HARVESTING GLACIER ICE 1/

584-74

By

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Potential Use for Glacier Ice

Glaciers contain frozen fresh water. About 75% of the earth's fresh water supply is locked up in ice sheets. In water short areas, thin vast seemingly unused resource offers an interesting challenge. In addition the ice sheets are a heat sink which could provide a welcome relief to some regions suffering from the adverse side effects of thermal pollution.

A glacier occurs because more snow accumulates during the year than is removed by evaporation and melting during the melting season. The snow accumulates and compacts the previous accumulation until a considerable depth of snow and ice exists. The density of glacier ice varies from 0.84 to 0.89 compared to 0.92 for a solid ice cube.

There are two parts in the hydrologic cycle for a glacier. The first is accumulation which occurs during periods of precipitation in the winter time. As the summer season approaches some of the surface snow melts, evaporates or runs off. This is a period of ablation, but for a glacier, the long-term mass ablation is less than the mass accumulation. Thus a glacier is a type of open-ended long term storage element in the hydrologic system. Obviously the accumulation cannot continue to exceed ablation year after year without removing entirely all of the water of the earth from the hydrological functions.

The glacier begins a slow viscous type of creeping in a down slope direction collecting in valleys. The glacier will continue movement down the valleys until warmer conditions prevail and ablation controls the glacier terminus or until the glacier reaches the ocean. At the ocean-glacier interface, the glacier ice is undermined by melting due to warmer water and slabs of the glacier break off, fall over and float away as icebergs. The glacier ice floats because the density is less than sea water. The formation of the iceberg is called calving.

The iceberg has much greater mobility than the glacier ice possessed. If we are interested in utilizing glacier ice, then we should carefully observe and monitor the calving process. Normally the icebergs float off to warmer regions where they eventually melt. Meanwhile the icebergs are a navigation hazard. We all remember the unsuccessful encounter of the Titantic with an iceberg in the North Atlantic Ocean. Harvesting glacier ice offers three advantages:

1) Provides a source of fresh water,
2) Provides a heat sink,
3) Removes a potential navigation hazard.

History of Use of Glacier Ice

The idea of using glacier ice as a potential fresh water supply was considered about 25 years ago when the Bureau of Reclamation was exploring various ways to augment the water supply to the Southern California region. At that time, it was thought that the iceberg would be towed into a dry dock and allowed to melt pumping out the fresh water. The idea was discarded because of adverse cost compared with other water sources.

Keithahn (1967) cites the fact that during the winter of 1853-54, a ship loaded glacier ice cut from the Baird Glacier for use in San Francisco. Prior to that time Alaskan lake ice had been harvested and transported by ship to San Francisco. According to Weeks and Campbell, C. Hoerning relates that small icebergs were towed by ship and sailed from Laguna San Rafael, Chile (at latitude 45^0 S) to Valparaiso and even to Callao, Peru

1/ Presented at Western Snow Conference, April 16-20, 1974, Anchorage, Alaska

2/ Associate Professor of Civil Engineering, Colorado State University, Fort Collins, Colorado 80523 (at 120° S) a distance of 3900 kilometers. This was in the period from 1890 to 1900. (By way of comparison, the distance between Yukatat, Alaska and Los Angeles is 3200 kilometers. The distance between southern Greenland and the entrance to the Mediterranean is 4000 kilometers.)

In more recent time, the feasibility of towing icebergs from the North Atlantic into the Mediterranean has been discussed (Jacobi, 1974). Even a superficial review of the literature discloses a long standing interest in the *use* of glacier ice in various parts of the earth.

Source Regions for Icebergs

With the advent of satellite weather observations and the new ERTS photographs, it is now possible to carry out a systematic study to gather the facts about calving frequency of large icebergs and their migrations. Swithinbank (1969) reports the tracking of two very large icebergs from the Amery Ice Shelf in Antarctica to the Weddell Sea using ESSA-3 satellite photographs.

These ice islands measured 45 km by 100 km and 70 km by 100 km. These were identified on ESSA-3 satellite photographs. These ice sheets are commonly about 250 meters in thickness and the figure of 250 meters was used in the Weeks and Campbell study.

The desirable tabular ice island type of iceberg forms when a very thick ice sheet moves without a great deal of fracturing into the ocean. The ice island simply breaks away. In the Arctic region this type of calving of the ice sheet occurs mainly to the north and west of Ellesmere Island, Sater (1969). From this region the ice islands move into the Beaufort Sea Gyre and do not become readily accessible for towing because the ice islands are embedded in pack sea ice. One of these was called Fletcher's Ice Island, T-3, formed in 1946, and has been occupied by an observation station since 1952. Sater (1969) relates how in 1961-62 the Ward Hunt Ice Shelf lost five large ice islands.

Another source of icebergs which calve from the tidewater inlets in southeastern Alaska is shown in Fig. 1. Since these icebergs are derived from highly contorted valley glaciers, the icebergs are smaller in volume and bear little resemblance to the tabular icebergs discussed by Weeks and Campbell. The redeeming feature of the southeast Alaska icebergs lies in the fact that 1) they are derived from a region having relatively high precipitation (accumulation zones), 2) they could be towed in a relatively strong southward California current a short distance off shore and 3) they are only about 3200 kilometers from an obvious region of need off southern California.

The strong orographic effect of the rugged mountain slopes accounts for the more than 1500 to 5000 millimeters of annual precipitation experienced here. Since the glaciers move in narrow valleys and discharge into narrow fjord-like inlets, they often tend to span the valley and to be blocked by a relatively prominent constriction. Post and La Chapelle (1971) have documented many of the facts of the glacier ice. They show graphically the retreat of Guyot Glacier between 1938 and 1963. Approximately 165 square kilometers of the glacier was lost during the 25-year interval. A major part of this loss occurred during a 6-year period when the glacier retreated from a promontory in the inlet to the next channel constriction upstream. The headlands seem to provide an anchor point where the glacier terminum achieves a temporary stability until the next sudden retreat.

Technical Problems Requiring Solution

In the early days, Alaska Glacier Ice was shipped to San Francisco by sawing the ice into blocks and loading aboard the ship. Obviously this technique is not feasible for the quantities of ice needed today. It would be much simpler to tow an iceberg to its destination.

