CHAPTER 198

CHURCHILL RIVER SALT-WATER TIDAL MODEL

by

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1. BACKGROUND

The Port of Churchill is located just inside the mouth of the Churchill River, on the western shore of Hudson Bay (Fig. 1, Photo 1). Each shipping season, about 25 x 10^6 bushels of grain are shipped to Europe and Britain. The Port opens just after mid-July when Hudson Strait and Bay become relatively clear of ice. However, it is forced to close 3 months later by ice forming upstream in the rapids, sweeping down as slush ice at ebb tide, jamming between the ships and the dock and breaking mooring lines. Since the route to Europe is shorter and therefore the laid-in cost of the grain slightly less than from other Canadian ports, there is a demand to extend the operating season at Churchill. A feasibility study and field survey in 1965 by Dick (Refs. 1, 2) showed that the Port could remain open about 2 weeks longer than the present October 23 closing if the slush ice could be kept out of the harbour. To this end, the National Harbours Board in 1974 commissioned the Hydraulics Laboratory of the National Research Council of Canada to do an hydraulic model study of the harbour and estuary.

Photo 1. The Port of Churchill, Manitoba

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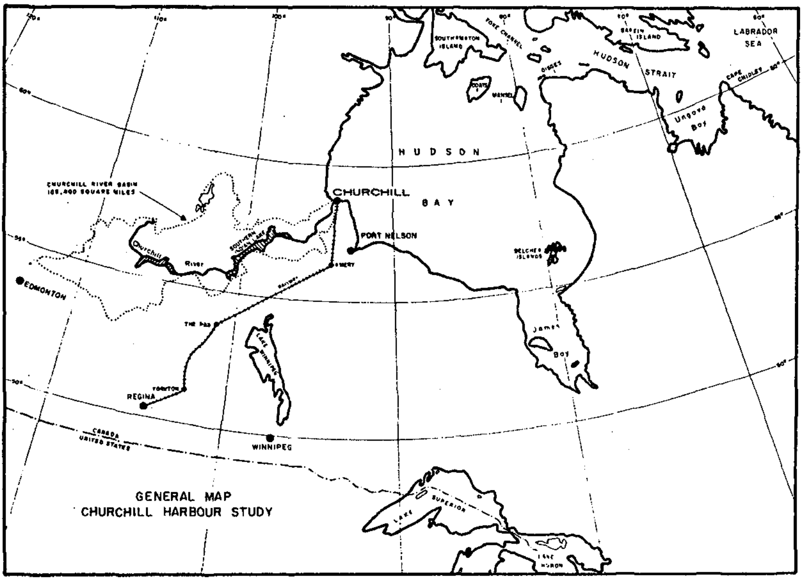

Fig. 1. Location Map of Churchill

2. OBJECT OF STUDY

The sponsor of the study required that various structures be examined for protecting the ships in the harbour from the current of slush ice, principally at ebb tide. Since the structure will be permanent, it must also not have detrimental effects during the rest of the year with regard to flow patterns and velocities and sedimentation. Although maintenance dredging is not a major problem in the harbour at present, averaging about 8,300 yd^3 per year, the season is so short that it would be undesirable if excessive dredging were caused by implementation of one of the schemes. Ideally, the structure should produce a quiet harbour so that loading and turning of the ships can go on without the present concern for the high outflow ebb velocities at the dock.

Fig. 2 shows the extent of the area modelled, and how the dock is situated on the outside of a bend in the flow. The most obvious structure would be a deflector just upstream of the dock, and various deflectors formed a large part of the model investigation. Another, but considerably more expensive scheme is a dam from the dock over to Cockle's Point, incorporating a section with a weir with crest elevation above the extreme tidal highwater. In addition to excluding the slush ice from the harbour, it could serve as a causeway to the west shore of the river, opening it up for development and access to historic Fort Prince of Wales.

