UNCLASSIFIED — MASTER COPY — FOR REPRODUCTION PURPOSES

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

AD-A209 131

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) ARO 22545.5-GS
6a. NAME OF PERFORMING ORGANIZATION Geophysical Institute University of Alaska 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION U. S. Army Research Office
6c. ADDRESS (City, State, and ZIP Code) Fairbanks, Alaska 99775-0800	7b. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211
8a. NAME OF FUNDING/SPONSORING ORGANIZATION U. S. Army Research Office 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DAAG29-85-K-0260
8c. ADDRESS (City, State, and ZIP Code) P. O. Box 12211 Research Triangle Park, NC 27709-2211	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
An Investigation of Frazil and Anchor Ice and Their Role in Ice Cover Development

12. PERSONAL AUTHOR(S)
J. P. Gosink and T. E. Osterkamp

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 10/15/85 TO 4/14/89	May 1989	14

16. SUPPLEMENTARY NOTATION
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Frazil Ice; Anchor Ice; Ice Cover; Ice; Freeze-up;

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The primary objective of this research has been to develop a basic scientific understanding of frazil and anchor ice including their formation (nucleation or sources), growth, characteristics, and evolution and to assess the roles that they play in the development of the ice cover during freeze-up particularly in edge ice formation, floe developement, and ice cover formation. The report contains the results of the above studies.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

ARO 22545.5-GS

FINAL REPORT

1. ARO Proposal Number: 22545-GS

2. Period covered by report: 15 October 1985 - 14 April 1989

3. Title of Proposal: An Investigation of Frazil and Anchor Ice and Their Role in Ice Cover Development

4. Contract or Grant Number: DAAG29-85-K-0260

5. Name of Institution: Geophysical Institute, University of Alaska

6. Authors of Report: J. G. Gosink and T. E. Osterkamp

7. List of manuscripts submitted or published under ARO sponsorship during this reporting period, including journal references:

i) Gosink, J. P., 1986a. Synopsis of analytic solutions for the temperature distribution in a river downstream from a dam or reservoir, *Water Resources Research*, *22*(6), 979-983.

(ii) Gosink, J. P., 1986b. Short-wave heating of lake surface water under a candled ice cover, Proceedings of the Cold Regions Hydrology Symposium, American Water Resources Association, Fairbanks, Alaska, July 1986, 31-37.

(iii) Gosink, J. P. and T. E. Osterkamp, 1986. Frazil ice nucleation by ejecta from supercooled water, Proceedings of the International Association for Hydraulic Research, Symposium on Ice, Iowa City, Iowa, July 1986, *3*, 249-264.

(iv) Chaco, E., W. Traub and J. Gosink, 1987. Frazil ice characteristics on the Tanana River as related to siting ice bridges, Technical Note, Corps of Engineers, U. S. Army Cold Regions Research and Engineering Laboratory, Ft. Wainwright, Alaska, 99709.

(v) George, T., W. J. Traub and J. P. Gosink, 1988. Monitoring river freeze-up with vertical aerial video data, Proceedings of the First Workshop on Videography, American Society for Photogrammetry and Remote Sensing, Indiana State University, Terre Haute, Indiana, 60-67.

(vi) Gosink, J. P. and W. Traub, 1989a. Minimum energy expenditure model for edge ice deposition: Development of the theory, to be submitted to Cold Regions Science and Technology.

(vii) Gosink, J. P. and W. Traub, 1989b. Minimum energy expenditure model for edge ice deposition: Comparison with measurements from video imagery, to be submitted to Cold Regions Science and Technology.

8. Scientific personnel supported by this project and degrees awarded during this reporting period:

Scientific personnel: J. P. Gosink and T. E. Osterkamp

Graduate students: W. Traub and T. Fei

FINAL REPORT

An Investigation of Frazil and Anchor Ice and Their Role in Ice Cover Development

Introduction

Increased resource development and utilization of northern areas and the need for military protection of strategic resources and associated transportation systems has introduced ice-related problems which urgently require solutions. However, development of rational design methods for alleviating or avoiding these problems is still hindered by the lack of a basic understanding of frazil and anchor ice formation, evolution, dynamics, properties and the roles that they play in the development of the ice cover during freeze-up.

The presence of frazil and anchor ice produces many challenging environmental and engineering problems in northern rivers. These problems are widespread because frazil and anchor ice types are so common. They are fascinating problems from both scientific and engineering points-of-view and have an immediate economic importance.

