Ice Requirements for Chilled Seawater Systems

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Introduction

Chilled Seawater (CSW) is becoming increasingly popular in the United States for the preservation of fish aboard certain fishing vessels. Also called "slush ice" and "the champagne system," CSW has found recent application in several fisheries, many of which make use of portable tanks (200-2,000 l) aboard small inshore vessels (Dagbjartsson et al., 1982; Hansen, 1982; Eddie and Hopper, 1974). Larger-tanked CSW systems aboard seiners and transport vessels may be even more common (Kelman, Undated).

Canadian researchers and fishermen have done much to demonstrate and develop CSW on the North American Pacific coast. Flooded hold systems have, for several years, been used on Pacific salmon, *Oncorhynchus* spp., transport vessels (or "packers") in Canada and, more recently, on bottomfish draggers. Nearly all of these systems use air, bubbled into the tanks from a grid of pipes on the tank or fish-hold floor, to circulate cold water through the mass of newly-loaded fish[1]. This basic design is increasingly being used in the Alaska fishing industry.

Adequate ice is necessary to chill the fish and water that will eventually flood the hold (in most cases), and to maintain low temperatures during the trip. One rule of thumb is to first fill the tank or hold 1/3 full of ice, then flood to the top of the ice mass with water, and finally fill the tank with either fish or water (Dagbjartsson et al., 1982; Kelman, Undated).

Canadian researchers have suggested a formula[1] to aid in loading the correct tonnage of ice at the beginning of a trip. Commonly employed by U.S. CSW users, the "Canadian Formula," in short tons, is: *TONS OF ICE NEEDED* = (1/6) (*MW* + *MF* + *TIME*), where *MW* = tons of water to be chilled, *MF* = tons of fish to be chilled, and *TIME* = days duration of the trip.

In some cases the tank is first filled with water and ice as the vessel awaits the loading of fish; under most circumstances, a full hold is necessary for adequate vessel stability. Excess water then spills as fish are stowed in the tank. When operating in quiet water, a partially-filled tank may allow the operator to load less ice, dump no water, and completely fill the tank or hold only when it is time to begin the trip home. In these cases, the quantity of fish and water (*MW* + *MF*) is taken as the capacity of the tank in short tons.

The Canadian Formula enables a vessel operator to get a generally conservative estimate of ice needs for typical summer British Columbia conditions, assuming a well-insulated hold (Gibbard[2]). Subsequent experience then allows the fisherman to adjust ice tonnage to more closely match the needs as influenced by local conditions.

However, fishing conditions and CSW applications in Alaska or California may differ substantially from those in British Columbia. Many boats are inadequately insulated, thus requiring more ice due to heat leakage into the hold during a trip. Conversely, sea, air, and fish temperatures in Alaska, for example, may be lower during much of the fishing season, thus calling for less ice than necessary during summer months at lower latitudes.

This paper describes results of an analytical approach which enables one to project ice usage for CSW systems under a variety of circumstances. A series of algebraic equations coupled with appropriate simplifying assumptions has been described in a BASIC interactive program operable on a personal computer (see Appendix II). The procedure can evaluate the consequences of installing CSW without having adequately insulated the hold, estimate ice expense saved when high-quality insulation is installed, project ice use as environmental temperatures and fish volumes change, and, when conditions permit (e.g., aboard a docked processor vessel), investigate the effects of

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ABSTRACT—This paper describes an analytical approach to estimate ice quantities required by fishing vessels using slush ice or chilled seawater (CSW) systems. The calculations specify ice required for different values of hold size, catch volume, and time at sea, under varying conditions of water temperature, hold insulation, and hold flooding strategy. Observations and measurements recorded during four trips on three different steel salmon packers were used to verify the procedure and support several recommendations for CSW system operation.

[1]Chilled sea water system data sheet. Undated (ca. 1975). Technol. Res. Lab., Can. Dep. Fish. Oceans, Vancouver, B.C. Unpubl. manuscr.

[2]Gibbard, G. A. 1982. Personal commun. Formerly with Technol. Res. Lab., Can. Dep. Fish. Oceans, Vancouver, B.C.

operating at various fill-levels in the tank. A series of measurements aboard Alaskan salmon packers verified the analytical procedure.

Model Development

The total tonnage of ice needed during any fishing trip must be adequate to serve four purposes: 1) Chill the expected volume of fish, 2) absorb heat which leaks into the hold throughout the trip, 3) absorb heat resulting from the energy of bubbled air, and 4) chill seawater taken aboard—first to "slush" the ice (make a slurry into which fish can be dumped), and then to fill the hold to a predetermined level. In most cases, the hold is completely filled to eliminate the unbounded free water surface which can lead to capsizing of the vessel.

Ice Requirements for Fish and Water

The mass of ice needed to cool fish or water to the final holding temperature can be calculated from the following equation, written for the case of fish:

$$(MI_f)(L) = (MF)(C_{pf})(T_1 - T_2) \quad (1)$$

Where MF = mass of fish added,
C_{pf} = specific heat of fish,
MI_f = mass of ice which melts,
L = latent head of fusion for ice,
T_1 = initial temperature of water added to tank, and
T_2 = final temperature of the mixture.

The initial temperature of water added to the tank, T_1, would be the sea surface temperature. The final temperature, T_2, is the temperature of the CSW mixture, generally taken as −0.6°C (31°F), slightly below the ice-melt temperature of 0°C (32°F) due to the salinity.

Based on recent measurements aboard Oregon bottomfish trawlers, this is also a good approximation for the initial fish temperature prior to stowage in the CSW tanks. While tests showed that some fish recently brought from the ocean floor will be colder than the sea surface temperature, and that some lying on deck will be warmer due to solar and air heating, the average appeared to be close to the temperature of the sea surface.

Ice Requirements for Heat Leakage

The mass of ice required to absorb the heat which leaks into the slush-ice tank during the voyage can be calculated as:

$$(MI_l)(L) = (U)(A) \times (T_{out} - T_{in})(TIME) \quad (2)$$

Where MI_l = mass of ice which melts,
L = latent heat of fusion for ice,
U = an overall heat transfer coefficient,
A = the boundary area through which heat is transferred,
T_{out} = external ambient temperature,
T_{in} = temperature of the slush ice mixture,
$TIME$ = length of voyage.

The value for T_{out} is assumed to equal the sea surface temperature. This is based on documentation of weather data from regions of Atlantic Canada which indicated that for summer conditions, sea surface and air temperature averages were quite similar (Merritt et al.[3]), an assumption verified by measurements taken during the series of trips reported below. The analysis ignored the fact that engine room temperatures will be much warmer than those of the surrounding sea[4]. This is a reasonable simplification since the bulkhead separating the engine room from the fish hold constitutes only about 10 percent of the total boundary area[3] and is typically insulated more heavily than the other walls, floor, and deckhead.

