Chapter 49

POTENTIALS OF TIDAL POWER ON THE NORTH ATLANTIC COAST IN CANADA AND UNITED STATES

Jan T. Laba

Asst. Professor, Dept. of Civil Engineering
University of Windsor, Windsor, Ontario, Canada.

In this paper the most suitable locations for erection of tidal power plants on the North Atlantic Coast are reviewed and classified in respect to the possible pool arrangement. The harnessing of the tides to produce power in various layouts is described. Due to the limited length of this paper, it was only possible to discuss and compare the power output from two proposed tidal power projects, Passamaquoddy Bay and Shepody Bay, and also to discuss some auxiliary power sources to supplement the varying output of tidal power. The tide producing forces and the effect of the coastline on the tide height is also briefly introduced.

TIDES

The principal movements of the ocean may be divided into three classes: ordinary or wind waves, ocean currents and tidal movements. The essential feature of any tidal movements is, as the name applies, its periodicy, which distinguishes it from the others.

Tides and tidal currents are the vertical and horizontal water movements which occur in response to the periodic tide-raising forces of the moon and sun. Tidal movements are periodic vertical oscillations above and below mean sea level. Tidal currents are periodic horizontal oscillations over a fixed point on the earth's surface, or in open waters, an elliptical movement around a fixed point. The periods of these oscillations are identical to those of the forces to which they respond, i.e. the rotation of the earth on its axis, the revolution of the moon about the earth and the revolution of the earth about the sun.

At the beginning of the period, the magnitude of the force increases from zero to a maximum in a positive direction, then diminishes to zero and increases to a maximum in the negative direction, and thence back to zero to end the period. Each of the periodic forces undergoes some modifications with changes in astronomical conditions. The length of the period varies only slightly but there are large variations in the magnitude of the forces.

The principal tide-raising forces fall into two groups those with a period of about half a day, which are termed semidiurnal forces: and those with a period of about a day, known as diurnal forces.

One of the principal semidiurnal forces is the lunar tide-raising force, with a period of half a lunar day (about 12h 25m). The magnitude of this force varies with the distance of the moon from the earth, being increased by about 20 per cent when the moon is in perigee and decreased by that amount when it is in apogee. The other principal semidiurnal force is the solar force, with a period of half a solar day (about 12h 00m). The magnitude of this force varies with the position of the earth in its orbit around the sun. It is increased by about 27 per cent at each equinox, decreased by about 32 per cent at the June solstice and decreased by about 22 per cent at the December solstice.

One of the principal diurnal forces is a combined lunar and solar (luni-solar) force. This force varies both with the distance of the moon from the earth and with the position of the earth in its orbit around the sun. The force is increased at perigee and decreased at apogee by about 13 per cent and is increased at the solstices and decreased at the equinoxes by about 33 per cent. The other principal diurnal force is purely lunar force, whose period is related to both the lunar and sidereal days. This force is increased when the moon is in perigee, and decreased when it is in apogee by about 20 per cent. (Ref 1).

Figure 1, greatly simplified, indicates how the two principal semidiurnal forces vary with the position of the moon in its orbit around the earth. When the moon is new or full, the range of the tides is considerably greater than the average. They are called spring tides, and are produced by combined tide-raising forces of the moon and sun. When the moon is either in first or third quarter, the tide-producing forces of the moon and sun are in opposition to each other, producing the neap tides with the smallest range.

Tidal energy cannot be harnessed wherever it presents itself, as in the open sea. However, the reflection of the tidal movements on the continental plateau, and the incidental resonances greatly amplifying the tide's height (up to 25 times), create the possibility for their energy to be harnessed.

The height of the tide is not only affected by the moon and sun, but to a large degree by the coastline. On the coast the range is usually greater, the oscillations of the ocean waters tend to grow higher as they run into shallow water. In shallow water the tidal waves move slowly, so that the time of high water could differ widely at stations only a few miles apart, but the period will be exactly that of the impressed force.

In the Gulf of Maine for example, where the continental shelf drops down towards the deep areas of the Atlantic Ocean,

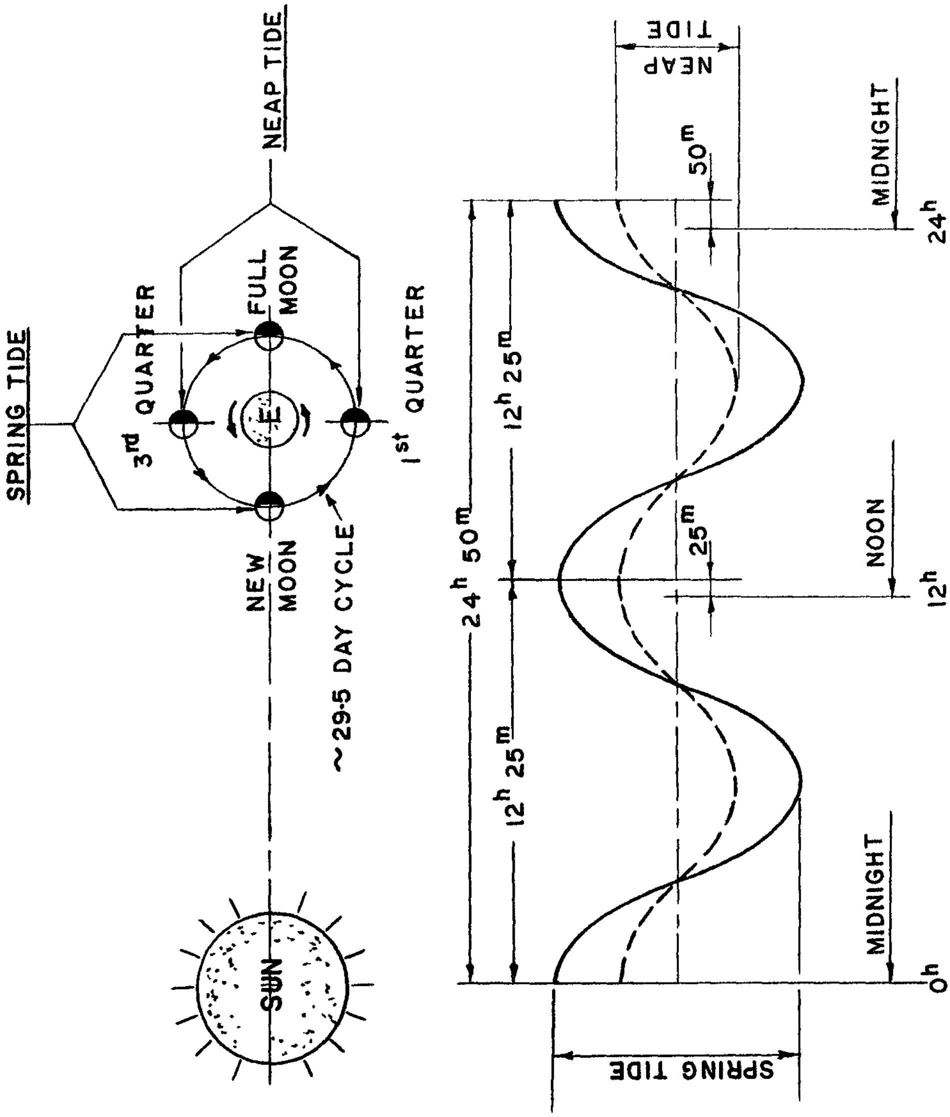

Fig. 1 Moon's Phases and Tidal Cycle.

the tides are amplified by the configuration of the shore line and the bottom of the ocean. Also, where configuration of the coast forces the tide into a corner, or where the natural period of oscillation of the water in a bay or gulf is nearly the same as that of the tides, the height becomes very great. The above conditions exist at the head of the Bay of Fundy where the mean range of spring tides is 50 ft, one of the greatest in the world, and also in the Hudson Strait.

