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# SOME THEORETICAL AND LABORATORY RESEARCH ON ICE COVER PROBLEMS

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In the Province of Quebec and more generally in countries under a cold climate, winter operation of hydro powerstations presents usually difficulties due to ice problems.

These problems are mainly as follows:

1)- to maintain a correct water discharge through the powerstation, that is, to avoid the formation of ice jams in the intake or tailrace channel. Ice jams not only reduce available head, but also may cause some flooding:

2)- to reduce as much as possible the discharge of ice through turbines.

The usual solution is to form an ice cover upstream of the power-station. For high and medium head power-stations, construction of a dam reduces usually upstream velocity sufficiently, and thus, ice cover formation is not a problem.

Sometimes, the artificial lake is so deep that temperature of the water no longer falls to freezing point.

With very low head hydro power-stations, ice problems are usually much more difficult to solve. Large and costly excavations may be needed to reduce sufficiently low velocity and allow the formation of an ice cover.

Thus, a better knowledge of flow velocities allowing ice cover formation and more precise methods of forecasting frazil ice deposit under existing ice covers are needed.

This is why the Quebec Hydro-Electric Commission has entrusted the La Salle Hydraulic Laboratory with experimental and theoretical research on these ice problems.

These studies are carried out under the Quebec Hydro supervision and in close cooperation with Cartier, Cotè & Piette, Consulting Engineers.

Our studies can be roughly divided in four parts:

1)- ice cover formation
2)- frazil transportation and deposit under a cover
3)- thermic exchanges between air and water
4)- special spillway designed to let ice pass downstream with safety and efficiency, that is, with as little water as possible.

We shall briefly present this study, giving more importance to the two first points, as number 3) is relatively well known, and studies on point 4) are just beginning, We must point out that these studies are not yet finished and are only a step to approach the solution of the difficult problem of forecasting ice cover progression on rivers.

## I - FORMATION OF ICE COVER ON RIVERS

On a river, the ice cover starts from where velocity is sufficiently low to allow formation of an ice bridge across the river. Afterwards, the ice cover progresses upstream by packing of ice floes against the ice bridge.

### A) - MECHANISM OF PROGRESSION:-

Field surveys and tests conducted in a glass flume with material chosen to reproduce ice characteristics (paraffin and polyethylene) have shown that the mechanism of ice cover progression may be schematized as follows.

Floes drifting against an existing ice cover remain in stable equilibrium and allow ice cover progression only if their thickness is sufficient. If not, they overturn and pass under the ice cover.

We first thought that the main factor was ice floe thickness. So we have studied the relation between floe thickness and critical velocity for non-submersion condition.

### B) - CRITICAL VELOCITY $V_o$ FOR NON-SUBMERSION CONDITION:-

Calculation established for the non-submersion condition at the upstream edge of the cover indicates that for a river which is neither too shallow nor too rough the cover may progress if flow velocity and floe thickness satisfy the following equation (figure No. 1):

$$\frac{V_o}{\sqrt{2g\,H}} \leqslant \sqrt{\frac{\rho-\rho'}{\rho} \quad \frac{t}{H}\left(1-\frac{t}{H}\right)}$$

H being the water depth in front of the cover, in feet
$V_o$ the mean velocity in front of the cover, in feet per second
t the thickness of the cover, in feet
and water and ice specific gravity.

It is necessary to correct this formula when bottom roughness is important or water depth is shallow.

Figure No. 1 gives practical results of the formula, and shows that the ice cover cannot progress upstream, for any kind of ice floes, if velocity is higher than $0.109\sqrt{2g\,H}$

Experimental verifications with ice blocks in Cartier, Cote, Piette field canal and with wood, paraffin and polyethylene blocks in laboratory flumes are good.

But the preceding theory cannot explain the fact that, mainly when snowfalls form a large amount of slush on the St. Lawrence River, ice cover progresses upstream against a velocity sometimes much higher than 1.5 ft./sec., even if drifting ice particles are much thinner than 1/2 inch.

We thus had to introduce another parameter, the discharge of ice. If ice discharge drifting from upstream exceeds the carrying capacity of the flow under the ice cover, all ice cannot be carried downstream and a certain proportion will pack against the ice cover and allow its progression, even if individually ice particles are too thin to be stable.

We thus have to define a critical velocity for ice floe transportation under ice cover.

## C) - CRITICAL VELOCITY $V_C$ FOR ICE FLOE TRANSPORTATION UNDER ICE COVER: -

Ice floes are transported under the cover more or less as pebbles on river bed, by opposition to transport by suspension.

We have thus adopted for this floe transport a law similar to the one used for bed transportation in a river. We have used Meyer - Peter's formula as the more widely verified of the existing laws.

Hydraulic radius can be assumed to be equal to half of the mean depth and Meyer-Peter's formula gives:

$$\frac{V_C^2}{C^2} = 3.75 \times 10^{-3} d + 5 \times 10^{-3} q_S^{2/3}$$

$q_S$ being ice discharge under the ice cover in pounds per second, per foot of width weighed under water (using 0.08 as specific gravity;

d mean equivalent diameter of ice blocks, in feet;

C Chesy roughness coefficient of the river;

This critical velocity $V_C$, as shown on figure No 2, is more sensitive to ice thickness, for ice blocks thinner than a few inches. That explains the fast progression of ice covers when snow-falls, for instance, cause a large discharge of slush.

## D) - EVOLUTION OF ICE COVERS: -

The preceding results allow us to define and calculate possible evolutions of ice covers.

Different cases may happen, as schematized on figure 4.

### 1) - Velocity is higher than maximum critical velocity for non-submersion conditions-

No ice floe can pack against the ice covers;the ice cover cannot progress upstream, except after ice carried underneath has built up downstream an ice jam high enough to raise water level and reduce flow velocity.