[3]Merritt, J. H., E. Kolbe, and W. Robertson. 1983. Refrigerated storage of fish at sea with particular reference to thermal insulation. Unpubl. Res. Rep., Can. Inst. Fish. Technol. Tech. Univ. Nova Scotia, Halifax, 250 p.

[4]Measurements during recent trips on Oregon bottomfish trawlers indicated engine room air temperatures of 18-39°C (65-102°F).

The total boundary area can be expressed as a direct function of a cubic tank volume:

$$A = (6)\,(V)^{(2/3)} \quad (3)$$

Where A = the boundary area through which heat is transferred and
V = tank volume.

However, holds or tanks which are not cubic in shape would have a greater surface-to-volume ratio. Dimensions of fishing boat holds compiled by Merritt et al.[3] indicate that use of a coefficient of 7.2 (rather than 6) in Equation 3 better describes the typical case; it is the relationship used in this analysis.

The overall heat transfer coefficient U accounts for thermal resistance of the wall plus both inner and outer fluid films. However, resistances of the convective films in water and wind will be small compared with those of the wall sections and are thus neglected.

Our analysis has assumed three levels of insulation for the representative wall sections shown in Figure 1 for the side walls and bulkheads of a 30 m (100-foot) steel vessel (Hanson, 1960; Merritt et al.[3]). Note that the "RESISTANCE" value given for each level in Figure 1 is the reciprocal of the overall heat transfer coefficient U. Calculations to determine these resistance values followed two procedures: For "Level 1" and "Level 2" in which steel frames directly contact inner and outer boundaries, the "Zone Method" outlined by ASHRAE (1981); for "Level 3" in which insulation covers the ends of the steel frames, an empirical method described by Munton and Stott (1978).

Heat Load From Air Flow

To the quantity of heat leaking from the outside environment must be added the quantity of heat due to throttling of compressed air injected into the CSW mixture to effect circulation. This rate of heat addition is equivalent to the rate of energy supplied by the air pump.

The analysis first assumes the rate of air flow to be 0.152 m^3/minute (at 1 atm and 21°C) per square meter of deck-

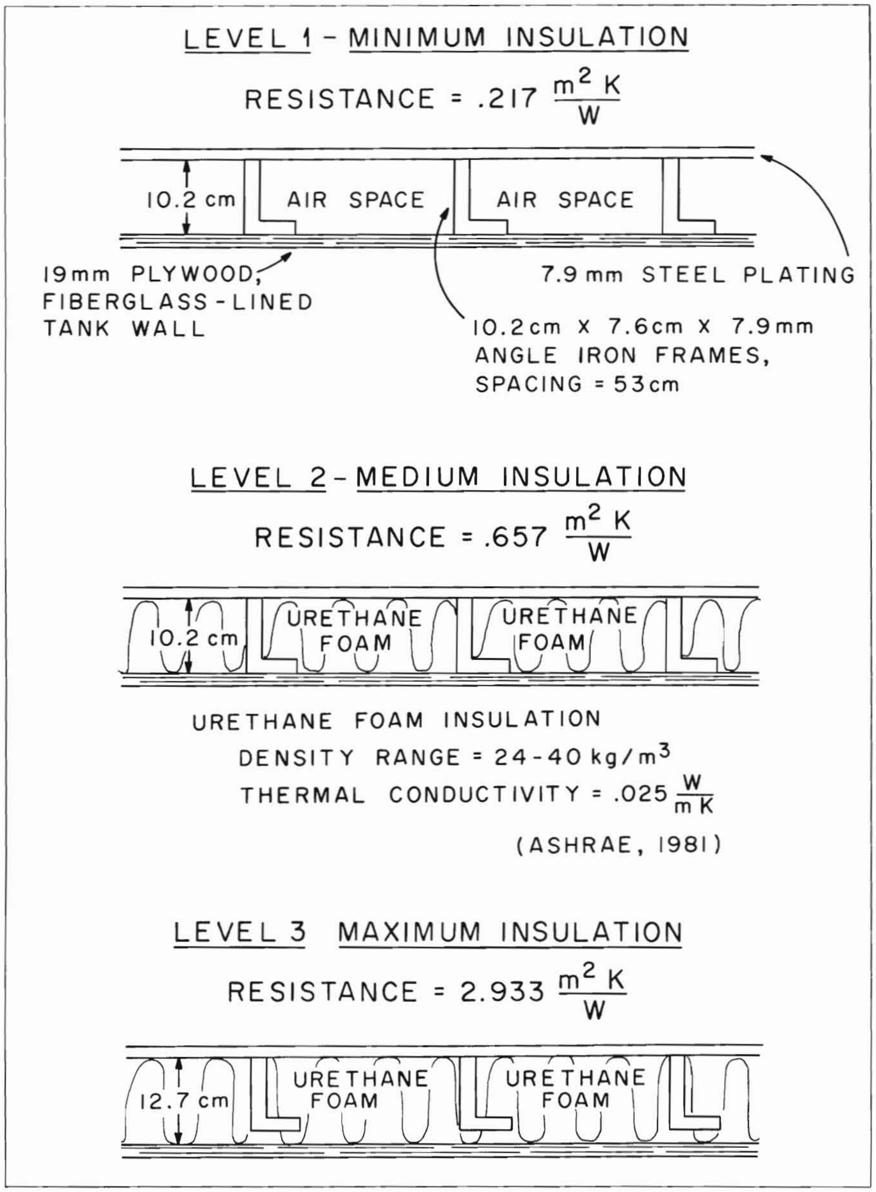

Figure 1.—Representative steel wall sections with calculated resistance values used in the analysis of ice consumption.

head (0.5 standard foot^3/minute per square foot of deckhead) following Canadian recommendations[1]. It next assumes deckhead area to be 30 percent of the boundary total, a figure representative for vessel lengths in the range of 25 m (80 feet)[3]. These assumptions with Equation 3 can then indicate volumetric flow rate of air injected into the CSW tank.

Air pressure required to overcome pipe friction and static head of water in the hold is typically 35-48 kPa gage (5-7 psig)[1]. Semi-empirical relationships (Baumeister and Marks, 1967) give power into the air based on the required flow rate and supply pressure. The entire rate of energy supplied is assumed dissipated in the CSW tank. As an example, the rate of ice melt due to bubbled air into a representative 30 m (100-foot) vessel having a hold volume of 176 m^3 (6,200 feet^3) will be on the order of 0.07 t/hour (0.08 short tons/hour).

