82401
5q
o.79-12

US-CE-C Property of the United States Government

CRREL REPORT 79-12

Point source bubbler systems to suppress ice

LIBRARY BRANCH
TECHNICAL INFORMATION CENTER
US ARMY ENGINEER WATERWAYS EXPERIMENT STATION
VICKSBURG, MISSISSIPPI

5149243

GB2401
C6q
no. 79-12

CRREL Report 79-12

Point source bubbler systems to suppress ice

George D. Ashton

May 1979

Prepared for
DIRECTORATE OF CIVIL WORKS
OFFICE, CHIEF OF ENGINEERS
By
UNITED STATES ARMY
CORPS OF ENGINEERS
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE, U.S.A.

Approved for public release; distribution unlimited.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER CRREL Report 79-12	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (*and Subtitle*) POINT SOURCE BUBBLER SYSTEMS TO SUPPRESS ICE		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) George D. Ashton		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S.Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS CWIS 31362
11. CONTROLLING OFFICE NAME AND ADDRESS Directorate of Civil Works Office, Chief of Engineers Washington, D.C. 20314		12. REPORT DATE May 1979 13. NUMBER OF PAGES 14
14. MONITORING AGENCY NAME & ADDRESS(*if different from Controlling Office*)		15. SECURITY CLASS. (*of this report*) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Air bubbler system
Docks
Ice
Ice formation
Ice prevention
Ice suppression
Inland waterways
Point source bubbler system

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

An analysis of a point source bubbler system used to induce local melting of an ice cover is presented. The analysis leads to a numerical simulation programmed in FORTRAN which may be used to predict the effectiveness of such systems. An example application is presented using a typical record of average daily air temperatures. The FORTRAN program for the point source simulation as well as a FORTRAN program for line source systems are included in the Appendix.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

PREFACE

This report was prepared by Dr. George D. Ashton, Chief, Snow and Ice Branch, Research Division, U.S.Army Cold Regions Research and Engineering Laboratory.

This study was conducted under DA Program, *Ice Engineering*; subprogram, *Ice Decay*; CWIS 31362, *Theoretical Study of Ice Suppression Possibilities.*

Appreciation is expressed to Dr. Y.C. Yen and K.L. Carey for their technical review of the report.

CONTENTS

ILLUSTRATIONS

POINT SOURCE BUBBLER SYSTEMS TO SUPPRESS ICE

George D. Ashton

INTRODUCTION

The use of air bubbler systems to suppress ice formation by inducing a flow of water against the underside of an ice cover is a commonly used technique. The analysis of line source bubblers for such purposes has recently (Ashton 1974, 1978) progressed to the extent that it is possible to simulate and predict the performance of these bubblers, and that analysis has been validated against field and laboratory data (Ashton 1975, 1978). This report presents a parallel analysis for point source bubbler systems, i.e., the suppression of ice that results from a single-point discharge of air bubbles. The installations of such systems would be useful, for example, in the protection of individual piles of a multipile dock installation.

OUTLINE OF ANALYSIS

This study begins with an analysis of the plume induced by the rising stream of bubbles emanating from an orifice submerged in the water and uses the results of Kobus (1968). It next determines the heat transfer coefficient using the plume parameters at the point of impingement of the plume on the underside of the ice cover by analogy with empirical results of Gardon and Akfirat (1966) for impinging axisymmetric air jets. It thus determines ice melting and thermal depletion by use of a simplified energy budget calculation. Finally, it applies the resulting analysis to the practical case of varying winter temperatures by a quasi-steady stepwise solution utilizing daily temperatures. An example simulation is presented. The FORTRAN computer program for the simulation is given in the Appendix.

PLUME ANALYSIS

The air discharge rate Q_0 (m^3 s^{-1}) from an orifice of diameter d (m) is

$$Q_0 = C_d \frac{\pi d^2}{4}\left(\frac{2\Delta p}{\rho_a}\right)^{1/2} \qquad (1)$$

where C_d is a discharge coefficient (on the order of 0.6; see e.g., Rouse 1946), Δp is the pressure difference across the orifice, and ρ_a is the air density inside the bubbler line. Typical orifice diameters used in existing installations are on the order of 1 mm. The pressure difference Δp is

$$\Delta p = P_{\text{inside}} - \rho_w g H \qquad (2)$$

where P_{inside} is the pressure inside the supply line, $\rho_w g H$ is the hydrostatic pressure at the submergence depth H in water of density ρ_w, and g is the gravitational constant.

Using the results of Kobus (1968), the centerline water velocity $U_c(x)$ (m s^{-1}) at distance x above the orifice is given by

$$U_c(x) = \frac{1}{c\,(x+x_0)}\left[\frac{-P_{atm}\, Q_0 \log_e[1-(x/H^*)]}{\pi \rho_w U_b}\right]^{0.5} \qquad (3)$$

where c is the rate of linear spread of the plume, x_0 is an empirical coordinate correction to account for various near-orifice effects, P_{atm} is the atmospheric pressure, $H^* = H + P_{atm}/\rho_w g$ (for sea level conditions $H^* = H + 10.3$ m), and U_b is the mean rising speed of the bubbles. These are further illustrated in Figure 1. Both U_b and c were found by Kobus (1968) to be weak functions of Q_0 and a fit of these data yields

$$c = C_c\, Q_0^{\;0.15} \qquad (4)$$

$$U_b = C_b\, Q_0^{\;0.15} \qquad (5)$$

where $C_c = 0.152$ m$^{-0.45}$ s$^{0.15}$ and $C_b = 1.83$ m$^{0.55}$ s$^{-0.85}$. The plume analysis of Kobus used a Gaussian distribution of vertical water velocity of the form

$$\frac{U(x,r)}{U_c(x)} = \exp\left[\frac{-r^2}{2c^2\,(x+x_0)^2}\right] \qquad (6)$$

where r is the radial coordinate from the plume centerline. The total volume flux $Q_w(x)$ is then given by