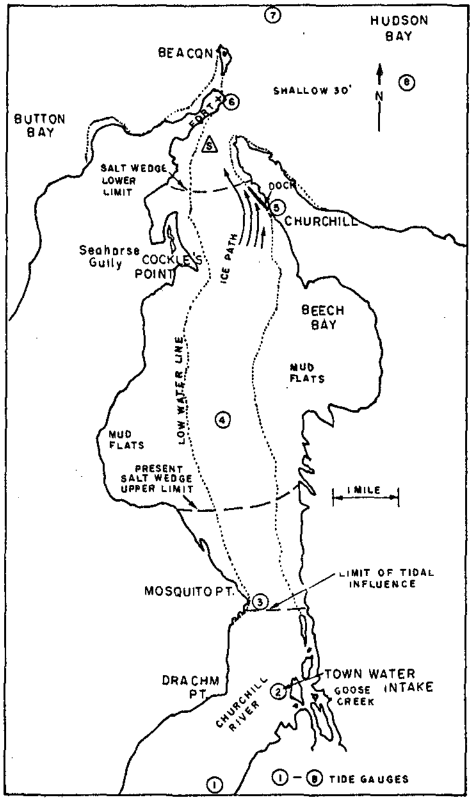

Fig. 2. Extent of Model

Since the river several hundred miles upstream is soon being partially diverted into the Nelson River system for power development, the freshwater discharge will be reduced in the harbour area from a present mean around 50,000 cfs down to about 20,000 cfs. However, there is the possibility of it going as low as say 2,000 cfs in the fall, so that the 1‰ salt-water limit of intrusion will move up the river past Mosquito Point. This will require relocating the town's fresh water intake pipe, presently at Goose Creek, Fig. 2, further upstream. The model was also expected to show how far upstream the salt will penetrate at extreme high tides and very low river discharges.

3. THE MODEL

To study all the required objectives, the model in Fig. 2 and Photo 2 was constructed of concrete over sand. It is 185 ft long, 55 ft wide, and extends the equivalent of 3 miles into Hudson Bay as the seaward salt water tidal boundary. The upstream end of the model is above the tidal limit and supplies a constant freshwater inflow by means of a head tank and vee-notch weir.

Photo 2. Churchill Tidal Model with Supply Manifold in Foreground, and a Dam Past the Dock.

3.1 Model Scales

Prototype/model length scales are $L_p/L_m = 400/1$ horizontal, $d_p/d_m = 50/1$ vertical, giving a vertical exaggeration or distortion of 8. This is necessary to achieve sufficient depth and turbulent flow in the shallow reaches of the river.

From the Froude (Fr) law for scaling of free surface flow phenomena, one derives the following relations:

since $Fr_m = Fr_p$, $V_m/\sqrt{gd_m} = V_p/\sqrt{gd_p}$,

the velocity scale is $T_p/T_m = \frac{L_p}{L_m} \times \sqrt{\frac{gd_m}{gd_p}} = 56.5685;$

(Thus a 12.4 hour tide cycle requires 13.1 minutes on the model.)

The discharge scale is $Q_p/Q_m = \frac{V_p L_p d_p}{V_m L_m d_m} = 141{,}421.$

Finally, the salt concentration, salinity or density is modelled in a 1/1 ratio, so that it is the same in model and prototype, namely 28‰ out in Hudson Bay near the tidal boundary. Because the harbour is in an area of density stratification where a fresher surface layer at times flows in quite different directions to the bottom seawater layer, it was necessary that the model be a salt-water one, with freshwater river discharge. This of course gives rise to considerably more complex model control, and measurement and calibration of velocity and density.

3.2 Model Control

A large sump is kept up to seawater salinity by a Robertshaw pneumatic controller which causes a small amount of saturated brine, obtained from a pit of dissolving rock salt, to be injected into the intake of the 6 cfs seawater pump. A Schlumberger Solartron density meter monitors the density of a continuously sampled portion of the flow leaving the pump. This instrument works on the principle of the change in frequency of an oscillating pair of tubes through which the fluid travels, and senses extremely small changes in fluid density. Any deviation from the controller's set-point density causes the appropriate amount of brine to be injected. The brine is needed to make up for the dilution of the seawater caused by the steady freshwater river inflow.