This ice jam will build up downstream where flow velocity is reduced so that the flow cannot transport farther all ice coming from upstream. We are using this method to calculate ice jam elevation at the foot of the Lachine Rapids and check it with field measurements.

2) - <u>Velocity is lower than maximum critical velocity for non-submersion conditions:</u> -

a) - Ice floes which are thicker than thickness "t" corresponding to non-submersion condition will not pass under the ice cover but will allow upstream progression of the cover.

b) - Ice floes which are thinner will pass under the ice cover and a certain percentage will be carried downstream according to Meyer-Peter's formula; it is thus possible to have an idea of ice cover thickening. This thickening increases the loss of head, causes a reduction of velocity upstream of the cover, and thus a larger number of floes will be allowed to pack up.

c) - If the number of these floes exceeds the carrying capacity of the flow under the ice cover, a certain percentage of them will pack against the cover and allow its progression, even if individually they are too thin to be stable.
Such ice cover progression is not stable and the cover will quickly recede when ice discharge is reduced except if it had time to consolidate in compact ice.

d) - <u>Hanging dam:</u>- In certain places, ice cover thickness becomes very large, forming what is called a "hanging dam". But often this only results from a normal thickening of the cover for the section considered.
Indeed, according to the formula giving the thickness, in certain cases a little increase of velocity due to a slight variation of the flowing section brings on a high variation of the thickness of the cover.
In general, the "hanging dam" phenomenon does not produce important loss of head and, on this account, it must be distinguished from the ice-jam phenomenon which manifests itself by an important loss of head.

e) - <u>Experimental and field verification:</u> - The submersion criterion has been checked by tests done in a 2-foot wide flume with paraffin and polyethylene blocks and by tests with natural ice in the Cartier Cote Piette experimental canal for ice study (figure No.5).

Tests in the 2-foot wide flume are shown on photographs Nos. 1, 2 and 3. The transportation criterion is much more difficult to verify. The only way in which we are engaged is to reconstitute ice cover progression by calculation, from field survey giving all needed information, that is, area and length of free water zone generating ice, meteorological conditions, water discharge, and river bed cross-sections. These studies are not finished and some coefficients must be determined more accurately; but we hope they offer, even at this stage, a valuable tool to forecast ice cover evolution.

## II - DEPOSITS OF FRAZIL UNDER COVERS

After an ice cover is formed, its thickness usually increases mainly because of sheet ice or frazil deposits. We have already discussed sheet ice deposits. Frazil being, by definition, transported in suspension, turbulence phenomena play an essential part and make similitude impossible.

We thus try to solve this problem by calculation and to check results obtained by field measurements.

Being less dense than water, frazil particles present an upward velocity similar to settling velocity of the particles heavier than water.

In laminar flow, it is easy to calculate the trajectory made by each particle before depositing under the cover; unfortunately, flows under ice covers are never in a laminar regime.

To solve this problem, we must have recourse to the basic laws of suspension in turbulent flow.

Without looking into detailed calculations and hypotheses, which are those all the classics have adopted, we shall only say that these calculations give us a relation showing in function of the Rouse number and the length travelled under ice covers, the proportion of ice in suspension to the quantity being introduced under the cover.

From this relation, it is thus easy to determine the shape of the deposit for well-known conditions.

### Application to the Beauharnois Canal: -

Figure No. 6 shows theoretical proportion of ice still in suspension at different abscissas from the beginning of the cover.

Figure 7 and 8 show, for the years of 1954-55 and 1956-57, curves of theoretical and measured accumulated deposits in function of the abscissas.

From these curves, we notice a very good comformity between calculated and measured results. Thus, this method seems to be satisfactory.

Besides, application of this method of calculation to the Beauharnois Canal, for the years included between 1953 and 1957, has furnished several interesting results.

a) - Comparison between quantities of ice computed directly from ice-free surface upstream of the covers and those determined with volumes of deposits, has proved to be in conformity.

b) - For the different years, ice particles appear to have constant hydraulic diameters of 0.09 mm.

The question is to know if this diameter can be used for other rivers. Future studies will, maybe, allow to check this point.

## III - THERMIC EXCHANGES

It was not our aim to do a systematic study of thermic exchanges between air and water, with and without ice cover, but we were interested in the following points:

### I) - Rate of ice production: -

Ice discharge forecasting is in fact essential to allow utilization of preceding theory of ice cover evolution. We found a discrepancy between ice volume calculated by using cooling of water due to convection, evaporation, wind, radiation... and MacLachlan's empirical formula, based on ice jam and cover volume measurement.

A calorimetric box has been built and placed near Cartier Cote Platte ice canal to obtain a better knowledge of the coefficient to use.

Warming of water flowing under ice cover has been studied in order to have an idea of its possible ice melting power and of the temperature evolution of the flowing water. Such a calculation allows to have an idea of the possible quantity of frazil which can be melted. This quantity has been found to be very low.

## IV - ICE SPILLWAYS

The aim of this study is to design a spillway able to allow ice to pass through a powerstation not protected by an upstream ice-cover.

First, the spillway must be safe and free of possible jamming by ice-floes.

Secondly, the spillway must be efficient, that is, its water discharge which bypasses power-house turbines must be as low as possible.