The primary objective of this research has been to develop a basic scientific understanding of frazil and anchor ice including their formation (nucleation or sources), growth, characteristics, and evolution and to assess the roles that they play in the development of the ice cover during freeze-up particularly in edge ice formation, floe developement, and ice cover formation.

Thermal Regime

Surface heat exchange across the water-air surface is controlled by local meteorological conditions. These conditions, primarily air temperature, wind velocity, barometric pressure, humidity, precipitation, and solar and long-wave radiation, change continually throughout the day. Some of these changes are clearly periodic, reflecting, for example, diurnal and seasonal variations in air temperature or radiation, while other variations are episodic, reflecting short term turbulent fluctuations as well as the passage of weather systems. If this variable surface forcing can be resolved into a sum of periodic series, it is possible to derive closed form solutions for the temperature regime in a river downstream from a dam or reservoir as it undergoes this forcing. Simple spatial variation of the surface heat exchange may also be resolved by the same method. We have derived two new analytic solutions for heat transport in a river with fluctuating and spatially varying surface heat exchange (Gosink, 1986a).

The first new solution describes the transient-convective temperature response in a river subjected to the combination of fluctuating and spatially varying surface heat transfer. Addition to the surface heat balance of a term varying linearly with distance from the dam introduces a function $H(x,t)$ which defines the effect on river temperature of the spatial variation in surface heat transfer. This function varies exponentially with distance from the dam up to the position of the thermal front ($x = Ut$), and varies linearly further downstream. The second new solution represents a complete transient-convective-diffusive solution to the equation for river temperature when the surface heat exchange is linearly dependent on water temperature and other periodically varying meteorological parameters.

In both of these new solutions the effects of the time varying atmospheric conditions are apparent. The river response lags the atmospheric forcing by the angle β_i, which increases with river depth and forcing frequency and decreases with heat exchange coefficient. The amplitude of the river thermal response to atmospheric forcing decreases with forcing frequency and surface heat exchange coefficient, and with river depth. A sudden change in water temperature at the release point at time $t = o$ propagates downstream as a thermal wave located at Ut. The solution which includes diffusion demonstrates that the thermal wave released from the dam disperses as $2(\upsilon t)^{\frac{1}{2}}$. Furthermore, the fluctuating components of the river response also disperse approximately as $2(vt)^{\frac{1}{2}}$. This is in contrast to the purely convective solutions which predict a jump in temperature at the thermal wave front.

Frazil Ice Nucleation

Frazil crystals may be nucleated by mass exchange mechanisms downstream where the water temperature has reached the freezing point. The mass exchange mechanisms include material transported from a distance such as ice particles (snow, frost, ice particles from trees, etc.), cold organic material, cold soil particles which may be introduced into a river by wind, precipitation, etc., and there serve as nucleation particles or sites for frazil ice crystals. They also include material originating in the river such as water droplets or water vapor transferred to the cold air above the water surface by splashing, wind spray, bubble bursting and evaporation. When the air temperature is less than the nucleation temperature of the water droplets, they may be nucleated with the resulting ice particles falling back to the water where they become frazil ice crystals. In addition to these mass exchange mechanisms, secondary nucleation, appears to be required to produce the high frazil ice concentrations observed in rivers ($\simeq 10^4$ to 10^7 m^{-3}).

Water droplets may be introduced into the cold air above the surface of a stream by splashing, wind spray, and bubble bursting. Any material at or near the water surface may be ejected along with the droplets. If the air temperature is less than the nucleation temperature, T_n, then some of these water droplets may be spontaneously nucleated in the air above the stream. The resulting ice crystals may fall into the water where they become frazil-ice crystals. To investigate this frazil ice nucleation mechanism field observations were made including measurements of the air temperature profile and photographs of water droplets above the surface of super-cooled water in a stream. The photographs produced evidence for the occurrence of this type of process (Gosink and Osterkamp, 1986). What appeared to be moving water droplets were seen in the photographs taken over the surface of a turbulent stream. The diameters of the drop are in the tenths of a mm range. It is estimated that there are about 10^2 - 10^3 droplets per m^2 of water surface distributed in a layer 10 cm thick. If this concentration is constant, assuming a residence time of a few tenths of a second and that 1% of the drops will freeze while in the cold air, then, as an order of magnitude estimate, about 10 frozen water droplets may fall into the stream per second for each square meter of water surface. This number is about the same as the estimated number of airborne ice crystals.

As noted above, bubbles in the stream, which rise to the surface and burst can be a source for the small droplets of water which were observed above the water surface. When the bubble bursts, surface potential energy is converted into kinetic energy and viscous dissipative losses.