Fill Strategies and Equation Development

As fish, water, and ice are added to the tank, the heat balances that match ice with heat sources are coupled with a volume balance to ensure that all necessary ingredients will fit into the tank. The analysis can select one of three cases for calculation: 1) Fill/Spill, 2) Fill/No-spill, or 3) No-fill/No-spill.

Fill/Spill

In the Fill/Spill case, the tank is first flooded to the top with water and ice. This ensures a stable vessel while operating in the open sea before fish are loaded. This case will require the greatest tonnage of ice because it must include a quantity to chill water that will be dumped later.

Fill/No-spill

In this case, water is initially filled to the level of the ice, creating a slush, after which fish are added. If the tank is not then full, more water plus the necessary extra ice is added until the tank is full.

No-fill/No-spill

In rare circumstances, such as in a docked or anchored processing vessel, tanks can safely remain partially filled. In this case, water is first filled to the level of the ice to create a slush, and then fish are added.

A summary of equations developed for each of these fill strategies appears in Appendix I.

Boundary Conditions

Throughout the calculation procedure, the program checks to ensure that certain boundary conditions are not exceeded. One check warns if the volume of the ice-water-fish mixture exceeds the total tank volume, a condition easily reached when loading excessive amounts of fish.

A second check warns if the volume of the bulk-loaded ice exceeds the tank

Table 1.—Specific volumes of loosely packed ice (from FAO, 1975; Merritt, 1978).

Type of ice	Specific volume
Flake	2.1-2.3 m³/t (67-74 feet³/short ton)
Tube	1.6-2.0 m³/t (51-64 feet³/short ton)
Plate	1.7-1.8 m³/t (55-58 feet³/short ton)
Crushed block	1.4-1.6 m³/t (45-51 feet³/short ton)

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THIS IS  SLUSH', A PROGRAM TO CALCULATE ICE REQUIREMENTS FOR CSW TANKED SYSTEMS


CASE  2  FILL/NO-SPILL

                    *****
 TANK CAPACITY IS INADEQUATE TO HOLD ALL THE FISH REQUIRED.
  THE PROGRAM HAS DECREASED THE INPUT AMOUNT OF FISH TO BE LOADED.
                     *****
INITIAL TEMPERATURE                  56 F
TANK VOLUME                          1152 CUBIC FEET
FISH TO BE LOADED                    21.3 TONS
NUMBER OF DAYS TO BE HELD            2 DAYS
HOURS PER DAY OF AIR BUBBLING        2 HOURS
ASSUMED INSULATION LEVEL             MIN
ICE MELT FROM FISH                   3.1 TONS
ICE MELT FROM HEAT LEAK              2.7 TONS
ICE MELT FROM BUBBLED AIR            0.1 TONS
ICE MELT FROM WATER ADDED             1.2 TONS
TOTAL ICE REQUIRED                    7.2 TONS
APPROX PERCENTAGE OF TANK
  OCCUPIED BY DRY
  BULK-LOADED ICE                    42
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Figure 2.—Sample output, representing the ice required for the center hold of Trip 4 (Table 4).

volume even before fish are added to the tank. Specific volumes (volume per unit mass) are given in Table 1 for various types of ice. Excessive ice volumes can occur when trips are long, tanks are small (and thus have high surface-to-volume ratios), and when insulation is poor. Even if bulk ice volume does not exceed the tank volume, there may be problems if so much ice were carried that inadequate space remained to initially load a large volume of fish. The program issues a warning if bulk ice volume exceeds 90 percent of the tank volume.

Because an adequate chill rate of the fish will be achieved only if the bubbled air-driven cold water can circulate, a third check is on the fish packing density. If this is too great, it will prevent adequate cold water circulation throughout the entire load. This analysis assumes a maximum permitted fish loading density of 670 kg/m³ (42 pounds/foot³), a value found by National Marine Fisheries Service researchers to be valid for small tanks[5]. This is slightly lower than the value of 720 kg/m³ (45 pounds/foot³) given by Gibbard and Roach (1976) for refrigerated seawater systems and used for large-tanked CSW systems as well[2,6].

Calculation of Results

The analytical procedures describing ice required under various conditions and loading strategies have been written as a BASIC computer program (Appendix II). Using thermodynamic values from ASHRAE (1981, 1982), and assuming the use of flake ice (Table 1), the program allows the user to select insulation level, loading strategy, and other operating parameters to generate an output similar to that shown in Figure 2. In this example, an attempt was made to input 22.5 short tons (20.4 t) of fish to simulate the loading rate observed during a summer trip in Alaskan waters. Because this exceeded the allowed packing density, the program has adjusted the fish tonnage to maximum capacity and has printed an appropriate message.

Methods and Materials

Four trips were made during summer 1984 on three CSW salmon packers operating out of Kodiak, Alaska. These trips provided opportunities to observe procedures, estimate ice use rates, and measure significant temperatures and chill rates aboard vessels having different levels of insulation. These data allow a comparison of observed ice requirements with those predicted using the calculations described.

Temperatures were recorded manually using a YSI Telethermometer Model 42-SC (Yellow Springs Instrument Co.[7]). Typically, an array of nine thermistor sensing probes was placed in fish and water as loading proceeded. The quantity of ice loaded at the trip start was reported by the supplier of ice to the vessel. The ice remaining at the end of the trip was an estimate based on the number of totes (boxes) filled with unmelted ice plus, in some cases, judgement of the vessel operator on the amount left aboard after draining the tanks.

All three vessels had commercially installed air blower and distribution systems layed out in general agreement with Canadian recommendations[1]. All travelled to areas having relatively quiet water before loading fish; all ended trips by first draining tanks before returning to home port through unsheltered water. The vessels differed in hold size, layout, and insulation characteristics, and general description of each is given in Table 2.

Results

Ice use rates, as well as data influencing these rates, recorded during the four trips at sea appear in Table 3.

The schedule of air circulation was similar for each vessel and trip. Air blowers typically operated for 20-30 minutes when the tank was first flooded with water, then for about 10 minutes each time a load of fish was added from a catcher vessel. Total air pumping time ranged from 1 to 3 hours per day. (This

[5]Collins, J. 1983. Personal commun. Formerly with Utilization Res. Lab., Northwest Alaska Fish. Cent., Natl. Mar. Fish. Serv., NOAA, Kodiak, Alaska.

[6]Lee, F. 1982. Personal commun. Formerly with Technol. Res. Lab., Can. Dep. Fish. Oceans, Vancouver, B.C.

[7]Mention of trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

Table 2.—Characteristics of vessels A-C used in trips 1-4.