The advantages of a tidal power plant are that the tides remain independent of the atmospheric movements, except for the amplitude which could be affected by the latter. Tides can also be predicted for many years to come and produce power unaffected by droughts, floods, ice jams or silting which usually decreases the output and limits the life of the hydroelectric plants.

The existing disadvantage of the tides as a source of energy is that the tides follow the lunar day of 24 hours and 50 minutes, rather than the solar day of 24 hours. This 50 minute daily lag has a great influence on the economics of tidal power. Since power output varies with the tides, tidal power is completely out of phase with the normal patterns of the daily use of electricity. Therefore, as a general rule the tidal plant should be supplemented by an auxiliary plant during the period of low generation.

POSSIBLE LOCATIONS FOR THE TIDAL POWER PLANTS ON THE NORTH ATLANTIC COAST

There are three main requirements governing the selection of a suitable location for a tidal power plant. The first requirement is the economic justification for such a project in a chosen area and distance to the possible present and future markets for the produced energy. The second and third requirements are: sufficient height of tides and favourable configuration of the shore line. The higher the tide range, the larger the amount of energy that could be produced. A shore line having a number of natural bays and estuaries creates an ideal location for a tidal power scheme, since this will allow the engineers to build artificial pools with a minimum length of enclosing dams, thus making the project more economical.

A study of the tide heights on the North Atlantic coast indicates that the tide range increases along the United States coastline from south to north, reaching the following average tide heights: in Newport 3.5 ft, in the gulf of Maine about 10 ft, and in Cobscook Bay between the United States and Canada 18 ft. In the Bay of Fundy along the New Brunswick coast, the tide range steadily increases towards the head of the bay, reaching at St. John 20.5 ft, and at the inlet of Chignecto Bay to Cumberland Basin 35 ft. Along the Nova Scotia shore the process is repeated and the average tide height at Burntcoat Head (Minas Basin) is 41.5 ft, at Digby 21 ft, at Yarmouth 7.5 ft and at Cape Sable 7 ft (See Fig 2).

Along the Atlantic coast of Nova Scotia, Gulf of St. Lawrence, Newfoundland and Labrador, the average range of the tides is rather small and varies from a few feet to a maximum not exceeding 10 ft. However, at the entrance to the Hudson Strait at the head of Frobisher Bay, the range of the largest semidiurnal tides is 40 ft, and 50 ft in Ungava Bay.

From the above, it seems that the Bay of Fundy area offers the best possibilities for the development of tidal energy on the North Atlantic coast.

The following are the most suitable locations for erecting a tidal power plant in the Bay of Fundy area:

(1) On the border between the United States and Canada, the configuration of the shore line creates two large bays; they are Cobscook Bay and Passamaquoddy Bay with the St. Croix River estuary. A number of islands located close to the shore at the inlets to the above mentioned bays create an ideal location for a tidal power plant. Although the average tide range is only 18 ft, the place itself offers large possibilites and flexibilities to produce a continuous supply of power, using more than one pool system.

(2) At the head of Chignecto Bay where the average tide range is 35 ft, two bays, Shepody Bay with the Petitcodiac River estuary and Cumberland Basin create the prospect of a very promising tidal power project. In view of the economi aspects, this two-pool project would be superior to the previously mentioned Passamaquoddy project in dependable power supply and amount of energy generated per year.

(3) The next possible place would be Minas Basin where the height of the tides is the highest in the world, the average being over 40 ft. The barrage could be built at the entrance to the basin, cutting off a large volume of water at high tide and a large amount of energy could be produced. This project could be a typical one-pool scheme (one or two-way operating plant), but could not produce alone a continuous supply of power.

(4) Another two places where energy from tides could be produced are located along the shores of Nova Scotia, They are St. Mary Bay and Annapolis Basin, where the average tide height reaches 21 ft. These two bays could also be develope into two separate single pool schemes, but much smaller than those previously mentioned.

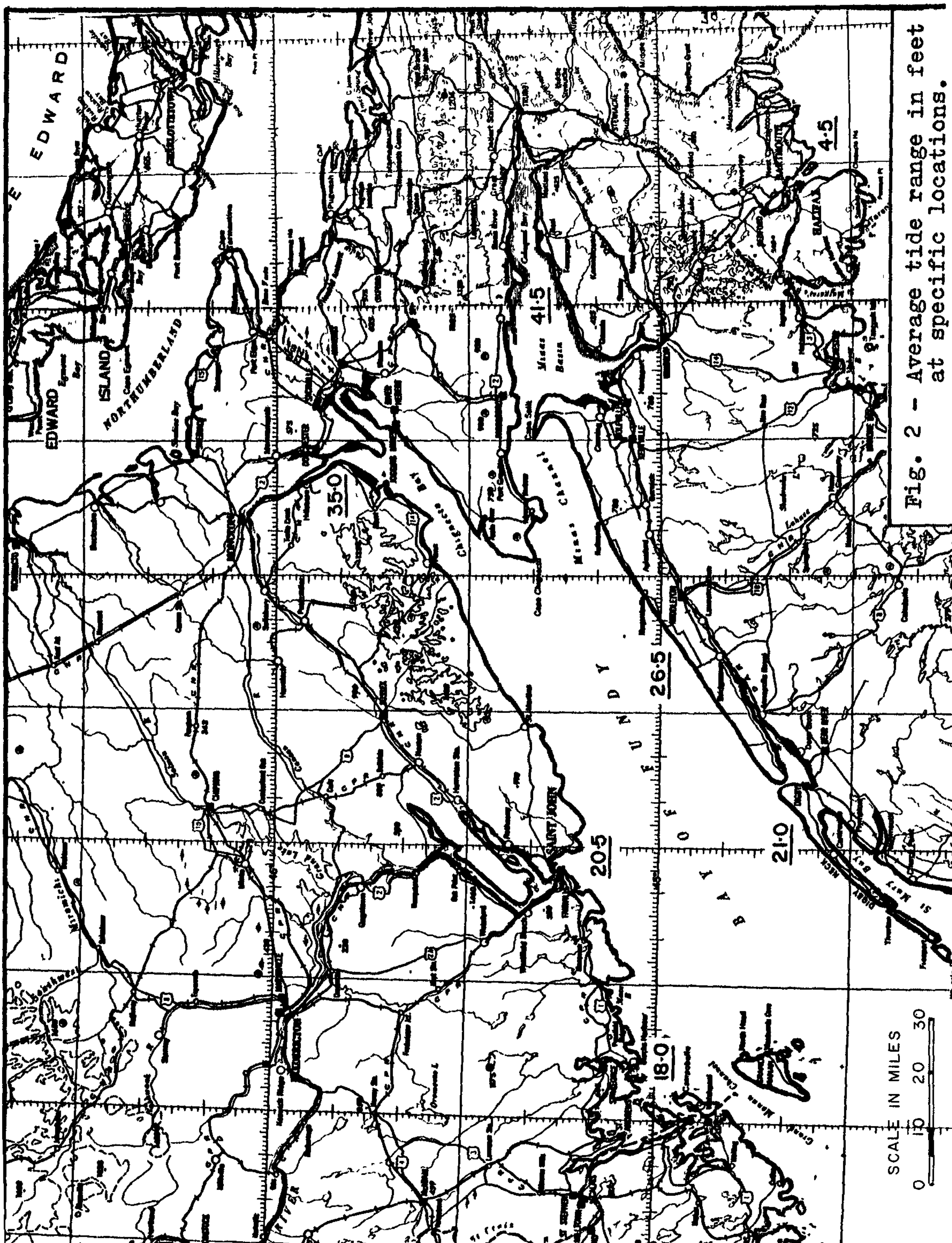

Fig. 2 - Average tide range in feet at specific locations.