The main seawater flow then enters a large head tank before flowing by gravity into the Hudson Bay end through a 32 feet long, 1 foot diameter manifold pipe. The 5 cfs inflow is constant. Tidal control is effected by a drain valve located in the corner of the model such that the flow drains toward it in the same direction as in the prototype. The valve is controlled by an on-line EAI-640 computer which compares the historical tide curve desired, to the level sensed by a floating water level sensor in Hudson Bay. Any error results in a signal to the valve to open (lower) or close (raise the water level). In addition to control of the tide, the computer also records for off-line plots and printouts, the water levels and velocities from gauges on the model to allow comparisons of different test conditions.

A 10 feet long weir near the valve follows the tidal water level. The overflow from this weir is set to twice the freshwater inflow rate, and passes through a 3-way 4 inch valve. When the tide is rising, this valve drains into the seawater sump. However, on falling tide when Hudson Bay gets a skin of fresher water from the river flow, this valve opens so as to bypass the "fresher" weir overflow down the sewer. Thus, the sump level is not filled up or degraded in salinity quite so much by the fresher water during a test.

3.3 Instrumentation

There are eight tide gauges located along the model. A glass ball float is attached to a stem which is free to move up and down inside a DCDT (direct-current differential transformer). Outputs of up to ±3 volts D.C. are sensed by the computer and converted to water levels by a calibration equation. Five velocity meters are located in the estuary, and each incorporates a DCDT mounted horizontally, and has a 2 x 4 cm drag plate in the water suspended from thin frictionless straps (Photo 3). Movement of the plate by fluid drag causes the stem or core to move freely inside the DCDT. This meter is sensitive enough to measure velocities, both upstream and downstream, down to about 1 cm/sec, and up to 30 cm/sec. One disadvantage of the meter is that it must be carefully levelled, and therefore is not suited for traversing through the flow depth.

A newly developed velocity meter was also used. It comprises a very sensitive strain-gauged Kistler transducer, connected by a rod to a flat circular cylinder drag body. Velocities coming from any direction in the horizontal plane can be sensed by this instrument, and the resultant vector obtained from computer analysis of the output of the x and y axis strain gauges. This instrument was located where the flow direction swings appreciably as the tide changes, in the center of the estuary between the dock and Cockle's Point.

Photo 3. Drag-Plate Velocity Meter

Photo 4. Traversing "Salinity" Probe

Vertical velocity profiles were very difficult to obtain since the velocities were often low and the sensitive levelled drag-body velocity meters could not be traversed. Even miniature Kent and Ott laboratory-type propellor meters were not adequate. Therefore, a dye injection system was devised, which involved timing a puff of dye (injected normal to the flow direction) past a ruler located at the same depth. This system worked very well, and allowed vertical traverses. However, by the time velocities were measured at say 10 depths, the tide cycle was quite different than when starting the traverse. Therefore, several tide cycles had to be repeated in order to get enough measurements at different levels at the same point in the tide cycle.

Vertical salinity profiles in the model test locations were made by traversing a specially developed conductivity probe which continuously sucks a tiny sample of the water through a fixed volume past platinized electrodes, Photo 4. This instrument is similar to that constructed by the Delft Hydraulic Laboratory. A motorized traversing rig moves the probe through the full range of the depth at about 1 cm/sec. Response is very good although electrical calibration in standard solutions of "known conductivity" must be made frequently. Temperature is also monitored to allow conversion of conductivity to salinity by standard equations. Again, several tide cycles of testing were needed before enough points were available to plot a near instaneous vertical salinity profile. This of course assumes the tides and salinity distributions repeat very well from cycle to cycle in the model.

To measure the 1‰ salinity penetration upstream towards Mosquito Point, a small Beckman conductivity probe was used.

4. MODEL CALIBRATION

In August 1974, temporary tide gauges were installed on the Churchill River at 4 and 2 , Fig. 1, in addition to the long-time permanent gauge at the dock. A survey of elevations at 3 and 1 allowed their levels also to be tied in to these tide gauges. In 1965, Dick (2) made a field survey of prototype vertical velocity and salinity profiles at various locations near the harbour and estuary entrance. Also, penetration of the 1‰ salt-water limit was found to be about as shown on Fig. 1 at high tide. Mosquito Point, near 3 is a region of very rapidly flowing water, with large 5 to 8 feet diameter boulders on the bottom in less than 8 feet of water. At low tide and average river flow of about 50,000 cfs, the salt limit is pushed down just past the dock. There is a very strong density gradient seaward of this point with a fresher layer on the surface moving rapidly (5 fps) out to sea, and a nearly stagnant sea water layer underneath trying to move up the estuary as a wedge. Surface movement of ice and of drogue bodies was observed or tracked by theodolite, giving vector paths as sketched in Fig. 1 approaching at about 30° to the dock.