We are studying three possible types of spillways:

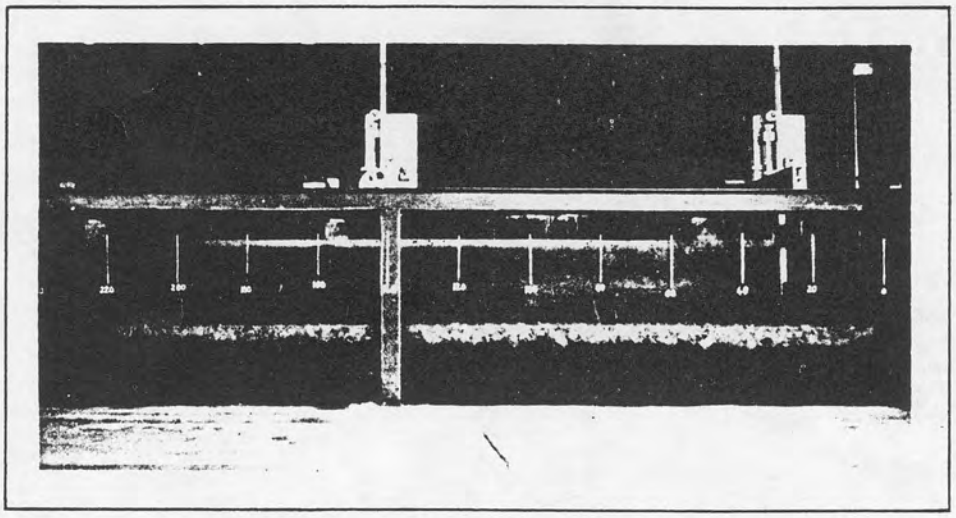
First, a more or less classical type with converging walls leading ice to an overflow gate (Photo No. 4).

Second, a vortex type. The large vortex formation reduces considerably water discharge, and possibly, will help to break ice floes (Photo No. 5).

Third, a shaft spillway which seems the most promising one (Photo No. 6).

In addition to tests carried out in our Laboratory, a large model of the vortex type is under test with natural in Cartier, Cotè & Platte ice canal.

