HYDRO
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THE Lower Churchill PROJECT

March 2008

DC1110 - Electrode Review
- Gull Island & Soldiers Pond

prepared by

HATCH™

in association with

RSW Inc.
Statnett
TGS TransGrid Solutions

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Table of Contents

Executive Summary

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This study addresses aspects of the use of electrodes for the return path of the HVdc current under certain system outage conditions. The work, which pertains to electrodes for the Gull Island and Soldiers Pond converter stations, involved the following activities:

- review of earlier report on potential locations for electrodes;
- comparison of electrodes with a metallic return;
- identification of the conditions that would lead to electrode use and their duration;
- detailed analysis of the electric fields produced by electrodes and their potential effect;
- discussion of alternative electrode locations;
- concept design and layout of the electrodes; and
- preliminary estimates of the capital costs.

The conclusions arising from the study are:

1. The use of electrodes to provide a return path through the earth for the HVdc line would be less costly than a metallic return. For the Labrador and Newfoundland sections only, a metallic return would cost at least three times the electrode arrangement, and for the entire system, the ratio would be much higher, primarily because of the long subsea portion to the Maritimes.
2. The experience in some other HVdc applications has shown that the electric field effect of electrodes has been sufficient, or has been perceived to be sufficient, to prevent the use of electrodes; however, for the current Lower Churchill application, the potential electric field effects can be reduced to acceptable levels or eliminated altogether through appropriate siting of the electrodes, or managed through mitigating measures, with associated costs.
3. The experience in other areas has also shown that the effect of electrodes on the marine environment has been negligible even with continuous operation of electrodes in monopolar mode. Nevertheless, the perceived potential for environmental effects has caused difficulty in some applications, and thus it is important to make stakeholders aware of the issues surrounding the use of electrodes in the Lower Churchill application.
4. From a review of the geological literature and the resistivity measurements made during the 2007 investigations program, it is concluded that a land electrode for either the Gull Island or Soldiers Pond converter sites would not achieve the required grounding; therefore, locations in sea water will be necessary. Locations in Lake Melville and the Strait of Belle Isle (SOBI) for the northern electrode, and in several bays around the Avalon Peninsula for the southern electrode are possible.
5. Except for the use of electrodes to carry small unbalance currents between poles in the HVdc system, usage is expected to be low and any associated effects to be small or negligible. Normally, usage would amount to at most a few tens of hours per year or a few days if major equipment replacement is required at a converter station. The longest potential period of usage would be during an extended cable repair period, which could be as much as one year or more depending on the time of year of the outage and the availability of repair

equipment. It is this extended period that is assumed in the study in determining potential electric field effects. The probability of such an occurrence is not currently known; however, the installation of the subsea cables would be designed to avoid such an occurrence.

6. Under prolonged usage during this worst case scenario, the electric field from the electrodes could cause corrosion. The most severe example would be the corrosion of the subsea cable armour if the northern electrode were placed in Forteau Bay near the termination of the overland HVdc line (to limit the length of the connecting electrode line) and the subsea cable. Minor corrosion would also occur to the Bell Island subsea power cable sheathing in the case of the southern electrode being located in Conception Bay.
7. While the northern electrode could be located in another bay to avoid corrosion of the subsea cable, or mitigating measures could be applied, in general it is concluded that an electrode should only be placed in the SOBI if contact with icebergs can be prevented. Placing the electrode in a dredged depression to avoid icebergs would likely lead to sediment coverage over time and a deterioration in electrode performance. This should be avoided. A more acceptable method would be to construct a rockfill berm around the electrode.
8. The preferred location for an electrode in the SOBI is L'Anse au Clair (to the south of Forteau Bay) due to its orientation which may prevent encroachment by icebergs. This location is also a sufficient distance from the subsea cable to avoid corrosion in the event of prolonged usage. While it may be determined that a berm is not necessary for protection against icebergs, such a berm would protect the electrode from heavy seas and boating activity as well as provide security and safety in what is a small, inhabited bay. A berm would cost approximately million.
9. The cost of an electrode located in L'Anse au Clair, including a protective berm and the interconnecting electrode line would be about $ million. This is approximately $ million more than one located in the southwest part of Lake Melville. The difference in cost is due to the costs of the interconnecting line from the electrode in L'Anse au Clair to the HVdc line about 15 km to the north and protective berm, the sum of which at $ million could be partially offset by the potential costs of mitigating electric field effects on converter transformers at an estimated $ million for the case of an electrode in Lake Melville.
10. The cost of an electrode line from Lake Melville to the Gull Island converter station can be minimized by connecting with the HVdc line to the south. The resulting electrode line cost is then approximately the same as the cost of mounting the electrode conductors on the HVdc towers to the SOBI for the case of an electrode in L'Anse au Clair, given the accuracy of the information on the corridor from Lake Melville to the HVdc interconnection.
11. In addition to the apparent cost advantage, an electrode located in Lake Melville would be in a more sheltered location since the marine environment is relatively benign. There is a possibility of sedimentation although the information obtained in this study suggests that it is largely confined to Goose Bay and Goose Bay Narrows areas. The site would also be remote from any community. Therefore, unless there are extenuating circumstances, a location in Lake Melville is preferred.
12. Placement of the southern electrode in Conception Bay in the general vicinity of the Holyrood Thermal Generating Station would be acceptable from an electric field effects perspective, and this location would minimize the cost of the electrode line to the Soldiers Pond converter station. No effects to the converter station transformer are anticipated given the relatively low electric field produced by the electrode. Any corrosion effects to metallic structures in the area through prolonged usage of the electrode can be mitigated

at minimal cost. The approximate cost of the electrode installation, including the interconnecting electrode line, would be $ million.

13. Because the electrodes are to be reversible, the material of construction will be a mixture of coke and graphite. Most of the construction materials and the installation equipment fleet can be supplied locally or within Canada. If the electrodes are operated in a non-reversible manner, the same or potentially less expensive materials may be used. The overall cost savings are not expected to be significant.

Recommendations arising from the study are as follows:

1. Hydro should proceed with the planning for the installation of sea electrodes for the Gull Island and Soldiers Pond converter stations. At an appropriate time but before final design, Hydro should conduct a public awareness program of electrode installations to ensure that any environmental, safety perception, and other issues are addressed.
2. A study of the probability of losing subsea cable transmission should be carried out to better determine the likelihood of a prolonged outage period. Such a study would entail an analysis of the potential for mechanical damage due to icebergs and shipping activity and any other events that could lead to a long period of usage of the electrodes. If it is concluded from such a study that a prolonged outage would be extremely unlikely to occur, any concern about electric field effects and mitigating costs may possibly be eliminated since the electrodes would operate only sporadically at full current.
3. In order to more clearly determine the preferred location for the northern electrode, a study of the electrode line corridor to the HVdc line interconnection from a Lake Melville location should be conducted, in a manner similar to the studies undertaken for the HVdc corridor. Any sensitive environmental or land ownership issues, that could significantly add to the cost or otherwise militate against the location, should be identified. A similar study should be conducted for a location in L'Anse au Clair, as well as to address other factors that may influence costs such as potential quarry locations, and the shoreline topography and accessibility.
4. Additionally, a more detailed assessment should be made of the potential effects of an electrode in Lake Melville on the converter transformers at Gull Island and the associated costs to mitigate any such effect should be determined more accurately.
5. At an appropriate time, the electrode location in Conception Bay near the Holyrood thermal generating station should be determined more precisely through a site visit and an assessment of any potentially conflicting usage issues.
6. During preliminary engineering, confirmatory sea bed and landfall surveys for both northern and southern electrode locations should be conducted. At the same time, a confirmatory water column salinity profile of a location in Lake Melville should be conducted if the results of the recommended additional work support the findings of this study.

1. Introduction

Newfoundland and Labrador Hydro (Hydro) is undertaking preliminary engineering studies of the development of the hydroelectric potential of the Lower Churchill River at Gull Island and Muskrat Falls. These sites are located downstream 225 km and 285 km respectively from the Upper Churchill hydroelectric facility that was developed in the early 1970's. The total potential capacity at the two sites is approximately 2800 megawatts (MW), the Gull Island site being the larger at 2000 MW. In addition to the development of these sites, the overall concept includes various potential alternative power transmission arrangements involving combinations of AC and DC lines of various capacities.

In April, 2007, Hydro contracted Hatch Ltd of St. John's to undertake a program of studies (Work Task Orders) to address aspects of this development relating primarily, but not exclusively, to hydrology/hydraulics and transmission components. Approximately thirty such WTO's have been carried out by Hatch and its associated subconsultants - RSW of Montreal, Statnett of Oslo, and Transgrid of Winnipeg. The program has been managed from Hatch's office in St. John's using the company's project management tools and a project services team that has liaised throughout with a similar group in Hydro.

The study which is the subject of this report pertains to a review of electrode requirements for the Gull Island and Soldiers Pond converter sites which would be constructed as components of a HVdc system taking power to the island of Newfoundland. The study includes an assessment of the feasibility of a land electrode at Gull Island, alternative sea electrodes for Gull Island and Soldiers Pond, a review of electric field distribution, possible impacts and mitigating actions, and cost estimates for an installation at each site. The lead consultant on this WTO was Statnett; this report is the result of their analysis and investigations together with contributions from other members of the consortium.

The work entailed a review of prior reports pertaining to the installation of electrodes for a HVdc line from Gull Island to the island of Newfoundland, with specific reference to ground conditions and resistivity at the specific converter station sites, discussion surrounding alternative sites, a compilation of relevant information at these sites, an analysis of the electric field produced by an electrode and its potential effects, layout of concepts for electrodes at the preferred sites, and the preparation of capital cost estimates for the sites.

2. The Use of Electrodes

2.1 System Schematic

The HVdc transmission system of the Lower Churchill Project (LCP) will be multi-terminal in that the plan is for transmission from a converter station at Gull Island in Labrador to stations at Soldiers Pond and another at a location in New Brunswick. A schematic of the arrangement is shown in Figure 2.1. The operating voltage for purposes of this study was assumed to be 500 kV; the optimum voltage is a subject of a separate study (DC1010). The results of this study and associated costs are dependent to a degree on the operating voltage; however, the overall conclusions are not expected to be affected by the selected voltage. A similar comment may be made about the effect of the number of cables. For this study, five cables are assumed. In the next phase of the project, the installations and costs would be firmed up and the design would proceed from that point.

Also for the purposes of this study, while the total HVdc system may encompass a line to the Maritimes, the primary focus was on electrode locations in Labrador and on the island of Newfoundland. The electrode in Labrador would be rated for a nominal 2000 A of current and the electrode near Soldiers Pond would be rated for a nominal 1200 A. The electrodes must also be able to operate in both directions; each will be capable of being anodic and cathodic. This will affect the choice of construction of the electrodes.

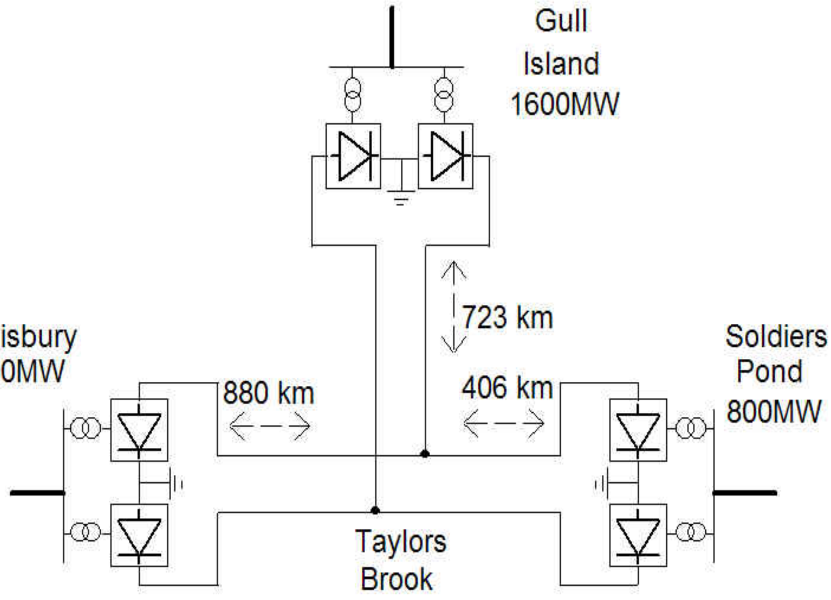

Figure 2.1 – HVdc System Schematic

Transmission Capacity

Soldiers Pond:

- Normal transmission capacity referred to AC busbar: 2 x 400 MW
- Monopolar operation:
  - 50% overload continuously; 600 MW
  - 100% overload for 10 min; 800 MW

New Brunswick:

- Normal transmission capacity referred to AC busbar: 2 x 400 MW
- No overload requirements

Electrode Current

Gull Island:

- 2000 A
- Overload for 10 min; 2400 A

Soldiers Pond:

- 1200 A
- Overload for 10 min; 1600 A

New Brunswick:

- 800 A

2.2 Types of Electrodes

The types of electrodes used in HVdc systems are described in CIGRE, 1998. This design guide loosely divides electrodes, according to their installation location, into land, shore and sea types. Of the 48 installations existing at the time of the publication, 28 were land electrodes indicating that most of the converter stations were located far from the ocean since a sea or shore location would be preferred normally. Shore electrodes are subdivided into beach and pond electrodes. The former would be located 10 to 50 m inside the waterline and the latter in a sea water filled “pond” near the shore and protected by some form of breakwater. Sea electrodes would be located further from the shore.

The Guide notes that sea and shore electrodes are generally preferred over land electrodes because (i) there is less uncertainty with respect to achieving the required grounding since resistivity is better known and (ii) overheating of the electrode is not normally a concern. And based on these criteria, sea electrodes would normally be favoured over shore electrodes. Other factors that may militate against the latter, particularly for beach installations, would be proximity to communities, accessibility by the general public, and aesthetics.

A land electrode could be shallow or deep burial. In the latter vertical or “deep hole” case, areal coverage would be minimized and better grounding may be achieved if a better conducting stratum is present at depth. Such an installation would likely be more costly than a shallow (or horizontal) burial, however, as subelectrodes would be installed in individual boreholes to depths of more than 100 m typically. A deep hole electrode was constructed as a prototype on the Swedish converter site of the Baltic Cable link, but was decommissioned due to a malfunction. It was determined that the cables inside the electrode were damaged due to a large pH drop created by a low buffer effect.

In general, it is concluded that where a sea installation is possible and economically viable, it is preferable to other types of installations.

2.3 Electrode versus Metallic Return

In a HVdc transmission system, the electrical current return path may be provided by a hard metallic conductor or through the earth by the use of ground (or sea) electrodes. In most of the existing installations worldwide (see Table 2.1), the choice has been for electrodes on the basis of economics; for most systems, using electrodes has proven to be less costly. This would be most evident in long HVdc systems in which losses in the return conductor plus the capital costs would significantly exceed the costs of electrodes, which would normally have a much smaller resistance. The difference in costs becomes even greater if the system includes submarine cables because the cost of the return cable (in the case of metallic return) will be a high percentage of the cost of the main cable. Thus in the case of the LCP, it is expected that the economic choice would be for electrodes rather than metallic return.

The relative costs of the two current return methods were addressed in a preliminary manner in an interim report of this study. The principal results of the study are shown in Tables 2.2 and 2.3. (Note that the distances in this preliminary work were nominal and are repeated here for purposes of comparing costs; the distances were later firmed up as the various studies progressed.) The losses in the various conductor and cable elements, based on a resistance of 0.05 ohm/km for the overhead conductor, 0.015 ohm/km for the subsea cable, and 0.5 ohm for the electrode resistance to remote ground, are as shown in Table 2.2. The costs of the system elements for the total arrangement are shown in Table 2.3. These are very preliminary numbers that were used for this interim analysis. At that time, the electrode locations assumed for costs comparison purposes were the Strait of Belle Isle(SOBI) for the northern (Gull Island) electrode, Conception Bay for the southern (Soldiers Pond) electrode, and a location on the coast in southeast New Brunswick (for the Maritimes electrode). In this comparison exercise, the costs of a metallic return conductor and an electrode conductor from Gull Island to SOBI are essentially the same and are not included here.

It is seen that for the entire system, the cost of a metallic return arrangement based on 1240 km of conductor would be more than 16 times the cost of an electrode arrangement (i.e. $ million versus $ million). For the Gull Island to Soldiers Pond (SP) section only, the shorter cable section across the SOBI has a much smaller effect on these costs than the cable to New Brunswick does on the overall costs, and the ratio of the costs is reduced to approximately 3 for this section. This is seen by taking the ratio of conductor lengths (680 km for SOBI to SP and 1240 km for the total system line) and the cost for the total length ($ million) plus the cost of the applicable electrodes (million) and the short sections of electrode line (million). Thus, the metallic return costs for the SOBI to SP portion only would then be approximately 680/1240 x $ million (for the conductor) + $ million (for the cable) = million versus million for the electrode costs. This cost comparison should be reviewed once all of the studies have been completed, in particular DC 1010, DC1080 and DC1130, although the overall result is not expected to change.

The conclusion from this interim study was that it would be more economic to use electrodes than a metallic return. There may be, however, related issues that would have to be addressed in the project regulatory process prior to receiving approval to proceed with electrodes; these are discussed in Section 3.