Theoretical modeling and data from other sources were used to define the energy and mass transfer which occur at the water surface as the bubble bursts, and consequently to estimate the maximum rise height of a water droplet ejected by a bursting bubble and the time that the droplet remains in the air. This time scale can be compared to the time required for the small droplets to supercool to a temperature sufficiently low that 1% of the drops freeze in the cold air.

Bubbles bursting at the water surface eject jet droplets which rise vertically above a thermal boundary layer into the colder ambient air. These droplets have a predicted residence time in the colder air of a few tenths of a second. It was determined that very small droplets ($r < 0.02$ mm) seldom rise above the thermal boundary layer because of surface drag forces, while large droplets ($r > 0.5$ mm) seldom rise this distance due to gravitational forces. The droplets in the colder air may supercool sufficiently such that a prescribed fraction will nucleate spontaneously. The time required for supercooling depends upon the droplet size. This analysis suggests that there is a preferential nucleation size for the droplets near r $\approx$ 0.1 mm, since both smaller and larger droplets are not airborne sufficiently long to allow strong supercooling.

Freeze-Up Processes

Frazil ice floes are produced when frazil pans come in contact with each other, the contact providing a certain amount of penetration and bonding. We have identified five processes that can produce large frazil ice floes in rivers (Osterkamp and Gosink, 1983). These processes include simple contact, compaction with drag cut-off, compaction and convergent flow with impact cut-off, extrusive flow and drag cut-off and direct agglomeration with cut-off controlled by river curvature. Floes exceeding 1 km in maximum dimensions in the Yukon River can be produced, however, almost nothing is known about the hydrological and meteorological conditions that control the development of large floes. As noted below, these large frazil ice floes can play an important role in the formation of ice jams on rivers during freeze-up and therefore on the nature and development of the initial ice cover.

Freeze-up is usually associated with a very cold night (about -20°C or colder) when sheet ice in the centers of the frazil pans becomes thicker and the rest of the pans become better bonded. At this time, the frazil ice being transported down river can jam in a number of ways. These include the jamming of frazil floes in slow or constricted stream sections and accumulation of frazil flocs and pans in pools. A key point regarding large frazil ice floes is that these floes can initiate ice jams by getting crosswise with the flow or by jamming in narrow reaches lower on the river. Frazil ice jams often form when frazil pans or floes are being extruded through narrow river reaches. The frazil ice jams interrupt the downstream transport of frazil ice which accumulates on the upstream side of the jams with only a small amount transported under the jams. The resulting river ice cover, which consists almost entirely of frazil ice, alternates with open water areas on the river. The open water areas freeze over by edge ice growth toward the center of the river.

A video documentation of the formation of a frazil ice jam located at Groin 1 on the Tanana River about 3 miles west of Goose Island was obtained as part of this study (Chaco et al., 1987). The sequence of events occurring during the first formation, breakage and final formation of the ice jam at this site provided an analogue for the problem of inducing ice cover formation on the Tanana River at a site near Goose Island. This site is the location of a naturally occurring ice bridge which connects the public road system of Fairbanks with the Bonnifield Trail on the Fort Wainwright Military Reservation. The ice bridge at the Goose Island site provides the 6th Infantry Division with access to the Reservation for winter maneuvers; thus there is a military advantage in shortening the time required for ice bridge formation at the Goose Island site, and it was proposed that an ice boom be extended across the Tanana River near Goose Island to accelerate ice bridging at that location. The video data of frazil ice, edge ice formation and ice jam formation obtained as part of this project provided the following information on the characteristics of natural or induced frazil ice jams on the Tanana River in the vicinity of Goose Island:

1. The case study site at Groin 1 was the site of the earliest frazil jam in this reach of the river. Ice jams form at other sites within a few days, so that observations at the Groin 1 site should be fairly representative of other ice jam sites.
2. The time interval from frazil ice first visible on the river to the formation of an immobile ice jam was 10 days. However, this jam released and the final immobile jam was formed 3 days later or 13 days after the initiation of the frazil run.
3. An immobile frazil ice jam may form and release at least once before the final ice jam forms.
4. After the formation of the immobile ice jam, frazil ice may continue to be transported beneath the jam.