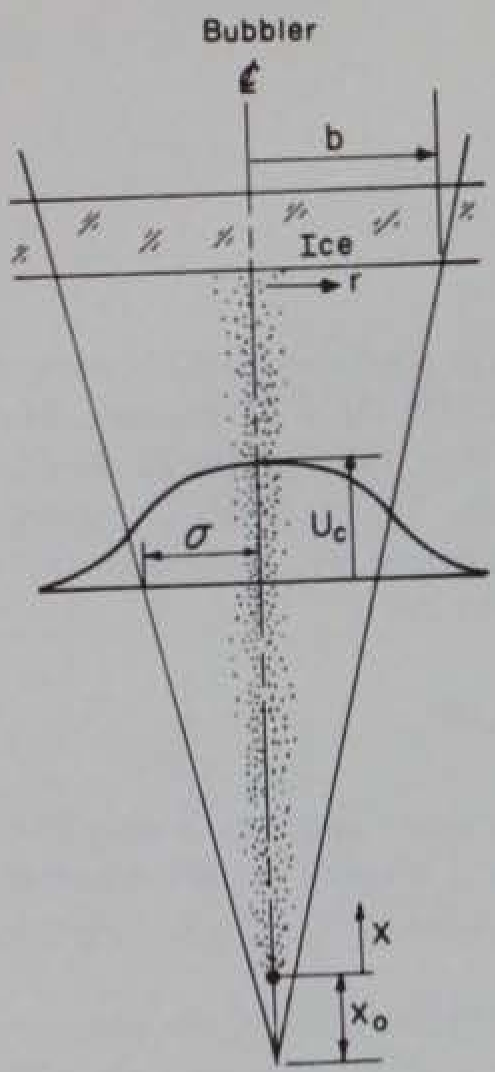

Figure 1. Definition sketch.

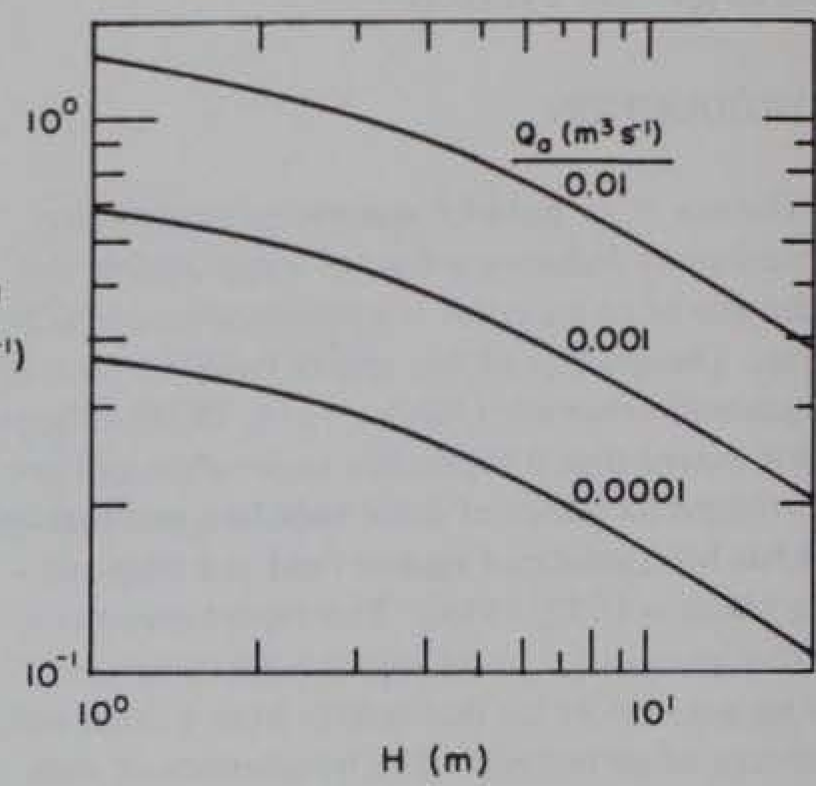

Figure 2. Centerline velocity of plume as a function of orifice discharge and submergence depth of orifice.

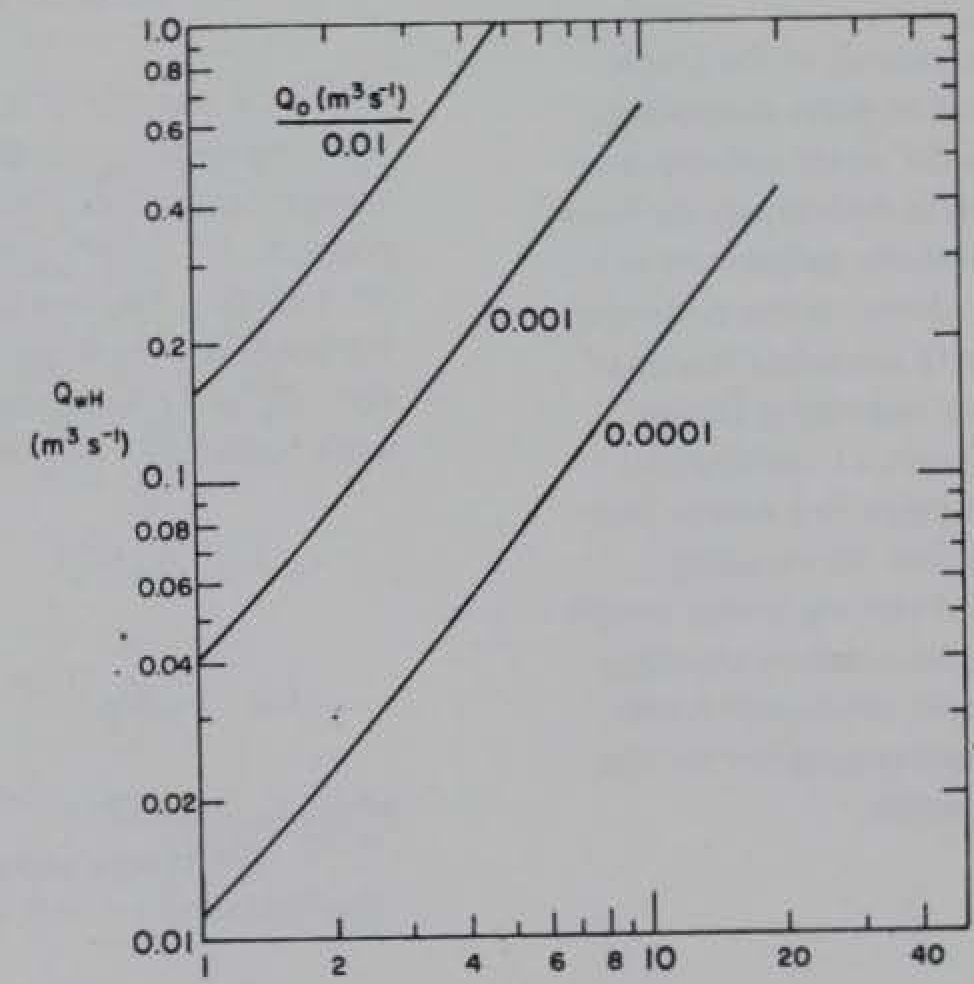

Figure 3. Induced flow of water at impingement as a function of air discharge rate and submergence depth of orifice.