Vessel	Trip no.	Length m	Length feet	Tanked hold volume m³	Tanked hold volume feet³	Tank layout	Insulation[1]
A	1, 2	22	75	86	3,037	Fiberglass partitions or bin boards separated one hold into smaller compartments, each approximately 2.1 m (7 feet) high, and each having air supply pipes on the floor.	20 cm (8 inches) of urethane foam on sides, floor, lazaret bulkhead, and deckhead; 30 cm (12 inches) of urethane foam on the engine room bulkhead. Insulation under center floor sump is unknown.
B	3	25	82	90.9	3,200	Bin boards to a height of 1.2 m (4 feet) from the floor separate one hold into smaller sections.	15 cm (6 inches) of urethane foam on all boundaries, including area under center sump.
C	4	22	75	[2]32.6 [3]32.6 [4]29.0	[2]1,152 [3]1,152 [4]1,024	Each of three holds is separate from the other. None of the holds had separating boards or partitions.	Except for tank liner and enclosed air space there was no insulation on boundaries of the forward and center holds. Boundaries of the aft hold had 15 cm (6 inches) of urethane foam.

[1]As reported by vessel operator.
[2]Forward hold—not loaded with fish.
[3]Center hold.
[4]Aft hold.

Table 3.—Observations during four trips at sea.

Item	1 A	2 A	3 B	4 C Forward hold	4 C Center hold	4 C Aft hold
Trip length, days	3	2	1.5		2	
Avg. SST (°C)	12.8	11.7	12.2		12.8-13.3	
Avg. air temp. (°C)	12.8	12.8	13.3		12.2-18.3	
Core temp. of several fish before loading (°C)	13.3-15.6	12.8-15.0	13.3-16.7		12.8-16.7	
Fish loaded (t)	22.7	26.8	51.8	0	20.5	8.6
Ice loaded (t)	13.9	9.1	16.4	8.2	8.2	7.3
Est. ice remaining at trip's end (t)	5.5-6.4	2.7-3.6	5.5-6.4	0	1.8-2.7	3.6
Est. ice used (t)	7.5-8.4	5.5-6.4	10.0-10.9	8.2	5.5-6.4	3.6
Fill level of tank after loading (%)	60	60	100		100	80

Table 4.—Recorded and calculated ice use rates.

Trip no. and vessel (letter)	Recorded values: Ice used (t)	Recorded values: Fill level after loading (%)	Computer Calculations: Fill level after loading (%)	Computer Calculations: Ice used (t)	Computer Calculations: Assumed insulation level (Fig. 1)	Canadian formula: Fill level after loading (%)	Canadian formula: Ice used (t)
1(A)	7.5-8.4	60	42 60	6.8 [1]8.1	Medium	100	15.2
2(A)	5.5-6.4	60	46 60	6.1 [1]7.4	Medium	100	15.0
3(B)	10.0-10.9	100	100 100	11.8 [1]11.0	Maximum	100	15.7
4(C)							
Fwd. hold	8.2		19	3.0	Minimum	100	5.9
Ctr. hold	5.5-6.4	100	100	6.6	Minimum	100	5.9
Aft hold	3.6	80	47 80	2.6 [1]3.3	Medium	100	5.3

[1]Corrected value.

period of air bubbling is shorter than that generally recommended from the Canadian experience[2,8]). Additional observations specific to individual trips are given below.

Trip 1

The 15 compartments within the hold of Vessel A were not initially filled with equal quantities of ice. Several had no ice remaining at the end of the trip, although CSW temperatures appeared to stay close to 0°C (32°F) owing to water circulation between compartments.

Trip 2

The loading and air pumping schedule for Vessal A was similar to that for Trip 1. Before the start of this trip, the vessel operator separated the bin boards slightly, enabling better circulation of cold water between the 15 compartments. This improvement, plus better initial ice distribution, led to unmelted ice remaining in each compartment at trip's end.

Trip 4

Vessel C's uninsulated forward hold, not loaded with fish, had no temperature probes so meltwater temperature at trip's end was unknown. Both fish and ice were poorly distributed in the center and aft tanks. Although some ice remained in the center tank at trip's end, it was all massed at one corner. Also, a small volume of chilled water was dumped from the center tank as the final fish loading took place. Temperatures in both tanks holding fish (center and aft) were uneven throughout the trip.

Comparisons

Table 4 compares recorded ice use rates with values calculated both with the analysis described above and with the Canadian formula. In addition to the influencing conditions reported above and data given in Table 3, the analysis used bulk ice volumes for flake ice, and an air pumping schedule of 2 hours per day.

The analysis for the case of partially-

[8]Operation of "Champagne" systems. Tech. Inf. Bull. 80-1 (unpubl.). Technol. Serv. Branch, Dep. Fish. Oceans, Environ. Can. 5 August 1980.

filled tanks (No-fill/No-spill) assumes fish to be loaded at the maximum allowable density, or minimum volume of water and ice. However for trips 1, 2, and 4 (aft hold), the operator loaded more ice and more seawater than necessary to achieve this maximum density, thus filling the tank fuller than the calculations would indicate. If the calculated "Fill level after loading" is corrected to match observed levels by adding seawater and the necessary extra ice to chill it down, the results (Table 4) allow comparison of calculated values ("corrected") with observed values at the same tank fill level.

Similarly, the analysis for the filled tank of trip 3 assumed that no unmelted ice remained at the end of the trip. In fact, unmelted ice did remain, occupying a volume that the analysis assumed was occupied by chilled water. The corrected value shown (Table 4) resulted from subtracting the amount of ice required to chill a volume of water occupied by the observed excess ice.

Discussion

Perhaps the greatest uncertainty in calculating ice consumption lies in estimating the heat which leaks into the hold during a trip. This is because these calculations depend strongly on several factors which may be unknown by the vessel operator—perhaps the second or third owner of the vessel—or which are highly variable during a trip. Examples include:

1) Nature of the fish hold boundary structure (e.g., frame spacing; connections between hold liner and frames; presence and thickness of concrete floor; deck covering; nature of penetrating structure like piping, manholes, and stanchions) and type, thickness, quality, or existence of insulation;

2) Nature and degree of separation of adjacent compartments (e.g., warm fuel tanks or net lockers, hot engine room, additional cold CSW tanks);

3) Area of the hold or tank boundary;

4) Level to which the flooded CSW tank is filled;

5) External heat transfer film coefficients—generally low and variable with wind speed if in air, and high if the surface is hit by spray or is below the waterline;

6) External sea temperature and air temperature which may vary from day to day or from day to night; and

7) Solar load on the deck or wall of the vessel.

Despite these uncertainties and the approximate nature of some observations documented in Table 3, the prediction of ice consumption shown in Table 4 for these documented trips at sea are close to recorded values. The predicted consumption in the uninsulated forward hold of Trip 4 shows the poorest agreement with the observed result. This hold, which was unused, uninsulated, and adjacent to the engine room, obviously had much worse heat leakage rates than what was described using the resistance value for the "minimum" level of Figure 1. Structural penetrations and an uninsulated shaft tunnel could account for most of this difference.