Power Required: The total drag on an iceberg is the sum of three drag components: (1) form drag, (2) skin friction and (3) wave drag. Since the towing velocity is likely to be so small, the wave making resistance *is* negligible. The form drag for a blunt object decreases as the length to beam ratio increases. Gordienko (1960) documented iceberg sightings and shapes in Antarctic waters. The length to width ratio was commonly 4 and the heights above water were between 30 to 50 meters which means that the total iceberg thickness must have been between 170 and 280 meters. (The thickness of the Amery Ice Shelf is in the order of 250 to 300 meters.)

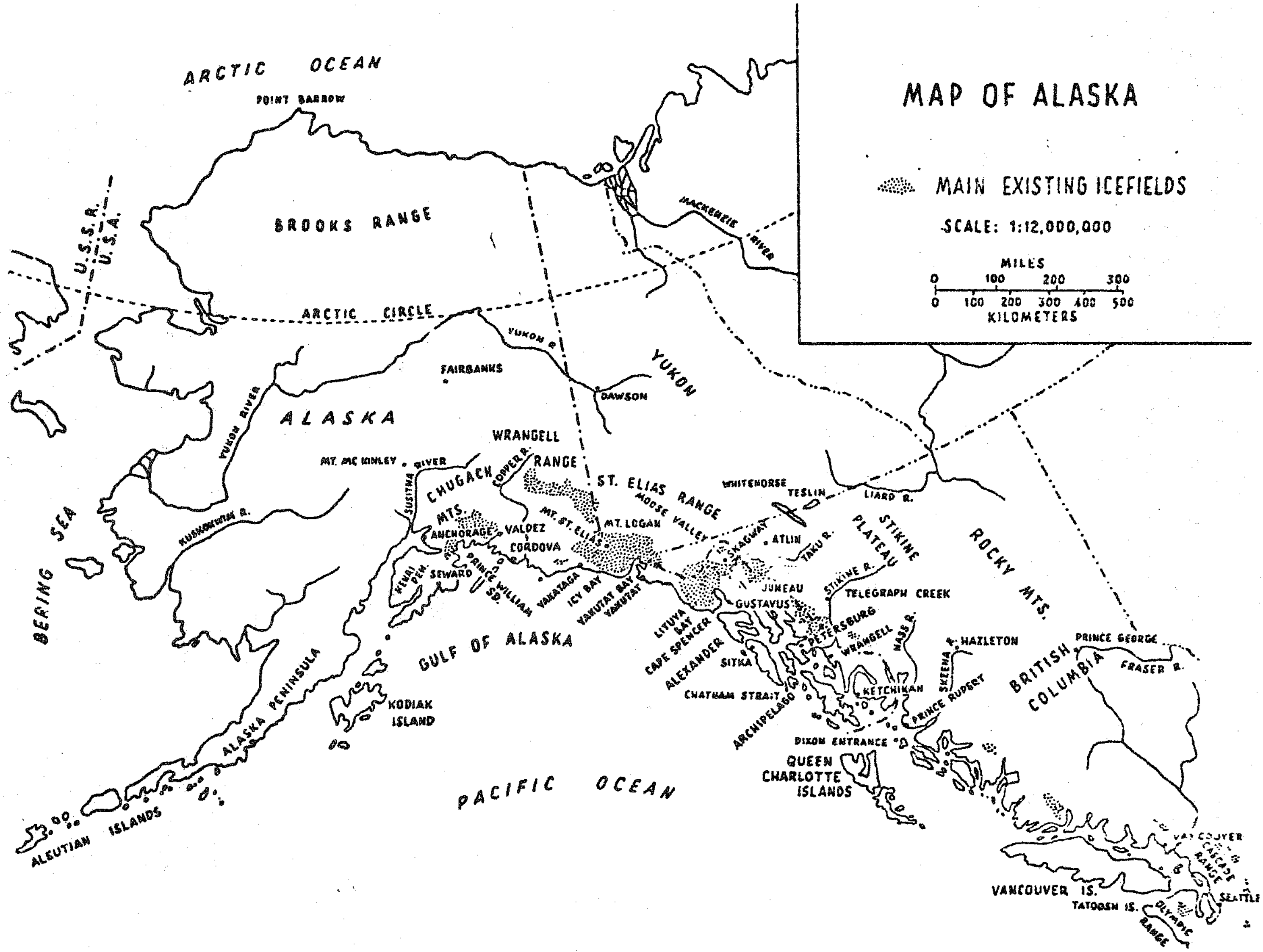


Fig. 1. Glaciers of Southeast Alaska, *adapted from Miller (1972).*

The form drag coefficient, $C_{D(form)}$, for a blunt object would be 0.9. As towing commenced the cold content of the iceberg would be more rapidly depleted by the warmer sea than if it were allowed to drift in the sea. The heat transfer into the iceberg would be increased by turbulent transfer. The most rapid heat transfer would occur at points of most intense boundary shear. This should result in most rapid melting at the shoulders and any prominences at the front. Toward the rear of the iceberg, the melting should be reduced because of the colder water having been cooled by melting farther forward. Weeks and Campbell (1973) assumed a gradual streamlining which would result in reducing the drag coefficient from 0.9 at the start to 0.4 at the end of the journey with an average value of 0.6 for the journey.

The skin friction drag, $C_{D(skin)}$, was estimated by Weeks and Campbell to follow the relationship.

$$\frac{1}{\sqrt{C_{D_{skin}}}} = 3.46 \log_{10} Re - 5.6. \tag{1}$$

This is the largest drag component.

The drag force required to tow the iceberg is

$$D = D_{form} + D_{skin} + D_{wave}$$

$$= \frac{1}{2} \rho_w C_{DF} A_F V^2 + \frac{1}{2} \rho_w C_{DS} A_S V^2 + 0$$

$$= \frac{1}{2} \rho_w V^2 (C_{DF} A_F + C_{DS} A_S) \tag{2}$$

where

D is towing force (Newtons),

ρ_w is sea water density (1030 kg/m^3),

V is the velocity (m/s),

C_{DF} is Form Drag Coefficient varying from 0.9 to 0.4 with an average value of 0.6,

C_{DS} is the Skin Friction Drag Coefficient from Eq. (1),

A_S is the wetted surface of the iceberg (m^2).

