bottom. This was expected in surface-flooded ice.

Salinity Measurements

The results of the salinity measurements made at 1-foot intervals are shown in Figure 6. The highest salinity measure was 15 parts per thousand (ppt) with an average of 9.7 ppt. This was about twice the average salinity for 1-year-old sea ice but again was considered normal for the flooded ice at that time.

A salinity measurement was also made on a sample of water and slush taken from one of the 24-inch-diameter holes drilled on 17 November for installation of bollards. This water was found to contain 104 ppt of salts or three times that for normal seawater. The water in the bollard holes originated as brine interspersed in the matrix of ice crystals. Based on the latter finding, it was recommended that the bollard holes be pumped dry immediately before bollard placement and that, if possible, fresh water and dirt be used as backfill. If the holes were pumped out too far in advance of backfilling, the holes would have again filled with high salinity water.

DOCKING PREPARATION AND PERFORMANCE

On 18 January 1974, the artificial ice wharf was finally put to the test when used to dock the cargo ship *USNS Private John R. Towle*. Prior to that date, measures taken to prepare the facility were: (1) a pontoon and timber bridge was built to span the tidal crack from the old wharf to the newly constructed ice wharf; (2) the wharf surface was cleared of snow and covered with a 10- to 20-inch layer of insulating fill material; (3) five bollards were installed along the seaward side in 11-foot deep holes drilled with a 29-inch-diameter drill bit; and (4) cables were strung between shore bollards and the five wharf bollards in order to maintain the appendage against the shore. By early January the single-most important preparation still undone involved cleaving the annual ice from the vertical seaward face. Figure 7 pictures the structure prior to breakout attempts. It was agreed that a weakened interface should be formed. A series of holes of 10-inch diameter, about 5-foot depth and located on about 5-foot centers was drilled in the annual ice at the construction interface.

The ice breaker *USCG Staten Island* moved into Winter Quarters Bay on 15 January to remove ice from the vicinity of the wharf. Initial passes were intended to break up the annual ice at some distance from the structure. Even so, a crack which began in the annual ice continued to propagate through the wharf, all the way to the tidal crack. In addition to this major full-depth crack, there were other hairline fractures. Operations were halted and two bollards installed in order to tie the two sections together.

The next day the ice breaker resumed maneuvers. It made good progress on clearing the wharf face. On the last pass, however, the ship moved too closely, and the resulting impact opened up several new full-width, full-depth cracks. Also, an end piece totally separated and floated away. The remaining sections were large and worth saving; two additional bollards (for a total of seven) were added, and the entire network lashed together. Figure 8 presents a sketch which shows crack and bollard configuration at the time of cargo unloading.

The ice breaker did not leave the seaward face even and smooth, but rather jagged and protuberant. Underwater benches of ice effectively prevented the *Towle* from docking alongside. Explosives were used to remove most of the appendant ice.

The ice wharf proved to be a very effective facility for cargo handling once the seaward face was adequately cleared. The *Towle* (Figure 9) was successfully unloaded twice in DF-74, during January and during the return visit in February. In addition, oil was discharged in late January from the tanker *Maumee* as she was berthed alongside the giant ice structure. No major problems were encountered in the wharf itself. It provided a good, solid platform with an abundance of space for cargo handling and vehicle traffic. The cables effectively held all the separate pieces together, as well as the entire assembly against shore.

CONCLUSIONS

Construction of the wharf facility was the major project of the 140-man winter-over work force. All in all, about 19 million gallons of water were pumped, about 20% of which was estimated as lost in seepage. It provided an efficacious remedy to the problem of resupply logistics during DF-74. The most pertinent question now is the following: Does this structure present an adequate long-term solution to the problem of shipping operations? This question cannot be answered with complete certainty. The storm during March 1972 was certainly testament to the strength and fury of polar weather. However, such natural calamities are completely unpredictable and unpreventable. Important is the fact that, at the present time, there is no alternative scheme which can be implemented immediately and guarantee a more efficient or more permanent solution. For this reason, every effort should be made to conserve the ice structure for future use and study.

RECOMMENDATIONS

The following steps should be taken to adequately prepare the wharf facility for service during DF-75.

1. Provide adequate drainage for surface melt-water run-off.

2. Maintain an effective layer of top-surface insulating fill so as to minimize surface melt-water formation.

3. Minimize both the period and area of open water around the ice wharf when Winter Quarters Bay is cleared just prior to arrival of the ships.

4. Develop methods for cutting the interface of the ice wharf and annual ice so that a smooth face without underwater benches is obtained.

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Figure 1. Ship traffic along the natural ice shelf in Winter Quarters Bay, DF-65.