POWER FROM TIDES

Tidal hydroelectric power similar to river hydro power, can be obtained by the flow of water from higher to lower levels through hydraulic turbines. Dams, gates, and powerhouses are needed for tidal projects as for a power project on a river. Other factors such as a rapidly varying head and problems of salt water corrosion must also be considered. A tidal power project may be arranged in many different ways, and these are described in the following.

A single pool equipped with turbines and gates can be created by building a barrage enclosing an estuary or bay. The pool can be filled during high tide and the potential energy of the water can be utilized when the pool is emptied at low tide. This is known as the single high pool emptying cycle. Alternatively, the pool may be emptied at low tide and receive discharge through the turbines from the ocean at high tide. In this case, the layout is known as a single low pool. These two cases are sometimes refered to as one-way operating tidal power plants.

Using a single pool layout, with turbines generating power from flow in either direction, the energy can be produced during both the filling and the emptying of the pool. Such a layout is known as a two-way operating plant or single-mean-pool arrangement.

If a selected site offers certain topographical characteristics, two separate pools equipped with emptying and filling gates may be used. One pool will be filled at the high tide and the other emptied at low tide, with the high pool discharging through the turbines into the low pool. This arrangement can be called a two-pool layout.

INTERNATIONAL TIDAL POWER PLANT

A few suitable sites for the location of the tidal power plant have already been described. Let us first conside the St. Croix River estuary with Passamaquoddy Bay and Cobscoc Bay. This project includes 100 square miles of Passamaquoddy Bay and 40 square miles of Cobscook Bay. (The 100 square miles represents pool area at an elevation of 6 ft above m.s.l. and the 40 square miles at elevation of 5 ft below m.s.l.). This would involve both New Brunswick (Canada) and Maine (U.S.A.) interests and therefore would be an internatiór al project. The range of tides in the above mentioned areas at the site of the proposed project, varies from a minimum of 11.3 ft at neap tide to a maximum of 25.7 ft at spring tide, averaging 18.0 ft. On the average, during each tidal cycle approximately 70 billion cubic feet of water enters and leave: both bays.

A design including both bays in one project would be more advantageous than the separate development of either bay by each nation. Independent separate projects would involve international complications concerning navigation, fish, wild life and other aspects.

PRELIMINARY CALCULATION OF THE POWER OUTPUT

Before the most suitable layout of a tidal power arrangement for this area can be chosen, let us consider the possible energy production from a few layouts. The purpose of this investigation is to compare the theoretical power outputs obtainable from different layouts. Some assumptions will be required to simplify the actual complicated problem.

The calculations will be carried out for an average tide height of 18 ft. The equation of the tide wave oscillation will be assumed to be:

$$y = z \cos \frac{2\pi}{T} t$$

where: amplitude z = 9 ft
period T = 12hr.25min.
variable t = time

The generated power will be expressed as a function of the average discharge through the turbines, and the average area of the pool or pools (160 sq miles) will be assumed to remain constant in the range of the tides. Also, the minimum required operational head for the turbines will be taken as 6 ft.

Single pool, one-way operating plant - In considering a one-way operating tidal power plant (Fig 3), built to trap water at high tide and discharge to the ocean at low tide, (high pool layout), four separate operating phases can be recognized:

(1) A waiting phase (A-B), when turbines are stopped and filling gates are closed.

(2) An energy production phase (B-C), when the turbines are operating and the gates are closed. In this layout the turbines are producing power operating under a head which is always in the same direction - from the pool to the ocean.

(3) A waiting phase (C-D), with the gates closed and the turbines stopped, after the generating head decreases below its minimum required value.

(4) A filling phase (D-A), when the turbines are stopped and the filling gates open. The tide is rising and the water flows from the ocean to the pool.

Figure 3, indicates that the pool is filled during high

LEGEND

----- Operation without pumping.

– —·· Operation with pumping.

T = Turbines

G = Gates.

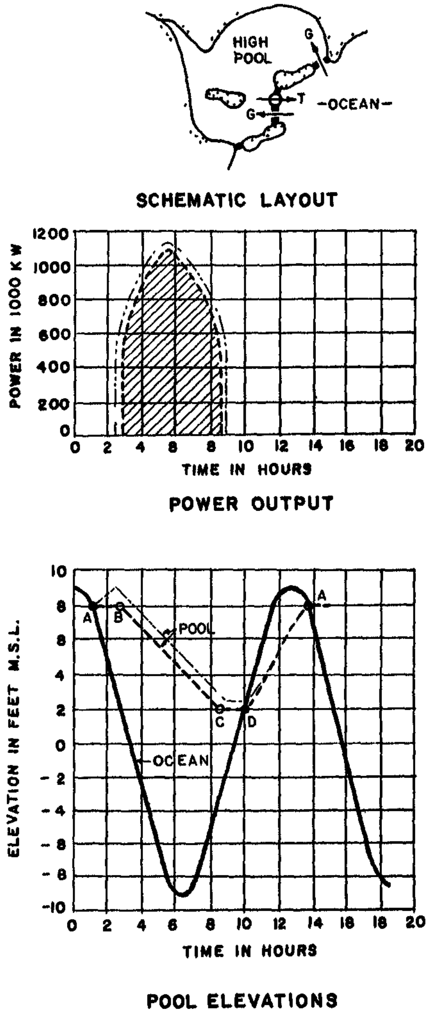

Fig. 3 - Single-Pool Layout. One-way operating plant.

tide up to 8 ft above m.s.l. As soon as the head from the pool to the ocean is large enough, power is generated during each tide cycle, over a period of 5.74 hours, in which the water level in the pool will drop 6 ft. No power is generated during the pool filling on the high tide.

In all the following tables, generated power indicated was calculated on the assumption of 88 per cent average efficiency of the power plants. Table I shows a relationship between time, operational head and theoretically generated power for a one-way operating plant.

TABLE I

Time t (hr)	Water Level in pool (ft)	Operational head (ft)	Generated power (kW)
2.66	+ 8.00	6.00	514,000
4.00	+ 6.59	10.51	904,000
5.75	+ 4.78	13.53	1,160,000
7.50	+ 2.92	10.10	865,000
8.40	+ 2.00	6.00	514,000

Note: water level in respect to m.s.l. and the first peak of high water occurs at t = 0 hours.

The total energy produced during the complete tidal cycle will be 5,150,000 kW-hr, and the next production phase will start after the waiting period of 6.68 hours.

If energy from outside sources is available, it would be advantageous for the above project to use turbines that also operate as pumps. Immediately after the filling gates are closed, the water level in the pool could be raised further by pumping at low head and increase the generating head for the following production phase. The energy gained in the power generating cycle would be larger than the energy used for pumping.

Single pool two-way operating plant - A single mean pool could be created by using turbines which can generate power from flow in either direction. It would operate as a high pool during low tides, and as a low pool during high tides, see Fig 4, where the mean pool is filled and drained respectively to ± 2 ft. This arrangement results in two separate generating periods and six operating phases can be recognized.

(1) A waiting phase (A-B). Generation can start as soon as the minimum head is available. If energy for pumping from outside sources is available, the water level in the

pool could be raised further. (The energy gained in both generating cycles will exceed the energy used for pumping at low head, adding to the benefit of the project).