Table 2.1
List of HVdc Links and Electrodes

List of	**A. Name of HVDC scheme**	**G. Average yearly operation hours**
HVDC LINKS AND	**B. Connected areas, states, etc.**	**H. Restrictions for ground operation**
ELECTRODES	**C. Operational mode of HVDC scheme**	**I. Also metallic return**
	D. Name of electrode stations	**J. In service year**
	E. Type of electrode **F. Function of electrode**	

A	B	C	D	E	F	G	H	I	J
Baltic Cable	Sweden- Germany	Monopolar Monopolar	Smyge Cathode	Sea Sea	Anodic Cathodic	8652	No	No	1994
Cahora Bassa	Mozambique- S. Africa	Bipolar Bipolar	Songo Apollo	Land Land	Reversible Reversible	168	No	Yes	1976
Cantons-Comerford	Quebec- New Hampshire	Bipolar Bipolar	Windsor Lisbon	Land Land	Reversible Reversible				
CU	North Dakota- Minnesota	Bipolar Bipolar	Coal Creek Dickinson	Land Land	Reversible Reversible	10	Yes	Yes	1979
East- South	India	Bipolar Bipolar		Land Land	Reversible Reversible	42	Yes max.900 A	Yes	2003
Fenno-Skan	Finland- Sweden	Monopolar Monopolar	Pampriniemi Dannebo	Sea Sea	Cathodic Anodic	8700	No	No	1989
Gezhouba-Shanghai	China- China	Bipolar Bipolar	Gezhouba Nan Qiao	Land Land	Reversible Reversible				
3 Gorges - Changzhou	Chayzhou China	Bipolar Bipolar	Zhengping	Land	Reversible Reversible	2			2003
3 Gorges-Guangdong	Guangdong China	Bipolar Bipolar	Jingzhou Huizhou	Land Land	Reversible Reversible	2			2004
3 Gorges-Shanghai	China	Monopolar		Land		2			
Gotland	Sweden Mld.- Gotland Isl.	Bipolar Bipolar	Eknö Massänge	Shore Shore	Reversible Reversible	300	No	No	1983/87
GRITA	Greece Italy	Monopolar Monopolar	Corfu strait Otranto cape	Sea Sea	Anode Cathodic	Full Time	No	No	2002
GUI-GUANG	China	Bipolar		Land					
Haenam-Cheju	Korea Mld.- Cheju Isl.	Bipolar Bipolar	Haenam Cheju	Shore Shore	Reversible Reversible				
Inga-Shaba	Congo/Inga Congo/Shaba	Bipolar Bipolar	Inga Kolwezi	Land Land	Reversible Reversible				
IPP Intermountain	Utah- California	Bipolar Bipolar	Sevier Coyoto	Land Land	Reversible Reversible				
Itaipu Bipole 1	Foz do Iguacu São Paulo	Bipolar Bipolar	Foz do Iguacu Ibiúna Substation	Land Land	Reversible Reversible	220	Yes	No	1984-86

List of HVDC LINKS AND ELECTRODES	**A. Name of HVDC scheme** **B. Connected areas, states, etc.** **C. Operational mode of HVDC scheme** **D. Name of electrode stations** **E. Type of electrode** **F. Function of electrode**	**G. Average yearly operation hours** **H. Restrictions for ground operation** **I. Also metallic return** **J. In service year**

A	B	C	D	E	F	G	H	I	J
Itaipu	Foz do Iguacu	Bipolar	Foz do Iguacu	Land	Reversible	220	Yes	No	1987
Bipole 2	São Paulo	Bipolar	Ibiúna Substation	Land	Reversible				
Kontek	Denmark- Germany	Monopolar Monopolar	Bøgeskov Graal-Müritz	Sea Sea	Anodic Cathodic	8700	No	No	1996
Konti-Skan	Denmark- Sweden	Bipolar Bipolar	Sørå Risö	Shore Sea	Reversible Reversible	160	No	No	1988/2006
Moyle	Ireland - Scotland	Dual monopolar						yes, only	2002
Nelson River 1	Manitoba- Manitoba	Bipolar Bipolar	Radisson Dorsey 1	Land Land	Reversible Reversible	73	no	no	1973
Nelson River 2	Manitoba- Manitoba	Bipolar Bipolar	Henday Dorsey 2	Land Land	Reversible Reversible	103	no	no	1978
New Zealand	North Island- South Island	Bipolar Bipolar	Haywards Bog Roy	Shore Land	Reversible Reversible	2500	No	no	1965/92
Pacific Intertie	Oregon- California	Bipolar Bipolar	Rice Flats Santa Monica	Land Sea	Reversible Reversible				
Rihand-Delhi	Uttar Pradesh- Uttar Pradesh	Bipolar Bipolar	Chapki Dankaur	Land Land	Reversible Reversible	150		yes	1990
Sacoi	Sardinia- Corsica- Italy Mld.	Monopolar (T-off) Monopolar	Punta Tramontana Lucciana La Torraccia	Shore Land Sea	Anodic Reversible Cathodic	Full time			1967 / 1992
Skagerrak	Denmark- Norway	3-polar 3-polar	Lovns Grosøysøyla	Land Sea	Reversible Reversible	1000	No	No	1975/76/93
Square Butte	North Dakota- Minnesota	Bipolar Bipolar	Center Arrowhead	Land Land	Reversible Reversible	20	Yes, max 4 hours	Yes, by pole-line	1977
SWEPOL	Sweden - Poland	Monopolar						Yes, only	2000
Tian - Guang	China	Bipolar							
Vancouver Island	Vancouver Isl.- BC Mld.	Bipolar Bipolar	Boundary Bay Sansum Narrows	Shore Shore	Reversible Reversible	50	yes	yes spare cable	1969/79
Volgograd-Donbass	Russia- Ukraine	Bipolar Bipolar	Volzhaskaya Mikhailowskaya	Land Land	Reversible Reversible				

Table 2.2
Electrical Losses in HVdc System

Gull Island – Soldiers Pond					
Metallic Return (MR) (1200 A)	**Length [km]**	**Loss [MW]**	**Electrodes (1200 A)**	**Length [km]**	**Loss [MW]**
Extra conductor			Electrode line		
			Forteau Bay	10	0.72
SOBI – Soldiers Pond	680	49	Conception Bay	10	0.72
MR cable			Electrode		
SOBI (2 cables)	30	0.3	Forteau Bay		0.72
			Conception Bay		0.72
Total		**49.3**	**Total**		**2.88**

Gull Island - New Brunswick					
Metallic Return (MR) (800 A)	**Length [km]**	**Loss [MW]**	**Electrodes (800 A)**	**Length [km]**	**Loss [MW]**
Extra conductor			Electrode line		
			Forteau Bay	10	0.32
SOBI - NB	620	20	New Brunswick	10	0.32
MR cable			Electrode		
SOBI (2 cables)	30	0.1	Forteau Bay		0.32
Cabot Strait (1 cable)	460	4.4	New Brunswick		0.32
Total		**24.5**	**Total**		**1.28**

Table 2.3
Comparison of Costs for Metallic Return and Sea Electrodes

Metallic Return (MR)	**Length [km]**	**Mill CAD**	**Electrodes**	**Length [km]**	**Mill CAD**
			Electrode line		
Extra conductor	1240	31	Forteau Bay	10	0.8
			Conception Bay	10	0.8
			New Brunswick	10	0.8
Extra MR cable			Electrode		
SOBI	33	48	Forteau Bay		10
Cabot Strait	463	350	Conception Bay		8
			New Brunswick		6
Total		**429**	**Total**		**26.4**

2.4 Frequency of Operation of Electrodes

During normal bipolar operation, the electrode lines will carry small unbalance currents between the poles more or less continuously. (These currents would be too small to cause any electric field effects.) Otherwise, unlike a monopolar system in which the electrodes would be in continuous operation with the full current rating, the LCP system would require the use of the electrodes to provide a return path for the full current only in certain circumstances.

In a bipolar system, a metallic return transfer scheme can be implemented to minimize the need to operate monopolar with ground or sea return when one pole is unavailable. The metallic return transfer scheme takes advantage of the fact that when one pole is unavailable due to converter maintenance or a fault within the converters, the de-energized pole conductor can be used as a metallic return conductor. A metallic return transfer switching scheme is used to automatically implement the metallic return configuration following blocking of the converters in the de-energized pole. The switching scheme basically disconnects the conductor from the high voltage end of the de-energized pole and reconnects it to the neutral point located between the two poles. The electrode line at one of the stations is then opened to force the dc current to flow through the conductor now connected for operation as a metallic return. For the LCP system, use of the de-energized pole as a metallic return is only possible if the converters in the de-energized pole at all three stations are blocked; therefore, this cannot be used in the case where the converter in only one station is unavailable.

Of all of the events that would require the operation of the electrodes, the most severe of these would be the loss of a subsea cable in the Strait of Belle Isle. The potential events related to cable failures are as follows (assuming four cables plus a spare with three cables along one route and two along another):

- If only one cable of one pole is damaged, the spare can be used in place of the single damaged cable and the need for electrode return is limited to the time required to get the spare cable connected in place of the damaged one. The time required to do this will depend on the system arrangement. The switchover would likely require manual intervention at the cable termination sites since an automatic switch configuration would be extremely complicated given the number of possibilities.
- If both cables of one pole are damaged, then the spare cable will not provide full current rating and it may be necessary to operate the poles in an unbalanced mode with the difference in currents between the two poles flowing in the electrodes. In theory, this would limit the electrode current to a maximum of 50 per cent of the rated current as the single spare cable used in place of the two damaged ones would be rated for 50 per cent current carrying capability (or more). The outage time would be dictated by the time it takes to get one of the damaged cables repaired to regain service with two cables per pole.
- If damage occurs to all three cables laid in one route there will be no spare cable and continuous full dc current will be required in the electrodes. The two cables in the other route could be used in one of two ways: either to provide full current carrying capability in one pole and use the electrodes for return, or to operate at a de-rated current level by using one cable per pole and run in a balanced mode. The latter mode would avoid the need for electrode return.

Other events that could lead to the use of the electrodes are those related to failures at the converter stations and in the overland transmission system. Faults within the converter stations or Island ac network that would require electrode return are as follows:

- dc overhead line faults which should be cleared automatically and restarted so this is a very short term electrode return (in order of hundreds of milliseconds).
- Outage of converter equipment either scheduled or forced which causes loss of a converter in one pole of either of the converter stations. Of most concern is the loss of a converter transformer. The impact can be minimized by having a spare unit on site either as a hot standby or one which can be moved into place relatively quickly. This can minimize the time needed with electrode return to the order of days.

Other dc equipment which can result in prolonged outages (i.e. more than ms) of one converter include the valves themselves, smoothing reactors, and control and protection equipment. The duration of the resultant outage and the time required to operate in electrode return is then determined by the spares kept on hand and the availability of those spares.

- Loss of a dc line caused by conductor or tower failure at any point along the line. Outage reports were reviewed for HVdc systems in North America to gain an appreciation of the potential duration of outages for the line from Gull Island to Soldiers Pond. It was determined that very few records exist of HVdc transmission failures that would cause the initiation of electrode use. More data are available of ac transmission systems, and an extrapolation was made from these records using relative lengths of transmission line. It was thus estimated that the line could experience failures amounting to a few tens of hours annually.

Of all of these events, the physical loss of a cable in the Strait of Belle Isle through breakage would result in the longest period of operation of the electrodes. Such a loss could result from contact with an iceberg, ship's anchor or fishing gear. The cable would have to be trenched in to a depth to avoid icebergs in water of less than a certain depth. For deeper water beyond the draft of icebergs but in which ships might anchor, rock protection would have to be provided. The probability of contacting or damaging a cable should thus be very low. If a cable were damaged and removed from the system, the time to reinstate could be a year or more depending on the time of failure, site accessibility, weather conditions, and availability of cable laying/repair vessels. It is this replacement period that is used in this study when analyzing potential locations for the electrodes, the most significant parameters being the extent and intensity of the electric fields produced by the electrodes and the potential effects on various installations.

2.5 Location of Electrodes

In general, the locating of electrode stations should consider the following:

- Ownership, if applicable, of the area, and the matter of obtaining permission to establish and operate the electrode station at the intended site, including the use of land for shore-based installations in the case of a sea electrode.

- Consideration of potential conflicting activities such as shipping or boating activities in the case of sea electrodes.
- Potential electric field effects on converter station installations as well as metallic objects such as pipelines, cables, and other infrastructure.
- The characteristics of the site with respect to resistivity, moisture content, thermal conductivity, water exchange, and water depth.
- Potential influences on the marine environment, in the case of sea electrodes.
- Cost considerations for alternative locations.

Previous studies (Teshmont, 1998) of an HVdc link to the island of Newfoundland from a development on the Lower Churchill River briefly addressed the locations and costs of electrodes at Gull Island and Soldiers Pond, where the converter stations would be located. The report concluded that the soil resistivity in the vicinity of both sites would be too high for a ground electrode and a location in the sea would be required. No actual resistivity measurements for electrode installation had been made at these locations up to that time; however, measurements were made during the 2007 field program conducted by Hydro. The results of investigations at both the Gull Island and Soldiers Pond sites are attached as Appendix A. It is seen that measurements were made to a depth of 38 m at Gull Island and 29 m at Soldiers Pond. While measurements at greater depths would be needed for a categorical determination of the quality of electrode grounding, the data do suggest that appropriate grounding would be unlikely. Also, the information available on the regional geology supports this belief. Moreover, as will become evident in this report, locating the electrodes in the vicinity of the converter stations is not advisable because of the potential electric field effects on converter equipment that could lead to high costs for mitigating measures.

Given that the electrodes would have to be located in a body of water, potential locations for the Gull Island site that were initially considered were Goose Bay, Lake Melville proper and Groswater Bay. Later, as noted in the previously referenced Interim Report, a location in the SOBI was also considered. Lake Melville and Groswater Bay were referred to in the Teshmont report, but no analysis was provided to support either location. The grounding that can be achieved is related in the first instance to the resistivity of the water body surrounding the electrode; the higher the salinity, the less the resistivity so it is intuitive that of the three locations, Groswater Bay would provide the lowest resitivity since both Goose Bay and Lake Melville, although being influenced by tides, would be expected to have lower salinities due to fresh water inflow, particularly from the Churchill River.

A review of the literature on the oceanography of Lake Melville (Cardoso and de Young, 2002) indicates that for Goose Bay, the salinity varies from near zero ppt (parts per thousand) at the surface to 20 ppt at depths of 20 m to 45 m. In Lake Melville proper, a similar situation exists to a depth of about 20 m, after which the salinity increases to about 25 ppt to depths of 250 m. In Groswater Bay, the salinity is about 25 ppt at the surface and 30 to 32 ppt from 20 m to 120 m. (The salinity in the SOBI would be similar, as documented in DC1130; see Amec, 2007.) A review of the literature suggests that the variation of sea water resistivity over a salinity range of 20 to 30 ppt is small and hence would not significantly affect grounding capability(DeGiorgi, undated). Thus, there appears to be no advantage from a resistivity point of view in locating an electrode in Groswater Bay. Additionally, the physical environment for installation and maintenance of an electrode there would detract from the location; access during winter could be difficult since the area could be ice-covered for much of the winter. Moreover, the cost of building a dedicated electrode line from Gull Island to Groswater Bay over a distance of some 300 km would be high. Servicing such a line would also introduce additional challenges. Thus, subject to confirmation of suitable resistivity characteristics and acceptable environmental effects, a location in Goose Bay or Lake Melville was initially considered to be more appropriate. Factors to be considered in these areas as well, however, are the potential difficulty in servicing an electrode in winter when the site would be covered by fast ice and the potential electric field effects on the converter station at Gull Island and metallic installations in the Happy Valley-Goose Bay area, which could be mitigated with distance.

An additional consideration for a location in Goose Bay or Lake Melville is the potential for sediment transport which could lead to covering of an electrode sitting on the lake bottom. This is best avoided to prevent potential overheating and build-up of electrolysis products as noted in Section 3.4. Studies of sedimentation in Goose Bay are currently being conducted as a part of the Lower Churchill project; these should be reviewed once complete. Information currently available suggests that practically all of the sediment moved by the Churchill River is deposited within Goose Bay itself although it is understood that dredging of the navigation channel in Goose Bay Narrows is required from time to time. The Kenamu River, which flows into Lake Melville beyond Goose Bay Narrows, also contributes to sediment deposits in the lake (Amec, 2008, pers. comm.).

For the Soldiers Pond converter site, a location in Conception Bay was initially considered. The oceanography of the bay is described in a paper by de Young and Sanderson (1995). Salinity is reasonably consistent at 32 to 33 ppt throughout the water column and over distance from the shore; hence, resistivity values would be favourable. Ice may be a consideration for servicing as pack ice from the open ocean may move into the bay under onshore winds in late winter. Shipping may be temporarily hampered during this time. In the event of unfavourable conditions in Conception Bay due to existing conflicting or potentially affected infrastructure, alternative sites were also considered in Bay Bulls and Witless Bay, both of which would be approximately three times the distance from the Soldiers Pond site as a location in Conception Bay, and in Trinity Bay, which would be about 60 km from Soldiers Pond.

There are other factors, however, that may preclude the use of some of these locations, and these factors are addressed in Section 3.

3. Other Issues Pertaining to Electrodes

A discussion of the current thinking with respect to environmental and other concerns surrounding the use of HVdc electrodes (and HVdc subsea cables) is provided in a paper by Faugstad, et al (2002), and much of the following presentation is based on the work for that paper. The concerns fall into the following categories:

1. Interference with electrical systems
2. Corrosion
3. Magnetic fields in the vicinity of dc and electrode cables
4. Impact on marine life of electrolysis products from sea anodes

Because of such concerns, the experience in recent years has been that it is becoming increasingly difficult to obtain permission for electrodes, most particularly with monopolar operations, but to some extent also with bipolar operations. In some cases, as a result, monopolar systems have opted for the use of a metallic return and bipolar systems have considered no backup system. This is not because of any proven ill effects, but to avoid uncertainty and delay in the approval process and the costs associated with the process.

3.1 Interference with Electric Systems

When current flows through sea and earth, an electric field is created. The magnitude and distribution will depend on the current transmitted from the electrode and the resistivity of the earth layers and sea in the area. The current from the anode may enter the grounded starpoint of a transformer leading to a constant magnetizing of the core which, superimposed on the symmetrical ac magnetizing, allows the flux to vary in an unbalanced way and possibly to cause saturation of the core. This vulnerability to dc magnetizing is different for different core types. Large monophase, and to a lesser extent, three-phase, five-legged transformers may be affected. Three-phase, three-legged transformers are not affected in the same manner and will withstand a high level of dc current excitation because the dc flux is developed only to a small degree due to the high magnetic reluctance from the top yoke to the bottom yoke.

The extent of the effect on converter and other transformers will depend on the voltage at the affected location. If the voltage is < 10 V, there appears to be no effect while voltages in the range of 30 to 100 V would definitely require mitigation measures for certain types of transformers, according to CIGRE, 1998. A first indication of a transformer saturation problem is the increased noise level caused by second order harmonics. The problem can be reduced by introducing resistances or blocking devices in the transformer neutrals; this procedure has been used, for example, by Hydro Quebec in one of its converter stations in northern Quebec. The ideal solution is to locate the electrode station far enough away from any large substation, including the converter stations, as long as the required grounding can be achieved for a cost that is less than the electric field mitigating measures.

3.2 Corrosion

Steep gradients along a metallic structure caused by the electric field from the electrode current will cause corrosion where stray currents leave the structure. Both insulated and non-insulated objects may be affected. Examples of non-insulated objects are cables with a conducting layer, lead or steel armouring, against the soil or, in the case of submarine cables, against the water. Other examples are water supply pipes, buried tanks and sheet piling or steel piles in harbours. Depending on the orientation of the metallic object, its length and the strength of the field, current is picked up in the part closest to the anode and discharged from the part closest to the cathode.

Corrosion on buried pipes and other long metallic structures can be mitigated in different ways, such as adding more material to sacrificial anodes or introducing insulating joints, impressed current or cathodic protection systems.

3.3 Magnetic Field Effects

Magnetic field effects in the sea are not related to the electrode itself but to the main HVdc subsea cable and the electrode cable. Any such effect is noticed over only a short distance from the cables, however, as the magnetic field due to a current of 1000 A in a cable corresponds to the natural field of the earth at a distance of 12 m. Compass deviation is thus possible in such instances but likely for only shallow areas and harbours. Nonetheless, in some cases in Europe, the potential or perceived effects have required installation arrangements of the electrode and main subsea cables to accommodate naval authority requirements to limit compass deviation. Other concerns in Europe pertain to potential effects on eel migration; however, tests have shown these concerns to be unfounded.

3.4 Electrolysis Products at Sea Anodes

At the anode surface where the current leaves the electrode, an electrochemical oxidation reaction takes place, and oxygen and chlorine are formed. Chlorine is unstable in seawater, and reacts with water molecules forming hypochlorous acid, and in secondary reactions, hypochlorite, chloride, hypobromite, and bromide may be formed. Chloride and bromide are natural compounds of seawater and are considered harmless. Hypochlorite and hypobromite can lead to the formation of chloroform and bromoform, which are toxic; however, bromoform is the dominating organic halogen in natural seawater, being produced by algae; and a short distance away from the electrode, its concentration would be similar to natural levels.

The chlorine selectivity (the part of the current resulting in the formation of chlorine) increases with

- low water temperature;
- high salinity;
- low pH (reflecting low seawater exchange); and
- high current density.

During the detailed design phase, these elements are taken into consideration to achieve an acceptable design from an environmental point of view.

3.5 Experience from Other Projects

Of the HVdc links listed previously in Table 2.1, thirteen (13) have sea or shore electrodes. At least four of these HVdc links have continuous monopolar operation using electrodes; Baltic Cable, FennoSkan, Kontek and GRITA, all with subsea cables and sea electrodes. The first three (in Scandinavia) have experienced corrosion problems on pipeline installations that had to be mitigated, but none of them have experienced negative effects on marine flora or fauna.

The following links use a metallic return, for a variety of reasons, as noted.