# ICE COVER STUDIES

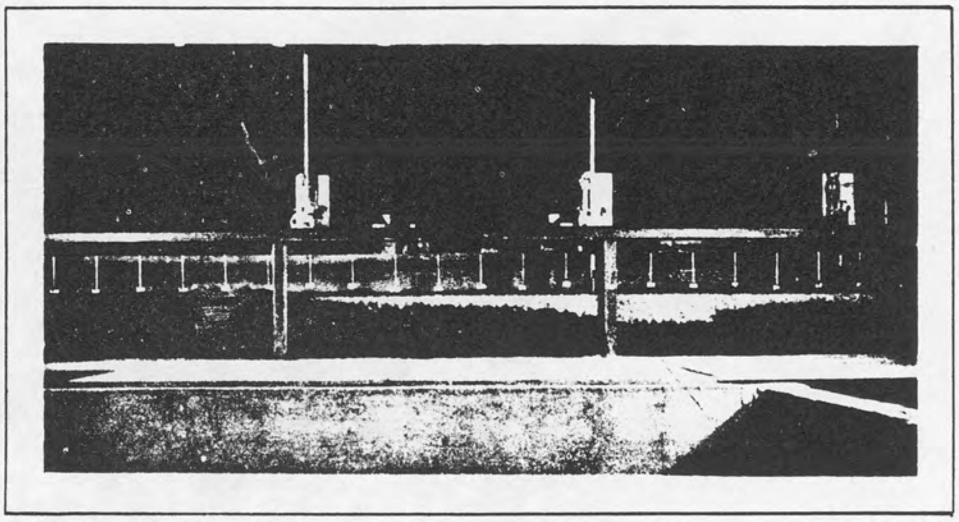


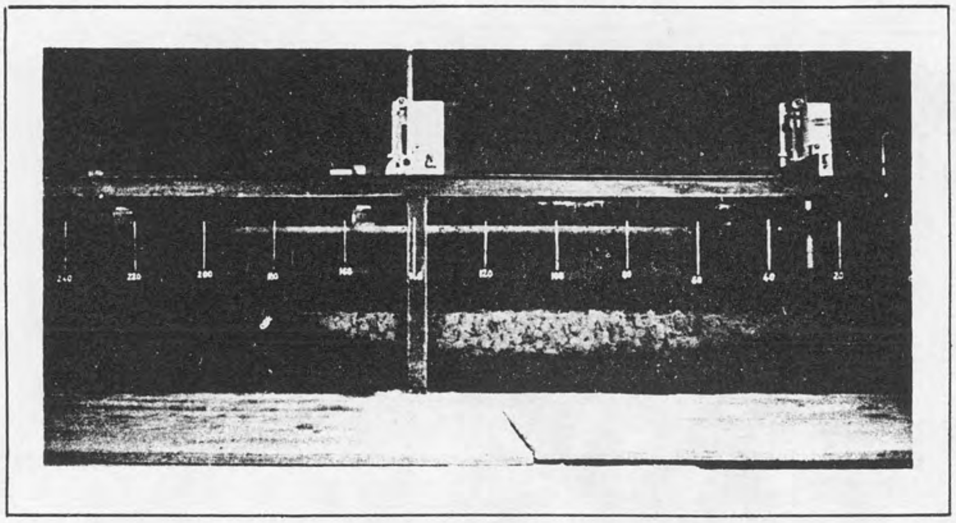
**ICE COVER FORMATION**

**1**

**HANGING DAM FORMATION**

**2**

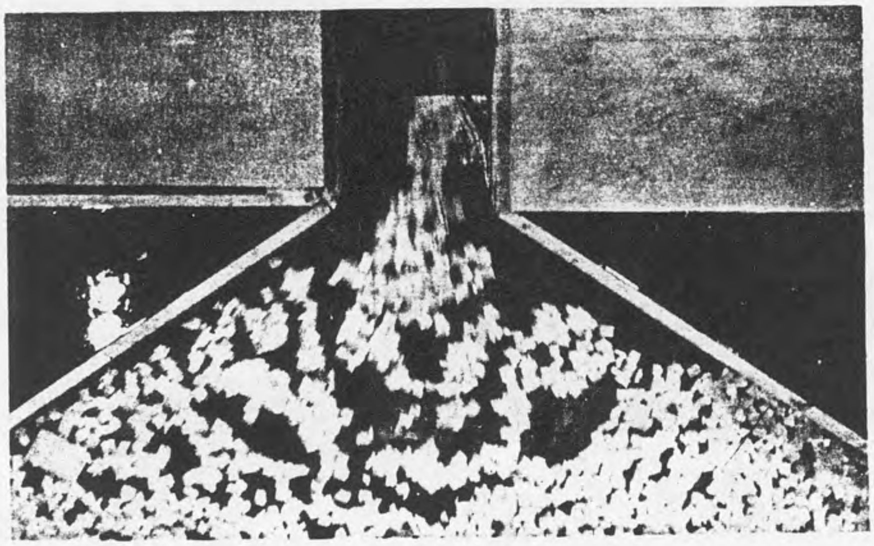




**ICE JAM FORMATION**

**3**

# DIFFERENT TYPES OF ICE SPILLWAYS



SURFACE