Model calibration involved placing 2 cm wide stainless steel strips vertically into holes in the concrete bed of the model in the area from the entrance up to Cockle's Point, and coarse gravel in the shallow areas further upstream. By trial, a distribution of this bed roughness was found which forced the model to reproduce the correct tide curves at each station. Due to the vertical distortion, $d_p/d_m = 8/1$, the deeper areas are exaggerated and tend to attract more flow in the model than would occur in the real river. Therefore, roughness was concentrated more in these deeper areas to create velocities in the various locations where measurements were available. The roughness of course has no effect at high water slack, but is very effective on falling or rising tide when velocities and head losses become significant.

Fig. 3 shows a comparison of model and prototype vertical velocity (from dye timing) and salinity profiles at 2.2 hours after low tide at location s , Fig. 1. The tide is rising and the seawater is flooding in beneath the fresher layer on top which even at this time is still ebbing seaward. By about 3 hours after low water, the surface layer itself will turn and start to be backed up into the estuary. The salinity profiles show the very marked stratified gradient at this station, in the estuary entrance, of 25‰ in the lower 35 feet and nearly fresh above. The thick lower layer

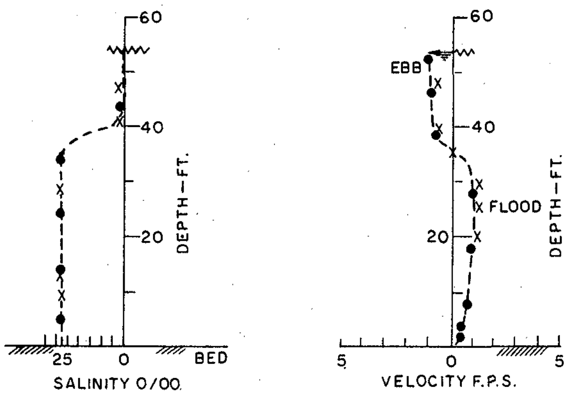

Fig. 3. Comparison of Model (x) and Prototype (o) 2.2 Hours after Low Tide

forces the freshwater layer to flow seaward at high velocity throughout the 2.5 hour period just after low water. This phenomena is of importance to the surface clearing of ice, as is the time, speed and duration of movement of the lower layer with respect to suspended sediment transport. Only with a salt-and-fresh water model can these effects be properly simulated.

Photographs of the movement of surface floats (styrofoam, paper punchings, or wood pieces) were also used in calibration of the model, and in testing various flow diverting structures. A Haselblad 500 EL camera mounted above the harbour area was computer-controlled to take a 5 second exposure at times of interest in the tide cycle, such as at maximum flood and ebb tide, and high and low water. Just after the shutter opened, an external blade was triggered to briefly cover the lens, producing a break in the streaks which the particles create on the film. This break is near the end of the streak where the particle came from. There are white strings 30 inches apart, or 1,000 feet prototype, stretched across the model just above the water surface, which allows one to scale off the length of each 5 second streak in the photograph, and determine the particle's velocity, direction and sense.

Velocity of the lower layer was measured by the current meters, but frequently dye was used to show flow direction and to colour the lower salt-water layer to observe its penetration up the dredged navigation channel, into the harbour, and further upstream. In fact, at low tide, the seawater layer was dyed just downstream of the dock, and the dye front observed to penetrate up to the same limit towards Mosquito Point as shown in Fig. 1 from the prototype observations of Dick. This dye limit corresponded well with that measured using the Beckman conductivity cell at the same spot but without dye.