Moyle Interconnector Ireland – Scotland
This has a rather short subsea cable (55 km) and was originally planned with electrodes. The decision to go with metallic return was mainly based on the need to reduce compass deviation and on the proximity of pipelines in the area. In 2002, the link commissioned two monopolar systems and was the first to make use of the special concentric cable concept (supplied by Nexans). This concentric cable would not be an option for a 1600 MW HVdc system operating at 400 kVdc and above.

Basslink, Victoria - Tasmania, Australia
This recent HVdc link has a rather long monopolar subsea cable and was originally planned with sea electrodes. Major environmental concerns for marine life were raised, but based on experiences well collected, documented and presented in licensing hearings, these concerns were allayed. The long gas pipelines in Southern Australia between Melbourne and Sydney were however affected by the electric fields and corrosion mitigation measures were proposed. The authorities accepted monopolar operation with electrodes on the condition that appropriate agreements were reached with the pipeline owners. These owners were commercial competitors of the HVdc link and were difficult to negotiate with. To avoid a delay, the project changed plans and a metallic return was adopted instead of electrodes.

NorNed kabel, Norway – the Netherlands
This 580 km, 700 MW subsea cable link is now under construction as a simplified bipole without electrodes or metallic return. It was originally planned as a monopolar link with sea electrodes in combination with another link from Norway to Germany (Viking Cable). Together they were meant to operate in a balanced mode, but the link to Germany was cancelled and full time electrode operation was needed for NorNed. During the engineering phase, it became clear that the congestion of inshore pipelines in the Netherlands required the sea electrode at this side of the NorNed cable link to be located about 60 km offshore due to the expected corrosion impact and strong compass deviation requirements. This would have led to a new offshore electrode design, high investments and operational costs for the electrode.

SwePol, Sweden - Poland
A 254 km, 600 MW, 450 kV subsea cable link commissioned in 2000 was originally planned with electrodes. To reduce project realisation time and costly environmental programs, they decided on metallic return cables. They then avoided environmental discussions on marine life and impact on military installations in the area.

The following Canadian projects use electrodes.

Cantons – Comerford in Quebec
The link from Quebec to New England has land electrodes. Early in the operation, a problem occurred with ground current into the neutral of the transformers at Radisson in Northern Quebec, and blocking devices were added.

Nelson River 1 & 2 in Manitoba
These large bipolar HVdc links from the seventies with about 900 km of overhead line and land electrodes operate in ground return mode during planned maintenance and faults, which are around 3 to 4 days a year. During ground return operation, a telephone company has experienced increased noise level on nearby overhead circuits and Manitoba Hydro try to limit ground operation. Currents have also been measured in association with cathodic protection on a pipeline, but no issues have arisen.

Vancouver Island link in BC
The link consists of an overhead line (41 km), two subsea cables (33 km), a spare cable and shore electrodes. It has been in operation since 1969 (pole 1) and 1979 (pole 2). When the link was placed into service, there were complaints from the local city government about excessive galvanic corrosion. These complaints were never substantiated, but use of the ground return was minimized once bipolar operation was possible. Monopolar operation uses a spare submarine cable as a metallic return conductor which is rated at 600A and, if required, the sea return path with shore electrodes to increase return current capability to 1800 A.

3.6 Results of Environmental Monitoring with Electrode Installations

Faugstad, et al (2007) provides a summary of the experience with environmental monitoring on sea electrode installations in Scandinavia and elsewhere, and this summary is repeated here.

At the Norwegian Skagerrak electrode, tests of seabed sediments and mussels showed no negative environmental impact. Video recordings of the Konti-Skan graphite electrodes showed that various marine organisms, such as crab and starfish, lived directly on the electrodes without any apparent disturbance. Fish close to the electrodes showed no reaction even at high electric fields.

The seabed flora and fauna near the Baltic Cable anode were studied over several years, before and after the anode installation. The organochlorine content, including bromoform in blue mussels, was analysed, and pH levels at the electrode mesh surface were measured. It was determined that the re-colonization of flora and fauna was normal, no organochlorines were detected in the mussels, and the pH level followed a normal variation for sea water.

Likewise at the Kontek anode in Denmark, the concentration of halogen compounds was measured in the sediment and mussels, and no increased levels due to the presence of the anode were detected.

Extensive monitoring studies in 1989 near the electrodes of the New Zealand HVdc link found no unacceptable environmental effects after 24 years operation.

It was concluded from these studies that there are no measurable environmental effects on marine flora and fauna in the vicinity of HVdc electrodes.

4. Electric Field Studies

A substantial part of the work in this study pertained to the analysis of electric fields at specific electrode locations. This work was done by a specialist consultant to Statnett and involved extensive 2-D and 3-D finite element analysis (FEA). Studies were carried out of sites initially in Lake Melville (near Goose Bay) and Conception Bay (as noted in Section 2.5) to determine the extent and strength of the field and the potential effect on metallic objects and electrical equipment in the vicinity of the field. These effects depend on the electrode current, the ground resistivity, the separation distance from the electrodes, the orientation with reference to the equipotential lines of the electric field, and the size (length) of the structure or object. Susceptible structures would be buried or submerged pipelines and cables, ac transmission networks and electrical transformers, steel pile wharves, and large steel storage tanks. The criteria used in the various analyses were as follows:

- nominal currents at the electrodes: 2000 A at location for Gull Island; 1200 A at location for Soldiers Pond;
- approximate electrode surface area: 500 m^2; and
- resistivities.

Material Resistivity (ohm-m)

Sea water	0.25
Fresh water	25
Limestone	50
Sandstone	20
Crystalline Basement/Granite	3000

The composition of soil layers in the substrata was obtained from Woodworth-Lynas, et al, 1992, AAPG Bulletin (Oct, 1987), Pinet and Bois (1990), and Can J of Earth Science (v.40, no. 2, 2002). Using these sources and resistivity values from other work (Statnett/Balslev, 2001; Maillol, 2001), the above values were determined for the various media. Besides the specific data in some of these sources, it is known from the general geological literature that Labrador is situated on the northwest side of the Appalachian structural front. Solid rock strata dominate from this front line up through Labrador. Newfoundland is situated on the southeast side of the front and also exhibits similar solid rock strata.

4.1 Preliminary Analysis of Electric Field Distribution

A 2-D model was initially developed for electrode locations for the Gull Island and Soldiers Pond converter sites. For the Gull Island site, a location in Lake Melville outside Goose Bay and off the Epinette Peninsula was selected (Figure 4.1). This location may be far enough away from the major river discharges to avoid sediment build-up, and the water becomes deep a short distance from the shore thus allowing an electrode to be installed in a high salinity location. Using a current of 2000 A, the deduced salinity at the location, the relevant geological characteristics of the substrata, and the configuration of the lake, it was determined that the potential at the electrode site would be 385 V and the resulting electric field distribution would lead to a potential of 85 V at the Gull Island site (Figure 4.2). According to a previous CIGRE reference (Section 3.1), this would entail mitigation measures being required at the site to prevent transformer saturation. To reduce or eliminate this effect, the electrode could be moved to a site further out in the lake with a subsequently longer electrode line to the converter site. Alternatively, the electrode could be located in the SOBI and the line mounted on the HVdc towers which would run from Gull Island to the Strait. The latter approach was recommended in the Interim Report of August, 2007, and the costs for the HVdc transmission line in Labrador were subsequently based on placing the electrode line on the HVdc towers, as reported in WTO DC1080. In this current report, additional consideration is given to these alternatives.

In the Draft Report, it was determined that for an electrode location at this Lake Melville location, the ratio of the straight-line distance between it and the converter station at Gull Island to the distance from Gull Island to the SOBI would be approximately the same as the ratio of the costs of the electrode lines in the two cases; therefore based solely on this comparison, there was no economic advantage of one site over the other. However, the potential difficulty in obtaining a new right of way from Lake Melville and the additional costs of servicing the line to that anticipated for the case of having the line mounted on the HVdc towers were thought to favour the latter approach. Additionally and of significance is the cost to mitigate any potential electric field effects at the converter station that would have to be considered in the case of having the electrode in Lake Melville. If the electrode were moved further out into the lake to reduce the electric field effects, the cost differential of the transmission lines would then favour the Strait location even more. Consequently, a new location in Forteau Bay on the Strait was selected at that time; this location would be close to the proposed terminus for the HVdc line and subsea cable (Figure 4.3). The subsequent analyses were then carried out for the northern electrode in this location. The electric field distribution at the Forteau Bay site (where the 2000 A are injected as well as at a Conception Bay site where 1200 A are collected) is shown in Figure 4.4. Here, the field is considerably lower than that in Lake Melville and the potential at the site is about 25 V. The resulting effect at the Gull Island converter station would be non-existent; however, the corrosion effect on the nearby subsea cable would have to be considered as discussed in Section 4.2.

For electrode locations near the Soldiers Pond converter station, two sites in Conception Bay and one in Trinity Bay were analyzed for electric field distribution (Figure 4.5). The highest electric field potential at these locations would be less than 15 V. Sites at Bay Bulls and Witless Bay were also initially considered in the event that unfavourable electric field conditions existed in Conception Bay. The electric field at these locations would be similar to the others. The resulting potential at the Soldiers Pond converter site would be less than 10 V and is unlikely to affect the converter transformers. (Further detail on the analysis and modeling output are contained in Appendix B.)