(2) An energy production phase (B-C), with the water flowing through the turbines from the pool towards the ocean. Generation will continue until sufficient water volume has been evacuated from the pool and the generating head decreased to its minimum required value.

(3) An emptying phase (C-D). By stopping all turbines and opening all gates, the water within the pool can be rapidly evacuated at the time of the low tide.

(4) A waiting phase (D-E), when the turbines are stopped and the gates are closed. Generation can start as soon as the minimum required generating head between the ocean and the pool is available. This period in relation to the tide could occur sooner if a reverse pumping operation would be available to lower the water level in the pool.

(5) The energy production phase (E-F). As the tide continues to rise, generation takes place until sufficient water has flowed into the pool to destroy minimum generating head.

(6) A filling phase (F-A), when the turbines are stopped and the gates are opened. As the high tide begins to drop down the water flows from the ocean to the pool, until both water levels are the same.

The required minimum operational head of 6 ft will occur in the pool 4.02 hours after high water and the power generation period will last 3.53 hours, and during this time the water level in the pool will drop 3 ft. Then the water from the pool will drain through the gates or turbines which could be changed to orifices bringing the water level down to 2 ft below m.s.l.

The reverse process will start again at $t = 10.23$ hours, but this time water from the ocean will flow to the pool through the turbines generating power again for 3.53 hours, and then the gates will be opened, or the turbines changed to orifices and the cycle will be repeated.

Table II shows a relationship between time, operational head and generated power for a two-way operating plant.

TABLE II

Time t (hr)	Water Level in pool (ft)	Operational head (ft)	Generated power (kW)
2.66	+ 2.00	0.00	0
4.02	+ 2.00	6.00	418,000
5.84	+ 0.46	9.31	650,000
7.55	- 1.00	6.00	418,000
8.87	- 2.00	0.00	0
10.23	Reverse operation will start		

The total developed energy in two generating periods during a complete tidal cycle will be about 3,800,000 kW-hr. Since the average pool level is about the same as mean sea level, the generating head is considerably less than for a high pool arrangement; because of this, total generated power for the mean-pool plan is less than for the previous layout by 26 per cent, but the waiting period between energy production phases will decrease to 2.68 hours, compared with 6.68 hours for a one-way operating plant.

Two-pool arrangement - The disadvantage of intermittent generation can be overcome by the simple two-pool plan illustrated in Fig 5. The high pool, having an area of 100 square miles is filled during high tide through one set of gates, and the low pool having an area of 40 square miles emptied during low tide through a separate set of gates. Since one pool is operated at a high level and the other at a low level, conventional turbines which permit flow in one direction can be used. The two-pool plan produces a varying but continuous supply of power.

To compare this operation with the previously described one-pool arrangement, let us assume that maximum water level in the high pool will reach 8 ft. Then during a period of 9.54 hours, the water level in the high pool will drop 3 ft and the filling gates for the high pool will be open at time t = 10.47 hours, as the high water is approaching. The filling process will take 2.88 hours, and the water level will again reach 8 ft at the time t = 13.35 hours after the first high water which occured at t = 0 hours.

The low pool having 2.5 times smaller area will drain its water volume at low tide to the lowest level (8.5 ft below m.s.l.) and then the emptying gates will be closed. In line with our previous assumption introducing the average discharge, there will be a continuous and constant flow rate of water from high to low pool, and the water level in the low pool will increase 2.5 times faster than it decreases in the high pool. This will last for 8.95 hours and at t = 15.85 hours, the water level in the

LEGEND

A-B , Power units generating. Filling gates closed.

B-A , Power units generating. Filling gates opened.

C-D , Emptying gates opened.

D-C , Emptying gates closed.

T = Turbines.

FG = Filling gates.

EG = Emptying gates.

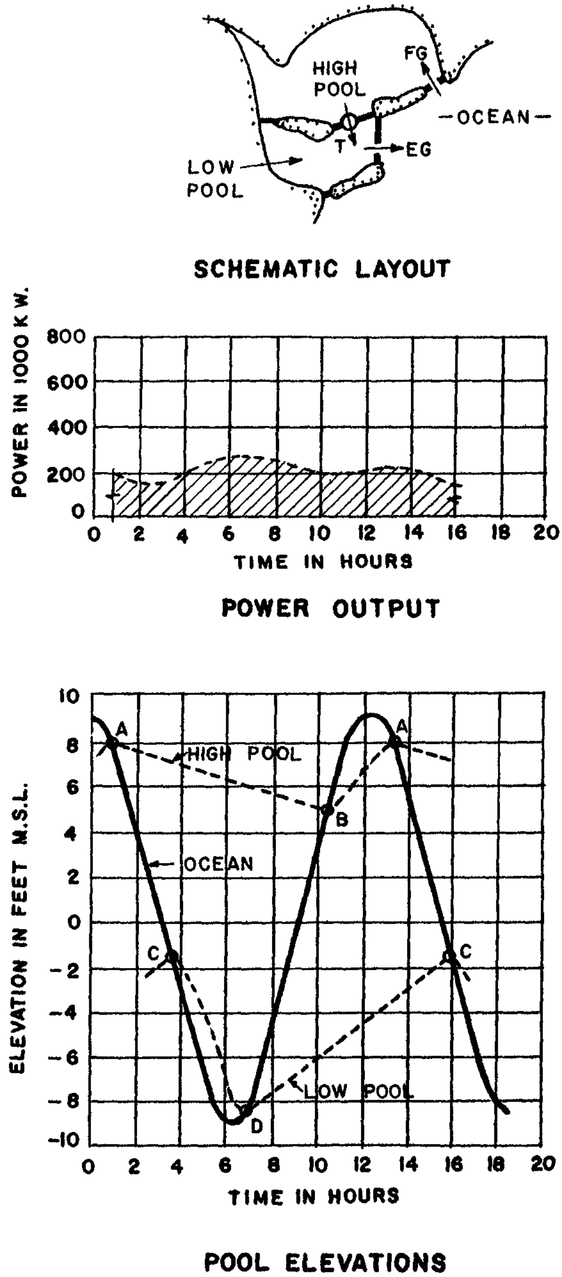

Fig. 5 - Two-Pool Layout.

low pool will reach its peak, 1.5 ft below m.s.l.

Table III shows relationship between time, operational head and generating power for the two-pool arrangement.

TABLE III

Time t (hr)	High Pool level (ft)	Low Pool level (ft)	Operational head (ft)	Generated power (kW)
0.93	+ 8.00	- 3.42	11.42	211,000
3.43	+ 7.21	- 1.50	8.71	161,000
6.89	+ 6.12	- 8.50	14.62	270,000
10.47	+ 5.00	- 5.68	10.68	196,000
13.35	+ 8.00	- 3.42	11.42	211,000
15.85	+ 7.21	- 1.50	8.71	161,000

Since the high pool level in the above is always above m.s.l. and the low pool is always below, and the difference between these two levels is creating operational head for the turbines which never drops below the minimum required head of 6 ft, a continuous supply of power is produced. During one complete tidal cycle energy equal to 2,680,000 kW-hr is produced.

Conclusion - From the above investigation of energy production from the average tide height (18 ft), it is evident that the single high pool will produce during one complete tidal cycle 1.92 times more energy and the single mean pool plan 1.42 times more energy than the two-pool system. However, the single pool layout with a one or two-way operating plant has the disadvantage of producing an intermittent power supply, because no power can be generated without sufficient difference between the levels of the pool and the ocean. Even with additional features such as auxiliary gates and pumps, a single pool would not be able to deliver on its own, an uninterrupted power supply to the network.