Although good insulation was reported by the operator of vessel A (Trips 1 and 2), the use of "medium" rather than "maximum" insulation resistance (Fig. 1) provided a closer calculation of the ice consumption rate. Again, undocumented structural penetrations would have decreased the effective boundary thermal resistance.

As shown by Table 4, the Canadian Formula did not match observed results well at all. This was expected because it was not intended for these situations.

The example calculation of Figure 2 presents values (in British units) corresponding to ice consumption in the center hold of Trip 4 and gives relative quantities for the different heat sources. With the short air bubbling periods experienced on these trips, expected ice consumption due to injected air is minor.

For most calculations using the "maximum" insulation level, ice consumption due to heat leakage is a minor fraction of the total. It is with less efficient insulation, as considered in the example of Figure 2, that heat leakage becomes significant and uncertainties more important. Research to gain a better understanding of thermal resistances of fish hold boundaries is presently underway at the Department of Agricultural Engineering, Oregon State University, Corvallis.

Acknowledgments

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Appendix I

Relationships for the mass of ice required to chill fish and to absorb heat leakage from the warm sea and air ambient are presented in Equations (1) and (2) respectively. The mass of ice required to absorb the energy of bubbled air is represented by the following equation:

$$MI_a = (0.08)(V/6{,}200)^{2/3}(TIME)(TAIR) \quad (4)$$

where 0.08 = ice consumption rate (in short tons/hour) in a typical 30 m (100-foot) vessel; and 6,200 = a typical hold volume (in feet ^{3}) of the same vessel. Other symbols are defined in Appendix Table 1.

The additional ice required to absorb the heat of added seawater while occupying the available volume in the tank, depends upon the fill strategy, as outlined in the report. The additional equations corresponding to these fill strategies appear below.

Appendix Table 1.—Symbols used in Equations (4) through (7).

C_{pw}	=	Specific heat of seawater.
L	=	Latent heat of fusion of ice.
MF	=	Mass of fish.
MI_a	=	Mass of ice required to absorb bubbled air energy.
MI_f	=	Mass of ice required to cool stowed fish.
MI_l	=	Mass of ice required to absorb heat leakage.
MI_w	=	Mass of ice required to cool added water.
T_1	=	Initial temperature of fish or water before stowage.
T_2	=	Final temperature of fish and water in CSW tank.
$TAIR$	=	Hours per day that air is pumped.
$TIME$	=	Duration of holding period in CSW tank.
v_i	=	Specific volume of bulk loaded ice (see text Table 1).
V	=	Tank or hold volume.
VP	=	Partial volume occupied by fish/ice/water mixture in the "Fill/No-spill" and "No-fill/No-spill" cases.
ρ_i	=	Density of ice particles.
ρ_w	=	Density of seawater.
ρ_f	=	Average density of fish flesh.

Fill/Spill

The mass of ice required to chill water originally added to flood the tank is given by:

$$MI_w = V\left[\frac{\rho_i - (MI_l + MI_a + MI_f)/V}{1 + (\rho_i/\rho_w)\left[\dfrac{L}{C_{pw}(T_1 - T_2)}\right]}\right] \quad (5)$$

Fill/No-spill

In this case the volume occupied by anticipated ice, water, and fish is first calculated by Equation (6). The computer routine adjusts quantities up or down to achieve a balance. The ice required for added water then results from Equation (7).

$$VP = \frac{v_i(MI_l + MI_a + MI_f)L}{L + (\rho_w/\rho_i)C_{pw}(T_1 - T_2) - v_i\rho_w C_{pw}(T_1 - T_2)} + \frac{MF}{\rho_f} \quad (6)$$

$$MI_w = \left[\frac{\rho_w C_{pw}\rho_i(T_1 - T_2)}{\rho_i L + \rho_w C_{pw}(T_1 - T_2)}\right]\left[VP - (MI_f + MI_l + MI_a)/\rho_i\right] \quad (7)$$

No-fill/No-spill

An estimated volume is first calculated using Equation (6); ice quantity for added water follows from Equation (7). But for this case, there is no concern to balance the volume to completely fill the tank.

Appendix II

This Appendix describes "SLUSH," a computer program which calculates ice required in chilled seawater (or slush ice) fish holding systems.

Holding fish in flooded-tank chilled seawater (CSW) systems provides several benefits. One is elimination of the need to shovel and distribute ice through the volume of bulk-loaded fish. Another is enabling rapid chilling of fish, especially significiant when large catches are brought aboard. A third is providing buoyancy to the fish and thus avoiding crushing that can occur in bulk-loaded iced fish systems.

Several conditions affect the success of these CSW systems. One is that the operator be aware of the vessel instability risks associated with partially-filled tanks. Another is that the bubbled air system normally used to bring about adequate circulation of cold water through the newly-loaded fish be properly designed and installed. And a third condition is that the operator use sufficient ice and avoid overloading the tanks with fish. Use of program SLUSH addresses this last condition and enables the user to learn how predicted ice consumption will vary with:

1) Fish hold or tank volume,
2) level of insulation in the boundaries,
3) filling strategy (whether the tank will be full or partially full),
4) seawater temperature,
5) amount of fish to be loaded,
6) length of time fish is to be held, and
7) length of time air is bubbled into the tank.

The program in BASIC language appears as Appendix Table 2 at the end of this section. It is "interactive," which means that the user enters information in response to questions which appear on the screen, and it requires a printer, since output appears both on screen and on printer. Input and output values are expressed in British ("Inch-Pound") units.

Program Operation

To operate the program, the user must enter information in response to requests appearing on the screen. The requests with required information are:

OCEAN TEMPERATURE (in °F). The expected sea surface temperature describes not only the warm seawater that will be chilled by ice in the hold, but also the approximate temperature of fish to be chilled.

HOLD OR TANK VOLUME (in feet^3).

NUMBER OF DAYS ICE WILL BE IN THE TANK.

NUMBER OF HOURS PER DAY BUBBLED AIR IS TO CIRCULATE.

CASE NUMBER TO BE CALCULATED, where
CASE 1 IS FOR FILL/SPILL,
CASE 2 IS FOR FILL/NO-SPILL,
CASE 3 IS FOR NO-FILL/NO-SPILL.

FILL/SPILL refers to a tank that is first filled to the top with sea water and ice before any fish are loaded aboard. This is the usual case where vessel stability dictates that the tank must remain full at all times. As fish are loaded, cold water is spilled—overboard or to another tank.

FILL/NO-SPILL refers to a tank that is loaded with fish, water, and ice in such a way that the tank is full at the end of loading. In this case a partially-filled tank is tolerated during loading; no cold water is spilled.