Since an indication of any large changes which various structures might create in the bottom sediment movement was also required, gilsonite, bakelite, and fine crushed walnut shells (shelblast) were tried as tracers. The walnut shells were found most useful for a qualitative idea of likely bed erosion and deposition areas. Although no tracer studies were made in the prototype, it is known from a few bed samples Dick obtained, that the harbour area deposits are mostly medium to coarse sand of 0.4 to 0.9 mm median grain diameter, felt to come from up river, plus some fine, silty grey mud of 0.075 mm size. This mud may come from the photographically evident littoral dirft zone aroung Button Bay, and be carried on flood tide up the estuary to settle out on the mud flats, and eventually in the harbour itself. Ignoring the cohesive effects of the silts, the sand may be expected to move as bed load for bed velocities greater than 0.5 to 0.8 fps.

5. TEST RESULTS

Since many tests were made, and since the results are proprietary information of the sponsor, only a few illustrative results of the investigation will be given here by permission. These results should not be considered as representing the sponsor's opinions or recommendations.

5.1 Deflector Upstream of Dock

Various configurations were tried, varying the length, angle to the flow, and tip curvature to lessen scour. Photos 5 and 6 show the ebb flow from left to right past the dock without and with a deflector. The deflector shown is a 1,200 feet long rubble mound structure. It provides adequate protection in the entire harbour area at ebb tide with the slush ice kept out, and with only a very weak clockwise recirculating eddy present.

Photo 5. Surface Ebb Flow Past Dock

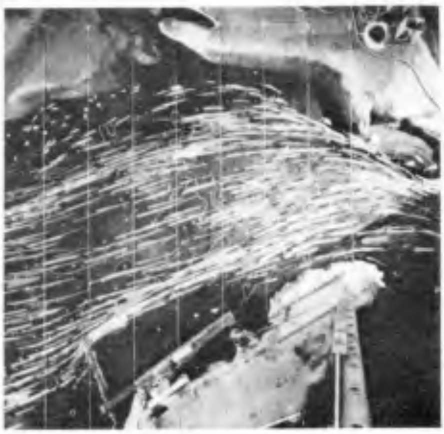

Photo 6. Harbour Protection with Deflector

At flood tide most of the returning ice flows up the shallow west side of the estuary across from the harbour, since that side then is on the outside of the bend for flood flow. Any ice trapped in the harbour on ebb tide was not packed in between deflector and dock on flood tide. Rather, the bottom seawater layer moves into the deep harbour area, locally raising the nearly stagnant freshwater layer on top and causing a superelevation so that the surface "ice" moves out around the deflector. This phenomena was unexpected, but indeed welcome since in the model, even a northwest wind failed to overcome the strong clearing effect. In the prototype, however, freezing cohesion of the real ice could alter this behaviour somewhat, and some small tugboat action might be needed to break up any persistent ice cover which forms.

Sediment placed in the harbour tended to stay there. However, walnut shells placed at A upstream of the deflector at ebb tide was vigorously moved northwest on the bed, at about 30° to the direction of the surface currents, Fig. 4. As the tide approached low water, the deflected flow slowed down, and was attracted more towards the deeper harbour, and a small number of walnut shells moved along the outer edge of the harbour at B , a few depositing in the downstream corner of the harbour at C and in the approach channel at D . Approximately 90% of the particles placed across the river section at A , simulating the sand bed-load coming down the river, were strongly moved out the narrow deep entrance mouth into Hudson Bay, not to return on flood tides. The few particles at D were carried up into the harbour on the next flood tide, and settled out in there in the areas hatched. Particles placed at E were cleared out by the strong bottom seawater currents at flood tide. Obviously