The above disadvantage is overcome by a two-pool plan which generates varying but continuous amounts of power. Furthermore, this layout could also deliver at any required time a sizable amount of energy, (independent of the water level in the ocean) after the operational water levels in both pools were obtained and the gates were closed.

As a continuous supply of power seems to be a very important factor in the development of the Canadian Maritimes, the two-pool system appears to be the most attractive, and will be discussed in detail.

PROPOSED TWO-POOL LAYOUT

Figure 6, shows one of the possible layouts which include Passamaquoddy Bay as the high pool and Cobscook Bay as the low, with a powerhouse located on Moose Island, north west from Eastport. The narrowest part of the island would be excavated to provide the headrace for the powerhouse. The location of the tidal power project and the general arrangement of the selected layout is shown on Fig 6, where the arrows indicate the direction of the flow. With 34 generating units rated at 10,000 kW each, operated at about 6 per cent above rated capacity for short periods during spring tides, the output of the tidal power plant would range from 73,000 to 360,000 kW. Average energy generation would be 1,890 million kW-hr a year.

About 36,000 linear feet of tidal dams will be required, which could be composed of clay core supported by flanking dumped-rock fills.

The proposed plan calls for 100 filling gates, 50 in Letite Passage and 50 at Deer Island Point. North east from Indian Island 67 emptying gates, and 5 more at Quoddy Roads similar to the filling gates but set at a lower elevation would be needed to empty the lower pool. A vertical lift gate 30 ft x 30 ft, (completely submerged), set in the venturi throat, with rounded rectangular entrance (1,600 sq ft would be recommended for this project as the venturi throat permits maximum discharge for a given gate area.

Four navigational locks would be required for this project. Two locks to pass fishing vessels, one in the passage between McMaster and Pendleton Islands, and the second at Quoddy Roads. Another two bigger locks, one at Head Harbour Passage and the second at Western Passage north at Eastport would pass large seagoing vessels.

The topography of the selected area permits many different arrangements of the components of a two-pool project. Cobscook Bay has much flatter shores in the tide range than Passamaquoddy Bay; for this reason the area and also the volume of the tidal pools would be larger if Cobscook Bay would be used as the high pool and Passamaquoddy as the low, this could produce more energy than the proposed layout. An important advantage of the proposed plan over Cobscook Bay high pool plan is that all Passamaquoddy Bay and Western Passage would be in the upper pool where the water surface would vary between el + 2.81 ft and + 11.85 ft instead of the present maximum variation between el ± 12.85 ft in respect to m.s.l. In consequence, the navigation and harbour depths for ports in Canada and U.S.A. would be improved. The now existing controlling navigational depth at St. Stephen, New Brunswick, would change from 7 ft at mean lc

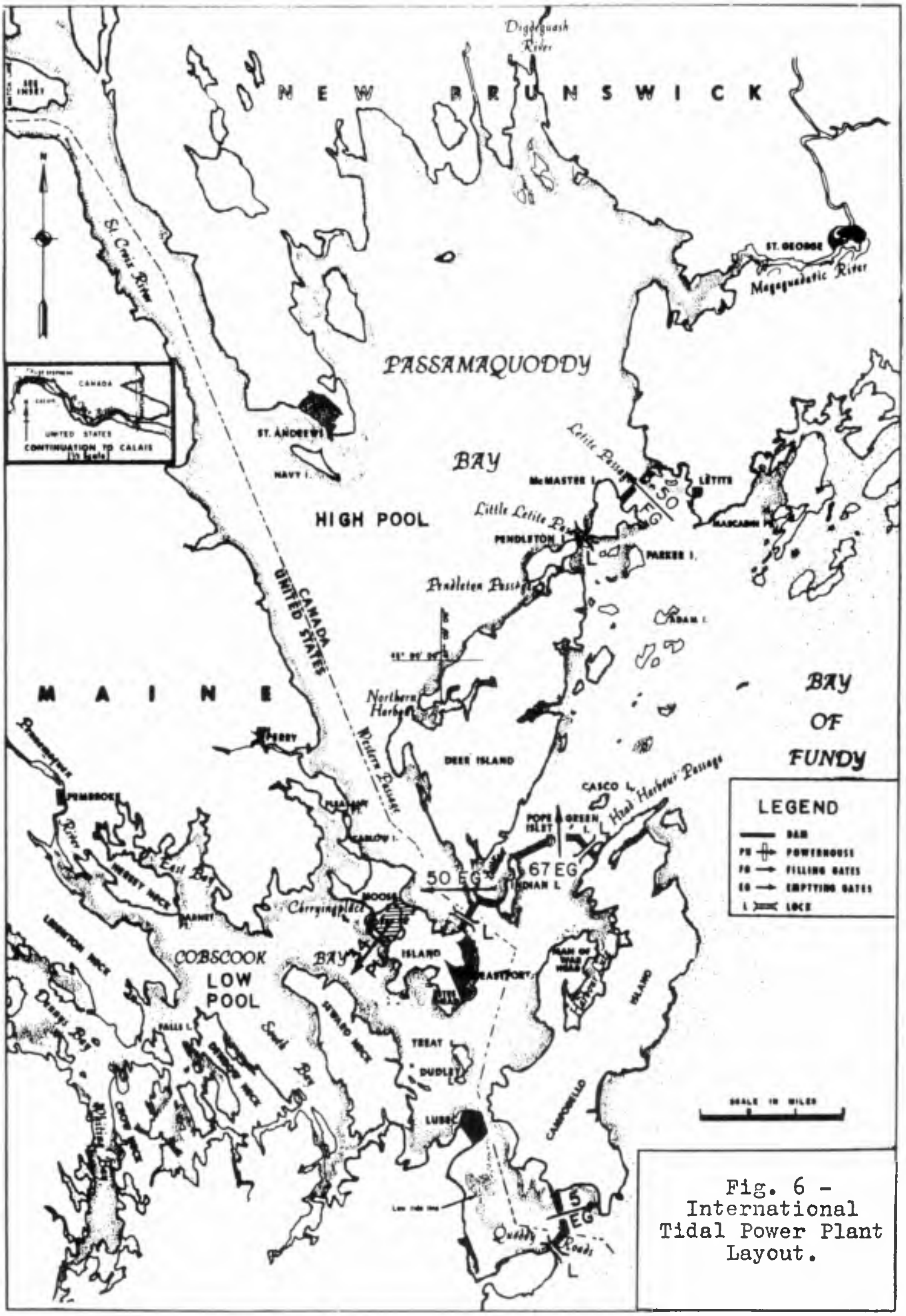

Fig. 6 - International Tidal Power Plant Layout.

tide, to about 22 ft at mean low stage of the high pool. For this reason, Passamaquoddy Bay as the high pool is the most attractive project.

Power output - Figure 7, illustrates typical tidal plant operation where the power output of the selected two-pool layout would vary with ebb and flood of the tides.

Table IV shows momentary tidal power output during the maximum and minimum tides:

TABLE IV

	Max. Generated Power (kW)	Min. Generated Power (kW)
Maximum tide	402,000	258,000
Minimum tide	122,000	73,000

The above figures were derived on the assumption that the highest spring tide and the smallest neap tide were preceded and followed by tides having on the average 1 ft smaller or larger amplitude respectively. If these conditions would not exist and the smallest neap tides appeared one after another, the minimum momentary output of the tidal plant would be reduced to 65,000 kW. In conclusion, the International Tidal Power Plant would have installed capacity of 340,000 kW, and operate slightly above rated capacity for short periods during spring tides.