NO-FILL/NO-SPILL refers to a tank that can be filled to whatever level is necessary to exceed the minimum allowed fish loading density—considered by the program to be 670 kg/m^3 (42 pounds/foot^3).

INSULATION DESCRIPTION AS MIN, MED, OR MAX, where
'MIN' DESCRIBES A TANK HAVING ESSENTIALLY NO ("minimum") INSULATION,
'MED' DESCRIBES A MARGINALLY ("medium") INSULATED TANK, and
'MAX' DESCRIBES A WELL-INSULATED ("maximum") TANK.

The levels represented by these three descriptors appear in Figure 1 in the main text. Values of U, the overall heat transfer coefficient, were calculated for typical bulkhead and sidewall construction of a 30 m (100-foot vessel).

TONS OF FISH TO BE ADDED TO THIS CSW TANK.

Program Output

For each case, program output will appear on the printout sheet; Figure 2 in the main text presents an example of this output.

During calculation, the program checks to see that certain limits are not exceeded, and if they are, issues a warning. These warnings include the following:

WARNING: FISH LOADING DENSITY EXCEEDS MAXIMUM ALLOWED VALUE OF 42 LBM/FT3. TRY LOADING LESS FISH.

Experience has shown that filling the tank more than about two-thirds full of fish will prevent the bubbled air from promoting adequate water circulation. The result is that fish in the center are too slowly chilled. If the user enters an excessive mass of fish for the tank, the program will print the above warning on the screen and then await a new value of "TONS OF FISH TO BE ADDED".

WARNING: INITIAL BULK ICE VOLUME EXCEEDS TANK VOLUME BY __ %. TRY BETTER INSULATION OR LESS FISH.

In a few circumstances of small tanks, poor insulation, or overloading, calculations indicate a required amount of ice having a bulk volume which is simply greater than the volume of the tank. When this happens, the above warning (or one similar, depending on the fill strategy being considered) appears on the screen, then returns to await new values of insulation level and fish. The program presently assumes the use of "flake ice" having a specific volume of 2.1 m^3/t (67 feet^3/short ton).

WARNING: INITIAL BULK ICE

VOLUME EXCEEDS 90% OF TANK VOLUME. MAY HAVE DIFFICULTY LOADING INITIAL CATCH.

This message, which appears on the printer for Case 1 (FILL/SPILL) warns if the initially-loaded ice exceeds 90 percent of the volume (but occupies less than the full tank volume). If this occurs, the crew will have difficulty loading fish until sufficient ice melts to provide the space. The program does not return for new input in this case, but continues on; the message appears with the printed output.

TANK CAPACITY IS INADEQUATE TO HOLD ALL THE FISH REQUIRED. THE PROGRAM HAS DECREASED THE INPUT AMOUNT OF FISH TO BE LOADED.

Calculations in Case 2 (FILL/NO-SPILL) automatically balance either the volume of fish or the amount of added water to arrive at a full tank. If the amount of fish was automatically decreased, the above printed message appears with the output of Case 2. If water (plus the required ice) is added to arrive at a full tank, the following message appears with the printed output: EXTRA WATER HAS BEEN ADDED TO FILL THE TANK.

PROGRAM HAS ADDED EXTRA WATER AND ICE TO REDUCE FISH PACKING DENSITY TO AN ACCEPTABLE VALUE.

The amount of water initially used in calculations for Case 3 (NO-FILL/NO-SPILL) has a volume equal to the voids within the bulk ice—that is, the water is filled to the level of the ice. If the volume of fish loaded exceeds the maximum loading density of 670 kg/m^3 (42 pounds/feet^3) in this partially-filled tank, the program adds more water (plus ice to chill it), and prints the above message with the calculation results.