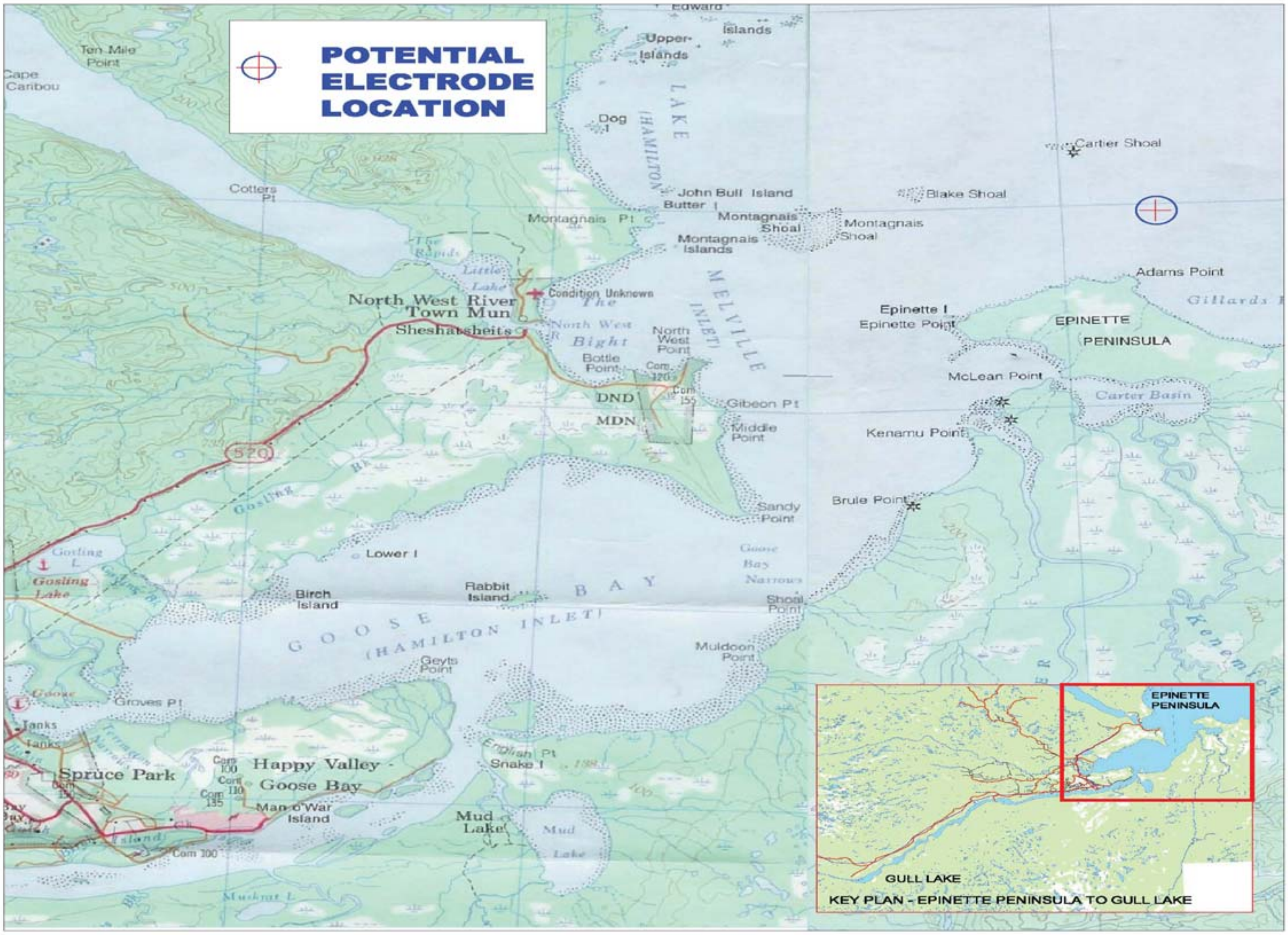

Figure 4.1 – Electrode Location in Lake Melville

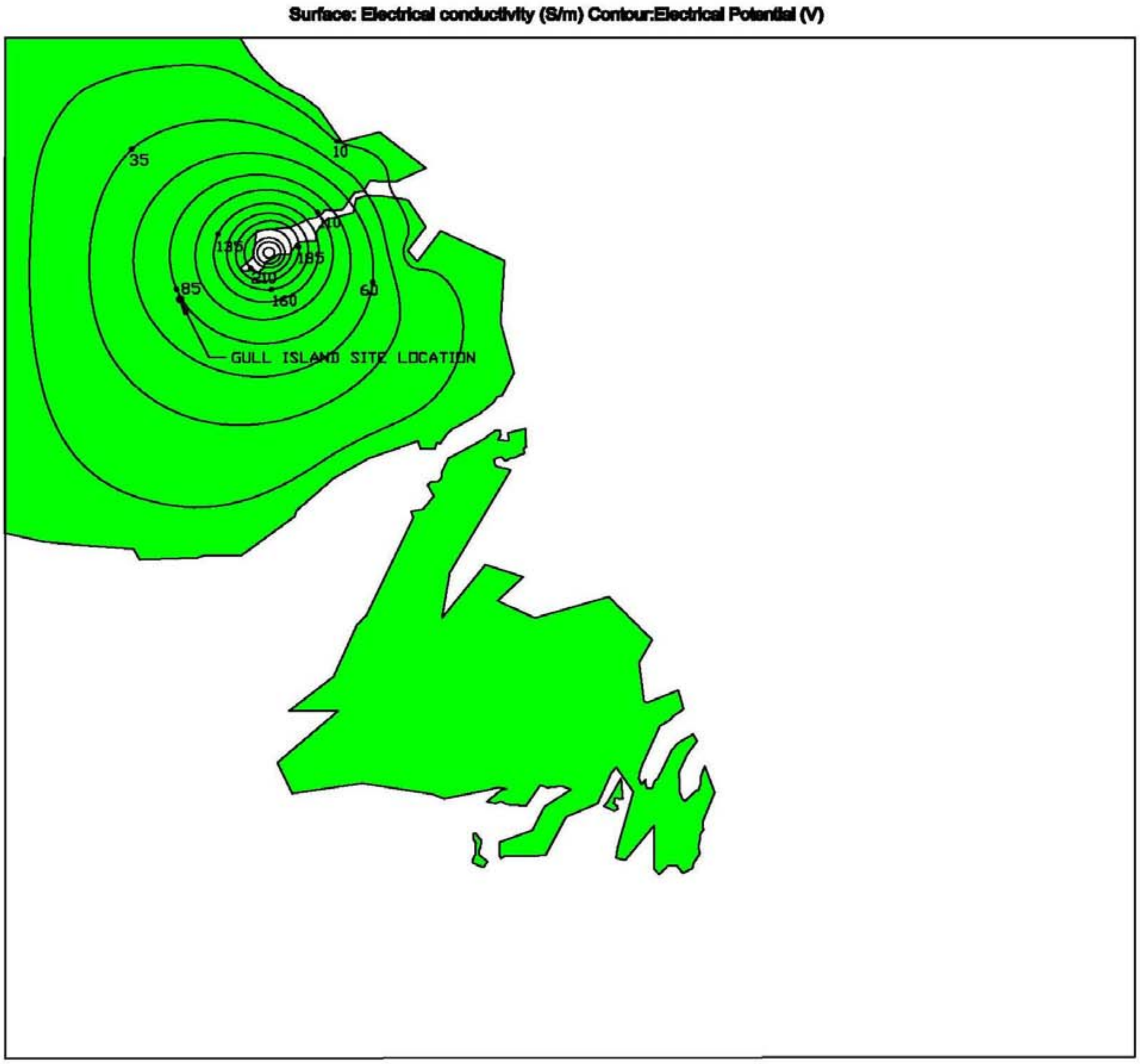

Figure 4.2 – Electric Field Distribution for Electrode in Lake Melville

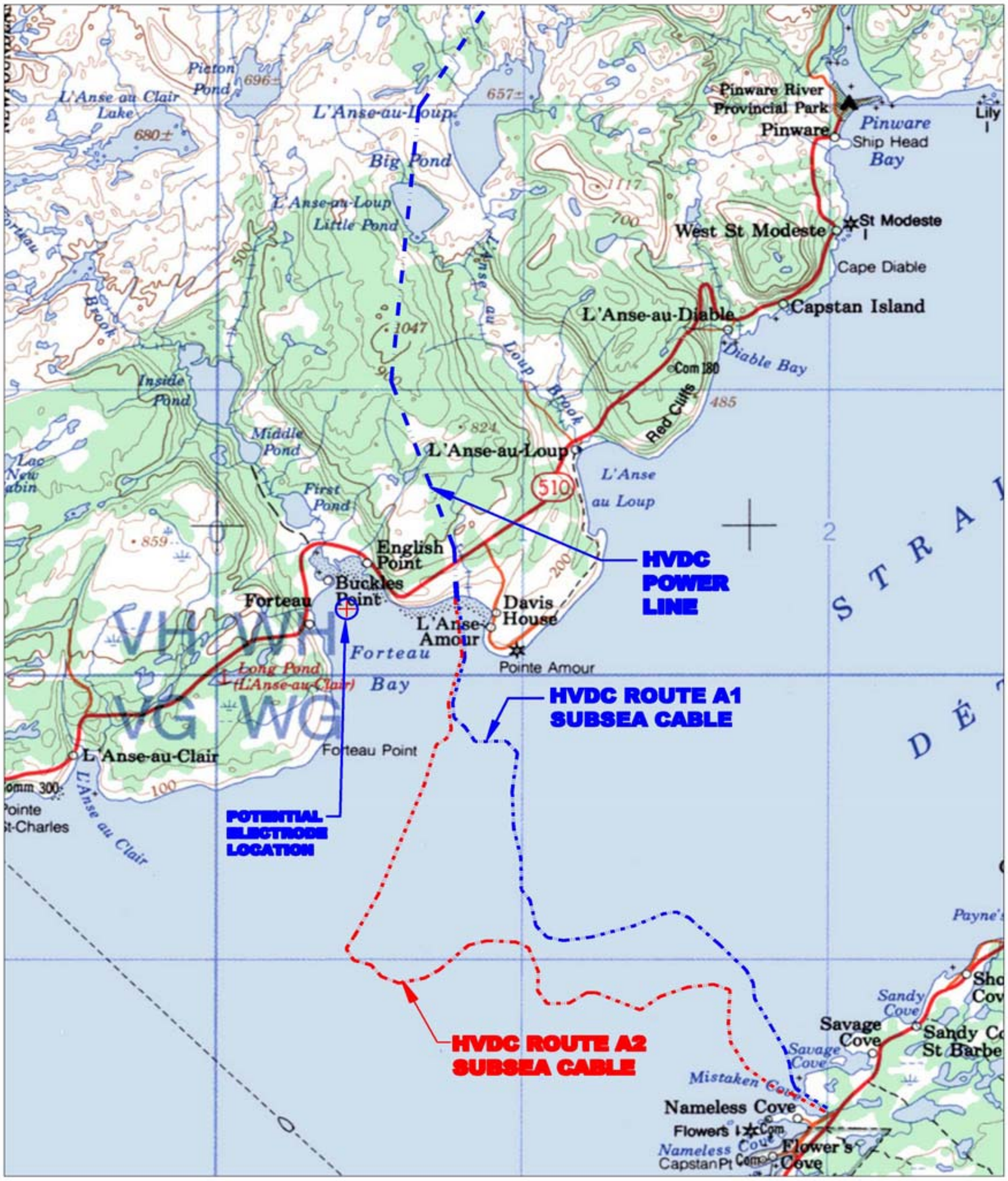

Figure 4.3 – Electrode Location in Forteau Bay

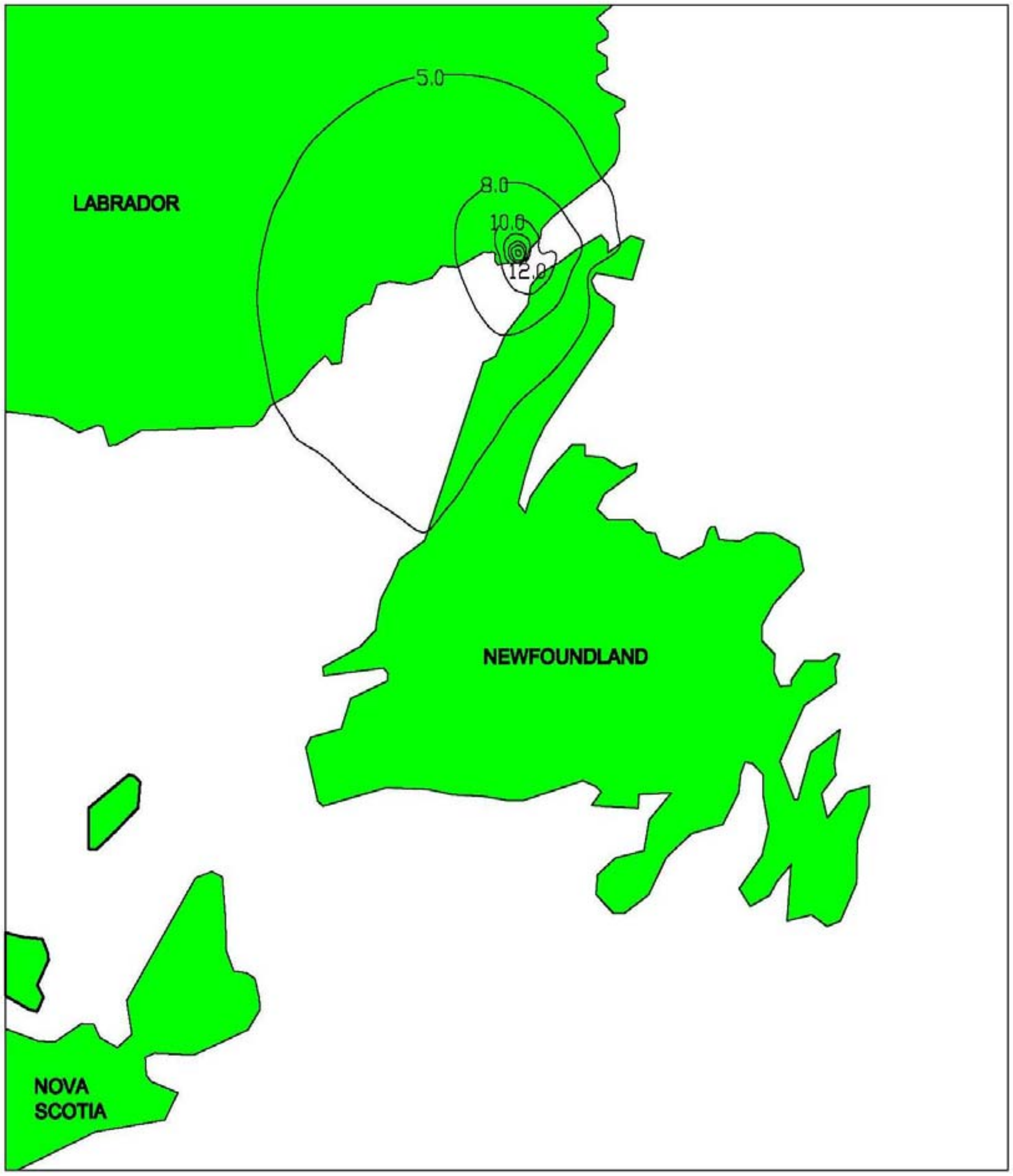

Figure 4.4 – Electric Field Distribution of Electrode in Strait of Belle Isle

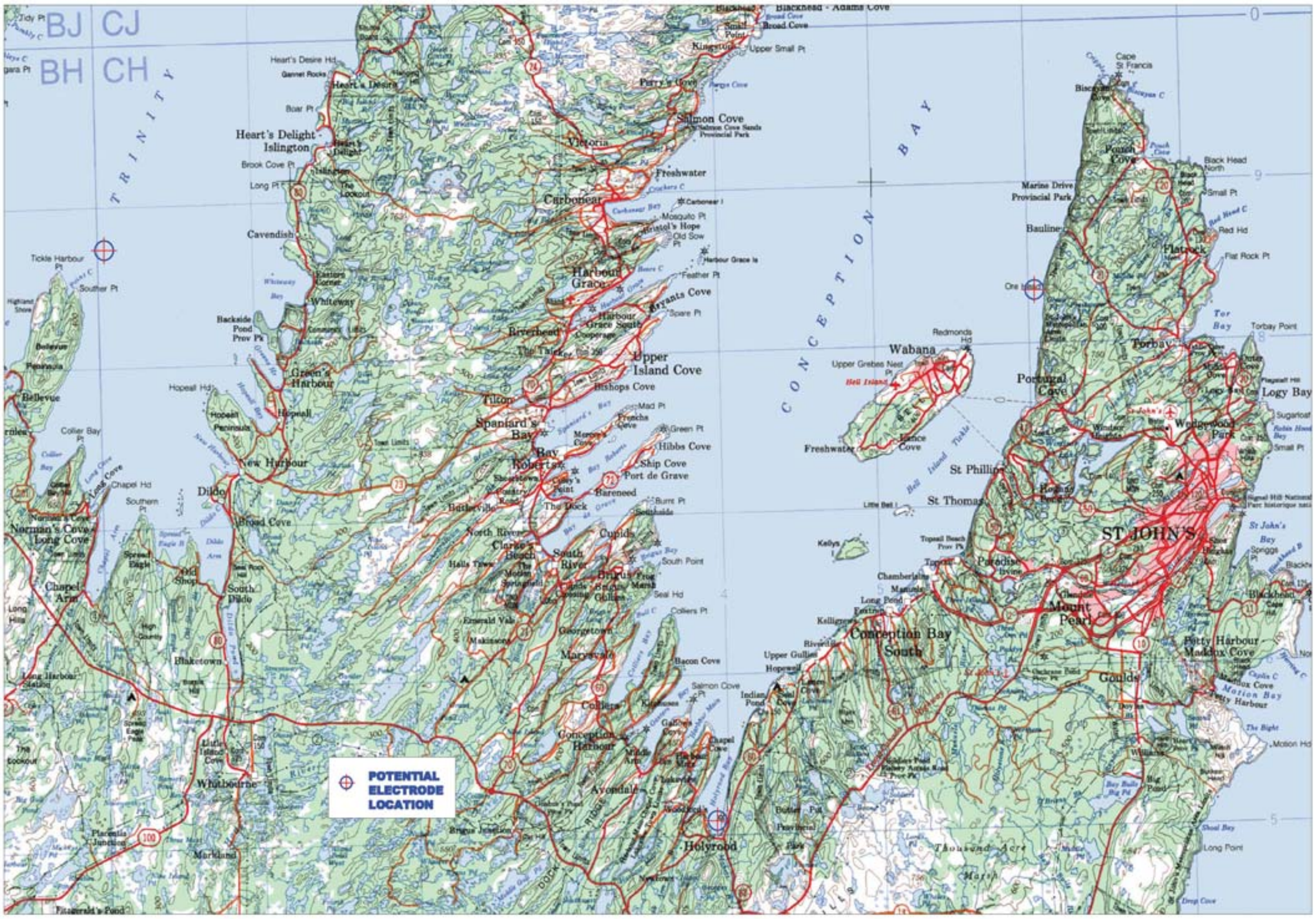

Figure 4.5 – Electrode Locations Around Avalon Peninsula

4.2 Analysis of Effects on Structures

A 3-D model of the underlying geologic strata was constructed for the entire area to encompass both anode and cathode. The modeled volume was 1200 km (north-south) by 1000 km (east-west) by 5 km deep (Figure 4.6). Computations of potential distributions and the subsequent stray current impact are based on a Cartesian co-ordinate system. The system selected is the UTM (Universal Transverse Mercator) co-ordinate system with a reference to the UTM zone 21U. Since the analysis volume stretches beyond the limits of UTM zone 21U, all co-ordinates in the neighbouring zones (used to describe the geography outside zone 21U) are converted to zone 21U co-ordinates (Figure 4.7). The geological strata within the volume indicated as a rectangle (on a spherical surface) in this figure is then divided into a finite number of discrete elements for which the electrical properties corresponding to the materials present can be defined. The geology is defined by cutting the 3-D model into 24 vertical 2-D slices (equidistant with 100 km between them), thirteen heading east-west and eleven heading north-south. In addition to indicating the geologic composition, these slices contain information on sea depth and positions of coastlines along the length of each slice.

Supplementary information on bathymetric lines is given in a format referred to as “Boolean maps”, which define the extension of domains with similar water depth. For each co-ordinate on the 24 slices and at each of the Boolean maps, the geological materials are defined by their resistivities, which allows for the compilation of a full 3-D FEA model of the geology, shore lines, water depths, etc. The model is then used to compute the surface potential distribution.

By injecting a current of 2000 A at the anode in the Strait of Belle Isle (the northern electrode) and collecting 1200 A at each of the three alternative southern cathode locations, the surface potential distribution was determined. These distributions are considered accurate outside a radius of 5 to 10 km from each electrode. Within this radius, a supplementary model was used for finer resolution and to assess the effect on structures near the electrodes. The resulting potential distribution is shown in Figure 4.8. (When the current in the electrode system is reversed, the distributed potentials will maintain their absolute values but change sign.)

4.2.1 Corrosion Risk

With the arrangement as defined, the current is intended to run from/to (for reversible operation) the electrode in the SOBI through the conductive geological layers and the ocean to/from the electrode associated with the Soldiers Pond converter station. Where part of the current, however, runs in metallic structures such as pipelines and cable sheaths, it is defined as stray current. At locations where there is a significant stray current entry to a structure, the surface may become excessively negatively (cathodically) polarized. This can initiate hydrogen production and the uptake of hydrogen into the metal surface, causing a risk of hydrogen induced cracking. Where a current leaves the metal surface of a structure, the surface will experience a positive (anodic) polarization, and the surface will experience an increased corrosion rate. Such an effect can be mitigated by the installation of cathodic protection. Also on land, buried pipelines and cable sheaths may experience corrosion which can be mitigated by cathodic protection and by reducing the length of the influenced structure by means of isolating devices.

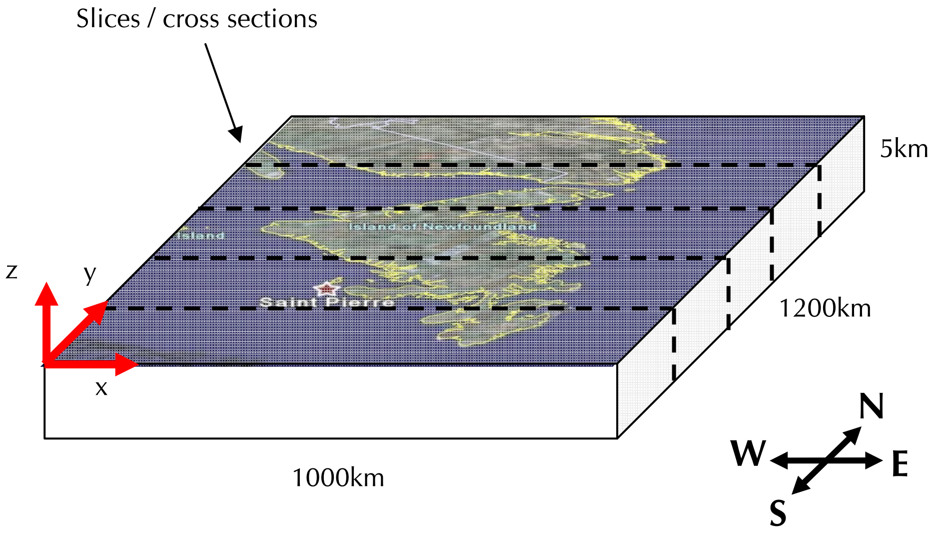

Figure 4.6 – 3D Model of Underlying Strata in Vicinity of the Proposed HVdc Electrodes

Figure 4.7 – UTM Zones

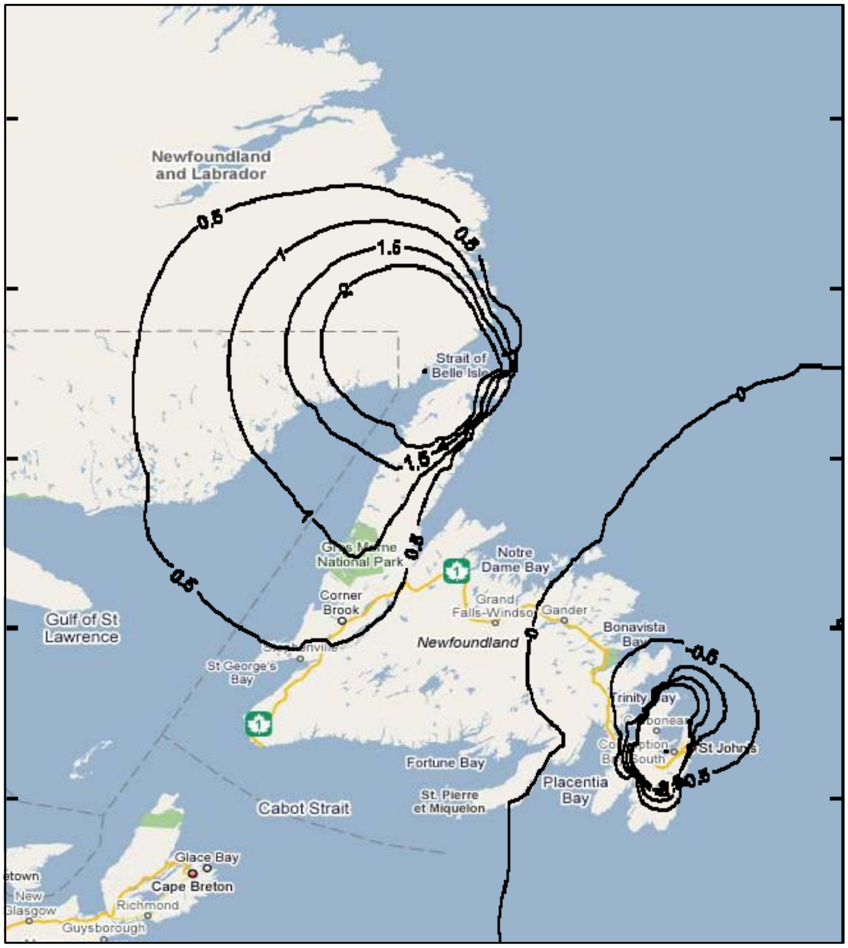

Figure 4.8 – Potential distribution by 2,000A injected at the electrode in Forteau Bay and collected at the electrode in Conception Bay. The equipotential lines are drawn in steps of 0.5V

The calculation of stray current in susceptible structures was done by applying a 3-D finite element model in steps of 100 m to determine the electric potential distribution along the length of the structures, in conjunction with geometry and material properties. An equivalent circuit was then established for calculating the current entering and leaving each of the 100 m sections. Once the current distribution was computed, the type of metal determined the rate of corrosion for each of these sections.

In the case of an electrode in Conception Bay, the structures of potential concern with respect to corrosion are the pipeline from the dock to the storage tanks, the dock piling and tanks associated with the Holyrood Thermal Generating Station, and telecommunications and power cables on the seabed in the bay. Although the hydrographic chart shows several transatlantic telecommunication cables, it was determined that these have been out of operation for many years. The relevant cables are the telecommunications and power cables running to Bell Island. To determine the degree of potential corrosion that could result, the analysis was applied to the power cable. The power cable specification was obtained from Newfoundland Power, and this information was used in the analysis to determine the potential rate of corrosion of the cable sheath (Appendix C).

In the analysis, the electrode was initially located at the bottom of Conception Bay, and using a continuous current of 2000 A injected at the electrode in Forteau Bay, the resulting potential distribution, current distribution, and steel depletion rate for the power cable sheath were determined. These are shown in Figure 4.9. By integrating the depletion rate over the length of the cable, the removal mass in one year was calculated to be approximately 0.3 kg. It is important to realize that this is based on the continuous operation of the electrodes for a full year. This would be an extreme case which would only apply if damage to the cables across the Strait of Belle caused the HVdc line to operate in monopolar mode while repairs were effected over a 12- month period. Even so, the removal of such a small amount of metal from the cable sheath, particularly since it would be distributed in some fashion over the cable, would represent a minute percentage of the total weight of the sheath.

The analysis was repeated for two additional electrode locations- one to the north of Bell Island and the other towards the bottom of Trinity Bay. In the first of these, the resulting depletion rate decreased by about one-third and in the second, the rate was reduced to essentially zero. If it is concluded at a future stage that no corrosion of the cable can be tolerated, it is estimated that cathodic protection can be applied for around $20,000.

Given the magnitude of the corrosion effect on the power cable, it is anticipated that the corrosion effect on metallic structures at the thermal generating plant would likely be very small. In the case of the pipeline from the dock to the storage tanks, any stray current would find a route into and out of the pipe by way of the pipe supports. This would not cause corrosion of the pipe but may affect the supports. While this may require further investigation in the next phase of the project, given the accessibility of these structures, it is expected that mitigating measures could be readily applied, if necessary.

4.2.2 Effect on Subsea Cable

A part of the analysis described above addressed the potential corrosion effect of an electrode in Forteau Bay on the subsea cable that would cross the Strait of Belle Isle in the same area. For the purposes of this analysis, the location at which the overhead HVdc line connects with the subsea cable is assumed to be as shown in Figure 4.3, which is based on the transmission corridor study (DC1050). The two surveyed routes for the subsea cable and the location assumed for the electrode are also shown. The electrode lines would run to the north side of the bay and then to a HVdc tower. The distance from the electrode to the closest part of the subsea cable would be about 4 km.

The calculations were based on cable steel armouring, consisting of 100 single wires of 7 mm diameter each and a nominal outer cable diameter of 250 mm. A "poor" coating of wrapped polypropylene yarn and bitumen, not watertight, enables a more or less continuous stray current flow into and out of the cable surface. The outer diameter of the armour is 250 mm and the specific coating resistivity is 100 ohm-m^2. Using the nominal 2000 A injected into the electrode results in a depletion rate of approximately 200 kg/y. If the electrode operates continuously for a year, sufficient cathodic protection would be required to prevent the loss of 200 kg of armour. This can be accomplished by integrating a layer of aluminum wires into the armour during the manufacture of the cable. The cost for this protection is estimated to be approximately $ million.