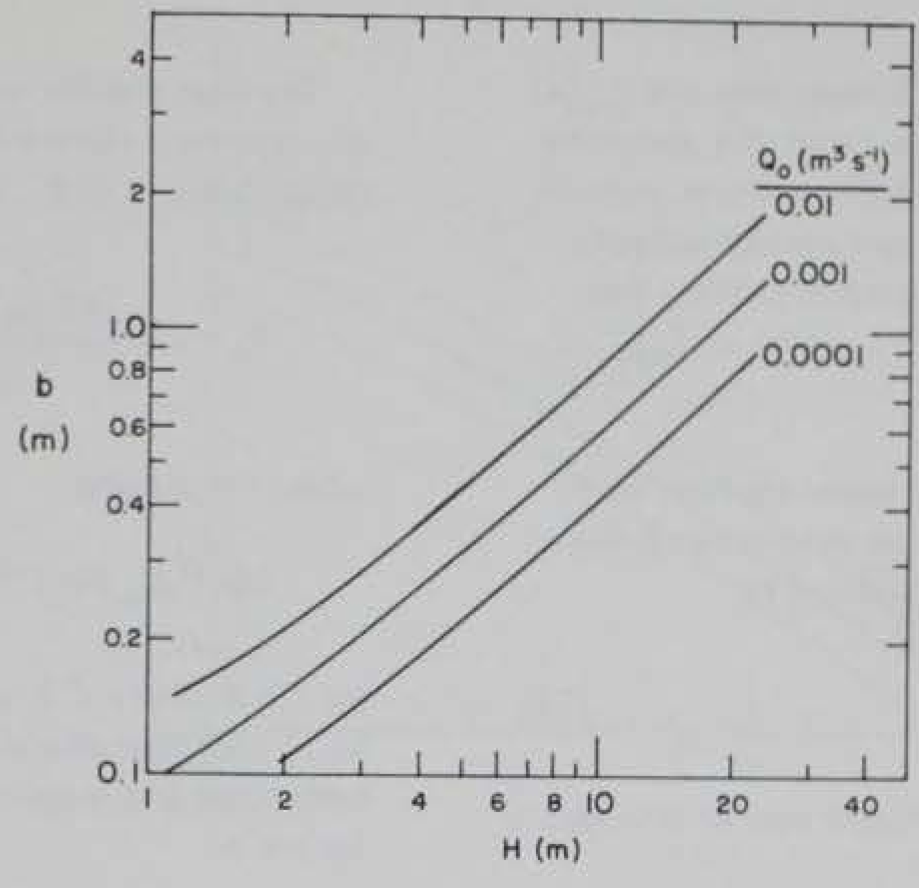

Figure 4. Diameter of impinging plume as a function of air discharge rate and submergence depth of orifice.

$$Q_w(x) = 2\pi\, U_c(x)\, c^2\, (x+x_0)^2. \tag{7}$$

Appropriate substitution for c and U_b into eqs 3 and 7 then yields, respectively,

$$U_c(x) = \frac{Q_0^{0.275}}{C_c\,(x+x_0)} \left[\frac{-P_{atm}\,\log_e\,[1-(x/H^*)]}{\pi \rho_w\, C_b}\right]^{0.5} \tag{8}$$

and

$$Q_w(x) = 2C_c\,(x+x_0)\,Q_0^{0.575} \left[\frac{-P_{atm}\,\pi\,\log_e\,[1-(x/H^*)]}{\rho_w\, C_b}\right]^{0.5}. \tag{9}$$

Defining $U_{cH} = U_c(x)$ and $Q_{wH} = Q_w(x)$ at $x = H$ yields

$$U_{cH} = \frac{Q_0^{0.275}}{C_c\,(H+x_0)} \left[\frac{-P_{atm}\,\log_e\,[1-(H/H^*)]}{\pi \rho_w\, C_b}\right]^{0.5} \tag{10}$$

$$Q_{wH} = 2C_c\,(H+x_0)\,Q_0^{0.575} \left[\frac{-P_{atm}\,\pi\,\log_e\,[1-(H/H^*)]}{\rho_w\, C_b}\right]^{0.5} \tag{11}$$

and the width b at $x = H$ is

$$b = (H+x_0)\, C_c\, Q_0^{0.15}. \tag{12}$$

In Figures 2, 3, and 4 are shown, respectively, the values of U_{cH}, Q_{wH}, and b as functions of air discharge rate Q_0 and submergence depth H.

HEAT TRANSFER ANALYSIS

The heat transfer analysis consists of determining the temperature of the plume impinging on the underside of the ice cover, estimating the heat transfer coefficient at the underside of the cover, performing a simplified analysis of the thickening (or thinning) of the cover, and depleting the thermal reserve as a consequence of the heat transfer to the cover.

Temperature of impinging plume

Since the water bodies in which bubbler systems are installed are seldom isothermal, it is necessary to evaluate the entrainment of water at different levels above the point of air discharge to arrive at the 'mixed' temperature at impingement. That is, the impingement temperature T_{wH}, referenced to the freezing point T_m, is given by

$$T_{wH} - T_m = \frac{1}{Q_{wH}} \int_0^H \left[T_w(x) - T_m\right] \frac{d\,Q_w(x)}{dx}\, dx \tag{13}$$

where $d\,Q_w\,(x)/dx$ is the entrainment rate and $T_w(x)$ is the water temperature as a function of x above the air discharge point. For a vertically uniform ambient water temperature T_{wA}, the impingement temperature $T_{wH} = T_{wA}$. Other temperature profiles may easily be integrated using eq 13 to arrive at T_{wH}.

Heat transfer coefficient

Gardon and Akfirat (1966) found the heat transfer coefficient associated with an axisymmetric impinging air jet (in air) to be correlated by

$$Nu_{av} = 0.78\,Re_a^{\;0.55} \tag{14}$$

where the Nusselt number averaged over an area of diameter $2\,r_0$ is defined by

$$Nu_{av} \equiv \frac{h_{av}\,r_0}{k} \tag{15}$$

and h_{av} is the average heat transfer coefficient and k is the thermal conductivity of the air. The associated Reynolds number is defined by

$$Re_a = \frac{U_a\,r_0\,\rho}{\mu} \tag{16}$$

where U_a is the axial velocity of the air jet and ρ and μ are the density and viscosity of air.