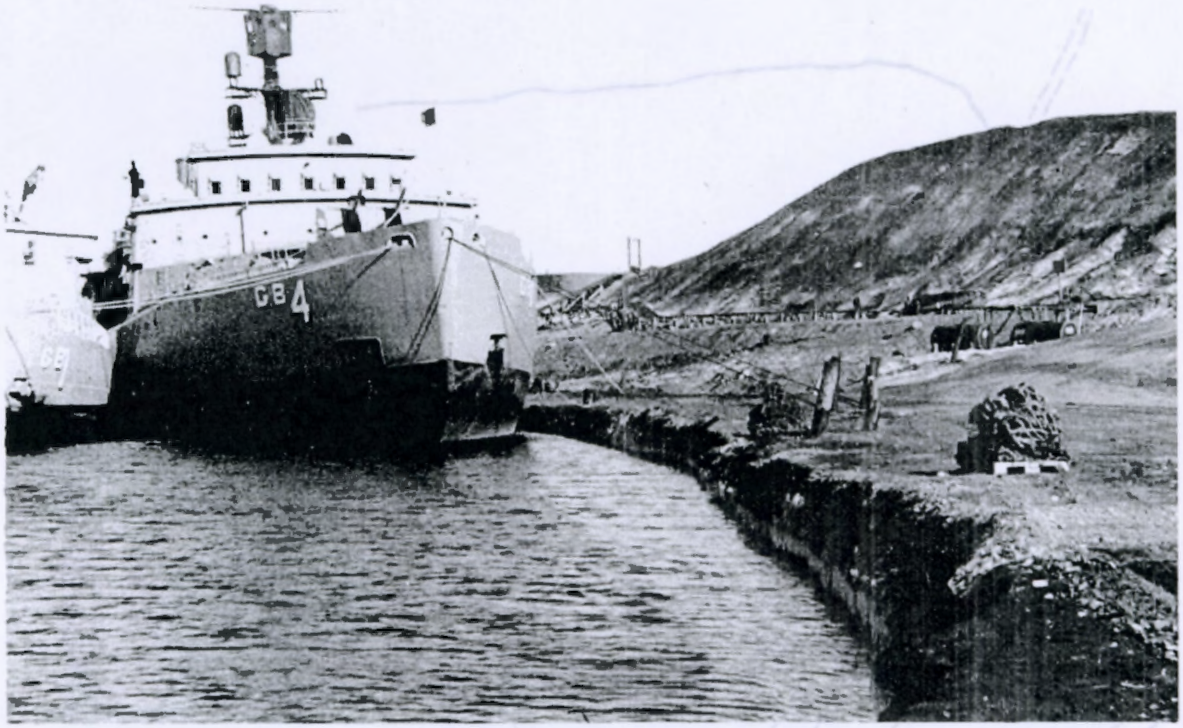

Figure 2. View of the smooth, natural ice wharf face during DF-65.

Figure 3. Jagged appearance of ice face due to undercutting after DF-65.