The experience in Europe suggests that if the electrode and cable are separated by 10 km or more, the corrosion effect should be negligible (CIGRE, 1998); in fact, there are several installations in which the separation is less. The specific conditions pertaining to these installations would need to be compared with the current case to better appreciate the likelihood of corrosion. In order to achieve a separation of at least 10 km, the electrode would have to be moved to another bay, the next closest bays being L'Anse au Loup, which is about 7 km to the north, and L'Anse au Clair, which is about 10 km to the south. An electrode in L'Anse au Loup would require a line of about 6 km to reach the HVdc line and one in L'Anse au Clair would require a line of about 15 km. A greater degree of certainty with respect to corrosion effects would be achieved by locating the electrode in Pinware Bay, which is about 20 km north of Forteau Bay. The electrode line to the main HVdc corridor would then be 15 km.

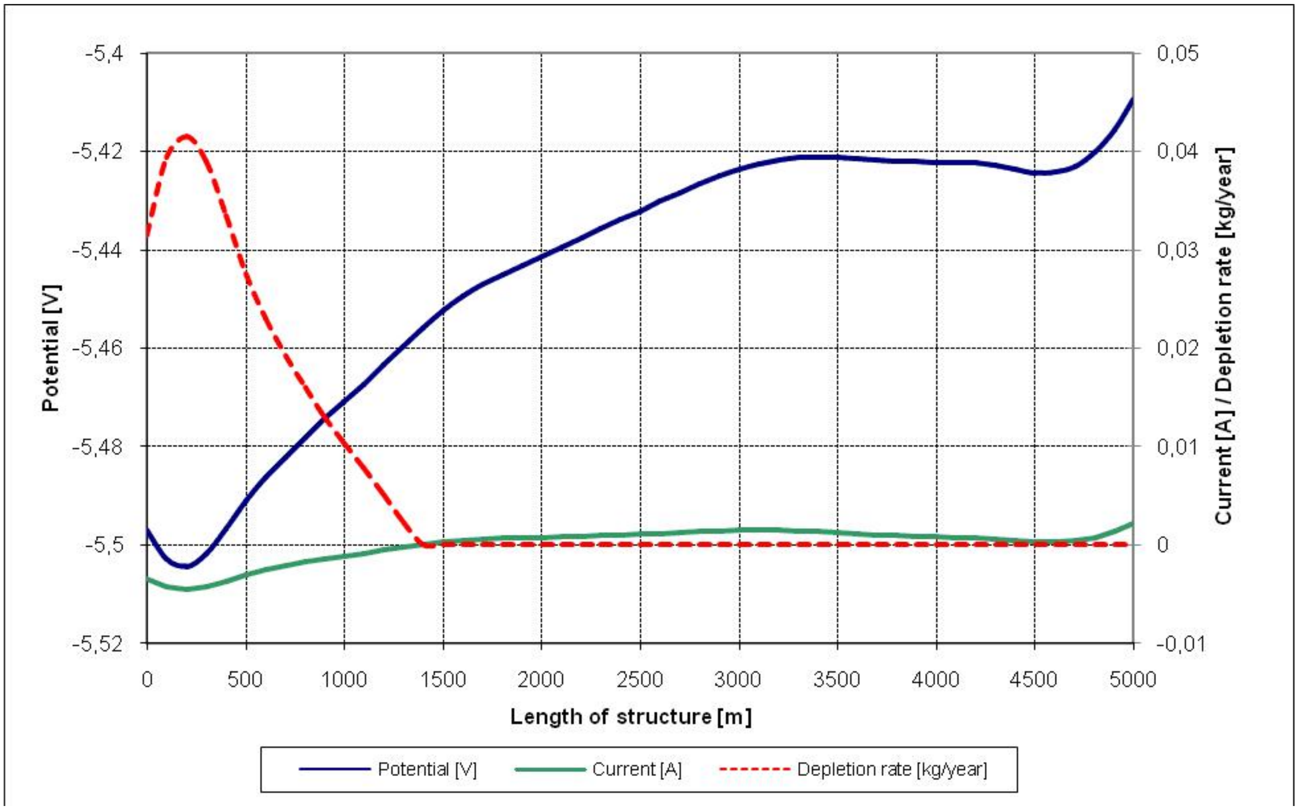

Figure 4.9 – Potential Distribution, Current Distribution and Steel Depletion Rate for Power Cable to Bell Island

4.3 Discussion of Results

As is evident from the preceding sections, locating an electrode is a matter of weighing a number of sometimes conflicting parameters and issues in an effort to find the most cost effective solution with an acceptable level of risk. In the case of the southern electrode, the matter is relatively straightforward as the electric field analysis suggests that the electrode for Soldiers Pond can be located in Conception Bay without causing electric field effects to existing installations that would be unacceptable or prohibitively expensive to mitigate. This electrode can be located within a km or so of the thermal generating station as long as it is away from the area frequented by vessels, and the electrode line could then follow the existing 230-kV line ROW to Soldiers Pond.

In the case of the northern electrode, there are a number of factors to address, and the choice of location is not as clear cut. When Forteau Bay was suggested as a location for this electrode, following the preliminary electric field analysis, the choice appeared to be a good one in that the cost of an electrode line that was mounted on the HVdc towers was thought to be less than that of a new line and ROW to Gull Island from an electrode in Lake Melville, and any electric field effect on converter transformers at Gull Island would be eliminated. Through additional analysis, however, it has become evident that there is a potential for corrosion of the subsea cable armour with the electrode being as little as 4 km from the cable in Forteau Bay; this distance increases of course as the cable extends into the Strait. In the previous section, it was suggested that a location in Pinware Bay would result in negligible corrosion of the cable, and from this viewpoint it would be a better location than Forteau Bay, although there would be an associated cost increase for the longer overland electrode line.

An additional factor to consider for an installation in the bays along the Strait of Belle Isle is the potential encroachment of icebergs into the bays and contact with the electrode installation. To prevent any such contact, the electrode could be placed in a dredged depression ("glory hole" in offshore oil industry terminology), and the electrode lines placed in trenches. Depending on the sea bed, such an operation may require specialized dredging equipment. An additional drawback to this installation is that the electrode could be covered with sediment over time which could lead to overheating and poor water flow over the electrode which, in turn, would inhibit the dilution and dispersion of electrolysis products. This would be quite likely in Pinware Bay since the Pinware River flows into the bay. Given these possibilities, it would be prudent to locate the electrode in a bay in which icebergs are known not to enter. While, at this stage, it is not possible to definitively say whether any of the bays along the Strait fall into this category, it is very likely that Pinware Bay, L'Anse au Loup and Forteau Bay do not, given that they are relatively open to the flow of water through the Strait from the northeast. L'Anse au Clair, on the other hand, is configured in a way that suggests that it may not experience iceberg encroachment. Subject to acquiring confirmatory information (likely through local residents), this bay appears to be the best choice for the installation of the electrode, if indeed it is concluded that the electrode should be located along the Strait at all. If it is determined that icebergs do drift into L'Anse au Clair, protection of the electrode could be provided by constructing a rockfill berm from shore.

The primary uncertainties associated with a location in Lake Melville versus one in the Strait of Belle Isle relate to the electric field mitigating measures for a location in Lake Melville and the presence of icebergs for a location in the Strait. The former are controllable and should be a one-time occurrence (if they are required at all) whereas the latter uncertainty would always exist. The comparative features of each location may be listed as shown below:

Lake Melville Location	Strait of Belle Isle Location
- higher resistivity due to lower salinity water leading to greater electric field; could possibly reduce by moving into deeper, more saline water - greater distance from converter station to minimize electric field effect implies longer transmission line - new ROW required with potential attendant environmental issues - area would be ice covered for six months - could locate in area of no shipping - site would be remote from communities - physical environment (waves, currents) is benign; the site would be protected	- corrosion effects on subsea cable with electrode in Forteau Bay; potentially higher mitigating costs than for converter transformers - could minimize/eliminate cable corrosion by moving to another bay - potential iceberg encroachment in all bays with lowest probability likely in L'Anse au Clair - would need glory hole or protective berm if icebergs can't be avoided; however, sediment transport could be a problem with a glory hole - short section of new transmission line required from electrode to HVdc line - area would be ice covered for three to four months - more shipping activity than in Lake Melville - site would be close to a community - site would be exposed to harsh marine environment

4.4 Additional Comparative Cost Analysis of Northern Electrode Location

The comparative cost analysis described in Section 4.1 was repeated following the receipt of more detailed cost information from DC1010 and DC1080 for the electrode lines, after the submission of the DC1110 Draft Report. It was determined from the costing exercise in these WTO's that the incremental cost of installing two electrode lines (rather than one for reliability purposes) on the HVDC towers is $ per km due to the additional conductor as well as the extra tower costs to accommodate the resulting additional loads. Similarly, the cost of a dedicated electode line using steel towers and two conductors would be increased to $ per km. The incremental cost of the electrode line mounted on the HVdc towers from Gull Island to the SOBI over a distance of 407 km would thus be 407 km x / km = $ million whereas the cost of a separate electrode line over this distance would be million.

The cost of the line from an electrode located in Lake Melville could be reduced by running the line south to meet the HVdc line and then back to Gull Island on the HVdc towers rather than running a separate line all the way back to Gull Island. The straight-line distance south from Gillards Bight (near the Epinette Peninsula) to the closest point on the HVdc line is approximately 95 km and the distance west is approximately 75 km. At per km and per km respectively, the cost of this line would be million or about $ million less than a line to the SOBI. Given the level of accuracy in the route from the electrode location south to the HVdc corridor, it maybe concluded that these costs are similar since the difference is less than 10 per cent. To obtain the same level of accuracy in the two estimates, it would be necessary to map out the corridor south from the electrode location.

The cost of an electrode installation in the SOBI would be increased by the cost of the short section of line from the electrode to the HVdc line plus the cost of any protection measures required. These are estimated in Section 6 to be approximately million in total.This cost difference would be partially offset by the cost of any measures that may be required to mitigate potential electric field effects from an electrode in Lake Melville. These are estimated to be approximately per transformer or million for 20 transformers. The overall difference would then be approximately million in favour of a Lake Melville location.

5. Conceptual Design of Electrode Installations

5.1 Design Criteria

Design Current

The design calculations are based on a continuous current of 2000 A injected at the Gull Island electrode and 1200 A collected at the Soldiers Pond electrode. The 800 A collected at the New Brunswick electrode is not a consideration in the design in this study.

Electrode Polarity

While the electrodes in normal operation would be anodic for the Gull Island station and cathodic for Soldiers Pond, the design allows for a reversal of current; hence both must be able to operate as anode and cathode. This influences the material of construction of the electrodes.

Seawater Resistivity

While seawater resistivity varies with salinity, over the range of salinities existing in the electrode areas, an accepted value is 0.20 ohm-m to 0.25 ohm-m.

Current Density

The current density is deduced from the voltage gradient and the conducting medium (seawater) resistivity. The generally accepted limit for the gradient on the electrode surface that may be accessible to marine life and humans, is 1.25 V/m (CIGRE, 1998). For a resistivity of 0.25 ohm-m, the current density would then be $1.25/0.25 = 5.0$ A/m^2. Because the current density affects chlorine selectivity (see Section 3.4), experience suggests a value of 4.0 A/m^2 would be more acceptable (corresponding also to a lower voltage gradient of 1.0 V/m).

5.2 Layout

The overall area of seabed required for the installations may be up to 200 m by 100 m but will depend on the size and number of elements. To obtain a uniform current distribution between elements, they should have individual cables from shore and be arranged along a predetermined semi-circular curve (Figure 5.1). The cables are bundled or enclosed within a conduit and run from the electrode to a small junction house on shore. In both electrode locations, the nearshore conduit/cables would be trenched in and protected as necessary from ice and wave action by rock armour. Additional studies will be needed prior to final design to determine how much protection will be needed. It will be important to prevent any siltation of the electrode to allow for good water exchange over the electrode elements to minimize chlorine concentration and to dilute and disperse electrolysis products. This applies to electrodes operating as anodes which, in this case, since the electrodes must be capable of reverse operation, applies to both. Non-coverage of the electrodes is also important to prevent heat build-up. These constraints are also important in determining how the electrode elements are weighted to prevent movement.

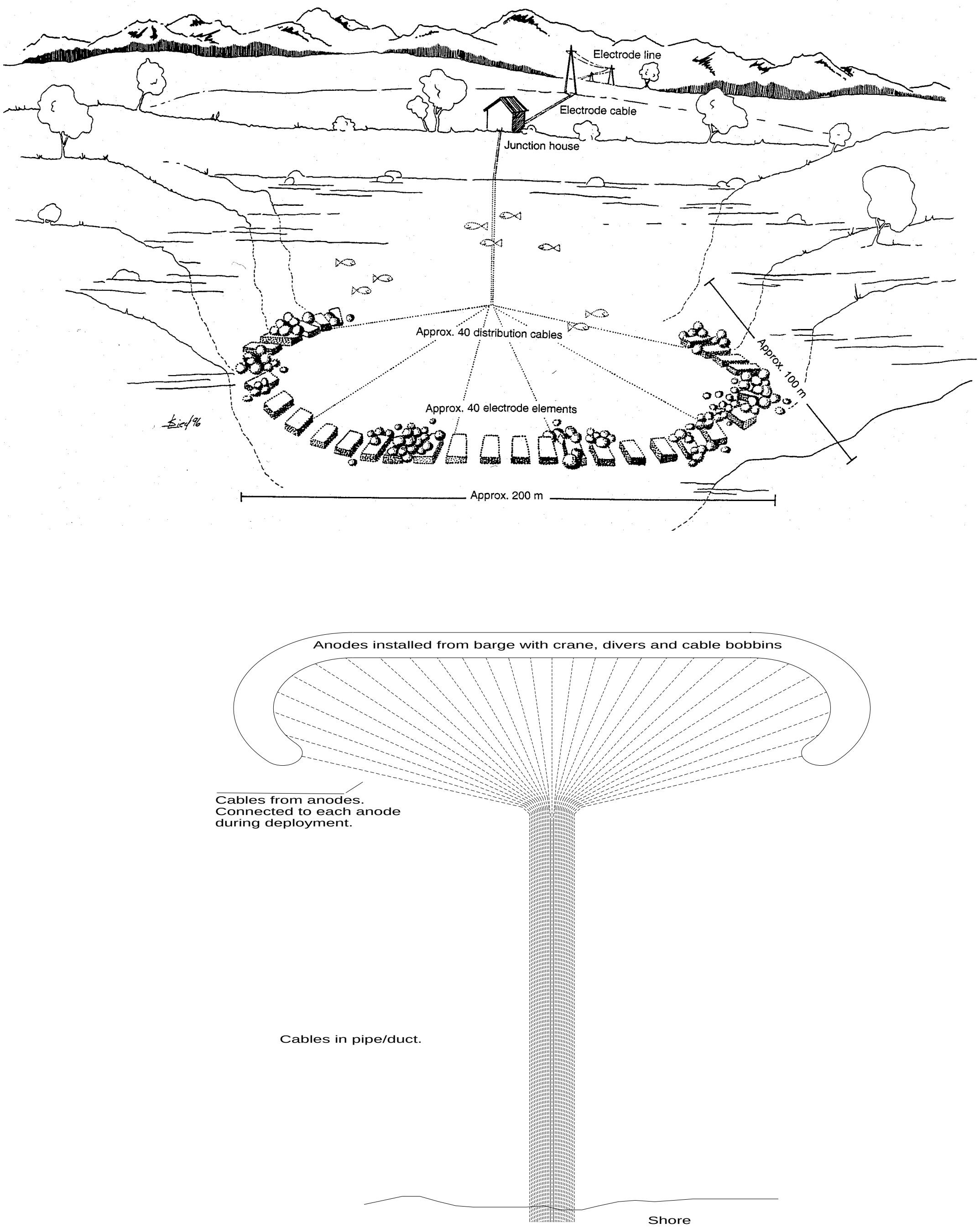

Figure 5.1 – Electrode Layout

5.3 Electrode Elements

Because the electrodes are to be capable of operating as anodes or cathodes, the material of construction is a combination of graphite and coke. Graphite/coke electrodes have been used in a number of installations including Skagerrak, Konti-Skan and Vancouver Island. A fundamental design issue with graphite/coke electrodes is, however, that because of the relatively low specific gravity (hence higher buoyant forces in water), the units need to be weighted down on the sea floor. Such ballasting tends to reduce the water flow over the electrode surface and thus higher chlorine selectivity is possible. A design which minimizes this effect and yet provides ballast is shown in Figure 5.2. The design relies on the concrete weight and stone placed within a fibre reinforced concrete enclosure to provide protection and ballast. The stone is sufficiently coarse to permit water flow over the conducting surface of the coke which is contained within a mesh. Graphite rods are encased within the coke matrix and the electrode lines are connected to these rods. The stone could be placed in non-conducting baskets (similar to gabions) for controlled placement.

The weight of each electrode element is determined by the practical lifting and installation limitations of the construction equipment, and this in turn, along with the total current injected or collected, will dictate the number of such elements. Using a weight of 20 tonnes, the area of each element would be about 3 m by 6 m. The coke conducting surface would be approximately 15 m^2. To obtain a current density of 4 A/m^2, a total of 35 elements would be required for the 2000 A electrode, and 20 would be required for the 1200 A electrode. If a separation distance of 3 m between elements is used and a ring arrangement as shown in Figure 5.1 is assumed, the areas of sea floor required would be about 200 m by 30 m for the northern electrode and 120 m by 30 m for the southern electrode.

The electrodes could be built in a local construction facility and installed using locally sourced marine equipment. The electrodes typically would require a barge or vessel with deck mounted crane. Guide wires and an ROV will be needed to secure the exact location and orientation on the seabed. The barge can be positioned with a system of wire winches and anchors or mechanically operated spuds. The electrode cables will be installed in a common pipe and buried to a depth to avoid mechanical damage from ice and shipping. A jet trencher has been used in Norway for this purpose.

There is a possibility that the system will not need to have reversible capability. While the materials for non-reversible operation could be the same as assumed here for the electrodes, some savings may be possible by using copper for the cathode. This would be determined in the preliminary engineering phase of the project.

5.4 Electrode Cables

The electrode cables run as a bundle from the electrode elements to the junction house (electrode building) on shore, a nominal distance of 500 m to 1000 m; from there two conductors run overhead to the HVdc line or converter station. The cables from the electrode elements will be of a low voltage type with an insulation level to withstand transient effects from the converters. The cable insulation must also be water resistant to avoid any dc leakage. Regulation of the current in the cables will normally be required to ensure equalization of the current density across the array of electrodes. Monitoring equipment would be installed in the electrode building for this purpose. The current distribution can be monitored by measuring voltage drops across a shunt in each cable.