The wave making drag is neglected.

The drag force for a square plan-form iceberg is shown on Fig. 2 for various towing speeds as a function of various sizes of iceberg. The total drag is shown as solid lines while the skin friction drag is shown as dashed lines. It was assumed that the iceberg draft was 200 meters.

Figure 3 is a diagram giving the estimated towing force for an elongated tabular iceberg having a draft of 200 meters and a width of 500 meters. The length to width ratio varies from 1.5 to 10 which is the reasonable range of tabular icebergs.

Figure 4 is a graph which expresses the total drag force on a tabular iceberg having a length to width ratio of 4. The graph is given in three parts. The total drag force when $C_{D(form)} = 0.9$ is shown on the left diagram. The skin friction drag is shown as dashed lines. The right diagram shows the total drag force assuming a $C_{D(form)} = 0.6$ which is the average value for the iceberg during its transit. These graphs are given in parameters of the iceberg width. In all cases it is assumed that the total thickness is 250 m of which 200 m is submerged. These graphs will give the total drag force for an assumed speed and iceberg size which will be used later under the discussion of tug boats.

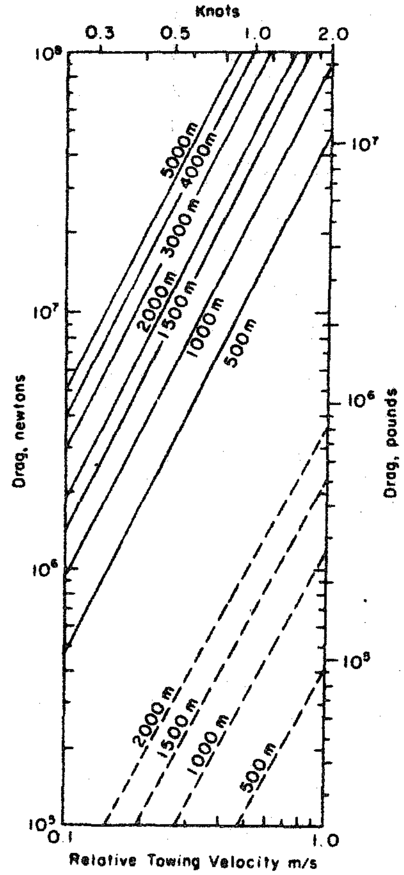


Fig. 2. Drag of Square Icebergs. Draft is 200 m. Solid Line is Total Drag. Dashed Line is Skin Friction.

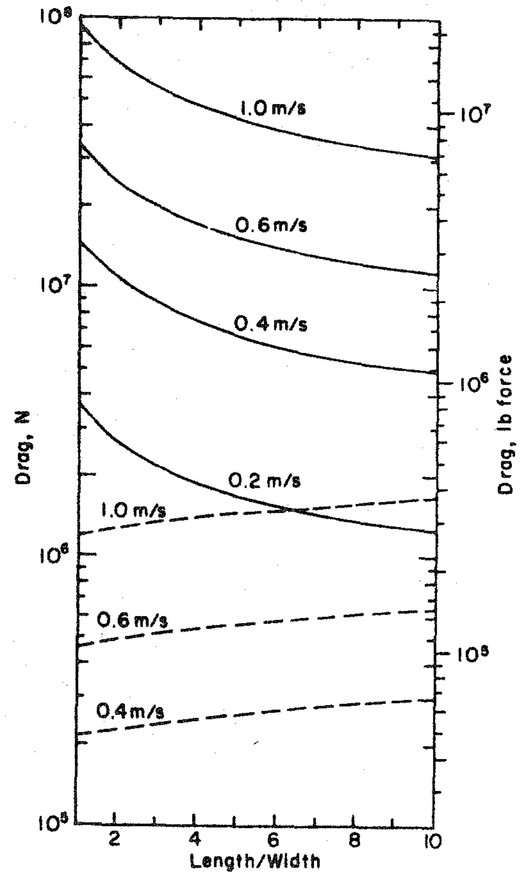


Fig. 3. Drag of Rectangular Icebergs. Draft is 200 m. Solid Line is Total Drag. Dashed Line is Skin Friction Drag.

adapted from Weeks and Campbell (1973)

Normally the icebergs melt when they arrive in warmer waters. Because they often travel in circuitous meandering paths, they do not arrive in regions of potential use before they melt. Deliberate towing would effectively extend the range of the iceberg. The towing speed is limited by the power available, the cost of fuel and the size of the iceberg. Since the cost is a function of the towing velocity squared, there is a definite advantage in keeping the speed small. At lower speed, the rate of cold loss from the iceberg is reduced. On the other hand, the slower velocity results in a longer transit time and attendant increase in mass melt loss. Also the iceberg cannot be maneuvered at very low speeds; however, the need for maneuvering would only be greatest at the end of the journey when the remaining mass is least. Given a tug of a particular size, the potential speed would be higher at the end of the journey than at the start.

The optimum towing speed, tug horsepower, iceberg size and delivery rate is a complex problem. The optimum solution is believed to be feasible using modern systems engineering methods.

The Melting Problem: The problem of melt loss of the iceberg was based on some observations of natural iceberg loss in the North Atlantic by Kollmeyer (1966). According to Weeks and Campbell, the melt loss is primarily the result of heat transfer by convection and condution. Since Kollmeyer treated the case of an iceberg drifting and rolling in the sea, it is possible that his treatment of the problem might be quite inadequate for the flow field around a towed iceberg even at a relatively low velocity.