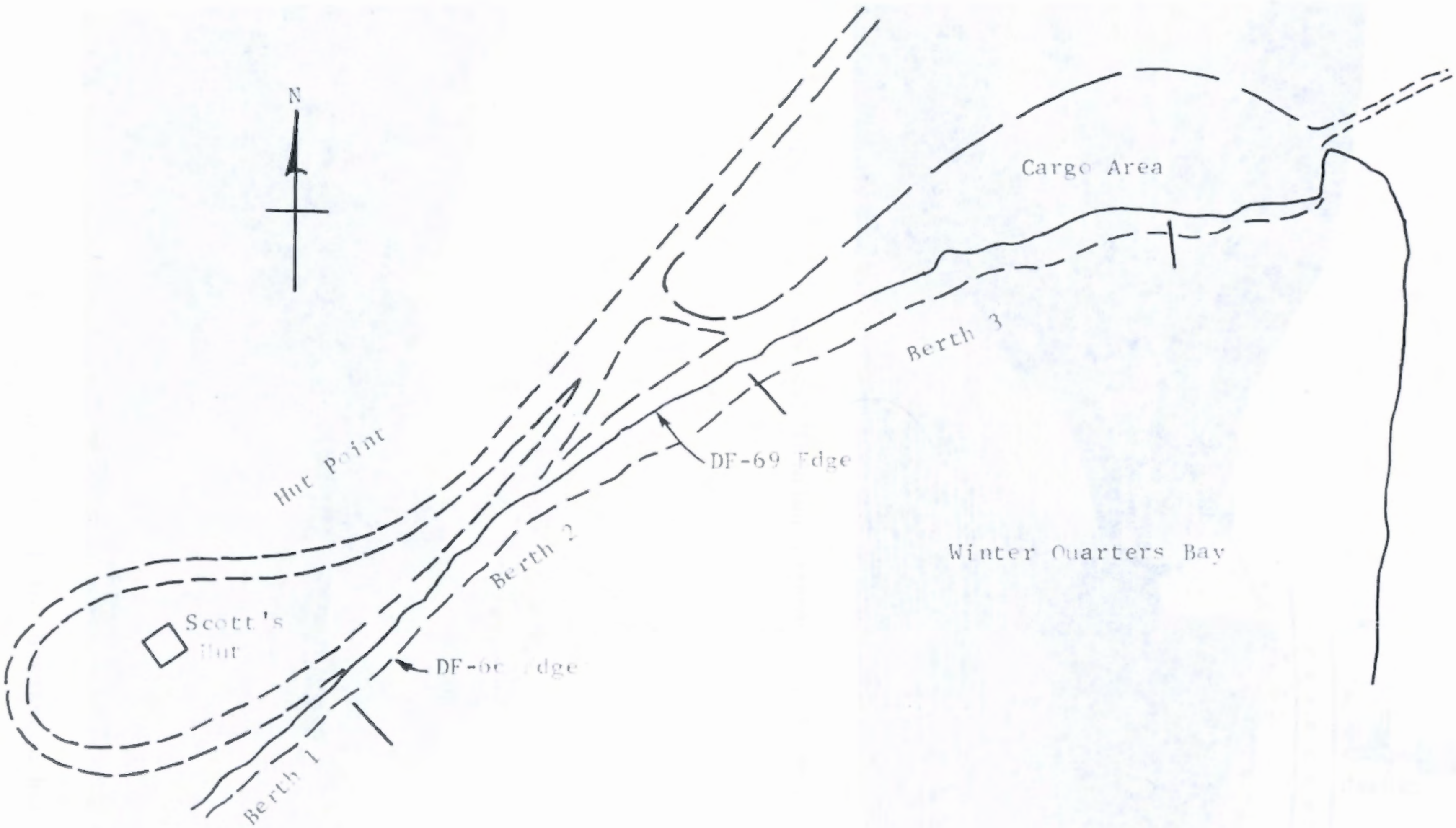

Figure 4. Sketch showing ablation history of natural ice wharf.