By analogy with other heat transfer results (see, e.g., Rohsenow and Choi 1961), we may convert eq 14 to a more general relationship by introducing the Prandtl number dependence in the form

$$Nu \propto \mathrm{Pr}^{1/3} \tag{17}$$

where Prandtl number Pr is defined by

$$\mathrm{Pr} \equiv \frac{\mu c_p}{k} \tag{18}$$

and c_p is the specific heat of the fluid. Assuming Pr = 0.7 for air and Pr = 13.6 for water at 0°C enables eq 14 to be transformed to apply to water flow in the form

$$Nu_{av} = 2.08\,Re_w^{\;0.55} \tag{19}$$

where the Reynolds number is now that for water; that is, $\mathrm{Re}_w = U_{cH}\,b_0\,\rho_w/\mu$.

The heat transfer coefficient at $r = b$ will be used as a reference value with which to normalize the radial variation of h. Thus

$$h_b = 2.08\frac{k\,U_{cH}^{\;0.55}\,b^{-0.45}}{\nu^{0.55}} \tag{20}$$

where $\nu = \mu/\rho$ and

$$h(r) = h_b\,(r/b)^{-0.45} \tag{21}$$

for $r > b$. For $r < b$, we simply fit a parabola to eq 21 such that $dh(r)/dr = 0$ at $r = 0$ and has the same slope and magnitude as eq 21 at $r = b$. Hence, for $r < b$

$$h(r) = h_b\,[1.225\text{-}0.225\,(r/b)^2]. \tag{22}$$

Variation of h_b as a function of submergence depth and air discharge is presented in Figure 5. The variation of $h(r)$ normalized by h_b is presented in Figure 6 as a function of r/b for $r > b$.

Melting of the ice cover

The actual melting of the ice is governed by the heat balance at the water/ice interface, given by:

$$q_i - q_w = \rho_i \lambda \frac{d\eta_i}{dt} \tag{23}$$

where q_i is the rate of heat conduction through the ice, $q_w = h(T_{wH} - T_m)$ is the rate of heat transfer to the undersurface of the ice, ρ_i is the mass density of the ice, λ is the heat of fusion of the ice, and $d\eta_i/dt$ is the rate of change of the ice thickness.

The model used for q_i is one-dimensional steady-state heat conduction, which assumes a linear variation in temperature through ice thickness (and snow thickness) together with an estimate of the transfer coefficient through the air boundary layer. Thus

$$q_i = \frac{(T_m - T_s)}{(\eta_i/k_i) + (\eta_s/k_s)} \tag{24}$$

where T_s is the top surface temperature of the ice (or snow, if present), and k_i and k_s are the thermal conductivity of ice and snow. In general, T_s is not the ambient air temperature. Within the context of the steady-state assumptions above, it is reasonable to represent the heat transferred through

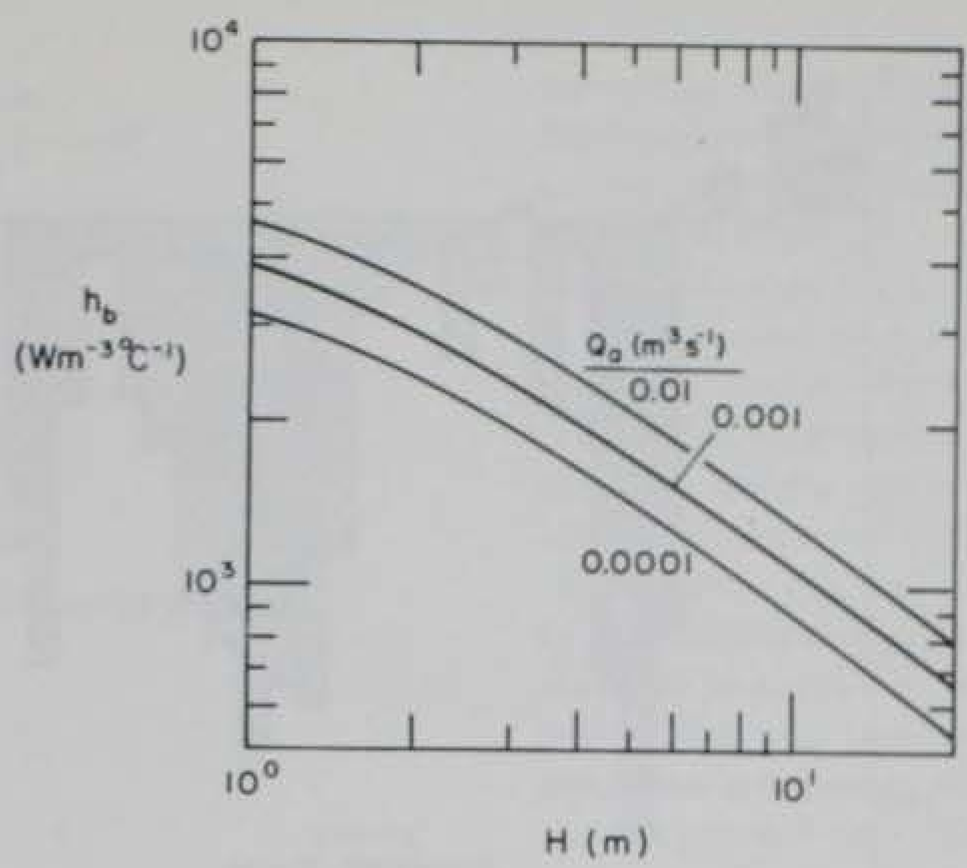

Figure 5. Variation of h_b as a function of orifice discharge and submergence depth of orifice.