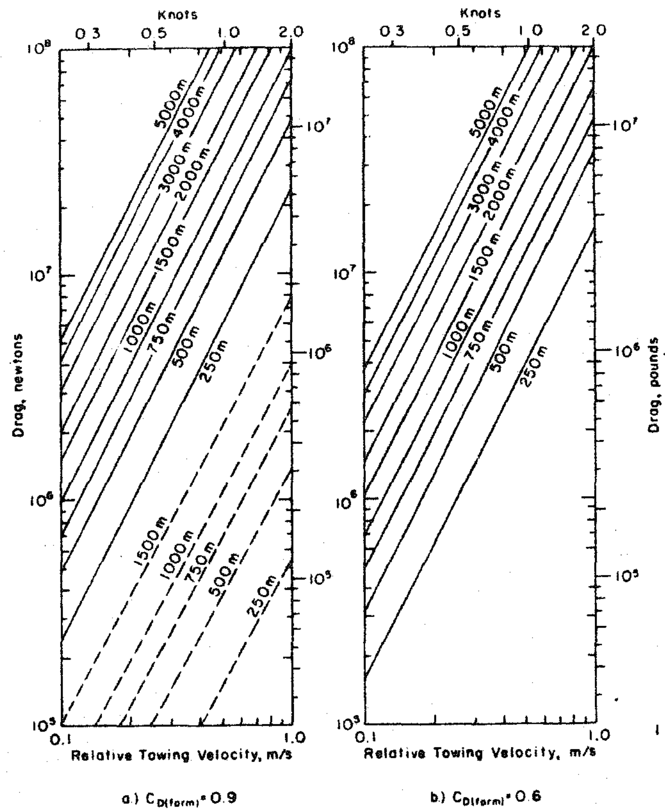


Fig. 4 Drag of Rectangular Icebergs. Solid line is Total Drag, Dashed Line is Skin Friction Drag.

adapted from Weeks and Campbell (1973)

Weeks and Campbell used a heat exchange model for the iceberg based on the calculation of an average heat transfer coefficient, $\bar{h}$, for fully developed turbulent flow over a flat plate:

$$\overline{Nu} = 0.037\ (Re)^{0.8}\ (Pr)^{0.33} \qquad (3)$$

where

$\overline{Nu}$ is the mean Nusselt Number, $\overline{Nu} = \frac{\bar{h}x}{\kappa}$

x is the distance along the side of the iceberg from the leading edge (distance along the flat plate),

κ is the thermal conductivity of the sea water,

Re is the Reynolds number, $Re = \frac{Vx}{\nu}$,

V is the velocity (m/s),

ν is the kinematic viscosity,

Pr is the Prandtl number, $Pr = \frac{C_p\mu}{\kappa}$,

C_p is the specific heat of the water,

μ is the dynamic viscosity.

Assuming κ, ν, μ and C_p to be constant, Eq. (3) can be simplified to:

$$\bar{h} = 1914 \left(\frac{V^{0.8}}{x^{0.2}}\right) \tag{4}$$

The heat flow rate, Q, for the submerged surface of the iceberg is:

$$Q = hA \, \Delta T \tag{5}$$

where ΔT is the temperature gradient between the ice and sea water. The melting rate of the submerged face, R, is:

$$R = \frac{Q}{AL\rho_i} \tag{6}$$

where

L is the latent heat of fusion of ice, $L = 3.3.4 \times 10^3$ J/kg,

ρ_i is the density of ice, $\rho_i = 850$ km/m^3,

x is the length of the side of the iceberg.

Equation (6) then becomes:

$$R = \frac{6.74 \times 10^{-6} \, V^{0.8} \, \Delta T}{x^{0.2}} \tag{7}$$

Equation (7) is expressed graphically in Fig. 5 assuming a temperature gradient of 1.0°C. This temperature gradient will increase toward the end of the journey.

Weeks and Campbell found that using Eq. (7) and Eq. (2) and reasonable values of ocean temperatures, a tabular iceberg having dimensions of 55 m x 200 m x 250 m and could be towed at 0.5 m/s by available ocean going tugs would melt entirely during the transit from Amery Ice Shelf to Western Australia (a distance of 7000 km).

Optimum Towing Path: The course selected for towing the iceberg will consist of a simultaneous solution to a number of problems. The basic steady state equation governing the towing is:

$$F + D_A + D_W + C + G = 0 \tag{8}$$

where F is the towing force, newtons,

D_A is the drag of air (wind) on the air exposed surface,

D_W is the drag of water on the submerged surface,

C is the Coriolis force,

$$C = 2 \, \rho_i \, X_T \, X_W \, X_L \, \omega \sin \phi \, V_T$$

G is the ocean current force,

ρ_i is the density of the ice,

X_T is the thickness of the iceberg,

X_W is the width of the iceberg,

X_L is the length of the iceberg,

ω is angular velocity of the earth,

ϕ is the latitude,

V_T is the transit velocity.

Weeks and Campbell produced simultaneous solutions to Eq. (7) and (8) for a range of iceberg sizes, possible routes considering both mean wind and ocean currents, and towing speeds. A field of V_T was computed for each iceberg choice and route area by graphically including the Coriolis and ocean current vectors. The towing force was varied at each point and the optimum transit route was chosen such that:

$$\int_0^L V_T \, dL = \text{a maximum.}$$

It is difficult to generalize the solutions found by Weeks and Campbell for the Alaska iceberg sources; however, their basic approach appears to be feasible.

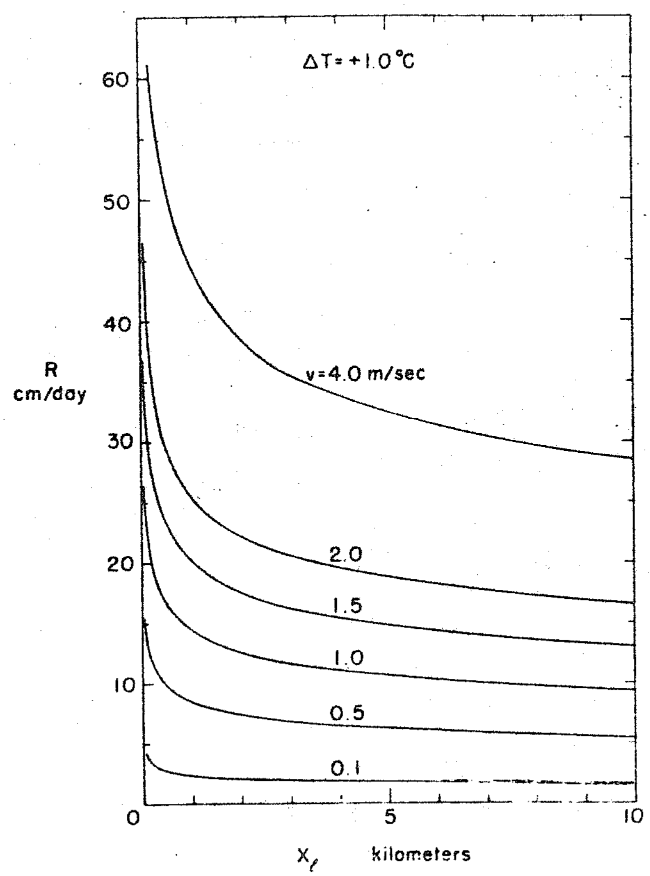


Fig. 5 Average Rate of Melting of the Submerged Surface of the Iceberg as a Function of the Length of the Iceberg, adapted from Weeks and Campbell (1973).