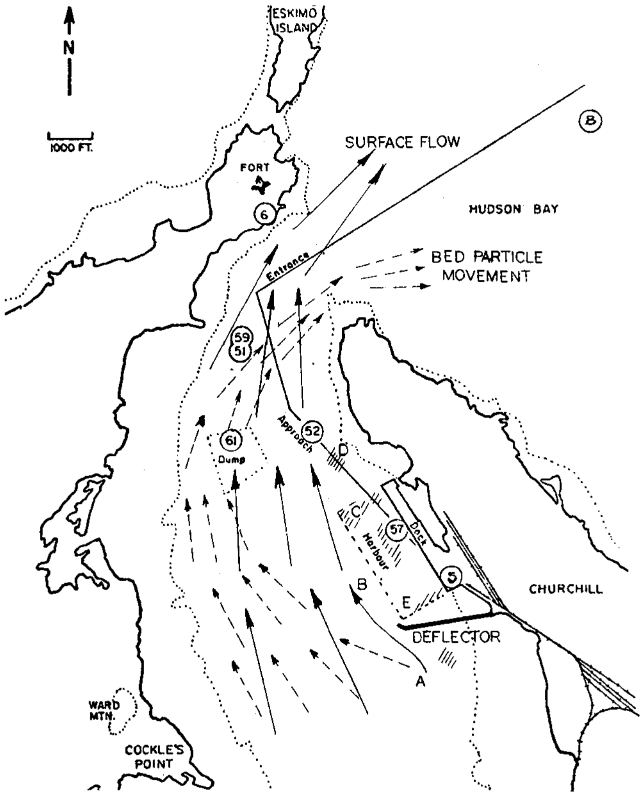

Fig. 4. Effect of Deflector on Ebb Bed Particle Movement Compared to Surface Flow Velocity Meter Locations Also Shown

sedimentation will be more of a problem in the harbour if this deflector were build, if indeed there is significant sediment coming down the river, a factor not yet well determined.

It is also expected that deposition of some sand, but mostly mud, will occur on the upstream side of the deflector, as shown by dye simulating any suspended silts brought in from Hudson Bay in the salt water layer.

5.2 Dam With Weir and Causeway

The second idea investigated was a dam extending the deflector over to Cockle's Point. Placement of a weir was tested for best results in the harbour. Photo 7 shows one scheme with a 2,600 feet long weir near the middle of the section. The crest elevation of +10 feet above mean water level was 0.4 foot above the highest recorded tide in the harbour of September 7, 1967, which had a 9.6 feet high water and a -6.9 feet low water. The weir length was chosen to pass the maximum expected flood flow of 100,000 cfs with a 5 feet head, giving a dammed level upstream of +15 feet, the highest suggested before significant flooding would occur.

Photo 7. Dam and Weir Upstream of Dock

The advantages of the dam were found to be as follows. First, the slush ice formed in the rapids becomes a static ice cover in the deep wide nearly-stagnant lake created by the dam. Therefore, no ice problem occurred in the harbour area, which in any case was protected from the direct weir overflow. Nest, the harbour velocities were lowered, with mostly seawater of very low velocity moving slowly back and forth to fill the much reduced tidal prism between dam and Hudson Bay. Third, river-borne sediment was trapped in the lake, and did not get past the dam. The lake created by the dam was non-tidal and fresh, forming a steady recreational area all year round, plus giving ready access to fresh water for the Port and town of Churchill. Finally, a roadway may be constructed on top of the dam and weir to provide safe access for development of the west shore and for tourism.

The disadvantages of the dam were found to be: firstly, extremely high cost due to material and equipment availability and overall size (almost 8,000 feet long); definite possibility of suspended material settling out due to the low velocities in the harbour area even though the surface freshwater layer from the weir is always moving seaward even at flood tide (except when river discharges are very low). The tests showed that at flows of 10,000 and 24,000 cfs, the tidal inflow near the bed predominates in duration over its outflow, allowing more time for littoral drift sediments to be brought in and deposit in the harbour. Thus, increased dredging is forecast, although conditions for dredging would be easier. The river is blocked to navigation, although small boats would likely be kept above the dam in any case. Some flooding of the area between the dam and Goose Creek will occur at flood flows nearing 100,000 cfs, requiring dykes and building relocations. Certain yearly maintenance costs would be incurred, and finally the harbour would not clear of ice until a few days later than normal.