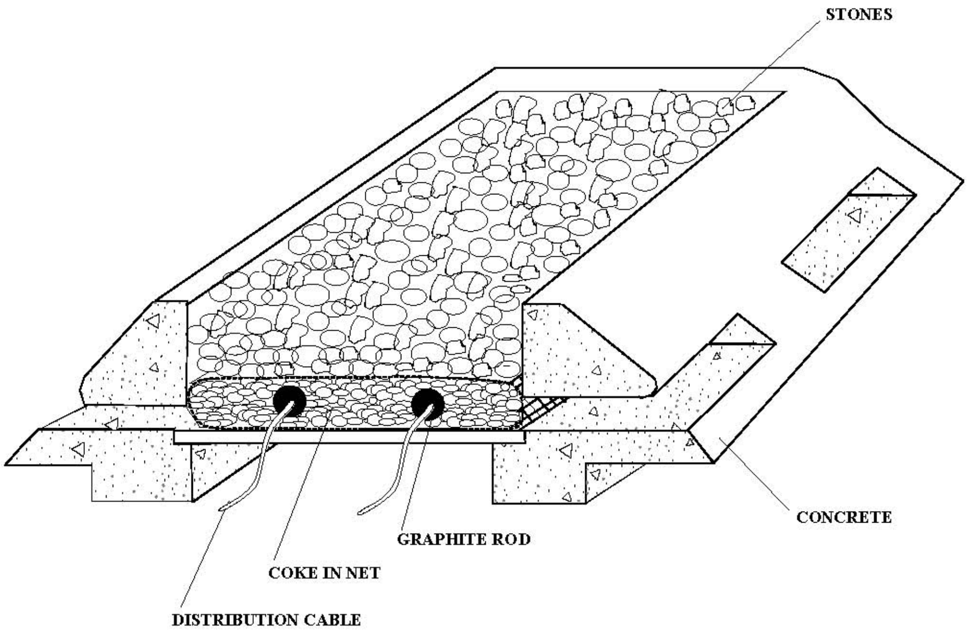

Figure 5.2 – Cross Section of Graphite / Coke Electrode Element

5.5 Electrode Overhead Line

The length of the overhead lines will be determined by the eventual locations of the electrode. For costing purposes in this study, the distance is taken to be 10 km for the southern electrode. This is the distance from a location near the thermal generating plant to the Soldiers Pond converter site. The construction of this line would be simplified if the existing ROW can be used. For the northern electrode, locations are considered in both L'Anse au Clair and Lake Melville.

6. Cost Estimate

6.1 Basis of Estimate

The estimate was based on information from other projects in Europe and from manufacturers. It is assumed that the electrode platform/enclosure would be constructed locally, the electrode conducting materials and cables would be supplied from within Canada, and the installation would be done using primarily locally available marine equipment. (A jet trencher, for example, may have to be brought from Norway.)

The contract could be a design/build or conventional EPCM (engineer, procure, and construction manage). The latter arrangement is assumed here and a nominal percentage of the construction cost is used for engineering and management. A high level of contingency is used at this stage to reflect the conceptual level of the design. The electrode contract is expected to include the installation of all equipment and materials related to the sea bed works and the cables to the electrode building. The overhead electrode line to the HVdc line or converter station could be a separate contract if desired. The cost of this line is also included here.

The northern electrode estimate is based on locating the electrode in L'Anse au Clair to minimize potential iceberg contact. The location is assumed to be on the east side of the bay in water depths (according to Chart 4470) of approximately 10 m. The cost of a protective berm is also estimated. While it may be concluded from further study that a berm is not needed for protection from icebergs, it is included here as a precautionary measure. Also, because the electrode is installed in a small bay that is used by residents of the community of L'Anse au Clair, it would be prudent to have the electrode protected and to prevent any (perceived) danger to users of the bay.

Assuming a distance to shore of 50 m, distance parallel to the shore of 200 m, average berm depth of 12 m with freeboard, top width of 8 m, and slope of 1 to 1.5, the volume of rockfill required would be approximately 95,000 m^3 for an enclosed area. Allowing for two culverts to permit an exchange of sea water over the electrode, access road, and distance to quarry of 5 km, the total berm cost would be approximately $ million. (Table D.1) It is possible that the electrode installation could be done as part of the subsea cable installation to avail of marine equipment. Alternatively, the installation could be facilitated by operating from the berm that would be constructed from shore.

The overland electrode line to the HVdc line would be about 15 km long. For a two-conductor line, the cost at $ per km would be million.

(Compared with an installation in Lake Melville, the cost difference, as noted in Section 4.4, would be equal to the cost of the berm and the electrode line minus the cost of any electric field effect mitigating measures, or approximately million - million = million, assuming that the basic electrode installation costs would be similar in both locations; this is a reasonable assumption at the current level of estimating. Without the berm, the cost difference would be about million.)

The southern electrode estimate is based on locating the electrode in Conception Bay as close as practicable to the thermal generating station for landfall purposes and running to the existing transmission line ROW. The distance to shore is nominally 0.5 km. At this stage of the project, a protective berm has not been costed for this southern location. Icebergs are not expected to be a problem, and the site would be sufficiently remote from any community to attract attention from boaters.

The estimate accuracy is considered to be order-of-magnitude or +/- 30 to 40 per cent. This corresponds to a Class 4 (Level 1) estimate in the AACE (American Association of Cost Engineers) estimate classification.

6.2 Northern Electrode Estimate

Item	Number	Unit	Unit Cost $	Total $'000
Total Estimate (excluding Owner's Cost, IDC, taxes)				18984

[1] Based on electrode being nominally 50 m from shore and trenching in all 35 cables over a length of 50 m prior to the conduit, which is also trenched in over a distance on shore of 500 m.

[2] The cost of the electrode line from Gull Island is included as part of the HVdc line cost (DC 1080).

[3] This contingency is applied to the electrode parts of the estimate. The berm and transmission line estimates have a 20% contingency built in.

6.3 Southern Electrode Estimate

Item	Number	Unit	Unit Cost $	Total $'000
Total Estimate (excluding Owner's Cost, IDC, taxes)				8323

[1] Based on a nominal distance of 500 m from shore.

7. Conclusions and Recommendations

7.1 Conclusions

The conclusions arising from the study are:

1. The use of electrodes to provide a return path through the earth for the HVdc line would be less costly than a metallic return. For the Labrador and Newfoundland sections only, a metallic return would cost at least three times the electrode arrangement, and for the entire system, the ratio would be much higher, primarily because of the long subsea portion to the Maritimes.
2. The experience in some other HVdc applications has shown that the electric field effect of electrodes has been sufficient, or has been perceived to be sufficient, to prevent the use of electrodes; however, for the current Lower Churchill application, the potential electric field effects can be reduced to acceptable levels or eliminated altogether through appropriate siting of the electrodes, or managed through mitigating measures, with associated costs.
3. The experience in other areas has also shown that the effect of electrodes on the marine environment has been negligible even with continuous operation of electrodes in monopolar mode. Nevertheless, the perceived potential for environmental effects has caused difficulty in some applications, and thus it is important to make stakeholders aware of the issues surrounding the use of electrodes in the Lower Churchill application.
4. From a review of the geological literature and the resistivity measurements made during the 2007 investigations program, it is concluded that a land electrode for either the Gull Island or Soldiers Pond converter sites would not achieve the required grounding; therefore, locations in sea water will be necessary. Locations in Lake Melville and the Strait of Belle Isle (SOBI) for the northern electrode, and in several bays around the Avalon Peninsula for the southern electrode are possible.
5. Except for the use of electrodes to carry small unbalance currents between poles in the HVdc system, usage is expected to be low and any associated effects to be small or negligible. Normally, usage would amount to at most a few tens of hours per year or a few days if major equipment replacement is required at a converter station. The longest potential period of usage would be during an extended cable repair period, which could be as much as one year or more depending on the time of year of the outage and the availability of repair equipment. It is this extended period that is assumed in the study in determining potential electric field effects. The probability of such an occurrence is not currently known; however, the installation of the subsea cables would be designed to avoid such an occurrence.
6. Under prolonged usage during this worst case scenario, the electric field from the electrodes could cause corrosion. The most severe example would be the corrosion of the subsea cable armour if the northern electrode were placed in Forteau Bay near the termination of the overland HVdc line (to limit the length of the connecting electrode line) and the subsea cable. Minor corrosion would also occur to the Bell Island subsea power cable sheathing in the case of the southern electrode being located in Conception Bay.
7. While the northern electrode could be located in another bay to avoid corrosion of the subsea cable, or mitigating measures could be applied, in general it is concluded that an electrode should only be

placed in the SOBI if contact with icebergs can be prevented. Placing the electrode in a dredged depression to avoid icebergs would likely lead to sediment coverage over time and a deterioration in electrode performance. This should be avoided. A more acceptable method would be to construct a rockfill berm around the electrode.

8. The preferred location for an electrode in the SOBI is L'Anse au Clair (to the south of Forteau Bay) due to its orientation which may prevent encroachment by icebergs. This location is also a sufficient distance from the subsea cable to avoid corrosion in the event of prolonged usage. While it may be determined that a berm is not necessary for protection against icebergs, such a berm would protect the electrode from heavy seas and boating activity as well as provide security and safety in what is a small, inhabited bay. A berm would cost approximately $ million.
9. The cost of an electrode located in L'Anse au Clair, including a protective berm and the interconnecting electrode line would be about $ million. This is approximately $ million more than one located in the southwest part of Lake Melville. The difference in cost is due to the costs of the interconnecting line from the electrode in L'Anse au Clair to the HVdc line about 15 km to the north and protective berm, the sum of which at million could be partially offset by the potential costs of mitigating electric field effects on converter transformers at an estimated million for the case of an electrode in Lake Melville.
10. The cost of an electrode line from Lake Melville to the Gull Island converter station can be minimized by connecting with the HVdc line to the south. The resulting electrode line cost is then approximately the same as the cost of mounting the electrode conductors on the HVdc towers to the SOBI for the case of an electrode in L'Anse au Clair, given the accuracy of the information on the corridor from Lake Melville to the HVdc interconnection.
11. In addition to the apparent cost advantage, an electrode located in Lake Melville would be in a more sheltered location since the marine environment is relatively benign. There is a possibility of sedimentation although the information obtained in this study suggests that it is largely confined to Goose Bay and Goose Bay Narrows areas. The site would also be remote from any community. Therefore, unless there are extenuating circumstances, a location in Lake Melville is preferred.
12. Placement of the southern electrode in Conception Bay in the general vicinity of the Holyrood Thermal Generating Station would be acceptable from an electric field effects perspective, and this location would minimize the cost of the electrode line to the Soldiers Pond converter station. No effects to the converter station transformer are anticipated given the relatively low electric field produced by the electrode. Any corrosion effects to metallic structures in the area through prolonged usage of the electrode can be mitigated at minimal cost. The approximate cost of the electrode installation, including the interconnecting electrode line, would be $ million.
13. Because the electrodes are to be reversible, the material of construction will be a mixture of coke and graphite. Most of the construction materials and the installation equipment fleet can be supplied locally or within Canada. If the electrodes are operated in a non-reversible manner, the same or potentially less expensive materials may be used. The overall cost savings are not expected to be significant.

7.2 Recommendations

Recommendations arising from the study are as follows:

1. Hydro should proceed with the planning for the installation of sea electrodes for the Gull Island and Soldiers Pond converter stations. At an appropriate time but before final design, Hydro should conduct a public awareness program of electrode installations to ensure that any environmental, safety perception, and other issues are addressed.

2. A study of the probability of losing subsea cable transmission should be carried out to better determine the likelihood of a prolonged outage period. Such a study would entail an analysis of the potential for mechanical damage due to icebergs and shipping activity and any other events that could lead to a long period of usage of the electrodes. If it is concluded from such a study that a prolonged outage would be extremely unlikely to occur, any concern about electric field effects and mitigating costs may possibly be eliminated since the electrodes would operate only sporadically at full current.

3. In order to more clearly determine the preferred location for the northern electrode, a study of the electrode line corridor to the HVdc line interconnection from a Lake Melville location should be conducted, in a manner similar to the studies undertaken for the HVdc corridor. Any sensitive environmental or land ownership issues, that could significantly add to the cost or otherwise militate against the location, should be identified. A similar study should be conducted for a location in L'Anse au Clair, as well as to address other factors that may influence costs such as potential quarry locations, and the shoreline topography and accessibility.

4. Additionally, a more detailed assessment should be made of the potential effects of an electrode in Lake Melville on the converter transformers at Gull Island and the associated costs to mitigate any such effect should be determined more accurately.

5. At an appropriate time, the electrode location in Conception Bay near the Holyrood thermal generating station should be determined more precisely through a site visit and an assessment of any potentially conflicting usage issues.

6. During preliminary engineering, confirmatory sea bed and landfall surveys for both northern and southern electrode locations should be conducted. At the same time, a confirmatory water column salinity profile of a location in Lake Melville should be conducted if the results of the recommended additional work support the findings of this study.

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Appendix A

Resistivity Data from 2007 Investigations

(from Newfoundland and Labrador Hydro)

Table A-1
Fall of Potential
Soldier's Pond

Northing	5253561	5253454	5253380	5253218
Easting	350767	350979	350625	350933
Distance	*Resistance (ohms)*			
(m)	***FP1***	***FP2***	***FP3***	***FP4***
3	789	3400	698	342
6	586	3350	663	365
9	506	3320	643	381
12	476	3280	628	390
15	463	3250	615	398
18	453	3220	602	405
21	444	3170	588	413
24	433	3090	567	421
27	433	2950	512	432
Tolerance				
Band %	2.2	1.6	2.3	2.0

Table A-2
Fall of Potential
Gull Island Converter Station

Northing	5870677	5870484	5870820	5870660
Easting	607589	607763	607782	607927
Distance	*Resistance (ohms)*			
(m)	***FP1***	***FP2***	***FP3***	***FP4***
3	1160	1380	750	1160
6	1170	1530	759	1220
9	1170	1580	767	1240
12	1170	1600	766	1250
15	1170	1610	768	1250
18	1170	1610	769	1260
21	1170	1620	771	1270
24	1170	1640	776	1290
27	1200	1700	785	1330
Tolerance				
Band %	0.0	0.3	0.1	0.0

Table B-1
Shlumberger Soundings
Soldiers Pond Converter Station

Northing		5253561	5253508	5253454	5253439	5253388	5253331	5253380	5253316	5253218	
Easting		350767	350878	350979	350742	350855	350934	350625	350848	350933	
	Median										
Spacing	**Depth**	***Resistivity (ohm-m)***									
(meters)	*(meters)*	**SS1**	**SS2**	**SS3**	**SS4**	**SS5**	**SS6**	**SS7**	**SS8**	**SS9**	**Average**
1	0.384	2344	205	186	497	2570	146	318	598	89	773
1.5	0.576	3889	257	317	784	3830	164	513	1040	168	1218
2.5	0.96	5334	395	573	1300	5350	287	801	1960	324	1814
3.5	1.344	6032	552	821	1640	7000	391	1070	2980	482	2330
5	1.92	8942	789	1139	2040	7990	557	1380	4520	712	3119
7.5	2.88	9131	1204	1609	2960	8950	804	1950	6000	970	3731
10	3.84	8273	1648	1935	3410	9100	1011	2370	7280	1111	4015
15	5.76	7626	2665	2296	4470	10600	1498	2850	9200	1454	4740
25	9.6	8518	5030	2491	5280	10200	2550	3650	11500	2064	5698
37.5	14.4	11219	6721	2534	6100	10200	3687	5070	12400	2673	6734
50	19.2	14214	7541	2576	7140	10200	4824	6000	12000	2857	7484
75	28.8	16434					4721	6400		2098	

Table B-2
Schlumberger Soundings
Gull Island Converter Station

Northing		5870677	5870580	5870484	5870749	5870661	5870572	5870820	5870741	5870660	
Easting		607589	607676	607763	607721	607783	607845	607782	607854	607927	
	Median										
Spacing	**Depth**	*Resistivity (ohm-m)*									
(meters)	*(meters)*	**SS1**	**SS2**	**SS3**	**SS4**	**SS5**	**SS6**	**SS7**	**SS8**	**SS9**	**Average**
1	0.38	423	751	1470	456	606	1710	292	338	641	743
1.5	0.57	401	1150	2340	571	854	2210	293	508	963	1032
2.5	0.95	395	1500	3670	658	1080	3750	407	615	1710	1532
3.5	1.33	400	1740	4300	657	1200	4200	459	615	1870	1716
5	1.9	360	1570	4790	638	1070	4510	467	578	2210	1799
7.5	2.85	306	1130	4640	519	612	4510	355	486	2080	1626
10	3.8	239	878	3450	401	920	3620	302	405	1790	1334
15	5.7	157	383	1650	233	228	2520	272	300	1120	763
25	9.5	144	123	465	171	117	1100	160	189	580	339
37.5	14.25	162	100	149	165	115	530	180	150	370	213
50	19	190	95	145	245	116	220	160	230	320	191
75	28.5	235	100	315	175	120	140	190	130	150	173
100	38	280	124	740	270	314	300	220	314	235	311

Table A-1

Fall of Potential

Gull Island Powerhouse

Northing	5869571	5869498	5869689	5869619
Easting	605076	605161	605176	605265
Distance	GI-PH-FP-01	GI-PH-FP-02	GI-PH-FP-03	GI-PH-FP-04
(m)		Resistance (ohms)		
3	4320	3160	2250	1220
6	4220	3010	2130	1140
9	4190	2950	2080	1100
12	4160	2910	2050	1090
15	4130	2880	2040	1070
18	4110	2850	2000	1060
21	4090	2780	1910	1050
24	4070	2670	1800	1030
27	3830	2480	1660	984
Tolerance Band %	0.5	1.8	3.3	0.9

Table A-2

Fall of Potential

Gull Island Switchyard

Northing	5871509	5871010	5871528	5871277
Easting	607509	607734	607807	608032
Distance		Resistance (ohms)		
(m)	GI-SY-FP-01	GI-SY-FP-02	GI-SY-FP-03	GI-SY-FP-04
3	7380	3750	2060	5920
6	7450	4300	2270	5680
9	7420	4510	2420	5560
12	7440	4610	2530	5490
15	7670	4620	2640	5430
18	7360	4630	2690	5350
21	7410	4670	2690	5280
24	7520	4760	2710	5150
27	7900	4950	2710	4860
Tolerance Band %	2.4	0.5	0.9	1.4

Table B-1
Schlumberger Soundings
Gull Island Powerhouse

Northing		5869571	5869544	5869498	5869630	5869605	5869601	5869689	5869689	5869659	5869619	
Easting		605076	605124	605161	605124	605108	605170	605176	605175	605216	605265	
	Median											
Spacing	**Depth**	**Resistivity (ohm-m)**										
(meters)	**(meters)**	**GI-PH-SS-01**	**GI-PH-SS-02**	**GI-PH-SS-03**	**GI-PH-SS-04**	**GI-PH-SS-05**	**GI-PH-SS-06**	**GI-PH-SS-07**	**GI-PH-SS-07C**	**GI-PH-SS-08**	**GI-PH-SS-09**	**Average**
(meters)	(meters)	Resistivity (ohm-m)										
1	0.38	1540	1560	1980	1450	1230	1290	1650	1290	521	1620	1413
1.5	0.57	2310	2630	2700	2500	1550	1690	1900	1690	745	2210	1993
2.5	0.95	3170	4110	4120	2720	2030	1600	2440	1600	684	2400	2487
3.5	1.33	3450	5100	5170	2660	2460	1420	4430	1420	663	3130	2990
5	1.9	3550	7000	6680	2900	2410	1120	5050	1120	639	4250	3472
7.5	2.85	4130	8550	7690	3220	3150	1090	4830	5560	614	4350	4318
10	3.8	4860	8170	7830	3360	3230	978	3880	5620	600	4240	4277
15	5.7	5460	8940	7480	2650	3800	1160	3660	5530	463	4750	4389
25	9.5	5300	7400	5550	2380	4710	1740	2010	4660	529	4950	3923
37.5	14.25	6760	6710	5880	2290	6200	3160	1490	2850	752	5300	4139
50	19	6500	6040	6120	2500	5960	4960	1630	3820	985	5730	4425
75	28.5	7500	7250	7450	3080	8500	5070	2490	6150	1310	5700	5450
100	38	8040	8300	23000	4200	13700	5700	3300	6000	1700	6050	7999

Table B-2

Schlumberger Soundings

Gull Island Switchyard

Northing		5871509	5871143	5871010	5871394	5871271	5871143.5	5871528	5871402	5871277	
Easting		607509	607618	607734	607657	607759	607883	607807	607925	608032	
		Resistivity (ohm-m)									
Spacing (meters)	Median Depth (meters)	GI-SY-SS-01	GI-SY-SS-02	GI-SY-SS-03	GI-SY-SS-04	GI-SY-SS-05	GI-SY-SS-06	GI-SY-SS-07	GI-SY-SS-08	GI-SY-SS-09	Average
1	0.38	1800	242	3290	1890	561	1120	2370	947	22300	3836
1.5	0.57	1950	253	6250	3600	648	2090	3370	1320	19000	4276
2.5	0.95	2490	300	10200	5070	817	3650	5300	1270	13900	4777
3.5	1.33	3530	210	13000	6830	847	4930	7440	1070	9530	5265
5	1.9	4700	151	16700	7290	825	6830	10400	555	9470	6325
7.5	2.85	6630	190	11400	9020	590	6840	14100	286	10900	6662
10	3.8	7830	230	13400	11400	433	10100	19100	183	13400	8453
15	5.7	8320	270	16300	13800	325	14500	24000	142	13800	10162
25	9.5	7290	350	12900	15100	369	16900	25000	156	12400	10052
37.5	14.25	5320	394	8450	13300	830	15500	22100	182	8800	8320
50	19	4800	444	5370	26800	704	12900	18400	200	9540	8795
75	28.5	4900	940	1900	30400	820	6840	5800	475	5100	6353
100	38	2800	500	1200	30400	860	2120	1800	330	7900	5323

Appendix B

Electric Field Analysis and Output

Expert Services / Seppo Orivuori

27 November 2007

Distribution
Henrik Rosenberg, BALSLEV A/S

Cc

CALCULATION OF 3-D ELECTRIC POTENTIAL DISTRIBUTIONS DUE TO ELECTRODES IN HVDC LINK BETWEEN LOWER CHURCHILL IN LABRADOR AND ST JOHNS IN NEWFOUNDLAND CANADA

1 INTRODUCTION

The aim of this study is to carry out calculation of electric potential distributions due to the electrodes in HVDC link between Lower Churchill in Labrador and St. Johns in Newfoundland Canada.