Methods of Towing: The problem of towing may be difficult. The submerged surfaces of the iceberg will melt more rapidly and undercut the top of the iceberg. There may be calving of ice from the overhanging parts. Eventually the iceberg will become top heavy and roll over. The towing systems will have to be designed with this rolling in mind.

Weeks and Campbell based their analysis on towing tabular icebergs of rather large dimensions. Figure 6 shows two ice anchors embedded in the sides of the iceberg approximately 100 m behind the face realizing that the forward end will lose most to melting.

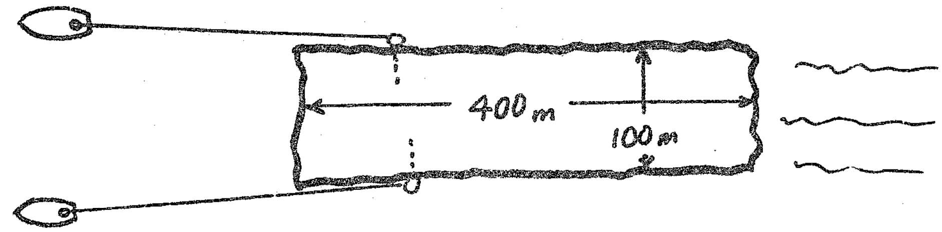


Fig. 6. Towing a Large Tabular Iceberg. One or more Ice Anchors are Embedded in the Iceberg on Either Side as Towing Points.

Two tugs are suggested at least for the start of the journey. If the ocean temperatures are colder here, higher velocities would be desirable until the iceberg became unstable and rolled over which would twist the towing lines. Prior to this time the tow could be taken by one tug through a suitable swivel. The second tug could then go back and assist another (third tug) to begin towing a second iceberg.

By this time the iceberg would have lost some of its mass and entered warmer waters where it might be desirable to reduce the towing speed somewhat in order to reduce the melt rate. It may be that the journey will have to be interrupted while new ice anchors are installed further aft because of the diminishing forward end. Refer to the discussion of the drag coefficient. This will be higher than for a longer tabular iceberg. Figure 7 shows a scheme for towing a smaller irregular shaped iceberg.

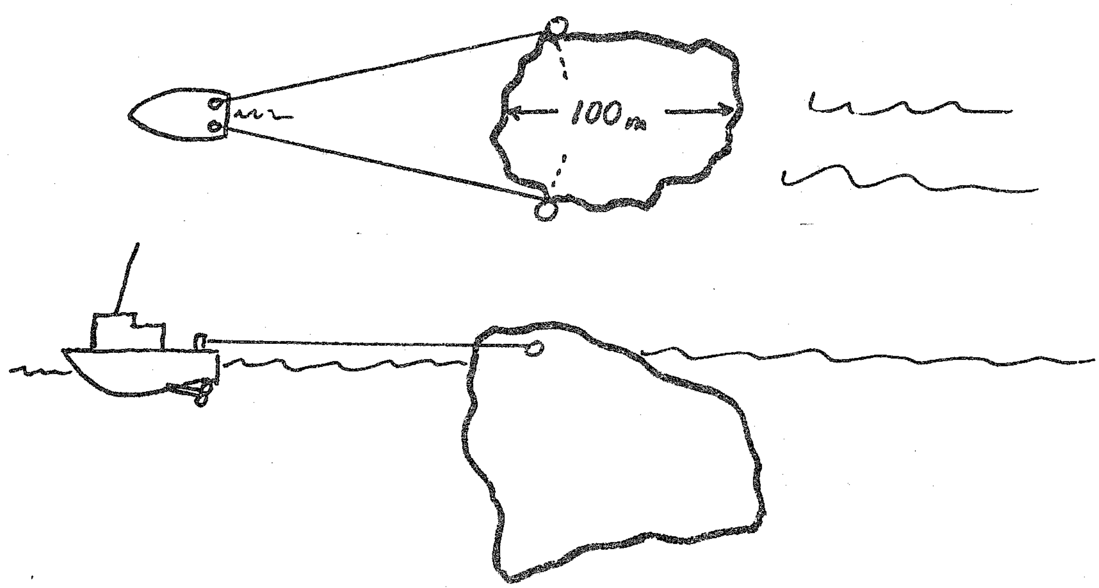


Fig. 7. Towing Smaller Irregular Icebergs.

Maintaining an ice anchor in the iceberg for towing purposes may prove to be difficult. If a secure anchor can be maintained, the tow would tend to be self stabilizing. If some type of cable net were passed around the iceberg several small icebergs might be brought together and the ice anchor would be no problem. Probably the cable would embed itself into the ice on the after end. Towing stability would be a problem. Unless carefully designed there would be a tendency for the iceberg to roll forward and escape the towing net. Figure 8 shows a towing scheme employing a bridle fabricated from two long towing cables passed around the iceberg.

The necessary experience for towing icebergs can be obtained by towing some smaller icebergs for shorter distances and carefully instrumenting the behavior of the tow and documenting the melt losses.