5.3 Reduction of River Flow by Diversion

The Churchill River will soon have much of its flow diverted into the Nelson River several hundred miles upstream for power development. The effect of severely reduced flows on conditions in the harbour was investigated. Fig. 5 shows the drag-plate current meter velocities over two semi-diurnal tide cycles, for two test conditions, one with present average river flow of 50,000 cfs, and the other for an admittedly very small discharge of only 2,500 cfs. These two tests demonstrate the effect of a reduction in river flow. First, although not shown here, the high water levels at the dock are influenced mainly by Hudson Bay, and so were found to be almost the same. The low water, however, is about 0.6 foot lower with the small flow since only a small slope is then required to get this amount of freshwater out to Hudson Bay. Water levels further upriver are lowered dramatically, by over 4 feet at gauge 1 , Fig. 2, so that the river becomes much narrower and shallower. The velocity meters located as in Fig. 4, showed interesting behaviour. Meter 51 was in the entrance in the surface layer and meter 59 was directly below it near the bed. With the 50,000 cfs flow, there was a 2.5 hour lag between the time the bottom seawater (59) began to move as inflow and the time when the surface layer (51) finally reversed also. However, with the 2,500 cfs river flow, the surface layer is so thin that virtually the whole flow from top to bottom reverses direction at the same time. The tidal prism of the estuary which at high flows is filled by river and tide, will then be mainly filled by inflow from Hudson Bay. Thus inflow times will be longer and the velocities higher, and outflows will be shorter. The end result will be more time for littoral drift sediments to be carried into the estuary, and less time to be cleared out. On the favourable side of the question of reduced river discharges is the fact that less river flow will bring down less sand and sediments. In addition, less ice should be produced in the rapids by the smaller river cross-section. These two factors may well more than compensate for the increased siltation expected from Hudson Bay. The best recommendation now is to wait and see if the results of the diversion bear out the predictions from the model tests.

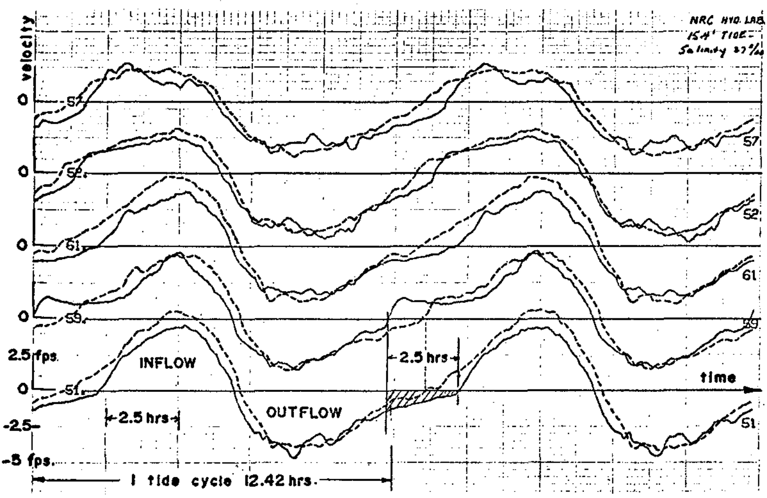

Fig. 5. Two Semi-Diurnal Tide Cycles Giving Velocities for 50,000 cfs (——) and 2,500 cfs (---) River Discharges

6. DISCUSSION

The purpose in presenting this model study is to encourage the use of salinity models in the study of flow phenomena where density effects are involved. Although not inexpensive to operate because of salt use, the model control and data acquisition by on-line computer was most effective in keeping testing to a minimum. Use of plastic pipe and concrete is recommended where possible to avoid corrosion problems. Even rusting, however, requires years before significant damage occurs, and by then the equipment has certainly paid for itself in allowing better knowledge to be gained than from all-fresh water tests. Instruments made of type 316 stainless steel were found to resist corrosion very well.

The results of a few of the schemes tested on the model to improve conditions in Churchill harbour, particularly under ice-run conditions were described along with their advantages and drawbacks. Obviously no scheme was perfect, but at least the results should allow a better appraisal of the merits of each when the time comes to implement one at Churchill.

7. REFERENCES

1. Dick, T.M., "Limits to Navigation by Ice in Port of Churchill", Proceeding of ASCE, Journal of Waterways and Harbours Division, WW4, November 1967.

2. Limited distribution of National Research Council documents by T.M. Dick; 1 report on Feasibility of Extending Navigation Season at Churchill Harbour, and 3 laboratory memoranda on field measurements of velocity, temperature and salinity, and assessment of littoral drift and sedimentation.

8. ACKNOWLEDGEMENTS

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