Three different cases are investigated with common anode in Forteau Bay in Labrador locating off-shore at (504529 mE, 5702619 mN) in UTM 21 reference system. Three alternative off-shore cathode locations in Conception Bay in Newfoundland processed are:

1. (792117 mE, 5255928 mN),
2. (810296 mE, 5290742 mN) and
3. (749734 mE, 5289478 mN).

HVDC link is considered to carry a current of 2000 A.

As an input data to the present 3-D calculation following documents are used:

1. Geologic and bathymetric data along vertical W-E cross-sections, file 071012 Geology cross sections.xls,
2. Bathymetric data along vertical N-S cross-sections, file 071022 Geology cross sections _ North_South.xls,
3 Conductivities of sea water and geologic layers are taken from 1,
4. Shore lines, file 071008 Land.jpg,
5. Shore line and sea depth information in the vicinity of the anode, files: 071011 FonteauBay land.jpg and 071011 FonteauBay Xm.jpg, where X=20, 25, 40, 50, 60, 75 and 150,
6. Shore line and sea depth information around in the vicinity of the cathode locations,

files: 071011 ConceptionBay land.jpg and 071011 ConceptionBay Xm.jpg, where X=20, 25, 40, 50, 60, 75, 150 and 250,

7. Letter to the author “LC HVDC/FEM model for prediction of stray current effects” dated 12 October 2007 describing the task and data above.

2 DESCRIPTION OF THE PROBLEM

The purpose of this study is to produce numerical values of the electric potential field for the top surface of the model.

Three different cases are handled: cathodes in the three alternative locations as given in the introduction.

Table 2-1 gives resistivity and conductivity values of the various materials used in this study.

Table 2-1. Resistivity and conductivity values of water and different geologic layers

Material name	Resistivity Ωm	Conductivity $(\Omega km)^{-1}$	Code in the model
Sea water	0.25	4000	1
Sandstone	20	50	2
Limestone	50	20	3
Granite and Crystalline Basement	3000	0.3	4

The current to/from the electrode is 2000 A. The electrode in Forteau Bay off-shore Labrador is an anode.

3 DESCRIPTION OF THE NUMERICAL FEM MODEL

The finite element method (FEM) is utilised in the numerical solution of the potential problem described above. The finite domain having horizontal dimensions 1000 km times 1200 km and vertical dimension of 5 km is modelled using 8-noded 3-D ‘brick’ elements.

The used domain extends from 3300 mE to 1003300 mE in the west-east direction and from 5004700 mN to 6204700 mN in the south-north direction.

Figure 3-1 depicts the layout of the FEM model together with the contours of the coastlines and the locations of the electrodes.

Zero-potential boundary conditions in the vertical bounding planes are used, bottom and top surface being non-conducting.

Spatial dimension used is km.

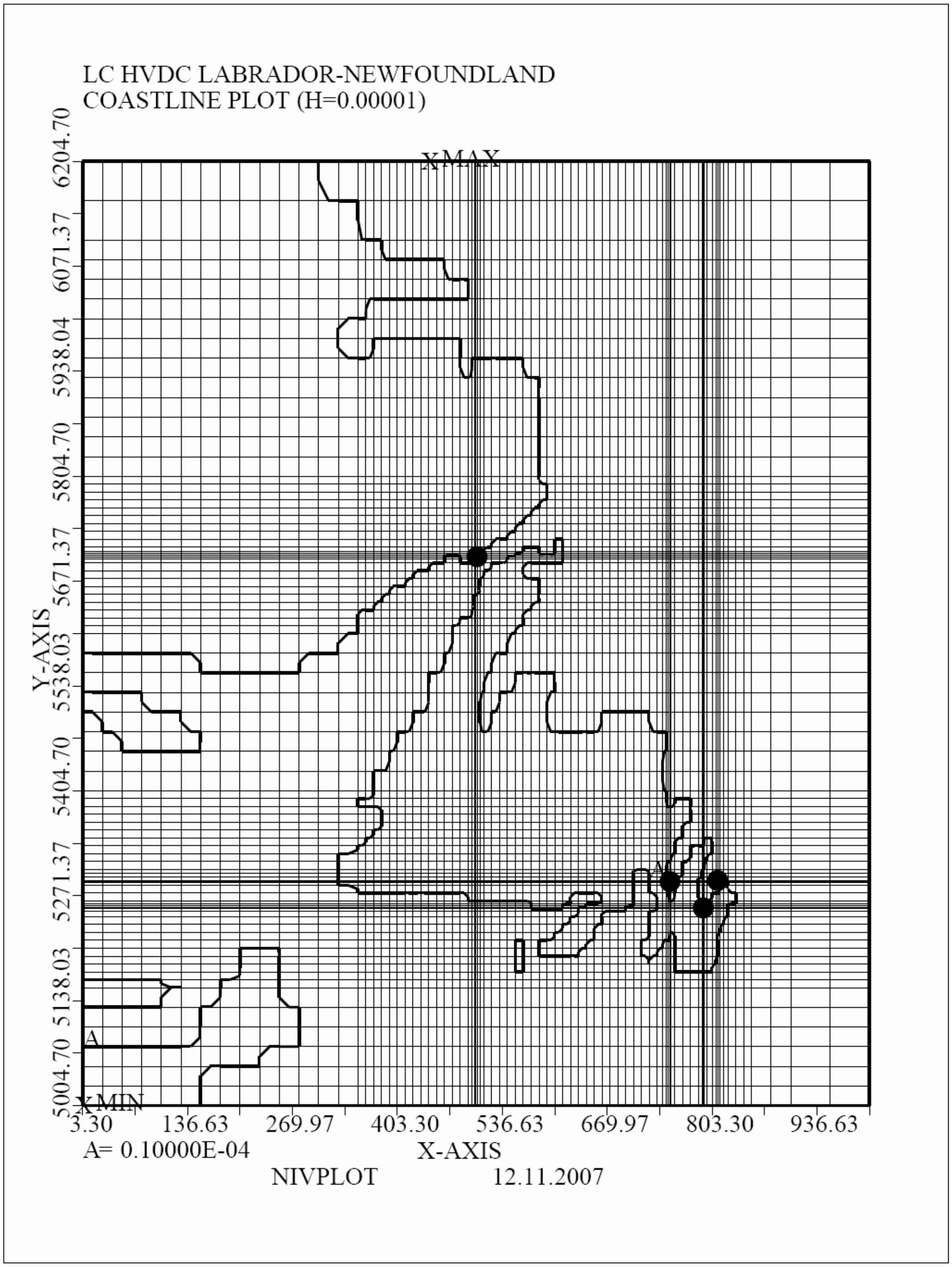

Figure 3-1. Top view of the model with approximation of the shore lines

Figures 3-1 gives the top view of the finite element model.

Element subdivision in the x-direction (west to east) has 82 intervals:

```
25., 25., 25., 25., 25., 25., 25., 25., 25., 25., 25., 25., 25., 25.,
10., 10., 10., 10., 10., 10., 10., 10., 10., 10., 10., 10., 10., 10.,
 5.,  3., 2.,1.229,3.771, 5., 10., 10., 10., 10., 10., 10., 10., 10.,
10., 10., 10., 10., 10., 10., 10., 10., 10., 10., 10., 10., 10., 10.,
 7., 5.,2.434, 2.,1.566, 4.5, 10., 10., 10.,4.5,1.817,1.183, 3.,  7.,
 5.,1.996,3.004,5.,  5., 10., 10., 10., 25., 25., 50., 50. km
```

and there are 85 intervals between nodal points in the y-direction as follows:

```
25., 25., 25., 25., 25., 25., 10., 10., 10., 10., 10., 10., 10., 10.,
10.,  7., 3.,1.228,2.772, 3.,  3., 10., 10., 3.,1.778,1.264,3.958,5.,
 5., 10., 10., 10., 10., 10., 10., 10., 10., 10., 10., 25., 25., 25.,
25., 25., 25., 25., 25., 10., 10., 10., 10., 10., 10., 10., 10., 10.,
 5.,2.919,2.081, 2.  3.,  5., 10., 10., 10., 10., 10., 10., 10., 10.,
10., 25., 25., 25., 25., 25., 25., 25., 25., 25., 25., 25., 25., 50.,
50. km.
```

In the vertical direction there are 10 elements and element subdivision from bottom to top is as given in Table 3-1.

Table 3-1. Vertical element subdivision

Element no. (from bottom to top)	Element thickness (km) (at land)	Element thickness (km) (at sea)
1	1.0	1.0
2	1.0	1.0
3	1.0	1.0
4	0.5	0.5
5	0.5	0.5
6	0.5	0.5
7	0.2	0.2
8	0.296	0.3-h
9	0.002	h/2
10	0.002	h/2

In Table 3-1 the symbol h means the depth of the sea in km. Areas with sea depth of 1 km and 3 km were handled separately by using value of 0.15 km for h in Table 3.1 and adjusting the material codes of the appropriate lower elements to water.

Bathymetric data from Excel files 1 and 2 in introduction were transferred manually to the top view of the sketch of the model. Sea depth values at nodal locations are extracted from this drawing. Value of zero means land.

Selected bathymetric contour lines have been presented in Figure 3-2. Contour lines plotted are: coastline, depth of zero, sea depth values of 40 m, 150 m and 1000 m.

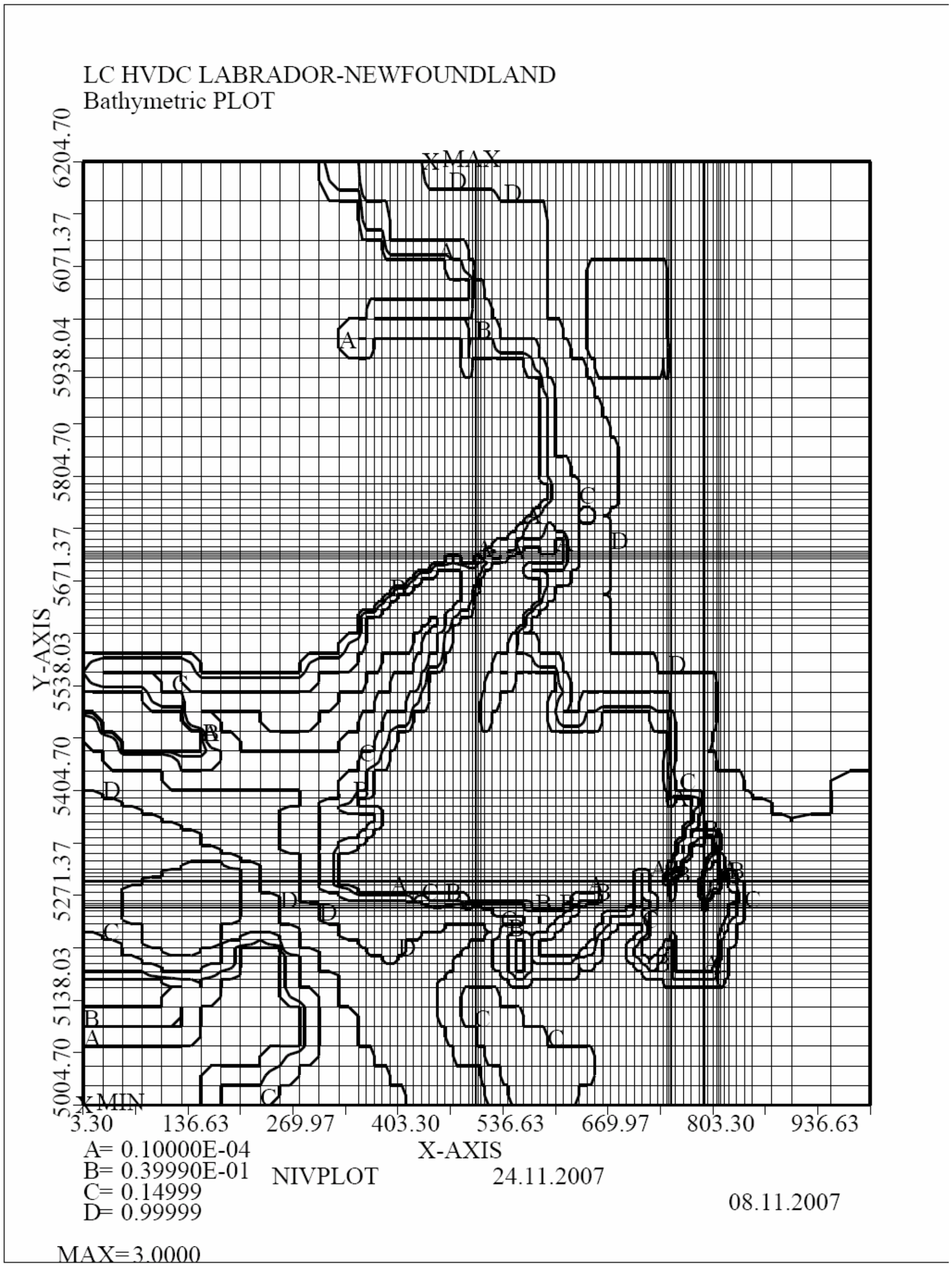

Figure 3-2. Some bathymetric lines; A=coast line, B=40 m, C=150 m, D=1 km

The geologic data in Excel file 1 in the introduction are used as follows: co-ordinates of centre point of each element is evaluated, nearest geologic data point in search, material code corresponding to this layer is assigned to appropriate element.

Figures 3-3...3-6 show typical vertical cross-sections in the model along selected lines having constant y-co-ordinate. These figures visualise the geological data assigned to each element in the way described above. Figures also show the vertical element subdivision of the model. The vertical dimension is exaggerated 200 times in these figures. Due to a quite course subdivision in the vertical direction the present model can not follow all the details of the geological data. Bathymetric data are more crucial to the accuracy of the results. Data given in the both files 1 and 2 given in the introduction are followed as accurately as possible.

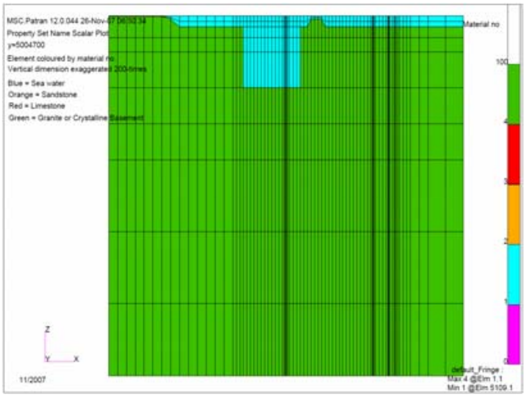

Figure 3-3. xz-section y=5004700

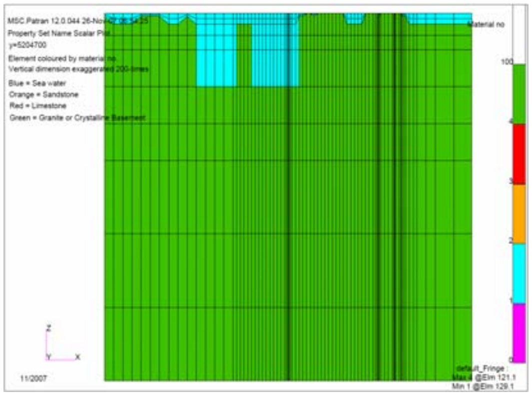

Figure 3-4. xz-section y=5204700

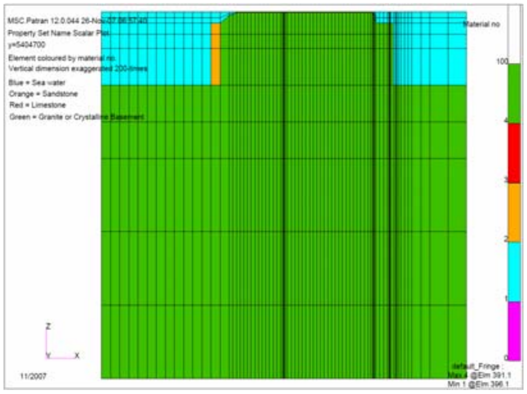

Figure 3-5. xz-section y=5404700

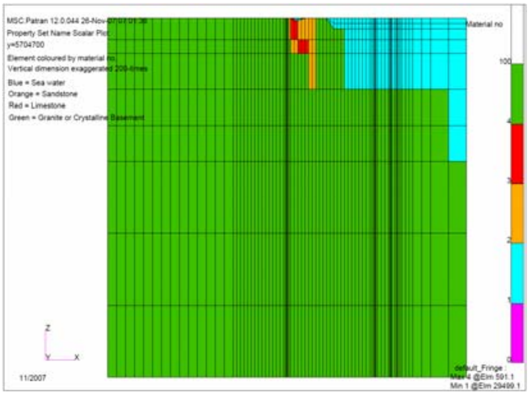

Figure 3-6. xz-section y=5704700

Figure 3-7 depicts the top view of the 3-D model showing the approximation of shore lines and land areas.