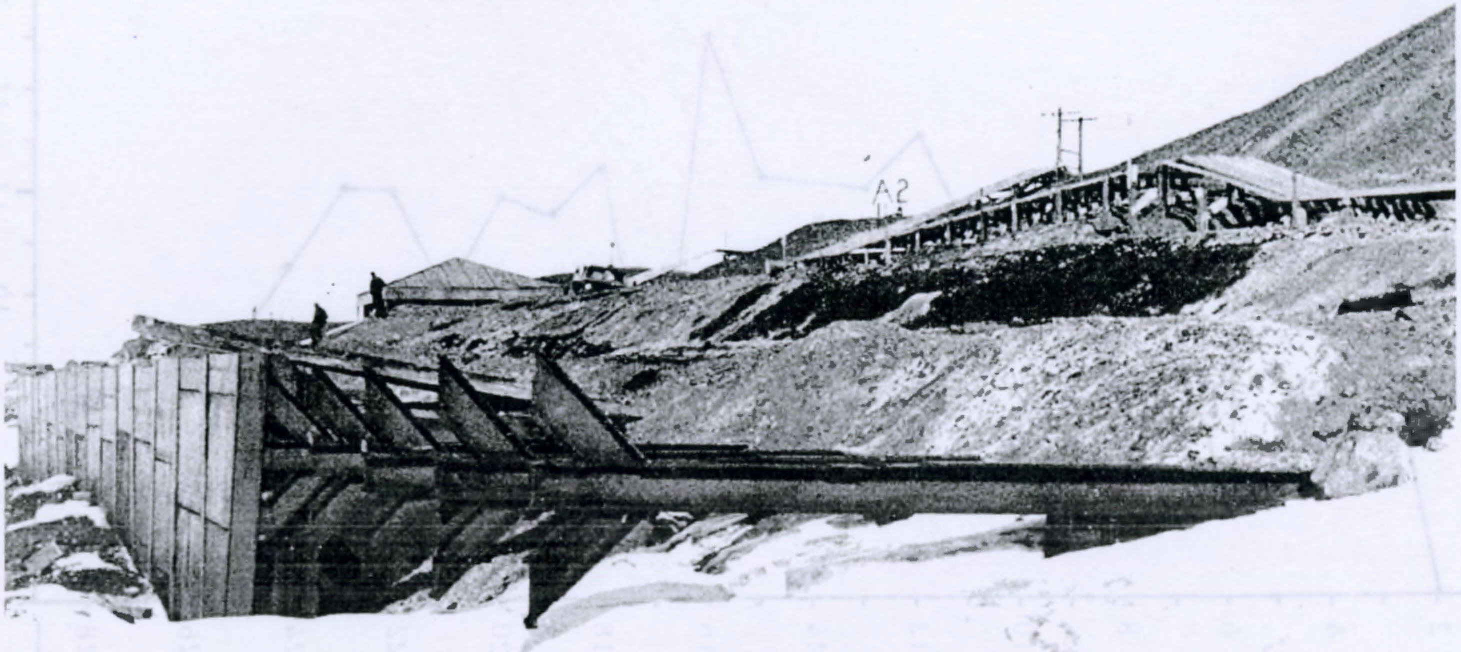

Figure 5. Construction of the steel-and-timber dock sections.

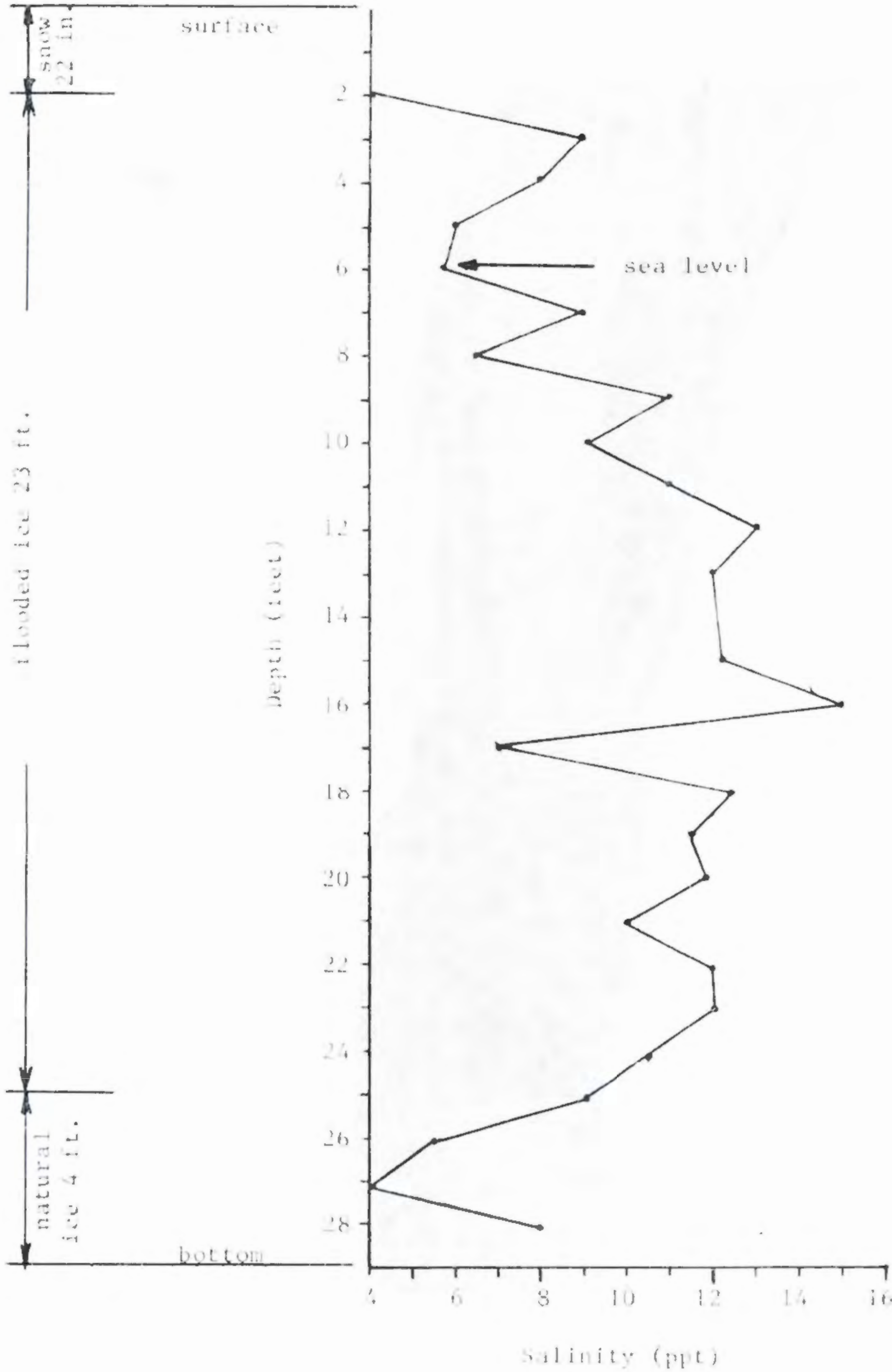

Figure 6. Salinity profile of core extracted from surface-flooded ice wharf, 25 November 1973.