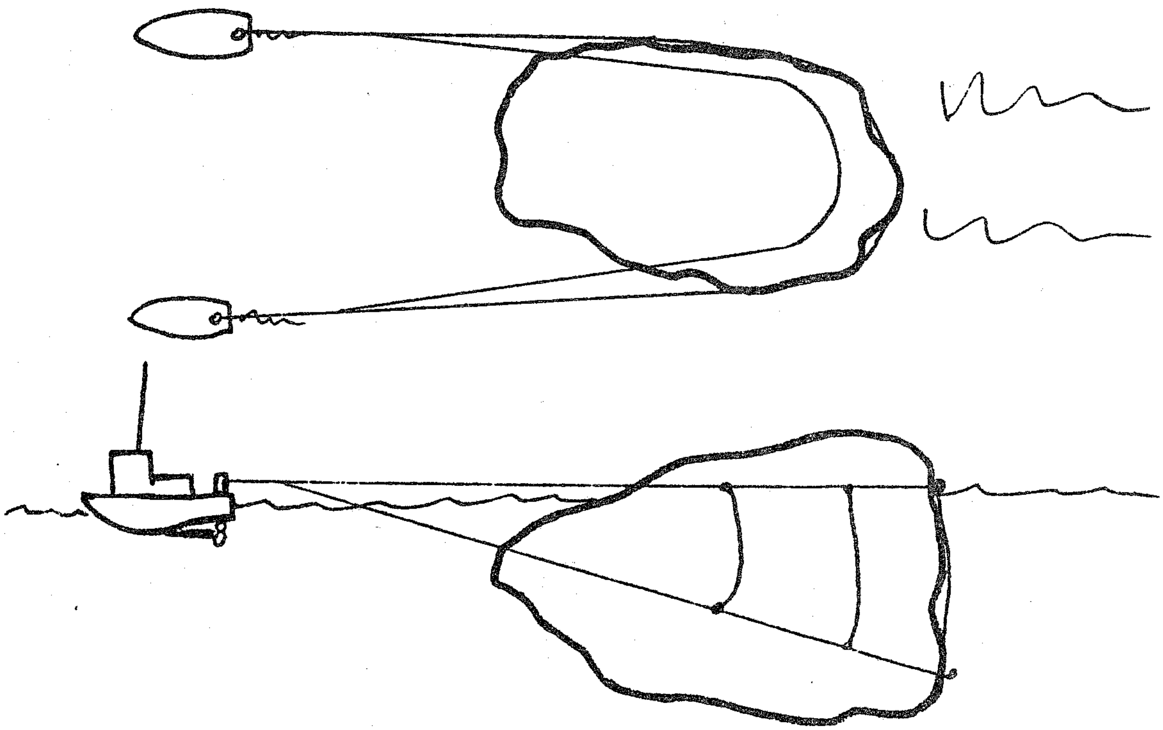


Fig. 8. Towing Icebergs with a Bridle.

<u>Towing Power</u>: The towing force for various combinations of towing speeds, iceberg configurations and iceberg sizes is given in Figs. 2, 3, and 4. Employing current empirical towing force and tug horsepower data, Weeks and Campbell gave this relationship for towing force:

$$F_B = 3.0\ d^{.67}\ p^{.67}\ (K_t/K_q{}^{0.67}) \tag{9}$$

where

F_B is the towing force under bollard conditions in newtons,

d is the propeller diameter in meters,

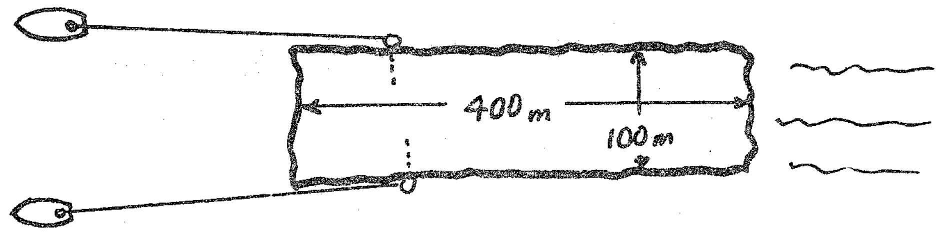
P is the shaft power in watts,

K_t is the dimensionless thrust coefficient,

K_q is the dimensionless torque coefficient.

For a propellor designed for towing, the thrust-torque ratio has a value of 3.0 for zero speed of advance. Equation (9) shows that for increasing shaft power, there is a decreasing gain in towing force. Therefore for a tug suitable for towing icebergs, a multiple propeller combination is advantageous.

Weeks and Campbell examined the configuration of one of the largest ocean-going tugs in operation, the Oceanic. The Oceanic has a total power of 1.3×10^7 watts on two screws. The rated towing force is 1.3×10^6 newtons. They found that the Oceanic could tow a tabular iceberg of the dimensions 55 m x 220 m x 250 m at a speed of 0.5m/s; however, this iceberg would have been melted by the time a 7000 km journey to western Australia was completed. They propose beginning the journey with a larger iceberg and a lower towing speed.



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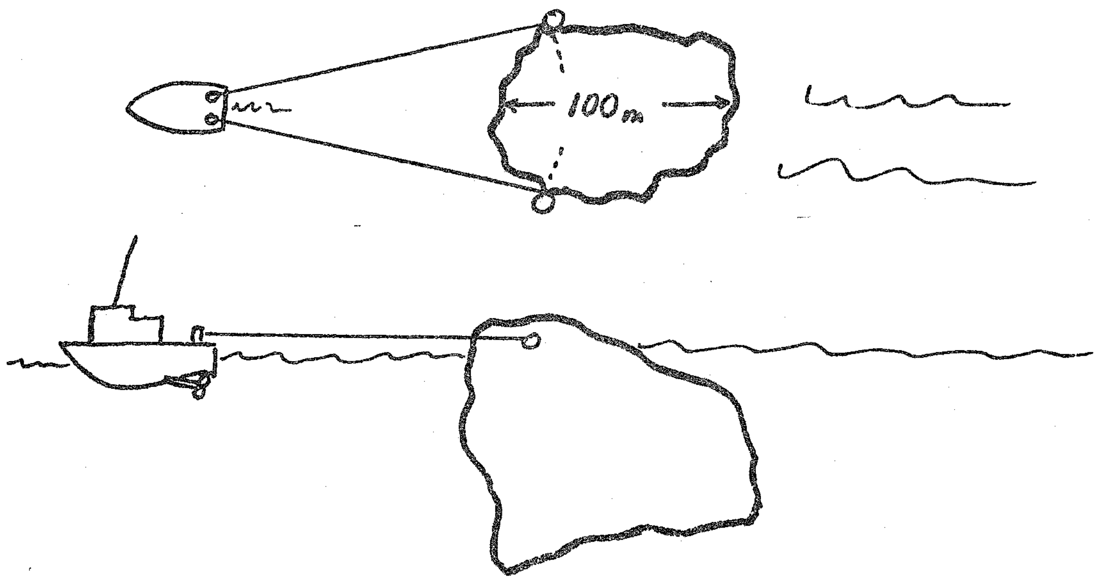