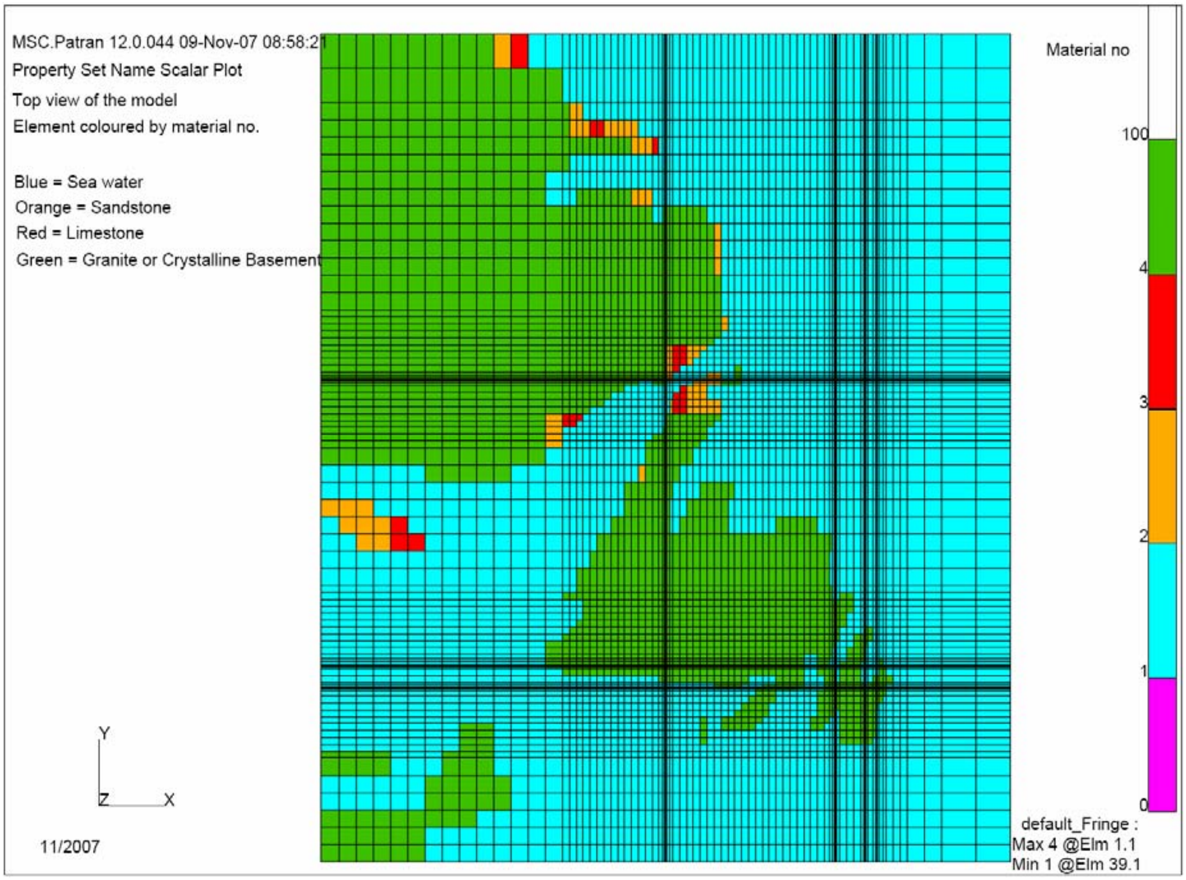

Figure 3-7. Top view of the 3-D model. Water elements coloured with blue

Model statistics:

- 69700 brick elements
- 78518 nodes of which 3674 have prescribed zero value.

4 RESULTS

The results for the three cases are given both in numerical and graphical form.

Results, numerical values of the nodal potentials at the top surface of the 3-D model, are collected in MS Excel spread sheet.

Portion of upper left corner of the spread sheet is pasted to this report for each case. Complete spread sheet is inserted into this report as an icon making it possible to carry out more detailed considerations.

Location of anode is (504529 mE, 5702619 mN) applies to all three cases studied.

4.1 Case 1

Location of cathode is (792117 mE, 5255928 mN).

Overview of top surface potential distribution is shown in Figure 4-1.

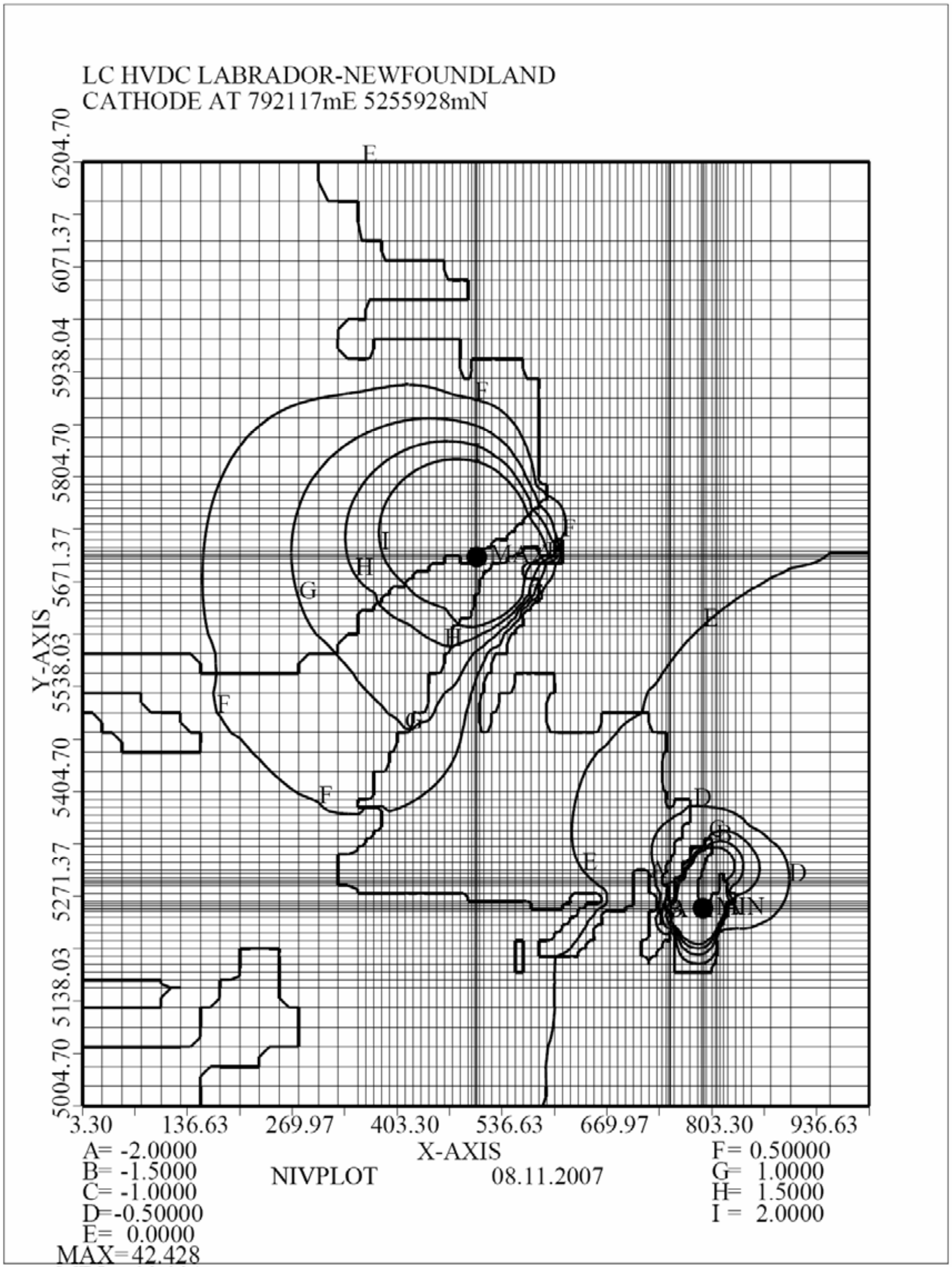

Figure 4-1. Overview of equipotential contours for case 1. Coastlines added

Results in numerical form are collected into MS Excel spread sheet.

Portion of the upper left corner of this spread sheet is shown below.

LC HVDC between Labrador and Newfoundland. I=2000 A							Nodal potential values at the top surface of the model in V	
Anode at (504529,5702619) and Cathode at (792117,5255928)								
		DX-->	25.000	25.000	25.000	25.000	25.000	25.000
DY	Y (km N)	X (km E)	3.3	28.300	53.300	78.300	103.300	128.300
↓			1	2	3	4	5	6
	6204.700	86	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
50.000	6154.700	85	0.00000	0.00492	0.00969	0.01412	0.01806	0.02129
50.000	6104.700	84	0.00000	0.01047	0.02064	0.03020	0.03883	0.04615
25.000	6079.700	83	0.00000	0.01364	0.02694	0.03952	0.05100	0.06092
25.000	6054.700	82	0.00000	0.01716	0.03394	0.04993	0.06470	0.07772
25.000	6029.700	81	0.00000	0.02105	0.04171	0.06156	0.08012	0.09683
25.000	6004.700	80	0.00000	0.02532	0.05027	0.07444	0.09734	0.11842
25.000	5979.700	79	0.00000	0.02996	0.05959	0.08854	0.11635	0.14250
25.000	5954.700	78	0.00000	0.03492	0.06959	0.10372	0.13698	0.16890
25.000	5929.700	77	0.00000	0.04012	0.08009	0.11975	0.15889	0.19718
25.000	5904.700	76	0.00000	0.04545	0.09089	0.13629	0.18159	0.22669
25.000	5879.700	75	0.00000	0.05080	0.10172	0.15290	0.20447	0.25655

4.2 Case 2

Location of cathode is (810296 mE, 5290742 mN).

Overview of top surface potential distribution is shown in Figure 4-2.

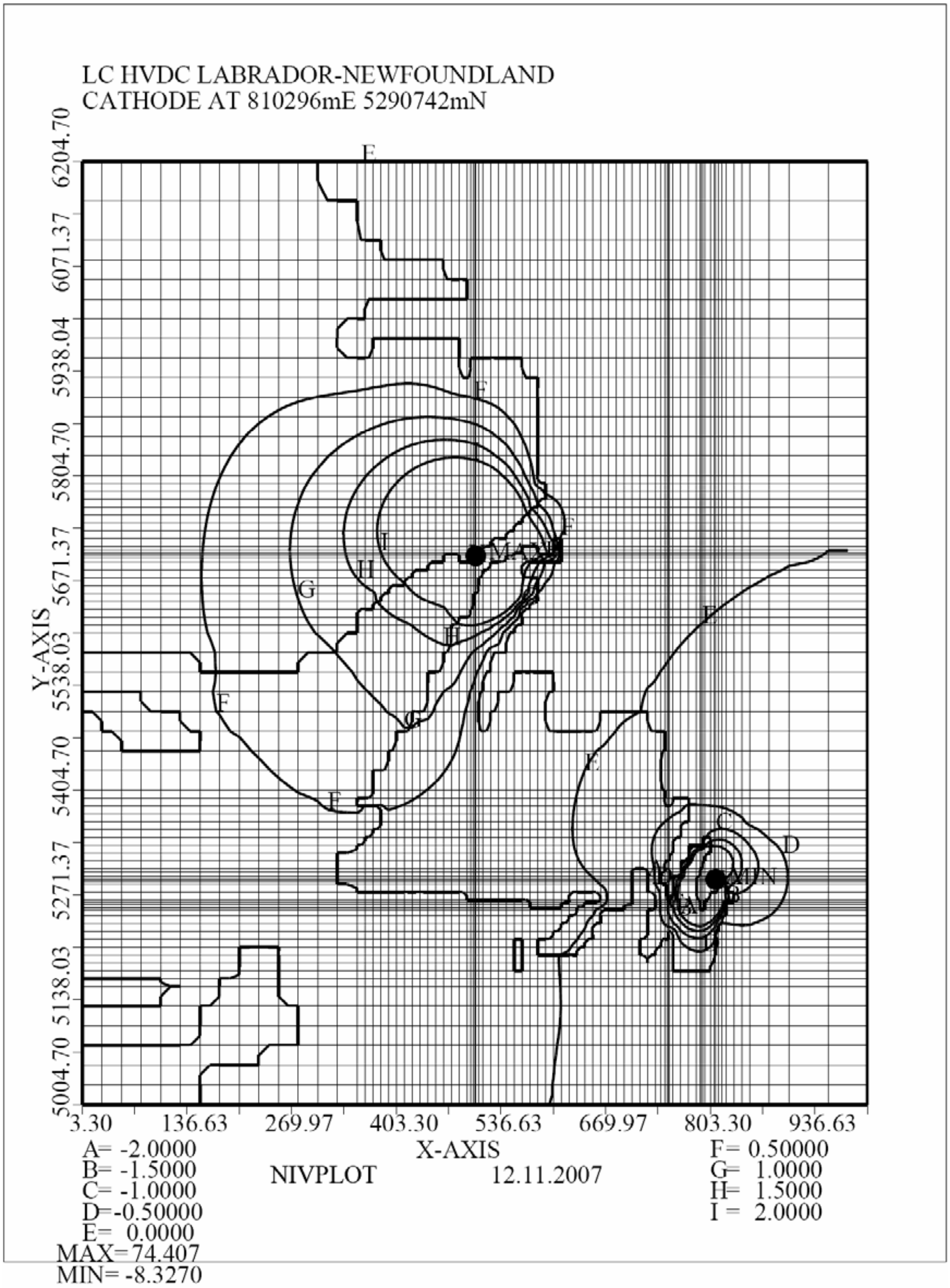

Figure 4-2. Overview of equipotential contours for case 2. Coastlines added

Results in numerical form are collected into MS Excel spread sheet.

Portion of the upper left corner of this spread sheet is shown below.

LC HVDC between Labrador and Newfoundland. I=2000 A							Nodal potential values at the top surface of the model in V	
Anode at (504529,5702619) and Cathode at (810296,5290742)								
		DX-->	25.000	25.000	25.000	25.000	25.000	25.000
DY	Y (km N)	X (km E)	3.3	28.300	53.300	78.300	103.300	128.300
↓			1	2	3	4	5	6
	6204.700	86	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
50.000	6154.700	85	0.00000	0.00496	0.00977	0.01424	0.01821	0.02148
50.000	6104.700	84	0.00000	0.01055	0.02081	0.03045	0.03915	0.04654
25.000	6079.700	83	0.00000	0.01375	0.02716	0.03985	0.05142	0.06144
25.000	6054.700	82	0.00000	0.01730	0.03422	0.05035	0.06524	0.07838
25.000	6029.700	81	0.00000	0.02122	0.04205	0.06206	0.08078	0.09764
25.000	6004.700	80	0.00000	0.02553	0.05067	0.07504	0.09814	0.11939
25.000	5979.700	79	0.00000	0.03020	0.06006	0.08924	0.11729	0.14366
25.000	5954.700	78	0.00000	0.03519	0.07012	0.10453	0.13806	0.17025
25.000	5929.700	77	0.00000	0.04042	0.08069	0.12066	0.16011	0.19873
25.000	5904.700	76	0.00000	0.04578	0.09155	0.13729	0.18295	0.22842
25.000	5879.700	75	0.00000	0.05115	0.10243	0.15398	0.20594	0.25844

4.3 Case 3

Location of cathode is (749734 mE, 5289478 mN).

Overview of top surface potential distribution is shown in Figure 4-3.

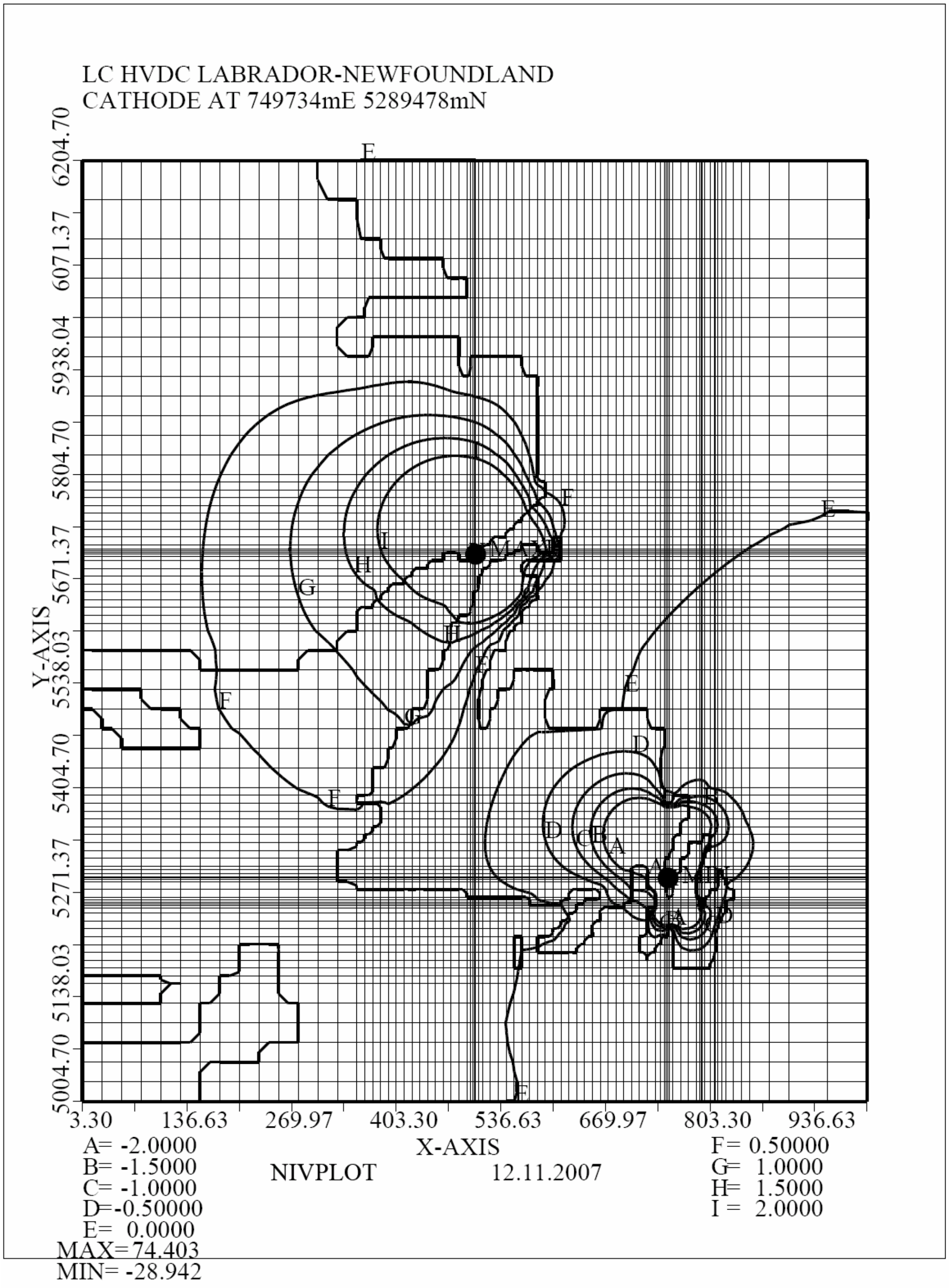

Figure 4-3. Overview of equipotential contours for case 3. Coastlines added

LC HVDC between Labrador and Newfoundland. I=2000 A							Nodal potential values at the top surface of the model in V	
Anode at (504529,5702619) and Cathode at (749734,5289478)								
		DX-->	25.000	25.000	25.000	25.000	25.000	25.000
DY	Y (km N)	X (km E)	3.3	28.300	53.300	78.300	103.300	128.300
↓			1	2	3	4	5	6
	6204.700	86	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
50.000	6154.700	85	0.00000	0.00495	0.00974	0.01420	0.01815	0.02140
50.000	6104.700	84	0.00000	0.01052	0.02075	0.03036	0.03903	0.04639
25.000	6079.700	83	0.00000	0.01372	0.02708	0.03974	0.05127	0.06125
25.000	6054.700	82	0.00000	0.01725	0.03412	0.05021	0.06505	0.07815
25.000	6029.700	81	0.00000	0.02117	0.04194	0.06189	0.08056	0.09736
25.000	6004.700	80	0.00000	0.02546	0.05055	0.07484	0.09788	0.11908
25.000	5979.700	79	0.00000	0.03012	0.05992	0.08902	0.11700	0.14330
25.000	5954.700	78	0.00000	0.03511	0.06996	0.10429	0.13774	0.16985
25.000	5929.700	77	0.00000	0.04033	0.08051	0.12040	0.15975	0.19828
25.000	5904.700	76	0.00000	0.04568	0.09136	0.13700	0.18256	0.22793
25.000	5879.700	75	0.00000	0.05104	0.10222	0.15367	0.20552	0.25791

Appendix C

Bell Island Cable Specification

(from Newfoundland Power)

Appendix C not included in
Public version

Appendix D

Cost Estimate for Protective Berm

Cost estimates not
included in Public version