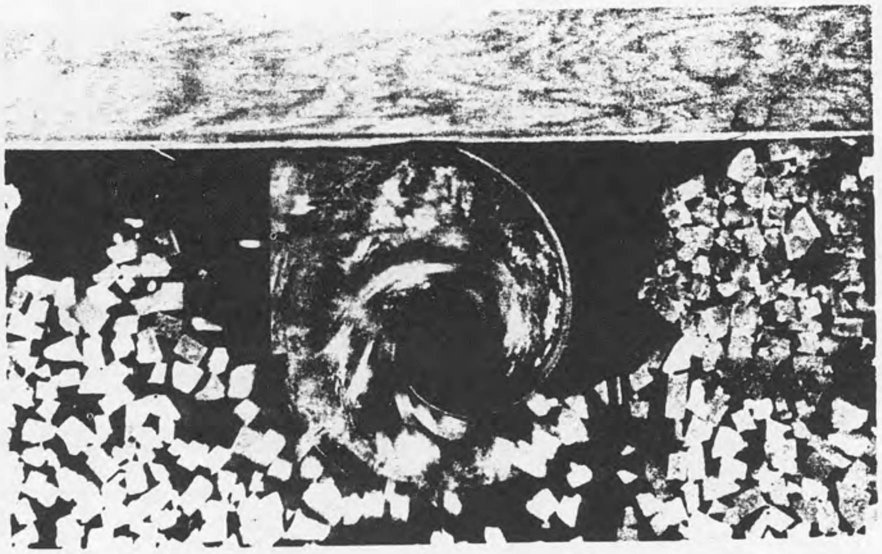
CONVERGING SLUICE

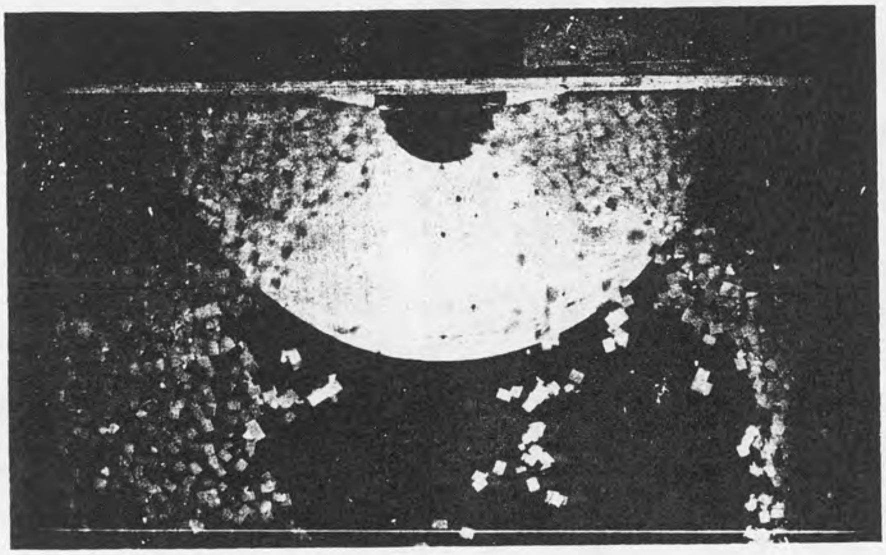
4

VORTEX TYPE

SPILLWAY

5

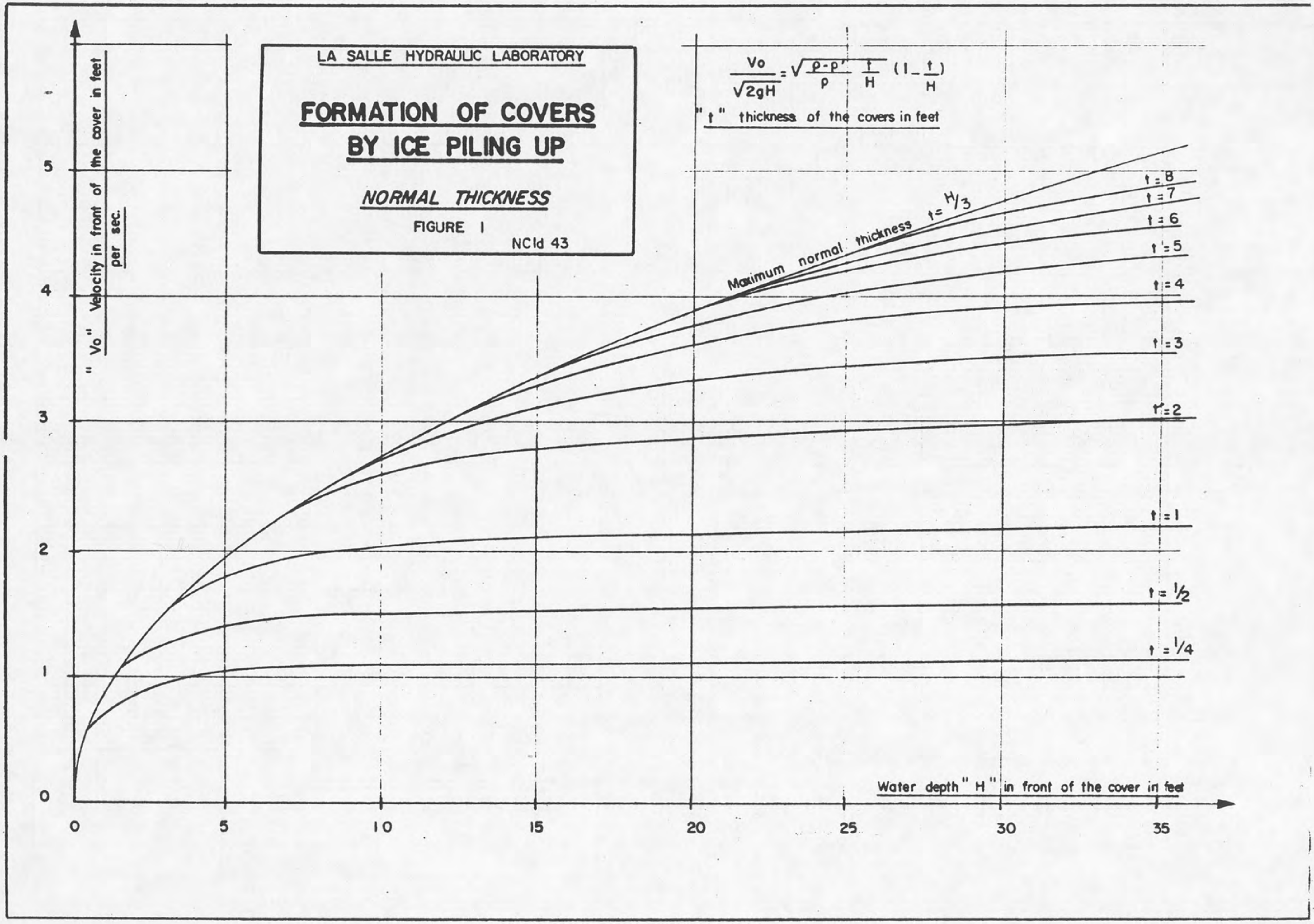




SEMI CIRCULAR

SHAFT SPILLWAY

6



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## FORMATION OF COVERS BY ICE PILING UP