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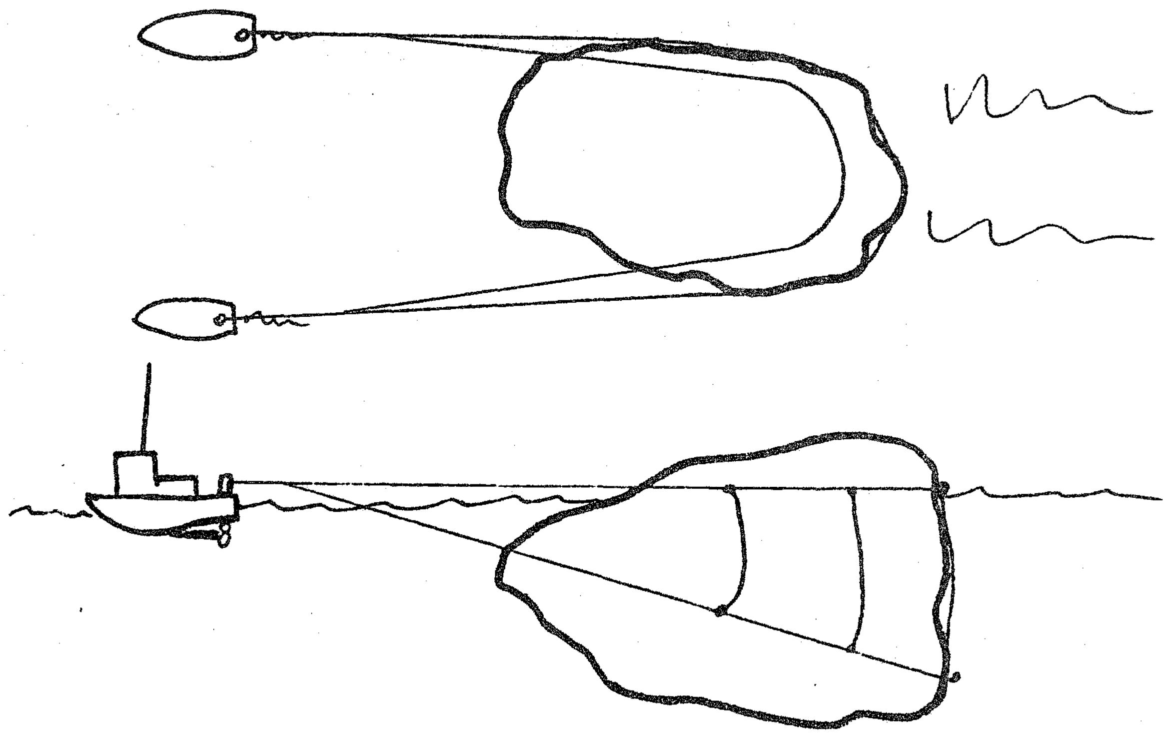

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Towing an iceberg of much larger initial size would require a larger tug. Weeks and Campbell considered a larger super tug having a power similar to that proposed for large icebreaking tankers. Assuming a power plant of 15.6×10^7 W (12 times the size of the Oceanic power plant but 0.67 times the size of the nuclear powered USS Enterprise) and assuming three propellers having diameters of 11 m, Eq. (9) shows that the super tug could produce a towing force of 18.50×10^6 newtons (14 times the bollard force of the Oceanic).

The drag graphs of Weeks and Campbell suggest that two super tugs towing a large tabular iceberg using the scheme shown in Fig. 6 could tow an iceberg 1500 m wide x 6000 m x 250 m at 0.5 m/s. This iceberg has sufficient cold content to survive the journey to either Western Australia, South America or Southwest Africa.

Salvaging the Fresh Water: The great draft of the iceberg will probably prevent its being towed into a harbor. The iceberg would probably have to be moored in a protected place to minimize problems with waves. A drilling-platform type of structure could be erected as a terminus for several pipelines from the shore. One pipeline would supply fresh hot water which would convey the waste heat to the iceberg. One or two pipelines would be needed to take the fresh water back to the shore. Figure 9 is a diagram of the proposed melting basin.

A floating melting barrier would be erected around the iceberg. The barrier would have to provide sufficient free board to prevent over topping by waves and to maintain a relatively quiescent condition inside. A plastic baffle membrane must hang vertically below the barrier. This would confine the melting fresh water. Since the fresh water is less dense than the sea water, the fresh water will float to the top inside the baffle. If a reasonably quiescent condition could be maintained, there would be no mixing between the fresh water and the underlying salt water. The fresh water would be pumped ashore by skimming from the top of the melting basin. A set of sensors on the legs of the platform would allow adjustment of the pumping rate to maintain the level of the salt water at some predetermined level. Part of the fresh water being pumped ashore would be recycled through heat exchangers to transport the waste heat back to the iceberg.

The heat could be transferred to the iceberg by a floating pipeline around the edge of the iceberg. A set of nozzles would spray hot water on top of the iceberg. The hot water would hasten melting of the iceberg and salvage its cold content.

Where Do We Go From Here?

This paper was prepared under the bias that the ice islands (tabular icebergs) in the Arctic Ocean and the ice locked in Alaska's fresh glaciers are a natural resource which are being wastefully neglected. Their fresh water supplies and cold content could be used in the coastal industrial areas of western United States and Japan.

A study by Weeks and Campbell (1973) has aroused a great deal of interest and promises to become a classic in this field. It is proposed to adapt the techniques used by Weeks and Campbell for a similar study of North Pacific routes. It is proposed to use more effective methods of systems analysis to search the optimum routes, iceberg sizes tug towing force, and tug combinations.

Because of the international implications, it is proposed to establish a study in one of the U.N. agencies (possibly under the IHP) to sponsor further development along these lines. This has begun on a regional basis in Arctic Ice Dynamics Joint Experiment (AIDJEX) which is a coordinated effort between USGS, USCRREL, NASA, U.S. Coast Guard, ONR and the Canadian Polar Continental Shelf Project. Preliminary experiments were carried out in 1970 and a more detailed AIDJEX experiment will take place in 1975-76.