5. After the final immobile ice jam has formed open leads may appear in the jam. However, for the case study site, the lead formation may be partially or completely caused by warm water input from the Fairbanks water treatment plant outfall located about 3 miles upstream. The water treatment is located between the ice bridge site at Goose Island and the case study site at Groin 1. Since the warm water input is located below the ice bridge site, a detailed analysis of its effect on the ice cover is not provided here. It is sufficient for the purpose of the ice bridge construction to realize that open lead formation in an established ice jam is possible.
6. The ice cover is formed relatively early in the year at frazil ice jam locations. In the areas between the ice jams, the formation of the ice cover is a very slow process. At the end of November, six weeks after the initiation of the visible frazil ice run, long, wide open channels still existed.
7. Relatively rapid growth of the ice cover occurred immediately downstream of the frazil ice jam, particularly when compared to the growth of the shelf ice on the banks of the river. This suggests that favorable ice bridge sites for early bridging may be located at or a short distance downstream of natural constrictions. In addition, it appears that if restrictive site conditions require an ice boom to be located a short distance upstream of a desired ice bridge site, then only a short time delay will be encountered before downstream ice cover growth reaches the crossing.

Edge Ice Studies

Vertical aerial video data were acquired during the fall of 1986 and 1987 to monitor freeze-up of the Tanana River near Fairbanks, Alaska. The video data were used to monitor the progression of frazil ice deposition in the river throughout the period from initial ice appearance until total ice cover. This information, combined with field data of river bed profile, is being used to develop a predictive computer model of edge ice progression (Gosink and Traub, 1989a and b).

Video data for this study was acquired from a light aircraft using VHS video components. The observation platform was a Cessna 185 single engine aircraft. During the first season, a side mount was fabricated which attached externally to the copilot door. By the second year, a small camera port had been installed in the floor of the aircraft, and an interior mount was constructed to hold the video camera. A Panasonic CCD color video camera (Model WV-F2) attached to a Panasonic VHS portable video cassette recorder (Model AG-2400) was used for data acquisition. The video signal was sent to a portable color monitor with an intercom which allowed voice communications to be recorded on the audio channel of the video tape. The equipment was powered initially by internal batteries; later a 12 volt gel cell was added which allowed the system to run 4-6 hours continuously without the need to change batteries in flight.

Videotaping of the river was used to gather data on ice deposition during the freeze-up seasons of 1986-1987. Flights were made approximately every other day from the time ice first started forming in the river, until total freeze-up had occurred.

For a typical flight, the video equipment was configured and tested on the aircraft prior to departure. Data was acquired from an altitude of 2000 feet (610 m) above ground level. Using the camera at its shortest focal length (8.5 mm), yielded ground coverage across the width of the field of 1400 feet (427 m). This scale was selected to allow coverage across the river and include a small amount of the river bank on each side, for orientation.

Following freeze-up, field measurements were made on selected reaches of the Tanana River. Key features on the river banks were located and distances measured to provide a basis for scaling the video data. A detailed study area approximately one mile in length was defined to develop a computer model to predict edge ice growth. In this area, cross section measurements were made to determine the bottom profile of the river channel. Holes two inches in diameter were drilled through the ice at 50 foot intervals at each of fourteen cross sections, spaced 500 feet apart. In these holes, lengths of galvanized pipe were used to measure the river depth at each point. Since this field work was conducted after freeze-up, features such as ice ridges which had formed in progressive stages could be verified and measured in the field.

Previous investigations (Osterkamp and Gosink, 1983) have described the process of edge ice growth as a "streamlining" of the river. The frazil ice tends to fill in meanders, embayments and irregularities in the river in such a way as to reduce the lateral energy transfer, and to increase the efficiency of water and ice transport in the river. These observations led to our hypothesis that edge ice deposition is controlled by a principle of minimal energy expenditure. It should be noted that for the flowing river system, the minimal energy expenditure principle is equivalent to obtaining the minimum power per unit length.

Minimal energy expenditure is obtained for an equilibrium condition, when the total energy gradient is constant along the river beach. The same principle has been applied to the morphological changes in rivers due to sediment erosion and deposition (Chang, 1985; Leopold and Maddock, 1953). Chang (1984, 1985) and others have developed successful models which predict sediment transport in terms of the energy minimization principle. However, full equilibrium is almost never attained for sediment deposition and erosion, since the time scales for geologic morphological changes are very long. Therefore, the energy minimization principle is not considered thoroughly proven. A secondary goal of our modeling efforts is to provide corroborating evidence for the validity of the energy minimization hypothesis by applying the concept to edge ice processes. These events occur over time scales of weeks in cold regions, and therefore may provide a good test of the hypothesis.