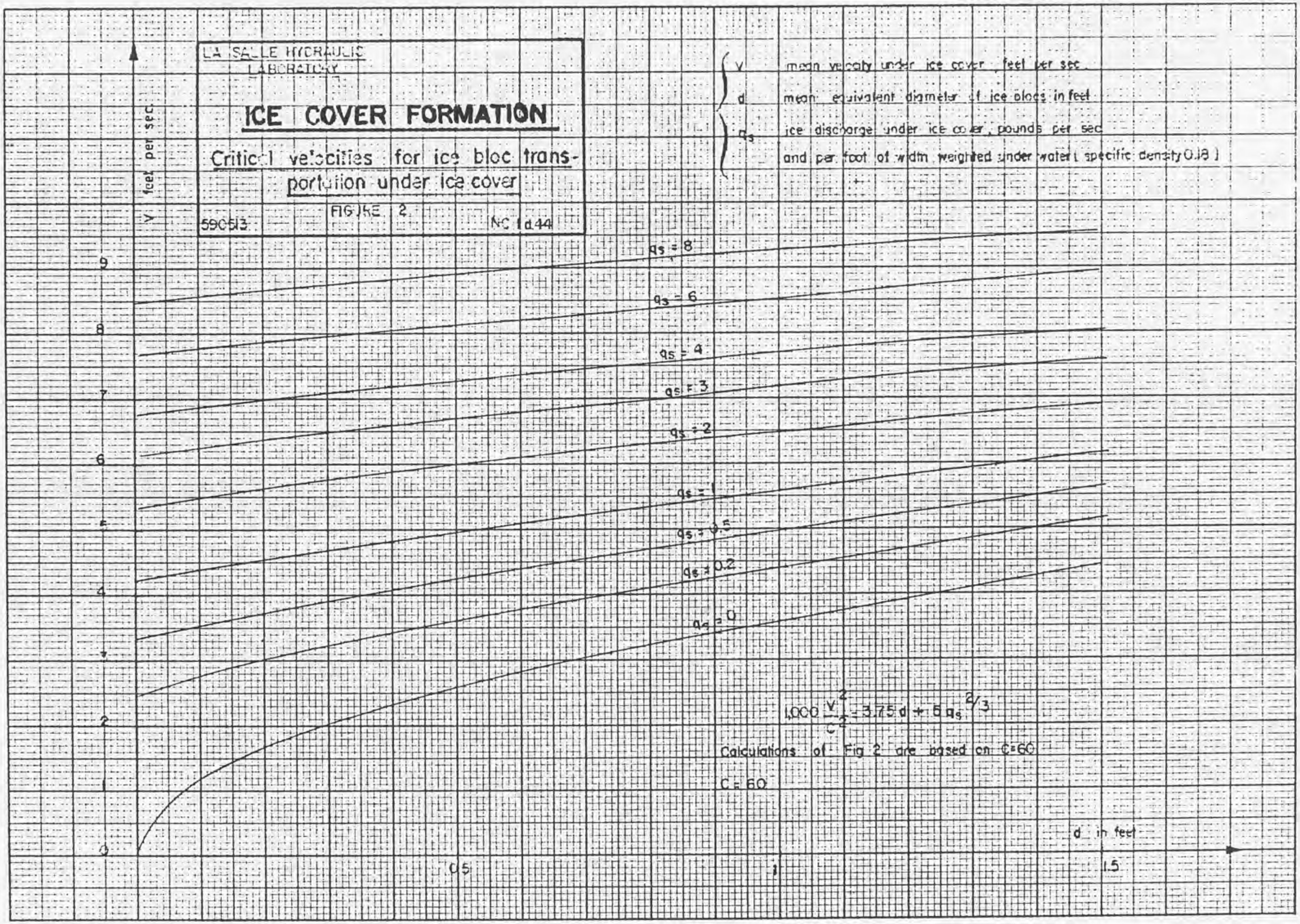
*NORMAL THICKNESS*

FIGURE 1

NCld 43

$$\frac{V_o}{\sqrt{2gH}} = \sqrt{\frac{\rho - \rho'}{\rho} \frac{t}{H} \left(1 - \frac{t}{H}\right)}$$

" t " thickness of the covers in feet



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ICE COVER FORMATION

Critical velocities for ice bloc transportation under ice cover

FIGURE 2

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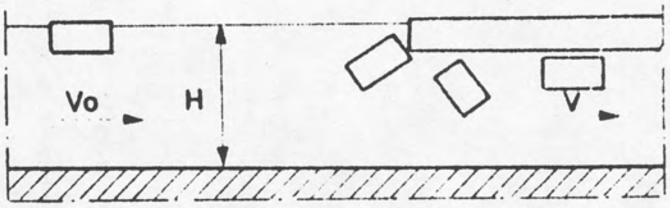
# ICE COVER EVOLUTION

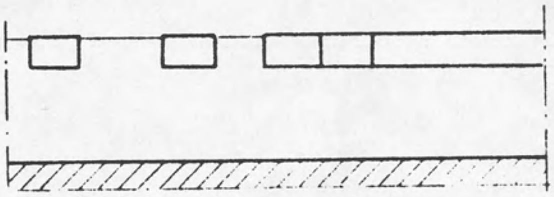
## FIGURE 4

① $\frac{V_o}{\sqrt{2gH}} \geqslant 0.109$



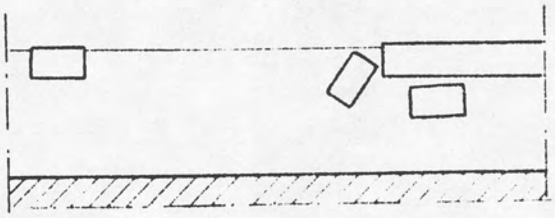
② $\frac{V_o}{\sqrt{2gH}} < 0.109$

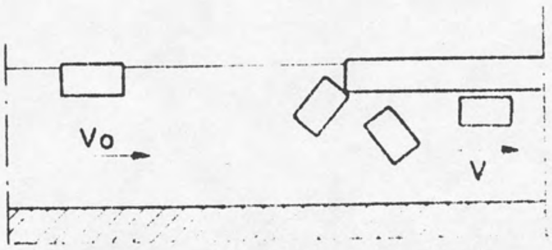
ⓐ $\frac{V_o}{\sqrt{2gH}} \leqslant \sqrt{\frac{\rho-\rho'}{\rho}\frac{t}{H}\left(1-\frac{t}{H}\right)}$



ⓑ
$\frac{V_o}{\sqrt{2gH}} > \sqrt{\frac{\rho-\rho'}{\rho}\frac{t}{H}\left(1-\frac{t}{H}\right)}$

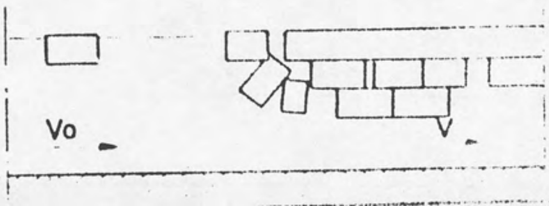
$\frac{V^2}{C^2} \geqslant 3.75\ 10^{-3} d + 5\ 10^{-3} q_s^{2/3}$