Appendix Table 2.—Program listing.

```
10   'PROGRAM SLUSH   VERSION   7/1/85
30   'THIS PROGRAM CALCULATES ICE REQUIREMENTS IN CSW TANKS
40   '           E. KOLBE
50   '           OREGON STATE UNIVERSITY
60   '           SEA GRANT EXTENSION
70   'Begin program by defining variables that are unlikely to change.
71   'Note that all quantities are in British units.
80   CF     = .85  'Specific heat of fish
90   CW     = .964 'Specific heat of sea water
100  LI     = 144  'Latent heat of fusion of ice
110  RHOW   = 64   'Density of seawater
120  RHOI   = 57.5 'Density of ice
130  RHOF   = 64   'Density of fish
140  MIN    = .811 'Thermal transmittance for uninsulated wall, Btu/hr-ft2-F
150  MED    = .268 'Thermal transmittance for partiallly
160                'insulated wall, Btu/hr-ft2-F
170  MAX    = .06  'Thermal transmittance for well-insulated wall (Btu/hr-ft2-F)
180  CLS
190  PRINT "THIS IS 'SLUSH', A PROGRAM TO CALCULATE ICE REQUIREMENTS FOR
     CSW TANKED SYSTEMS"
200  LPRINT
210  LPRINT
220  LPRINT "THIS IS 'SLUSH', A PROGRAM TO CALCULATE ICE REQUIREMENTS
     FOR CSW TANKED SYSTEMS"
230  PRINT
240  PRINT "SPECIFIC HEAT OF FISH              ";CF;"BTU/LBM-F"
250  PRINT "SPECIFIC HEAT OF SEA WATER         ";CW;"BTU/LBM-F"
260  PRINT "HEAT OF FUSION OF ICE              ";LI;"BTU/LBM"
270  PRINT "DENSITY OF SEAWATER                ";RHOW;"LBM/FT3"
280  PRINT "DENSITY OF ICE                     ";RHOI;"LBM/FT3"
290  PRINT "DENSITY OF FISH                    ";RHOF;LBM/FT3"
300  PRINT "THERMAL TRANSMITTANCE,MIN. INSULATION  ";MIN;"BTU/HR-FT2-F"
310  PRINT "THERMAL TRANSMITTANCE,MED. INSULATION";MED;"BTU/HR-FT2-F"
320  PRINT "THERMAL TRANSMITTANCE,MAX. INSULATION";MAX;"BTU/HR-FT2-F"
330  'Next define variables that will change only under program development
340  TF = 31  'Final temperature of slush ice mixture, Fahrenheit
350  D  = 42  'Maximum allowed fish loading density, Lbm/Ft3
360  VOLBKLICE = 67  'This is the volume (Cubic feet per ton) of dry bulk flake ice
370  PRINT
380  PRINT "CSW TEMPERATURE                              ";TF;"F"
390  PRINT "MAXIMUM PERMITTED FISH PACKING DENSITY";D;"LBM/FT3"
400  PRINT "SPECIFIC VOL OF DRY BULK-LOADED ICE ";VOLBLKICE;"FT3/TON"
410  PRINT
420  PRINT
430  'Now define variables that may vary with each case
440  INPUT "TYPE IN OCEAN TEMPERATURE, IN DEGREES FAHRENHEIT";TI
450  PRINT
460  INPUT "TYPE IN HOLD OR TANK VOLUME, IN CUBIC FEET"; VTOT
470  PRINT
480  INPUT "TYPE IN THE NUMBER OF DAYS ICE WILL BE IN THE TANK";TIME
490  PRINT
491  INPUT "TYPE IN THE NUMBER OF HOURS PER DAY BUBBLED AIR IS TO
     CIRCULATE";TAIR
492  PRINT
500  PRINT "IF CASE 1 IS FOR FILL/SPILL"
510  PRINT "   CASE 2 IS FOR FILL/NO-SPILL"
520  PRINT "   CASE 3 IS FOR NO-FILL/NO-SPILL"
530  PRINT
531  INPUT "TYPE IN THE CASE NUMBER TO BE CALCULATED";CASE
538  LPRINT
539  LPRINT
540  LPRINT
541  LPRINT "CASE";CASE;
542  IF CASE=1 THEN LPRINT "FILL/SPILL"
543  IF CASE=2 THEN LPRINT "FILL/NO-SPILL"
544  IF CASE=3 THEN LPRINT "NO-FILL/NO-SPILL"
545  LPRINT
550  PRINT
560  PRINT "IF 'MIN' DESCRIBES A TANK HAVING ESSENTIALLY NO INSULATION"
580  PRINT "   'MED' DESCRIBES A MARGINALLY INSULATED TANK,"
590  PRINT "   'MAX' DESCRIBES A WELL-INSULATED TANK,"
600  PRINT
610  INPUT "TYPE INSULATION DESCRIPTION AS MIN, MED, OR MAX";U$
620  IF U$ = "MIN"   THEN U = MIN
621  IF U$ = "min"   THEN U = MIN
630  IF U$ = "MED"   THEN U = MED
631  IF U$ = "med"   THEN U = MED
640  IF U$ = "MAX"   THEN U = MAX
641  IF U$ = "max"   THEN U = MAX
650  PRINT
660  INPUT "TYPE IN THE TONS OF FISH TO BE ADDED TO THIS CSW TANK"; MF
670  IF MF*2000/VTOT <= D GOTO 740
680  PRINT "                    *****"
690  PRINT "WARNING: FISH LOADING DENSITY EXCEEDS MAXIMUM ALLOWED
     VALUE OF";
700  PRINT D; "LBM/FT3"
710  PRINT "TRY LOADING LESS FISH"
720  PRINT "                    *****"
730  GOTO 660
740  PRINT
750  PRINT
760  MIFISH  = MF*CF*(TI-TF)/LI 'Total ice melt for fish
770  MILKDA  = .0864*U*VTOT↑.6678*(TI-TF)/LI 'Ice melt per day for heat leak
780  MILEAK  = MILKDA*TIME
781  MIAIR   = .08*((VTOT/6200)↑.667)*TAIR*TIME 'Ice melt per trip due to air
790  ON CASE GOSUB 1110, 1370, 1700
860  L PRINT "INITIAL TEMPERATURE                       ";TI;"F"
870  LPRINT "TANK VOLUME                               ";VTOT;"CUBIC FEET"
880  LPRINT "FISH TO BE LOADED                         ";
881  LPRINT USING  "###.#";MF;
882  LPRINT "  TONS"
890  LPRINT "NUMBER OF DAYS TO BE HELD                 ";TIME;"DAYS"
891  LPRINT "HOURS PER DAY OF AIR BUBBLING             ";TAIR;"HOURS"
900  LPRINT "ASSUMED INSULATION LEVEL                  ";
910  IF U=MIN THEN LPRINT "MIN"
920  IF U=MED THEN LPRINT "MED"
930  IF U=MAX THEN LPRINT "MAX"
```