Turbines - The generating units previously mentioned would be comprised of large European Kaplan turbines, and due to the low and variable operating head, the turbines would be connected to generators with the relatively low rating of 10,000 kW. The average generating head for the turbines would be about 11 ft, normal (operating) speed 40 r.p.m. and a runner discharge diameter of 24 ft.

INTERPROVINCIAL TIDAL POWER PLANT

A very promising Canadian tidal power project could be created by combined use of Shepody Bay and Cumberland Basin, located at the head of the Bay of Fundy, between the provinces of New Brunswick and Nova Scotia.

Shepody Bay, with an approximate area of 75 square miles could be used as the high pool, which also would improve navigation on the Petitcodiac River. Cumberland Basin with an area equal to 50 square miles (after some improvements), could be used as the low pool.

Figure 8 shows the proposed Interprovincial Tidal Power Project layout. At the entrance to Shepody Bay 140

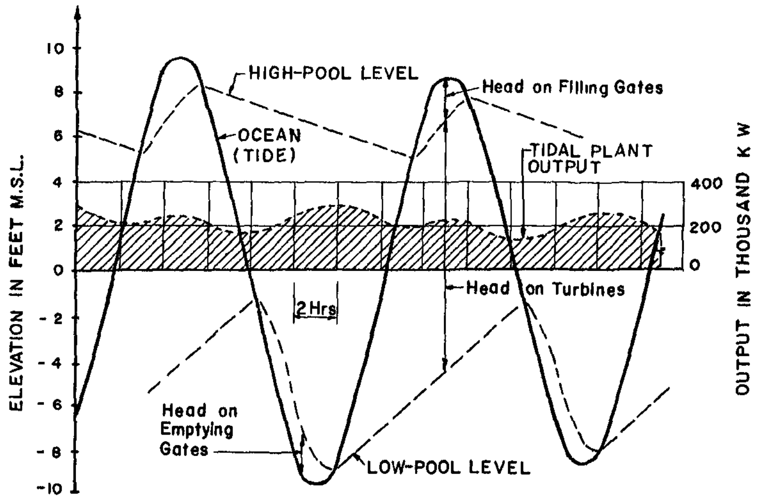

Fig. 7 - Typical International Tidal Plant Operation.

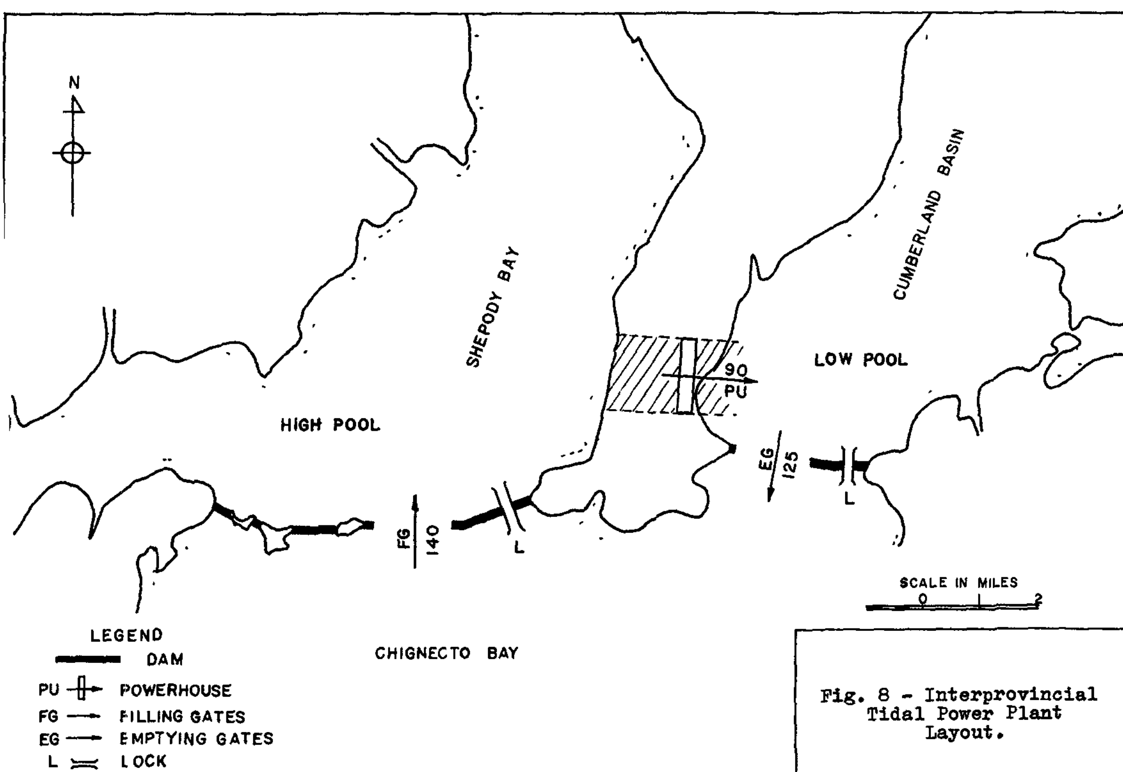

Fig. 8 - Interprovincial Tidal Power Plant Layout.

filling gates and one navigation lock to pass seagoing vessels would be located. A smaller lock to pass fishing vessels and also 125 emptying gates would be located at the entrance to Cumberland Basin. The filling and emptying gates would be the same shape and size as previously described for the Passamaquoddy Tidal Power Project.

The best location for the power house would be at the narrowest point of the peninsula, separating two pools at Peck's Cove, with an excavated area for the head and tailrace. With 90 generating units rated at 10,000 kW each, operated at 6 per cent above rated capacity for short periods during spring tides, the output of the tidal power plant would range from 272,000 kW to 954,000 kW. Average energy generation would be about 5,670 million kW-hr a year.

Height of tides - At Cape Hopewell in the lower reaches of Petitcodiac River (Shepody Bay), the largest tides rise and fall to about 24 ft above and below m.s.l. Further north in Petitcodiac and Memramcook estuaries, the tides range from 21 ft at neap (lowest) tide to over 51 ft at spring (highest) tides.

Maximum tide height for the above project will be assumed as 49 ft, average height 35 ft, and minimum tide height of 21 ft.

Two-pool arrangement - To produce a continuous supply of power, a two-pool plan must be selected. Economic efficiency of the whole project will depend on the proper selection of the flow-rate from high to low pool and also on the number of gates installed.

Figure 9, shows typical operation and power output for a proposed Interprovincial Power Plant, using the average tide height of 35 ft.

The filling gates will be closed when water level in the high pool reaches its maximum level of + 16.5 ft at time t = 0.67 hr after high water. The water level in the high pool will drop 6 ft in 9.87 hr, and at t = 10.54 hr the filling gates will be open again.

The low pool having a smaller area will drain its water volume at low tide to the lowest level - 17.0 ft, and then the emptying gates will be closed. As there is a continuous and constant flow-rate of water from the high to the low pool, the water level in the low pool will increase approximately 1.5 times faster than it decreases in the high pool. This will last for 9.85 hr and at t = 16.52 hr, the water in the low pool will reach its highest level, and then the emptying gates will be opened. With an assumed average efficiency of the power plant of 88 per cent, the total energ

LEGEND

A-B , Power units generating. Filling gates closed.

B-A , Power units generating. Filling gates opened.

C-D , Emptying gates opened.

D-C , Emptying gates closed.

T = Turbines.

FG = Filling gates.

EG = Emptying gates.