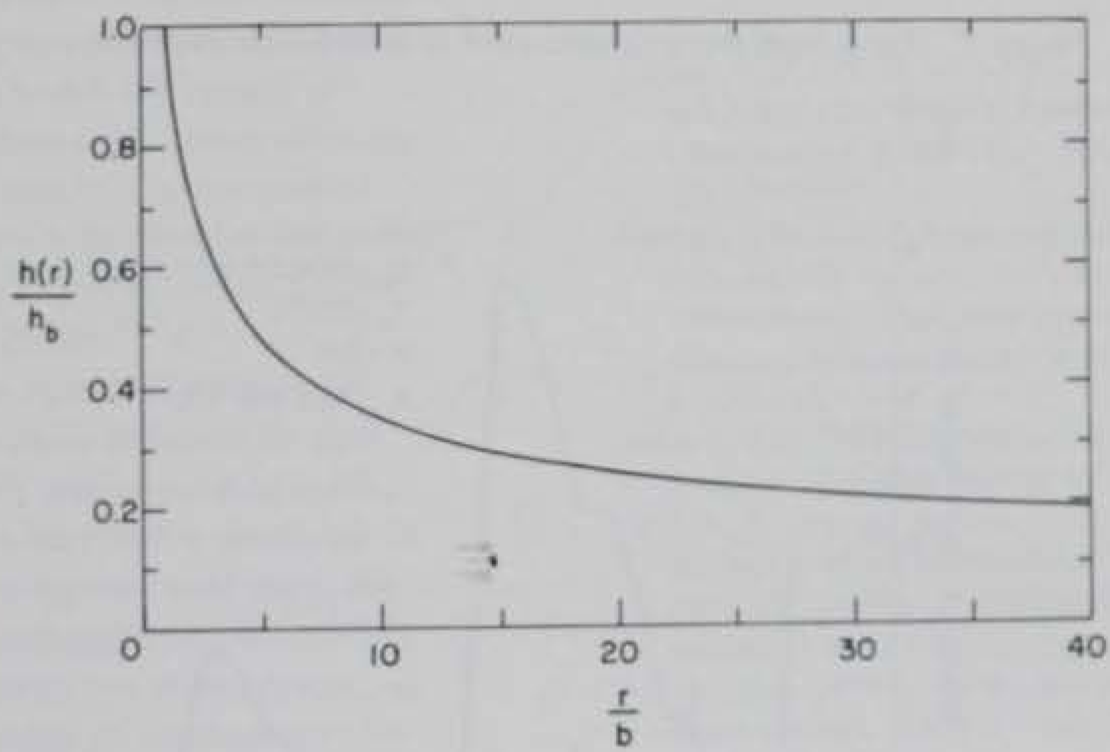

Figure 6. Variation of local heat transfer rate as a function of radial distance from centerline of impingement.

the air boundary layer in the form

$$q_i = \frac{(T_s - T_a)}{1/h_a} \tag{25}$$

where $1/h_a$ represents a thermal resistance due to the air boundary layer. Assuming q_i values in eqs 24 and 25 are equal (equivalent to a series representation of the thermal resistances), then T_s may be eliminated and

$$q_i = \frac{(T_m - T_a)}{(\eta_i/k_i) + (\eta_s/k_s) + (1/h_a)}. \tag{26}$$

The difficulty is to obtain a reasonable estimate of h_a. Jobson (1973) examined the energy budget terms and found that a good approximation for h_a from a water surface is of the form

$$h_a = 3.4 + 4.4\, U_a \tag{27}$$

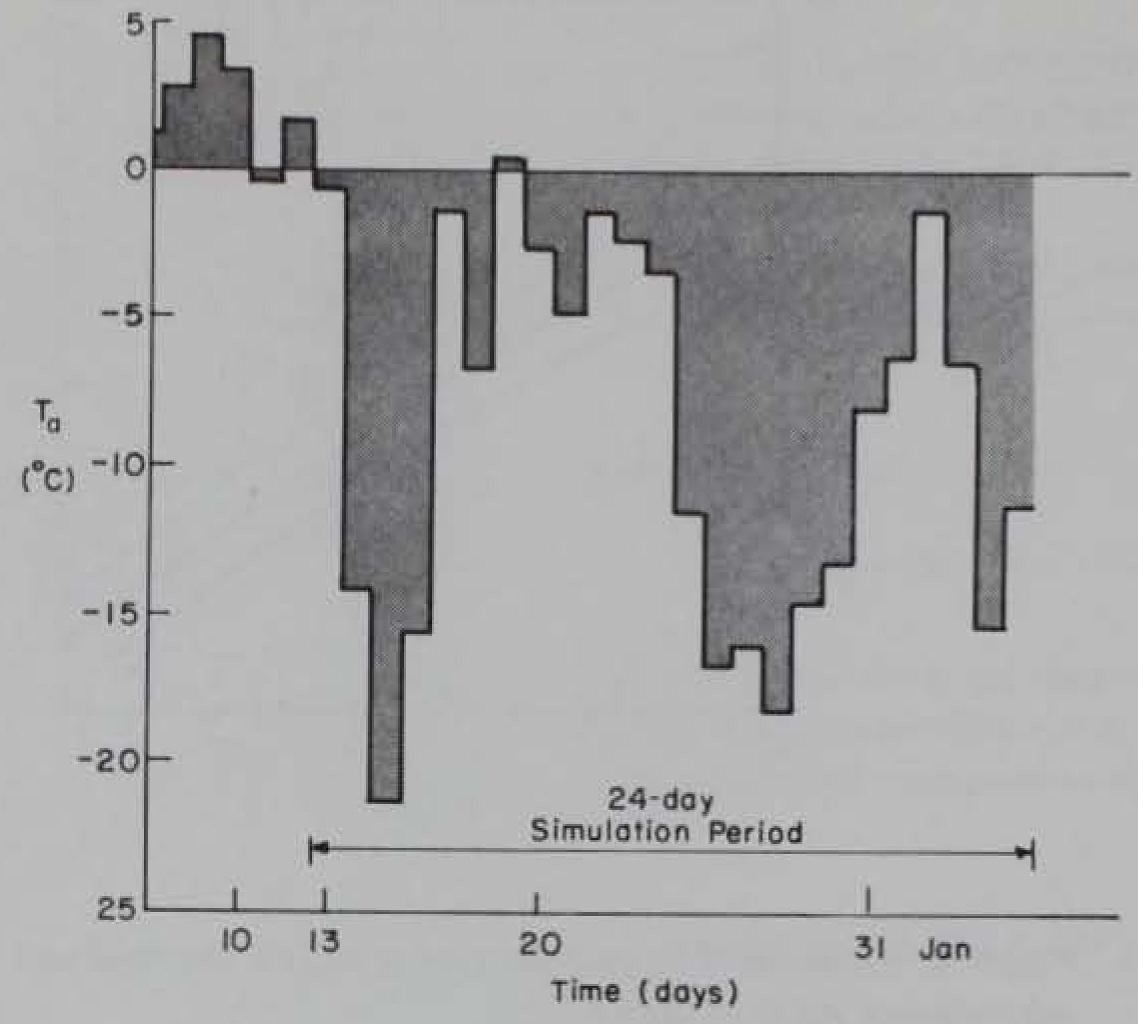

Figure 7. Air temperature record used in simulation example.