Conclusions

The Weeks and Campbell study demonstrate that the use of icebergs as a water resource for western Australia and western South America is feasible.

A similar possibility exists for the west coast of the United States and possibly Japan. The Arctic icebergs and the Alaskan icebergs appear to be less desirable. To fully assess the potential of the Alaskan icebergs, it is proposed to:

1. Conduct a study of the calving frequency of all Alaskan tidewater glaciers,

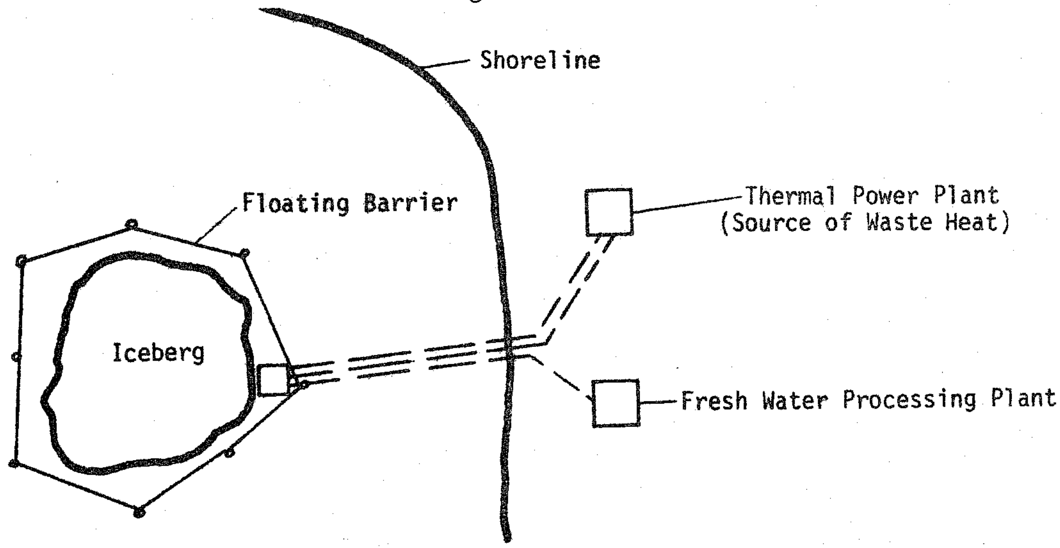
2. Document the life and migrations of the larger Alaskan glaciers,

3. Document the life and migrations of the Arctic Ocean ice islands,

4. Conduct model studies to document the hydrodynamic performance of a towed melting iceberg,

5. Develop towing techniques to be able to assure the delivery of a sufficient supply of icebergs for industrial or agricultural purposes,

6. Develop mooring techniques to be able to efficiently utilize the fresh water and cold content of the iceberg.



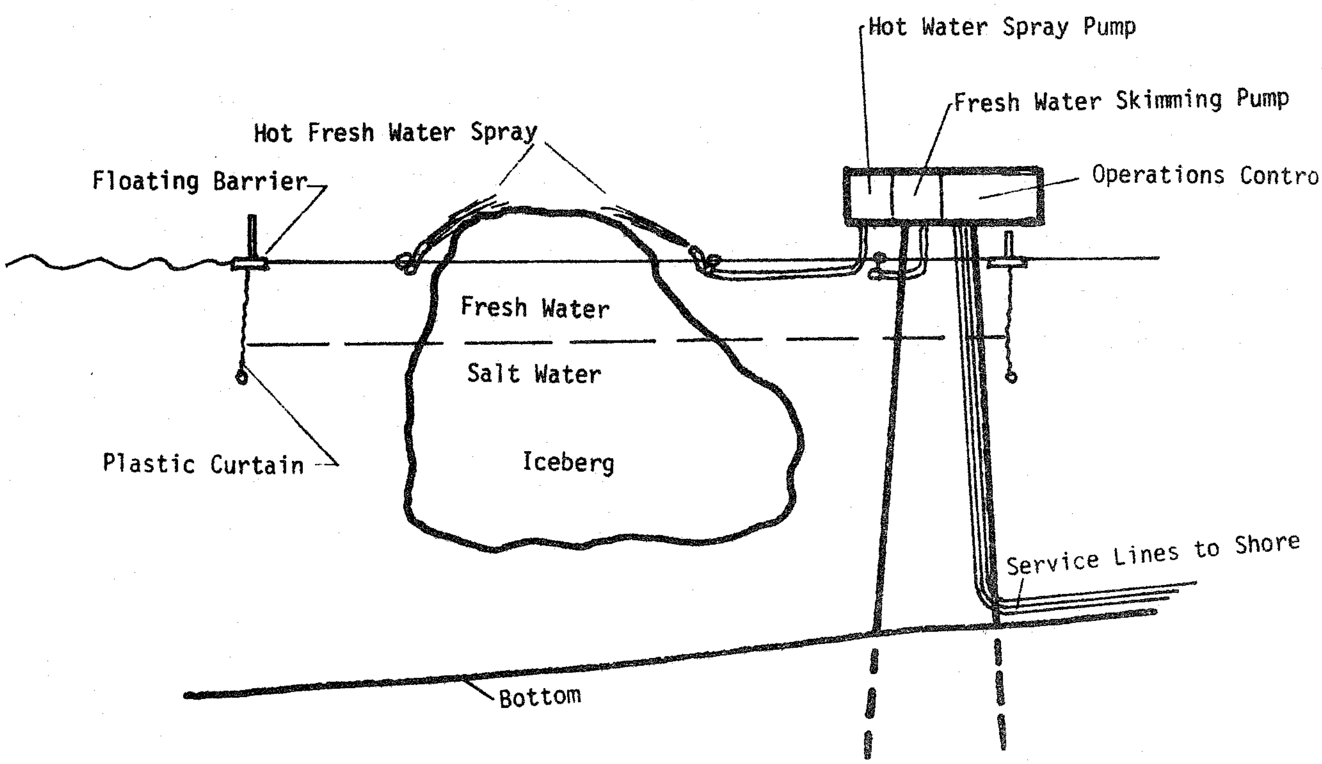


Fig. 9. Proposed Iceberg Melting Basin. Floating Melting Barrier is Drawn around the Iceberg to Capture Meltwater.

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