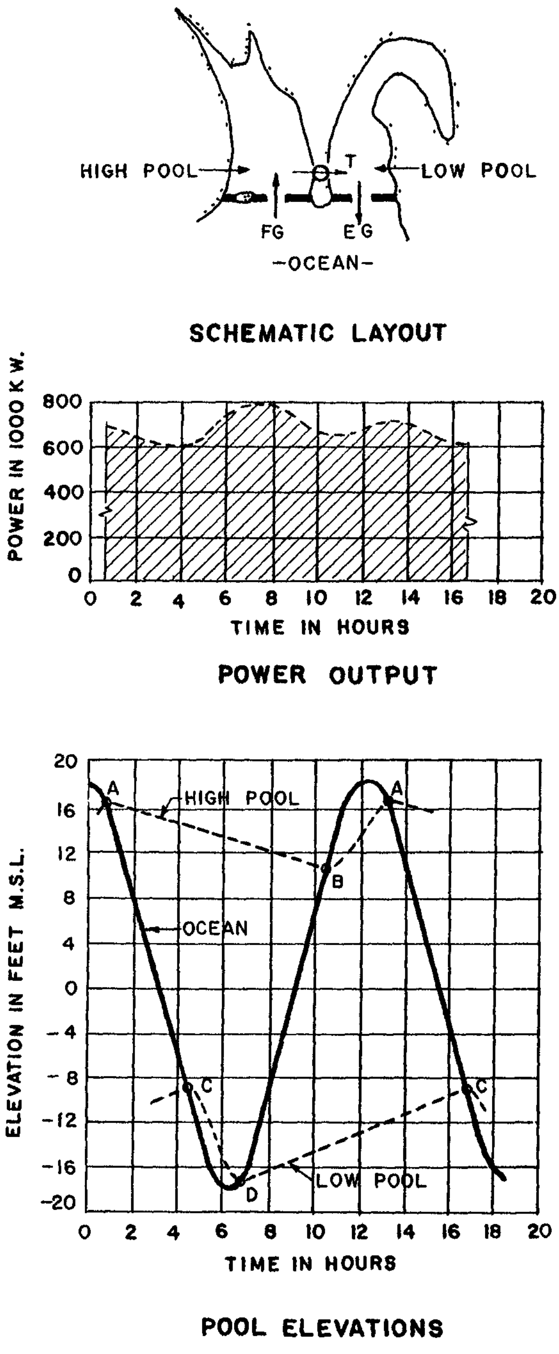

Fig. 9 - Interprovincial Tidal Power Plant output from the average tide height.

produced during the complete tidal cycle will be 8,300,000 kW-hr.

Table V shows momentary tidal power output during the maximum and minimum tides:

TABLE V

	Max. Generated Power (kW)	Min. Generated Power (kW)
Maximum tide	1,180,000	870,000
Minimum tide	342,000	272,000

The above figures were derived on the assumption that the highest spring tide and the lowest neap tide were preceded and followed by tides having, on the average, 2 ft smaller or larger amplitudes respectively.

Turbines - Since the purpose of this paper is only to compare tidal power output of each tidal plant, the turbines used in this case were assumed as before to be European Kaplans, with an average power generating head of 25 ft normal (operating) speed of 90 r.p.m. and a runner discharge diameter of 15 ft.

COMPARISON OF INTERPROVINCIAL AND INTERNATIONAL TIDAL POWER PLANTS

From the preceding discussion, the superiority of the Interprovincial (Shepody Bay) Tidal Power Plant over the International (Passamaquoddy Bay) can be expressed as follow

(1) The dependable firm power supply would be 3.73 times higher.

(2) The average energy generated per year would be 3 times more.

(3) The ratio of the high pool area to the low pool area is closer to unity, which creates a more economical operating plant.

(4) The average design head for selection of the turbine is 25 ft, as compared with 11 ft in the case of the International Tidal Power Plant; this will permit the use of smalle sized turbines to produce the same amount of power i.e. 10,000 kW per turbine.

(5) Only two navigation locks will be required to pass sea-going and fishing vessels.

(6) As the higher tides in Shepody Bay have greater powe

producing potential, the number of filling and emptying gates indicated on Fig 8, could be reduced if desirable for economical or other reasons. The amount of energy produced by the above project could still compare favourably with Passamaquoddy Bay.

Comparison of tidal power output with normal load pattern - Figure 10, shows the output of the two previously discussed tidal power projects compared with the typical load curve for a period of one week. In this particular case, maximum power output for both plants occured Sunday after midnight and minimum power output occured the following Saturday before midnight. The load curve shown has a total annual energy of 8,450 million kW-hr and a load factor of 60 per cent. It represents the combined utility loads of Maine and New Brunswick expected in about the year 1975. (Ref 2).

In New Brunswick alone, with the present population of 615,000, the energy requirements of the utility market are estimated at 1,220 million kW-hr for 1965, and at 2,240 million kW-hr for 1975. The corresponding peak demand will be 260,000 and 455,000 kW. The load factor is expected to increase from the present 52.3 to 56.5 per cent in 1975. (Ref 2).

AUXILIARY POWER PROJECTS

Each tide will fill the upper pool of the tidal project regardless of the amount of water used to generate energy in the preceding cycle. Water left unused would be wasted; therefore, power must be generated from each tide before the next tide occurs or it will be lost.

It was mentioned previously, that the tides follow closely the gravitational pull of the moon as it circles the earth at varying distances, once every lunar day (24h 50m). Due to existing difference between the lunar and solar day, the high and low waters will occur 50 minutes later each day. On the other hand, the use of electricity follows the pattern of a 24-hour solar day, following the nature of demand, the work and play habits of consumers. This 50-minute daily time lag could be directly responsible for the maximum power demand occuring during the time of minimum tidal power production, and also for minimum demand during the maximum tidal power generation.

For load carrying purposes, power from the tidal project is limited to the amount it can furnish under the most adverse conditions, which will be 73,000 kW for the International Tidal Power Project and 272,000 kW for the Interprovincial. All output in excess of this amount is not dependable for serving loads and would have value only as non-firm energy. Since this excess is large, it should be