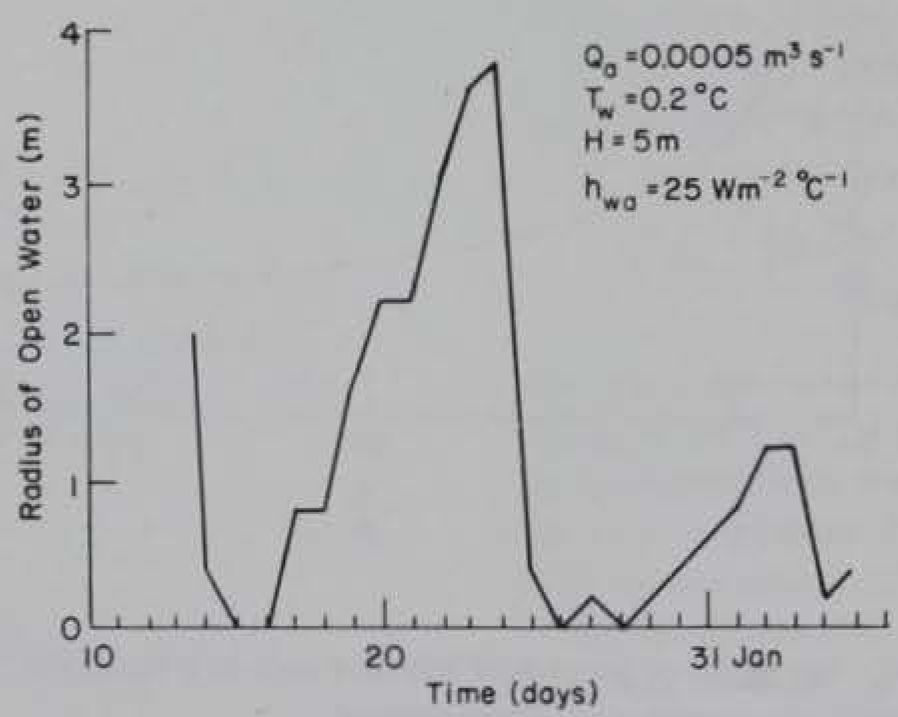

Figure 8. Variation of open water area for simulation example.

where U_a is the wind velocity ($m\ s^{-1}$) and h_a is the heat transfer coefficient in W m^{-2}°C^{-1}.

In the following simulation example, we will arbitrarily take h_a = 24 W m^{-2}°C^{-1} corresponding approximately to a windspeed of 4.5 m s^{-1}. Although h_a is derived for open water, we will assume it is also applicable to the ice/air interface. Similarly, the heat loss from open water above the bubbler uses eq 26 with $T_s = T_w$ and the same value of h_a. It is recognized that a more detailed energy budget approach could be used, but the detail is considered inappropriate in view of other uncertainties in the analysis and the lack of detailed input data other than daily maximum and minimum air temperatures usually available. h_a = 24 W m^{-2} °C^{-1}, incidentally, is equivalent to the thermal resistance of approximately 0.096 m of solid ice.

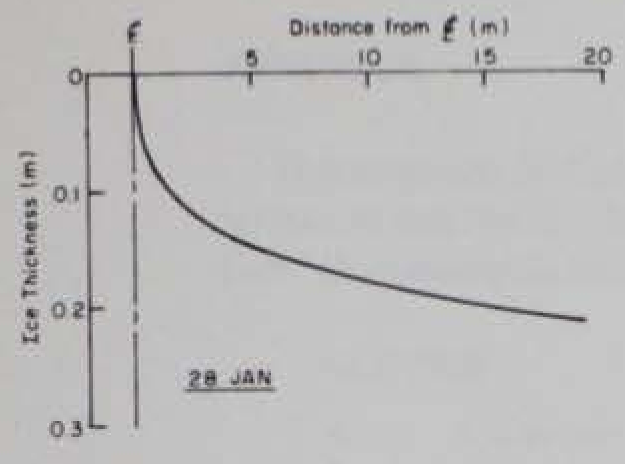

Figure 9. Ice thickness profile on 28 January of simulation example.

Simulation example

Figure 7 shows a daily average air temperature record taken from a midwestern location. It shows the patterns of alternating very cold periods with somewhat warmer periods which are typical of winter periods. Figure 8 shows the results of using that record in the present simulation as a plot of radius of open water extent with time for the parameters of $Q_a = 0.0005\ m^3\ s^{-1}$ ($\approx 1\ ft^3/min$), $T_w = 0.2°C$, $H = 5$ m, and $h_a = 25\ Wm^{-2}°C^{-1}$.

Figure 8 shows that the extent of open water responds to the air temperature variation by contracting during cold periods and expanding during warmer periods. While the ice cover is predicted to freeze over the bubbler during very cold days, the thickness is considerably reduced from that which would exist if the bubbler had not been present, as shown in the simulated profile of ice thickness for 28 January of Figure 9, but the effect extends only a few meters. The FORTRAN computer program for the simulation is given in the Appendix.

Thermal reserve analysis

The thermal reserve available in a closed water body is often quite limited and may prove to be the limiting factor in the operation of a bubbler system. In a water body of length L, width B, depth D, and average water temperature T_w, the total heat content available for melting ice is:

$$Q_{total} = LBD\ \rho_w c_p\ (T_w - T_m). \qquad (28)$$

As the bubbler functions, it draws on this reserve, lowering the average water temperature. Since the rate of heat transfer is proportional to $(T_w - T_m)$, this decreases correspondingly the heat flux to the ice and the rate of ice suppression. The bubbler system may eventually reach a point where no more ice will be melted and ice begins to re-form.

The computer program uses the result of the numerical integration of heat transferred to the ice cover and through open water, if present, to calculate the thermal reserve removed from the water body by each point source bubbler. This depletion of the thermal reserve is reentered into the program by uniformly scaling down the original temperature profile in proportion to the relative depletion. A new impingement temperature is calculated and the simulation is repeated. By appropriately varying the input at each time step, we may follow the evolution of the suppressed ice cover through a weather change (or season).

LITERATURE CITED

Ashton, G.D. (1974) Air bubbler systems to suppress ice. U.S.Army Cold Regions Research and Engineering Laboratory (USACRREL), Special Report 210. AD-A008867.

Ashton, G.D. (1975) Experimental evaluation of bubbler induced heat transfer coefficients. *Proceedings Third International Symposium on Ice Problems, August 1975, Hanover, New Hampshire* (G.E. Frankenstein, Editor), p. 133-142.