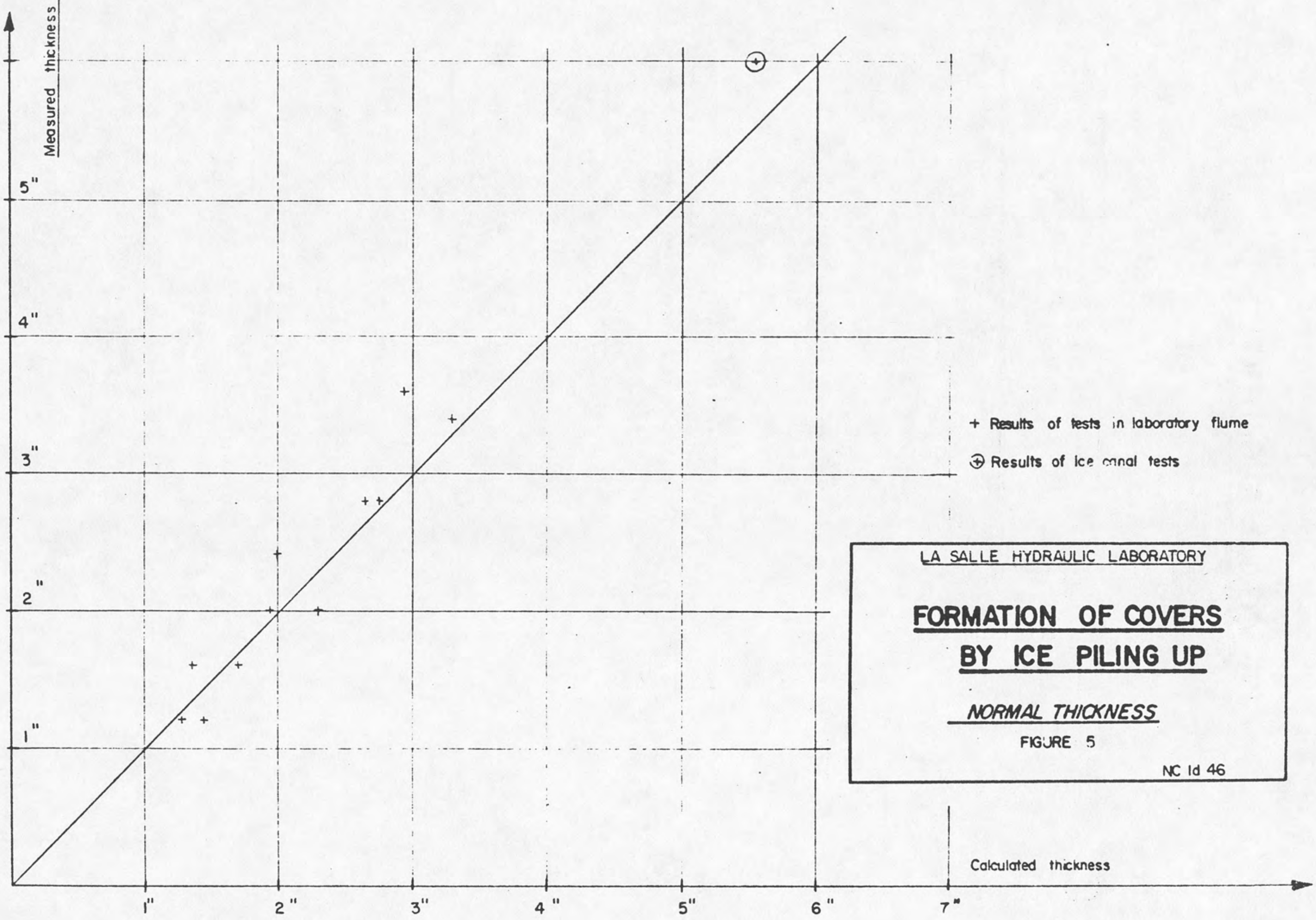




ⓒ
$\frac{V_o}{\sqrt{2gH}} > \sqrt{\frac{\rho-\rho'}{\rho}\frac{t}{H}\left(1-\frac{t}{H}\right)}$

$\frac{V^2}{C^2} < 3.75\ 10^{-3} d + 5\ 10^{-3} q_s^{2/3}$





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**FORMATION OF COVERS**
**BY ICE PILING UP**