(Continued on next page.)

```
940  LPRINT "ICE MELT FROM FISH                          ";
950  LPRINT USING "##.#";MIFISH;
960  LPRINT "  TONS"
1000 LPRINT "ICE MELT FROM HEAT LEAK                     ";
1010 LPRINT USING "##.#  "; MILEAK;
1020 LPRINT "  TONS"
1021 LPRINT "ICE MELT FROM BUBBLED AIR                   ";
1022 LPRINT USING "##.#"; MIAIR;
1023 LPRINT "  TONS"
1030 ON CASE GOSUB 1300, 1630, 1950
1040 VOLICE = VOLBLKICE*MI*100/VTOT
1050 LPRINT "APPROX PERCENTAGE OF TANK  "
1060 LPRINT "  OCCUPIED BY DRY  "
1070 LPRINT "  BULK-LOADED ICE                          ";
1080 LPRINT USING "###"; VOLICE
1081 CLS
1082 PRINT "***********************************************************"
1083 PRINT
1084 PRINT " IF YOU'RE FINISHED RUNNING CASES,"
1085 PRINT"TYPE 'CANCEL' (WANG) OR 'CONTROL - BREAK' (IBM)"
1086 PRINT
1087 PRINT "***********************************************************"
1088 PRINT
1089 PRINT
1090 GOTO 440
1091 STOP
1092 END
1100 END
1110 'Case 1 is for continually flooded tank; cold water spilled as fish added
1120 MIWATVOL = (RHOI/2000 - (MILEAK + MIAIR + MIFISH)/VTOT) / (1 +
     (RHOI*LI)/(RHOW*CW*(TI -TF)))  'Mass of ice per unit volume to chill water
1130 MIWAT = MIWATVOL*VTOT
1140 MI = MIFISH + MILEAK + MIAIR +MIWAT
1150 IF VOLBLKICE*MI <= VTOT GOTO 1210
1160 PRINT "     *****"
1170 PRINT "  WARNING: INITIAL BULK ICE VOLUME EXCEEDS TANK VOLUME BY  ";
1171 PRINT USING "###."; (VOLBLKICE*MI-VTOT)/VTOT*100;
1172 PRINT "  %"
1180 PRINT "  TRY BETTER INSULATION OR LESS FISH."
1190 PRINT "     *****"
1200 GOTO 560
1210 IF VOLBLKICE*MI <= .9*VTOT GOTO 860
1220 LPRINT "     *****"
1230 LPRINT "WARNING: INITIAL BULK ICE VOLUME EXCEEDS 90% OF TANK
     VOLUME."
1240 LPRINT "  MAY HAVE DIFFICULTY LOADING INITIAL CATCH."
1250 LPRINT "     *****"
1260 GOTO 860
1300 LPRINT "ICE MELT FROM WATER ADDED                   ";
1310 LPRINT USING "##.#"; MIWAT;
1320 LPRINT "TONS"
1330 LPRINT "TOTAL ICE REQUIRED                          ";
1340 LPRINT USING "##.#";MI;
1350 LPRINT "  TONS"
1360 RETURN
1370 'Case 2 is for an ultimately flooded tank; no water is spilled
1380 'as fish is added
1384 VOLPRIME = (VOLBLKICE*(MILEAK+MIAIR+MIFISH)*LI)/(LI+(RHOW/RHOI)*CW*
     (TI-TF)-(VOLBLKICE/2000)*RHOW*CW*(TI-TF))
1385 MIWAT = ((RHOW*CW*RHOI*(TI-TF)/2000)/(RHOI*LI+RHOW*CW*(TI-TF)))*
     (VOLPRIME-(MILEAK+MIAIR+MIFISH)*2000/RHOI)
1386 IF VOLPRIME < VTOT GOTO 1394
1387 PRINT "                                *****"
1388 PRINT "WARNING: ICE/WATER MIXTURE EXCEEDS TANK VOLUME. NO ROOM
     FOR FISH."
1389 PRINT "                          TRY BETTER INSULATION OR LESS FISH"
1390 PRINT "                                *****"
1391 GOTO 560
1394 N=0
1395 VOLWAT = MIWAT*LI*2000/(RHOW*CW*(TI-TF))
1400 IF (VOLPRIME + MF*2000/RHOF) < VTOT GOTO 1440
1405 IF (VOLPRIME + MF*2000/RHOF) = VTOT GOTO 1470
1410 IF N< 0 GOTO 1470
1415 MF = .99*MF
1420 MIFISH = MF*CF*(TI-TF)/LI
1425 VOLPRIME = (VOLBLKICE*(MILEAK+MIAIR+MIFISH)*LI)/(LI+(RHOW/RHOI)*CW*
     (TI-TF)-(VOLBLKICE/2000)*RHOW*CW*(TI-TF))
1426 MIWAT = ((RHOW*CW*RHOI*(TI-TF)/2000)/(RHOI*LI+RHOW*CW*(TI-TF)))*
     (VOLPRIME-(MILEAK+MIAIR+MIFISH)*2000/RHOI)
1430 N = 1
1435 GOTO 1400
1440 IF N > 0 GOTO 1470
1445 VOLWAT = 1.01*VOLWAT
1450 MIWAT = VOLWAT*RHOW*CW*(TI-TF)/(LI*2000)
1455 VOLPRIME = (MIWAT + MILEAK + MIAIR + MIFISH) *2000/RHOI + VOLWAT
1460 N = -1
1465 GOTO 1400
1470 MI = MIFISH + MILEAK + MIAIR + MIWAT
1472 IF N<1 GOTO 1500
1475 LPRINT "     *****"
1480 LPRINT "TANK CAPACITY IS INADEQUATE TO HOLD ALL THE FISH REQUIRED."
1485 LPRINT "THE PROGRAM HAS DECREASED THE INPUT AMOUNT OF FISH TO
     BE LOADED."
1490 LPRINT "     *****"
1495 GOTO 860
1500 LPRINT "     *****"
1505 LPRINT "EXTRA WATER HAS BEEN ADDED TO FILL THE TANK"
1510 LPRINT "     *****"
1515 GOTO 860
1630 LPRINT "ICE MELT FROM WATER ADDED                   ";
1640 LPRINT USING "##.#"; MIWAT;
1650 LPRINT "  TONS"
1660 LPRINT "TOTAL ICE REQUIRED                          ";
1670 LPRINT USING "##.#"; MI;
1680 LPRINT "  TONS"
1690 RETURN
1700 'Case 3 is for a partially flooded tank
1710 VOLPRIME = (VOLBLKICE*(MILEAK+MIAIR+MIFISH)*LI)/(LI+(RHOW/RHOI)*CW*
     (TI-TF)-(VOLBLKICE/2000)*RHOW*CW*(TI-TF))
1711 MIWAT = ((RHOW*CW*RHOI*(TI-TF)/2000)/(RHOI*LI+RHOW*CW*(TI-TF)))*
     (VOLPRIME-(MILEAK+MIAIR+MIFISH)*2000/RHOI)
1720 IF VOLPRIME < VTOT GOTO 1780
1730 PRINT "     *****"
1740 PRINT "WARNING: ICE/WATER MIXTURE EXCEEDS TANK VOLUME. NO ROOM
     FOR FISH."
1750 PRINT "TRY BETTER INSULATION OR LESS FISH"
1760 PRINT "     *****"
1770 GOTO 560
1780 VOL = VOLPRIME +MF*2000/RHOF
1790 IF VOL <= VTOT GOTO 1850
1800 PRINT "     *****"
1810 PRINT "WARNING: VOLUME OF FISH AND CSW EXCEEDS TANK VOLUME."
1820 PRINT "TRY PACKING LESS FISH"
1830 PRINT "     *****"
1840 GOTO 660
1850 VOLWAT = MIWAT*LI*2000/(RHOW*CW*(TI-TF))
1851 N=0
1852 IF MF*2000/VOL <= D GOTO 1930
1855 VOLWAT = 1.01*VOLWAT
1860 MIWAT = VOLWAT*RHOW*CW*(TI-TF)/(LI*2000)
1865 VOLPRIME = (MIWAT + MIAIR + MILEAK +MIFISH)*2000/RHOI + VOLWAT
1870 VOL = VOLPRIME + MF*2000/RHOF
1875 N = 1
1880 GOTO 1852
1930 MI = MIWAT + MILEAK + MIAIR + MIFISH
1931 IF N < 1 GOTO 1940
1932 LPRINT "     *****"
1933 LPRINT "PROGRAM HAS ADDED EXTRA WATER AND ICE TO REDUCE FISH
     PACKING DENSITY"
1934 LPRINT "  TO AN ACCEPTABLE VALUE"
1935 LPRINT "     *****"
1940 GOTO 860
1950 LPRINT "ICE MELT FROM WATER ADDED                   ";
1960 LPRINT USING "##.#"; MIWAT;
1970 LPRINT "  TONS"
1980 LPRINT "TOTAL ICE REQUIRED                          ";
1990 LPRINT USING "##.#";MI;
2000 LPRINT "  TONS"
2010 LPRINT "FISH LOADING DENSITY                        ";
2020 LPRINT USING "##.#";MF*2000/VOL,
2030 LPRINT "  POUNDS PER CUBIC FOOT"
2040 LPRINT "PERCENTAGE OF VOLUME OCCUPIED"
2050 LPRINT "BY ICE/WATER/FISH MIXTURE                   ";
2060 LPRINT USING "##.#"; VOL*100/VTOT
2070 RETURN
```