Ashton, G.D. (1978) Numerical simulation of air bubbler systems. *Canadian Journal of Civil Engineering* (in press).

Gardon, R. and J.C. Akfirat (1966) Heat transfer characteristics of two-dimensional air jets. *Transactions, American Society of Mechanical Engineers, Series C, Journal of Heat Transfer*, Feb., p. 101-108.

Jobson, H.E. (1973) The dissipation of excess heat from the water systems. *Journal Power Division*, ASCE, vol. 99, no. PO1, p. 89-103.

Kobus, H.E. (1968) Analysis of the flow induced by air-bubbler systems, Chapter 65 of Part 3. *Coastal Structures*, vol. II. *Proceedings Eleventh Conference on Coastal Engineering, London, England.* New York: American Society of Civil Engineers, p. 1016-1031.

Rohsenow, W.M. and H.Y. Choi (1961) *Heat, mass, and momentum transfer.* Englewood Cliffs, New Jersey: Prentice-Hall.

Rouse, H. (1946) *Elementary Mechanics of Fluids.* New York: J. Wiley and Sons.

APPENDIX

This appendix includes the FORTRAN program for the point source bubbler simulation described in this report. Also included is the FORTRAN program for the line source bubbler simulation. Documentation for the line source simulation is presented by Ashton (1974, 1978).

POINTBUB

```
*      G ASHTON   14 JUNE 1978   POINT SOURCE BUBBLER SIMULATION
*
*          PROGRAM SIMULATES OPERATION OF A POINT SOURCE BUBBLER
*          TO MELT ICE
*
       DIMENSION ETA(100),QWI(100),DAT(60)
       READ 301,H,QA,ETAZ,TWH,HWA,DELR,DELT
       READ 302,ALB,ALW
       READ 303,ND
       READ 304,(DAT(I),I=1,ND)
301    FORMAT (7F10.0)
302    FORMAT (2F10.0)
303    FORMAT (I10)
304    FORMAT (F10.0)
*
       PRINT 401,H,QA
401    FORMAT (1H1,10X,'H = ',F6.2,' METERS'/10X,'QA = ',F10.6,' M3/S')
       PRINT 402,ETAZ,TWH
402    FORMAT (10X,'ETAZ = ',F6.2,' METERS'/10X,'TWH = ',F7.3,' DEG C')
       PRINT 403,HWA
403    FORMAT (10X,'HWA = ',F7.2,' W/M2-DEG C')
       PRINT 404,ND
404    FORMAT (10X,'SIMULATION IS FOR ',I4,'DAYS')
       PRINT 405
405    FORMAT (1H0,10X,'DAY   AIR TEMP')
       PRINT 406,(I,DAT(I),I=1,ND)
406    FORMAT (10X,I3,3X,F7.2)
*
*      H is depth of diffuser (meters)
*      QA is air discharge (square meters per second)
*      ETAZ is initial ice thickness (meters)
*      TWH is initial water temperature (deg C)
*      HWA is heat transfer coefficient water to air (W/M2-DEG C)
*      ND is number of days of simulation
*      DAT(I) is daily air temperature (deg C)
*      DELR is radial increment distance (m)
*      DELT is time step (sec)
*      ALB and ALW are width and length of the water body
*
       PATM = 101325.
       RHOW = 1000.
       RHOI = 916.
       CP = 4215.
       AKI = 2.24
       AKW = 0.54
       ALAM = 3.34E5
       CC = 0.152
       CB = 1.83
       G = 9.807
       ANU = 1.79E-6
       PI = 3.14156
       HSTAR = H + PATM/(RHOW*G)
       DUM = -PATM*ALOG(1.-H/HSTAR)/(RHOW*CB)
       DUM = SQRT(DUM)
       QWH = (QA**0.575)*DUM*2.*CC*(H + .08)*SQRT(PI)
       B = (H+0.8)*CC*QA**0.15
       UCH = QWH/(2.*PI*B*B)
       PRINT 407,UCH,QWH
       PRINT 408,B
       HB = 2.10*AKW*(UCH**0.55)/((ANU**0.55)*(B**0.45))
       PRINT 409,HB
       NTD = 86400./DELT
```

```
407   FORMAT (1H0,10X,'UCH = ',F8.4,'M/S/10X,'QWH = ',F8.4,' M3/S')
408   FORMAT (10X,'B = ',F8.4,' METERS')
409   FORMAT (1H0,'HB = ',F8.2,' W/M2-DEG C')
      DO 80 I=1,100
      ETA(I) = ETAZ
80    CONTINUE

      DO 250 ID=1,ND
*     Establish lateral variation of QWI at DELR intervals
      R = 0.
      DO 110 I=1,100
      IF (R-B) 101,102,102
101   QWI(I) = HB*(1.225 - 0.225*R*R/(B*B))*TWH
      GO TO 103
102   QWI(I) = HB*((B/R)**0.45)*TWH
103   R = R+DELR
110   CONTINUE
*       Now calculate thickening and melting of ice
      DO 195 J=1,NTD
      DO 190 I=1,100
      IF (DAT(ID)) 115,115,116
115   QI = -DAT(ID)/(ETA(I)/AKI+1./HWA)
      GO TO 117
116   QI = 0.0
117   CONTINUE
      DELETA = (QI - QWI(I)) * DELT/(RHOI*ALAM)
      ETA(I) = ETA(I) + DELETA
      IF (ETA(I)) 121,122,122
121   ETA(I) = 0.0
122   CONTINUE
190   CONTINUE
195   CONTINUE
*        Find ice edge
      REDGE = 0.0
      DO 197 I=1,100
      IF (ETA(I)) 196,196,197
196   REDGE = REDGE + DELR
197   CONTINUE
      PRINT 410,ID,REDGE
410   FORMAT (1H0,10X,'AFTER ',I4,'DAYS ICE EDGE IS AT R = ',F6.2,'M')
*         Calculate thermal depletion
      DTHERM = PI*REDGE*REDGE*HWA*TWH
      NR = REDGE/DELR
      IF (NR - 100) 201,211,211
201   DO 210, I=NR,100
      RLR = REDGE + DELR/2
      DTHERM = DTHERM + 2.*PI*RLR*QWI(I)
210   CONTINUE
211   CONTINUE
      TWH = TWH*(1. - DTHERM/(ALB*ALW*H*RHOW*CP))
      PRINT 411,TWH
411   FORMAT (10X,'NEW TWH = ',F6.3,' DEG C')
      DELRR = 5.*DELR
      PRINT 412,DELRR
412   FORMAT (10X,'ICE THICKNESS AT CL AND DELRR = ',F5.2,'METERS')
      PRINT 413,(ETA(I), I=1,100,5)
413   FORMAT (10X,10F6.3)
250   CONTINUE
      END
```