*NORMAL THICKNESS*

FIGURE 5

NC Id 46

# TRANSPORT AND DEPOSIT OF ICE PARTICLES IN SUSPENSION

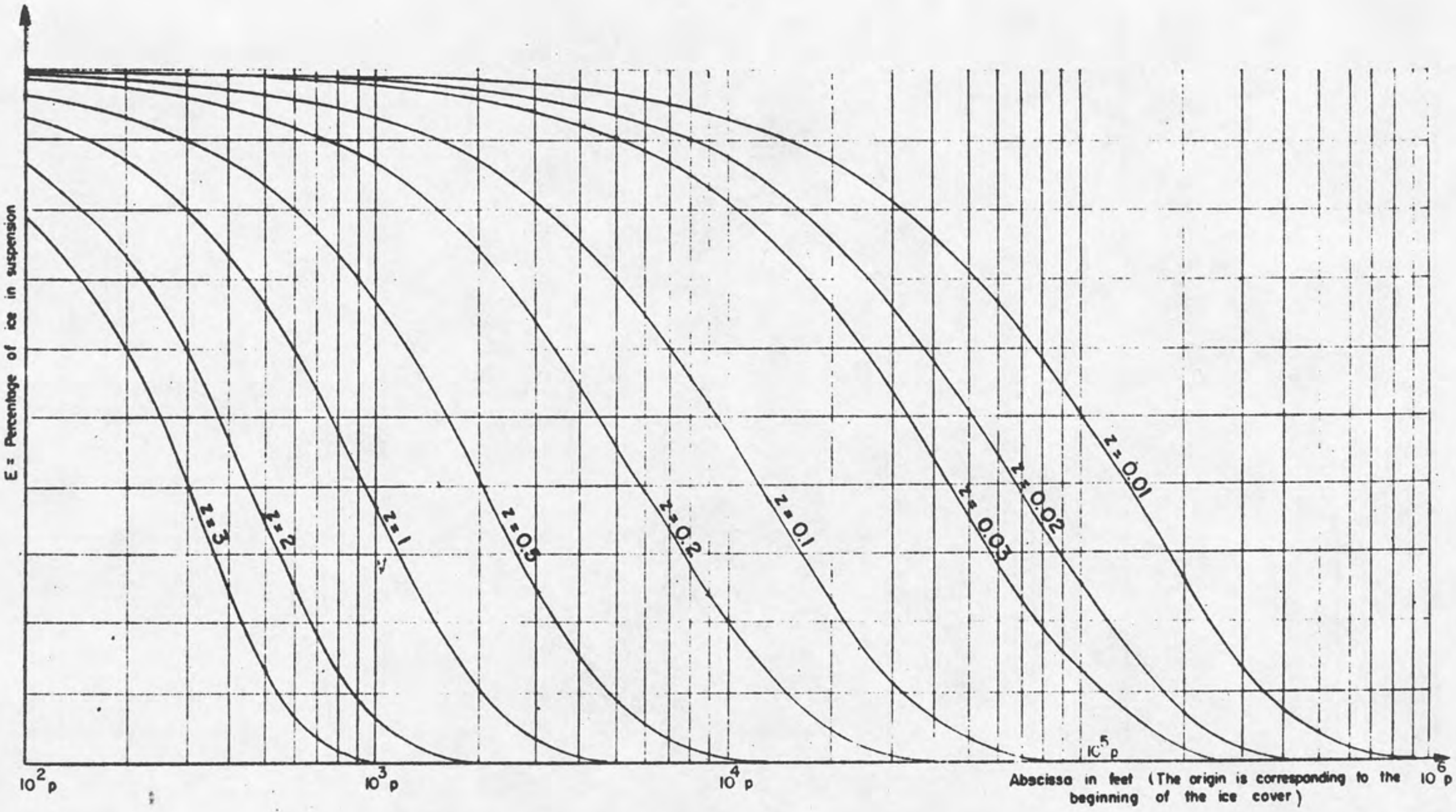
## *FIGURE 6*

### SHOWING ICE CONCENTRATION IN SUSPENSION FOR DIFFERENT VALUES OF "Z" IN THE BEAUHARNOIS CANAL

" Z " is the Rouse number

*Mean depth = 25 feet.*

NC Id 47



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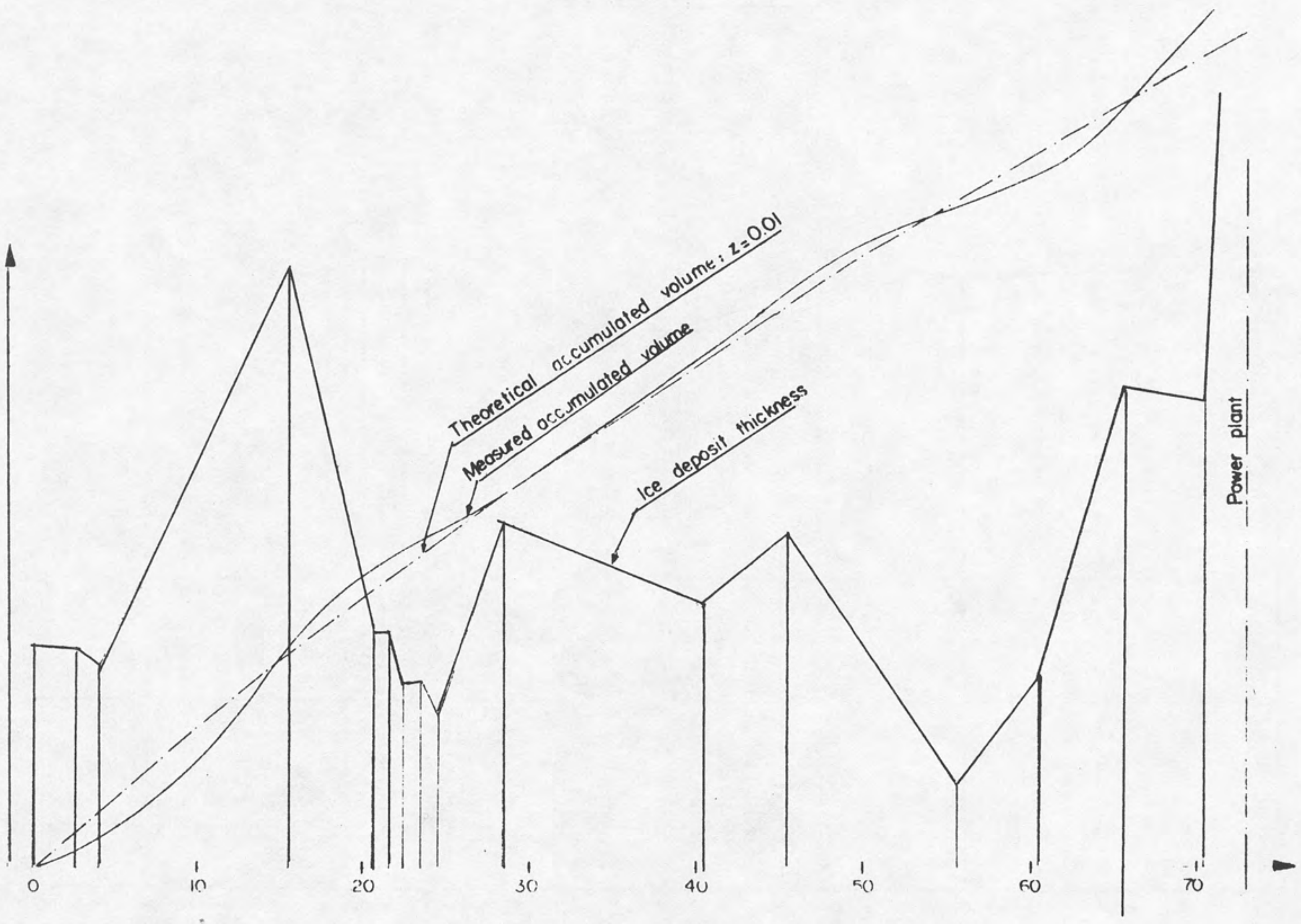
# TRANSPORT AND DEPOSIT OF ICE PARTICLES IN SUSPENSION

## ICE DEPOSIT THICKNESS IN BEAUHARNOIS CANAL

*FIGURE 7*

*YEAR: 1954-55*

NC I d 48



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# TRANSPORT AND DEPOSIT OF ICE PARTICLES IN SUSPENSION

## ICE DEPOSIT THICKNESS IN BEAUHARNOIS CANAL

FIGURE 8

YEAR : 1956-57

NC Id 49