The computer model for the prediction of edge ice growth is an extension of standard open channel flow models for river stage and velocity (Fread, 1978). Turbulent drag is simulated by a variable roughness coefficient, Manning's n, which is a function of the ratio of ice/river bottom parameters (Uzuner, 1975; Ashton, 1986). Since n decreases as the fraction of ice in the cross-section increases, then for constant discharge, the energy gradient at a particular cross section decreases as the fraction of ice increases. Thus, in effect, ice forms as a mechanism to smooth those river reaches with high values of energy gradient, and the ice formation (both edge ice and anchor ice) acts an agent to decrease energy expenditure. This mechanism is consistent with often-observed phenomenon of anchor ice forming frequently on river bottoms with coarse gravels, and rarely on river bottoms of fine sand, silt and clay.

In the model, an iteration procedure is set up in which a few feet of edge ice are introduced at each river section (stability criteria suggest that river sections are less than two times river depth). The edge ice addition is made permanent only if the variation in energy gradient is reduced by the addition of the ice. The process is repeated until the appropriate volume of ice is expended. In effect, energy gradients are forced toward a constant value with this procedure, thus assuring equilibrium and minimization of energy expenditure.

This model produces very good agreement with the measured values of edge ice position obtained by the video imagery. Significantly, the location of the smallest energy gradient which was calculated for open-water conditions along the study reach was a location where, in the field, virtually no edge ice accrued. Conversely, the location of the greatest calculated energy gradient along the study reach was a location where, in the field, the largest absolute accumulation of edge ice took place.

This alone suggests a strong cause and effect relationship between edge ice formation and total energy gradient.

Two manuscripts describing the development of the edge ice model, and which are to be submitted to Cold Regions Science and Technology, are listed in section 7 of this report. Although section 7 normally would include only published and submitted papers, these two manuscripts are listed here since major sections of the drafts are prepared and since considerable time and thought has already gone into their preparation.

REFERENCES

Ashton, G., 1986. River and lake ice engineering, Water Resources Publication, Littleton, CO., 485 pp.

Chaco, E., W. Traub and J. Gosink, 1987. Frazil ice characteristics on the Tanana River as related to siting ice bridges, Technical Note, Corps of Engineers, U.S. Army Cold Regions Research and Engineering Laboratory, Ft. Wainwright, Alaska, 99709.

Chang, H. H., 1984. Modeling of river channel changes, *J. Hydraul. Eng. ASCE, 110(2)*, 157-172.

Chang, H. H., 1985. River morphology and thresholds, *J. Hydraul. Eng. ASCE, 111(3)*, 503-519.

Fread, D. L., 1978. National Weather Service Operational Dynamic Wave Model, National Weather Service, NOAA, Silver Springs, MD.

George, T., W. J. Traub and J. P. Gosink, 1988. Monitoring river freeze-up with vertical aerial video data, Proceedings of the First Workshop on Videography, American Society for Photogrammetry and Remote Sensing, Indiana State University, Terre Haute, Indiana, 60-67.

Gosink, J. P. and W. Traub, 1989a. Minimum energy expenditure model for edge ice deposition: Development of the theory, to be submitted to Cold Regions Science and Technology.

Gosink, J. P. and W. Traub, 1989b. Minimum energy expenditure model for edge ice deposition: Comparison with measurements from video imagery, to be submitted to Cold Regions Science and Technology.

Gosink, J. P., 1986a. Synopsis of analytic solutions for the temperature distribution in a river downstream from a dam or reservoir, *Water Resources Research, 22(6)*, 979-983.

Gosink, J. P., 1986b. Short-wave heating of lake surface water under a candled ice cover, Proceedings of the Cold Regions Hydrology Symposium, American Water Resources Association, Fairbanks, Alaska, July 1986, 31-37.

Gosink, J. P. and T. E. Osterkamp, 1986. Frazil ice nucleation by ejecta from supercooled water, Proceedings of the International Association for Hydraulic Research, Symposium on Ice, Iowa City, Iowa, July 1986, *3*, 249-264.

Leopold, L. B. and T. Maddock, Jr., 1953. The hydraulic geometry of stream channels and some physiographic implications, *USGS Professional Paper 252*.

Osterkamp, T. E. and J. P. Gosink, 1983. Frazil ice formation and ice cover development in interior Alaskan streams, *Cold Regions Science and Technology*, *8*, 43-56.

Uzuner, M. S., 1975. The composite roughness of ice-covered streams, *J. Hydraul. Eng. ASCE*, *HY9*, 1365-1383.