LINEBUB

```
*     G ASHTON   14 JUNE 1978   LINE SOURCE BUBBLER SIMULATION
*
*        PROGRAM SIMULATES OPERATION OF A LINE SOURCE BUBBLER
*        TO MELT ICE
*
      DIMENSION ETA(100),QWI(100),DAT(60)
      READ 301,H,QA,ETAZ,TWH,HWA,DELY,DELT
      READ 302,ALB,ALW
      READ 303,ND
      READ 304,(DAT(I),I=1,ND)
301   FORMAT (7F10.0)
302   FORMAT (2F10.0)
303   FORMAT (I10)
```

```
304   FORMAT (F10.0)
*
      PRINT 401,H,QA
401   FORMAT (1H1,10X,'H = ',F6.2,' METERS'/10X,'QA = ',F10.6,' M2/S')
      PRINT 402,ETAZ,TWH
402   FORMAT (10X,'ETAZ = ',F6.2,' METERS'/10X,'TWH = ',F7.3,' DEG C')
      PRINT 403,HWA
403   FORMAT (10X,'HWA = ',F7.2,' W/M2-DEG C')
      PRINT 404,ND
404   FORMAT (10X,'SIMULATION IS FOR ',I4,'DAYS')
      PRINT 405
405   FORMAT (1H0,10X,'DAY   AIR TEMP')
      PRINT 406,(I,DAT(I),I=1,ND)
406   FORMAT (10X,I3,3X,F7.2)
*
*     H is depth of diffuser (meters)
*     QA is air discharge (square meters per second)
*     ETAZ is initial ice thickness (meters)
*     TWH is initial water temperature (deg C)
*     HWA is heat transfer coefficient water to air (W/M2-DEG C)
*     ND is number of days of simulation
*     DAT(I) is daily air temperature (deg C)
*     DELY is lateral distance increment (meters)
*     DELT is time step (sec)
*     ALB and ALW are width and length of the water body
*
      PATM = 101325.
      RHOW = 1000.
      RHOI = 916.
      CP = 4215.
      AKI = 2.24
      AKW = 0.54
      ALAM = 3.34E5
      CC = 0.182
      CB = 2.14
      G = 9.807
      ANU = 1.79E-6
      PI = 3.14156
      HSTAR = H + PATM/(RHOW*G)
      B = (H+0.8)*CC*QA**0.15
      DUM = -PATM*ALOG(1.-H/HSTAR)/(RHOW*CB)
      DUM = SQRT(DUM)
      UCH = (QA**0.425)*DUM/(PI**0.25*SQRT(B))
      QWH = SQRT(2.*PI)*B*UCH
      PRINT 407,UCH,QWH
      PRINT 408,B
      HB = 0.96*AKW*UCH**0.61/(ANU**0.62*B**0.38)
      PRINT 409,HB
      NTD = 86400./DELT
407   FORMAT (1H0,10X,'UCH = ',F8.3,'M/S/10X,'QWH = ',F8.5,' M2/S')
408   FORMAT (10X,'B = ',F8.3,' METERS')
409   FORMAT (1H0,'HB = ',F8.3,' W/M2-DEG C')
      DO 80 I=1,100
      ETA(I) = ETAZ
80    CONTINUE

      DO 250 ID=1,ND
*     Establish lateral variation of QWI at DELY intervals
      Y = 0.0
      DO 110 I=1,100
      IF (Y-B) 101,102,102
101   QWI(I) = HB*(1.190 - 0.190*Y*Y/(B*B))*TWH
      GO TO 103
102   QWI(I) = HB*((B/Y)**0.27)*TWH
103   Y = Y+DELY
110   CONTINUE
*       Now calculate thickening and melting of ice
      DO 195 J=1,NTD
      DO 190 I=1,100
      IF (DAT(ID)) 115,115,116
115   QI = -DAT(ID)/(ETA(I)/AKI+1./HWA)
      GO TO 117
116   QI = 0.0
117   CONTINUE
      DELETA = (QI - QWI(I)) * DELT/(RHOI*ALAM)
      ETA(I) = ETA(I) + DELETA
```

```
      IF (ETA(I)) 121,122,122
121   ETA(I) = 0.0
122   CONTINUE
190   CONTINUE
195   CONTINUE
*       Find ice edge
      REDGE = 0.0
      DO 197 I=1,100
      IF (ETA(I)) 196,196,197
196   REDGE = REDGE + DELY
197   CONTINUE
      PRINT 410,ID,REDGE
410   FORMAT (1H0,10X,'AFTER ',I4,'DAYS ICE EDGE IS AT Y = ',F6.2,'M')
*         Calculate thermal depletion
      NR = REDGE/DELY
      IF (NR - 100) 201,211,211
201   DO 210, I=NR,100
      RLR = REDGE + DELY/2
      DTHERM = DTHERM + 2.*QWI(I)*DELY
210   CONTINUE
211   CONTINUE
      TWH = TWH*(1. - DTHERM/(ALB*ALW*H*RHOW*CP))
      PRINT 411,TWH
411   FORMAT (10X,'NEW TWH = ',F6.3,' DEG C')
      DELYY = 5.*DELY
      PRINT 412,DELYY
412   FORMAT (10X,'ICE THICKNESS AT CL AND DELYY = ',F5.2,'METERS')
      PRINT 413,(ETA(I), I=1,100,5)
413   FORMAT (10X,10F6.3)
250   CONTINUE
      END
```

A facsimile catalog card in Library of Congress MARC
format is reproduced below.

Ashton, George D.
Point source bubbler systems to suppress ice / by George D. Ashton. Hanover, N.H.: U.S. Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1979.
iii, 17 p., illus.; 27 cm. (CRREL Report 79-12.)
Prepared for Directorate of Civil Works, Office, Chief of Engineers, by U.S. Army Cold Regions Research and Engineering Laboratory under CWIS 31362.
Bibliography: p. 7.
1. Air bubbler systems. 2. Ice suppression. 3. Point source bubbler system. I. United States. Army. Corps of Engineers. II. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. III. Series: CRREL Report 79-12.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1979—601-497/84