Figure 7. Surface-flooded ice wharf just prior to breakout, DF-74.

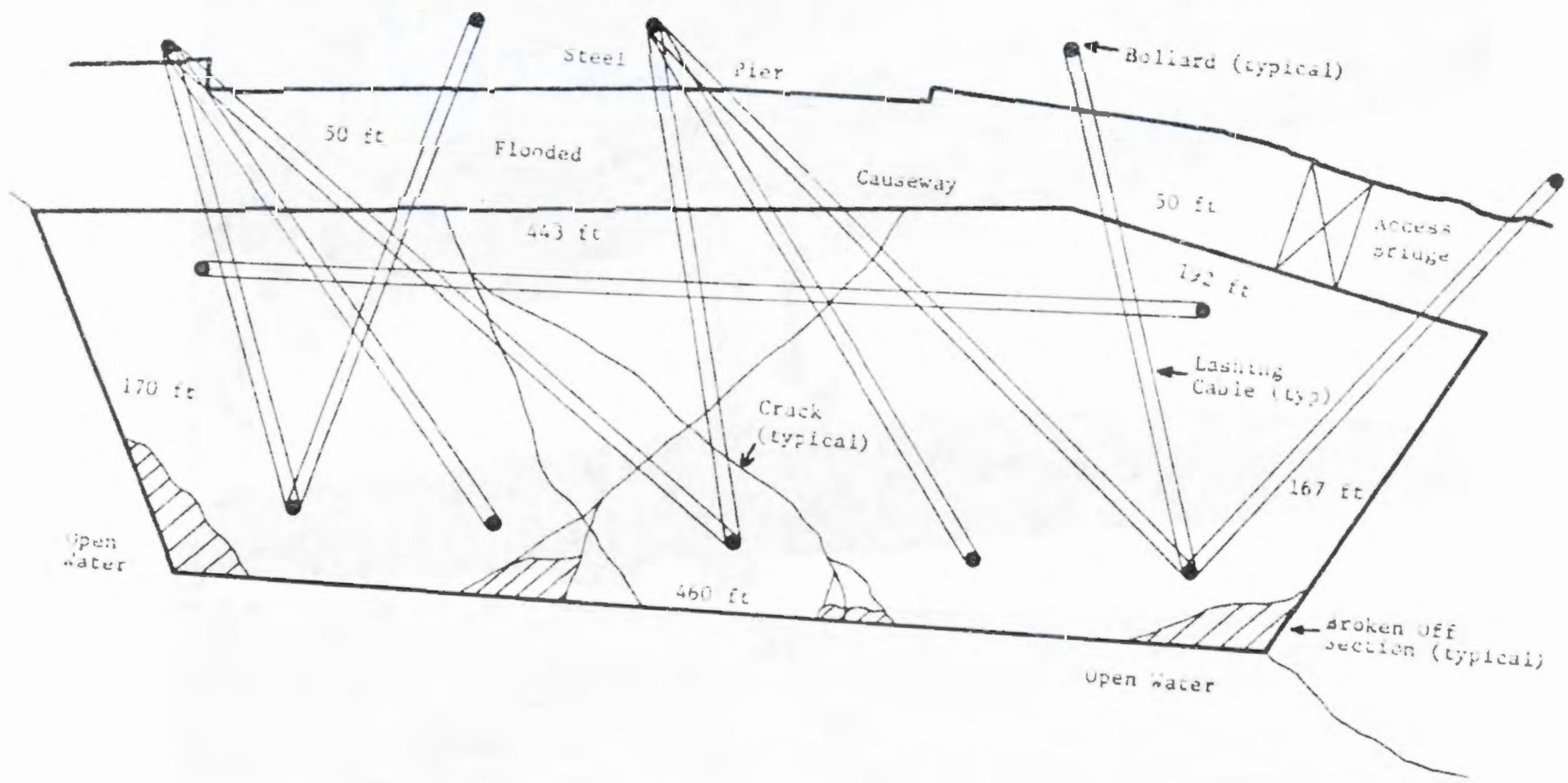

Figure 8. Surface-flooded McMurdo ice wharf during breakout, 16 January 1974.

Figure 9. *USNS Private John R. Towle* docked against the man-made ice wharf, DF-74.

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