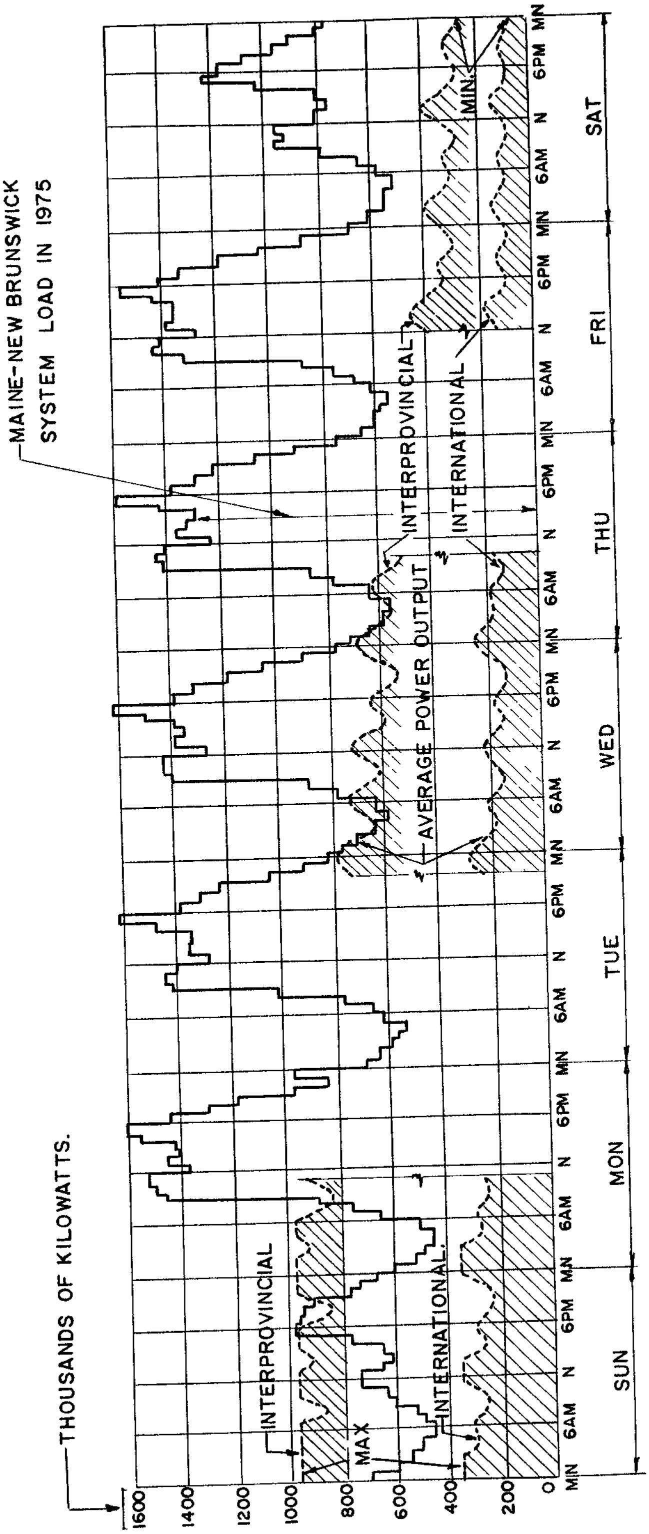

Fig. 10 - Load pattern showing maximum, average and minimum output from the Interprovincial and International Tidal Power Plants.

firmed by an auxiliary source of power to make it dependable for serving loads.

Firming of the tidal power output - The tidal power plant should be supplemented by an auxiliary plant during the period of low generation to increase the dependable power supply. Also in the case when combined output of both sources will supply only a portion of the required system load, the auxiliary source of energy should firm the tidal power output in such a way that the pattern of the remaining load would be acceptable to the other generating plants of the system. The power output could also be combined with one or more hydroelectric, nuclear, steam or combustion power plants. The combined energy obtained from the above sources should form a pattern similar to the required load curve.

In the areas where water storage could be provided, it would be possible to firm the tidal power output by pumping water to the storage reservoir at times of high tidal energy output, and then use the stored water to generate power during low tidal power output. This continuously repeated process of generating and pumping could regulate the tidal power output to deliver the required amount of power to the network. This type of operation however, will result in the loss of a certain amount of energy consumed by pumping and other losses in the system.

FINDINGS OF THE INTERNATIONAL JOINT COMMISSION

In 1961, The International Joint Commission, a six man board, with equal U.S.A. and Canadian representation, stated that the International Tidal Project could work if tied to a St. John plant. One of their proposed layouts, similar to the one shown on Fig 6, could deliver the net average annual energy of 1,843 million kW-hr, with installed capacity of 300,000 kW and power output varying from 345,000 kW to 95,000 kW (dependable 98 per cent only). The construction cost of the tidal plant alone would be close to $500 million.

(1) Among a number of river hydroelectric sites examined, Rankin Rapids on the upper St. John River in Maine, was selected by the commission as the best source of auxiliary power. The Rankin Rapids project could provide 2.8 million acre-feet of usable storage capacity. If the output of the tidal power project would be combined with all of the capacity and energy available at Rankin Rapids (460,000 kW dependable, and 1,220 million kW-hr) it would provide a total dependable capacity of 550,000 kW and an average annual generation of 3,063 million kW-hr.

Assuming an equal division of power output and of first costs between U.S.A. and Canada, construction of the tidal power project with all of Rankin Rapids as auxiliary plant is not an economically justified project for Canada.

(2) As a possible alternative plan of development, Rankin Rapids could be constructed initially with 200,000 kW of dependable capacity to carry part of the load in the State of Maine. An additional 260,000 kW of dependable capacity would also be provided as an auxiliary power supply for the tidal project. Energy thus borrowed from the Rankin Rapids project when using the "incremental capacity" would be repaid when tidal output is greater than the load. In this way, Rankin Rapids and the tidal project would provide 355,000 kW dependable capacity and 1,843 million kW-hr of average generation without a serious effect on the basic Rankin project (200,000 kW and 1,220 million kW-hr).

(3) Tidal power could also be supplemented by pumped storage, located on the Digdeguash River near the outlet into Passamaquoddy Bay east of St Andrews. This pumped storage plant could increase dependable capacity of the tidal plant by 228,000 kW. The average annual generation however, would decrease to 1,759 million kW-hr.

In conclusion, the International Commission stated that power rates would not be competitive if Canada and the U.S.A. built the tidal project together. Canadian interest rates would be higher, because of differences in interest rates existing in the two countries, and because of different values of alternative power. Assuming a 50-year amortization period and initial cost equally divided, the cost of power for alternative plan (2) would be 11.5 mills per kW-hr for U.S.A. and 15.8 mills for Canada, and this would not be economical at the present time (Ref 2).

In the summer of 1963, the late President Kennedy approved a modified plan of a low interest project entirely financed by the U.S.A. As the two-pool system could hold its power until it is needed, the Passamaquoddy project could operate for one hour, twice a day to take peak lunch and dinner power loads. The tidal project could also be tied to a hydroelectric plant at Rankin Rapids, and the combined peak period operation of the two plants would be 1,250,000 kW to meet the 5 to 6 p.m. greatest power demand period of the New England - Maritime Provinces area. This project would cost over $1 billion, and the Province of New Brunswick would receive a share of the power at cost price.

CONCLUSION

All plans concerning the future of the International Tidal Power Project (Passamaquoddy Bay) are unpopular among some Canadian officials. The reasons could be economic as well as political, but there still exists a very important factor which should not be overlooked. Shepody Bay and Cumberland Basin (at the head of the Bay of Fundy) with much higher tides, offers more potential and therefore should be given first consideration. If natural resources are not going to be considered as the most important factor, but political and national aspects only, the International Project may remain only as a dream and a toy for politicians.

Another challenge to the proposed Canadian - U.S.A. partnership in the development of the Passamaquoddy Bay Tidal Power scheme is created by Minas Basin which has the highest tides in the world. With an area over three times larger than Passamaquoddy and Cobscook Bays combined, and with the average tide height exceeding 40 ft, and a narrow channel connecting the basin to the Bay of Fundy, this creates a very inviting prospect for harnessing of the tides. It is beyond the scope of this paper to arrive at any definite conclusion regarding the possible amount of harnessable energy produced by this project, but on the average, during each tidal cycle, approximately 500 billion cubic feet of water enters and leaves Minas Basin, compared with 70 billion for Passamaquoddy and Cobscook Bays combined.

In view of the preceding discussion, and that the erection of the International Tidal Project as proposed by U.S.A. authorities would take about 15 years, it is the author's belief that a plan on a larger scale should be prepared first. This plan should include the possible development and combined utilization of all available tidal potentials of the entire area of the Bay of Fundy, including a larger number of Canadian Provinces, also a greater area of the U.S.A. Only such a plan would be beneficial to all interested parties.

REFERENCES

(1) Canadian Hydrographic Service (1955 - 1963), Atlantic Coast Tide and Current Tables, Ottawa.

(2) The International Joint Commision United States and Canada (April 1961), Report on the International Passamaquoddy Tidal Power Project, Washington - Ottawa.