Reliability Study
of the
Strait of Belle Isle HVDC
Cable System

#R74-85

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1.0 INTRODUCTION

As a follow-on to work performed in 1981 by Power Technologies, Inc. for Newfoundland and Labrador Hydro, PTI was asked to perform reliability studies for three new HVDC undersea cable alternatives for the Strait of Belle Isle. The studies involved:

- Reviewing operating histories of HVDC cable systems similar to those proposed for the Strait of Belle Isle.
- Estimating iceberg scour risk.
- Evaluating the reliability of the proposed cable alternatives using state space techniques.
- Merging the cable reliability statistics with statistics for the remainder of the HVDC system.
- Expressing the resulting system reliability statistics in terms of single generating unit capacity and forced outage rate models.

Section 2 of this report summarizes the operating history of similar HVDC cable systems, specifically the average failure rate and repair time, and also analyzes the risk of cable damage due to iceberg scour. Section 3 describes the reliability analyses performed on both the cable alternatives and the remainder of the HVDC system. References can be found in Section 4.

Some of the significant results of the work performed can be summarized as follows:

- The average failure rate for HVDC cable systems similar to that proposed for the Strait of Belle Isle was 0.95 failures/100 km-yr. Recognizing improvements in design operating and repair procedures over the past ten years, a failure rate of 0.5 failures/100 km-yr. was used in the study.
- Cable repair times (exclusive of the time required to outfit the repair ship) were varied from one to four months.
- The annual expected number of iceberg scours were estimated to be 0.1/yr. for Crossing 2/A. 0.13/yr. for Crossing B, and 0.39/yr. for Crossing C.
- Cable crossing locations 2/A and B have essentially the same probability and frequency of partial transfer, with location C being somewhat less reliable; the principal cause of the difference in reliability can be attributed to the increased risk of iceberg scour at Crossing C.
- For 400 MW loading conditions, the ability to achieve full transfer is somewhat degraded due to single cable outages.
- The reliability of the various cable alternatives is quite sensitive to both the cable failure rate and the repair time.

2.0 DC CABLE OPERATING DATA & ICEBERG SCOUR RISK

Before an analysis of the proposed HVDC cable alternatives can be accomplished, it is necessary to compile and review the operating performance of existing DC cable systems similar to those proposed in the Strait of Belle Isle. From this review, it is possible to determine the most likely failure modes to be encountered, and to quantify the frequency of failure due to these various failure modes. Section 2.1 presents the results of this research, along with a brief review of cable repair methods and their effect on repair time.

In addition to the failure modes discussed in Section 2.1, the possibility of cable failure due to iceberg scour was investigated, using information obtained in previous research (Refs. 8-12).

Section 2.2 covers the effects of iceberg scour on cable outage statistics.

2.1 DC Cable Operating Data

More than 1100 km of solid paper insulated (mass-impregnated) cable is in operation in submarine installations in the 200 to 300 kV voltage range (285 kVDC is the higher operating voltage at present). A 180 km DC submarine link between Finland and Sweden, possibly operating at 350 kVDC, is in the planning stages and may be commissioned as early as 1989.

Table 2-1 was developed through review of References 1 through 7 and by correspondence with the users of the Skagerak circuit.

The reported failures can be categorized as follows:

- Fishing - specifically beam trawling.
- Anchors.
- Joint failures - some of the earlier repairs failed again.
- Mechanical damage to the cable during laying after repair.

Table 2-2 summarizes the cable failures; the failure rate in failures per 100km years has been calculated for the individual circuits, along with the average failure rate for all operating systems. The average failure rate is calculated to be 0.95 failures per 100km years. The Skagerak circuit has a failure rate of

.13 over a nine-year operating span, clearly indicating improvements in operation over that of the Konti-Skan circuit.

TABLE 2.1
FAILURE SUMMARY 1971 - 1982
HVDC SUBMARINE CABLE
SOLID PAPER INSULATED CABLE (MASS IMPREGNATED)
200-300 KV

Name	Distance km	Total Cable Length km	Rated Voltage kV	No. of Cables	Year of Commissioning	Failures: 1971-72	1973-74	1975-78 ②	1979-80	1981-82 ⑤
Konti-Skan 1	60	60	250	1	1965 ⑧	9 ⑨	4 + 3 ① (1A)	9 ③	0	7 ⑥ ⑦
Sardinia - Italy	121	242	200	2	1967 ⑩	Failures!	Failures!	4	19 ④	NA
Vancouver Pole 1	33	33	260	1	1968/69	1	0	0	0	0
Skagerak Pole 1	127	127	250	1	1976/77	NA	NA	2	0	1 ⑪
Skagerak Pole 2	127	127	250	1						
Vancouver Pole 2	33	33	260	1	1977/79	NA	NA	0	0	0 No cable joint
Cross-Channel 2	68	544	270	8	1984	NA	NA	NA	NA	NA

Total Cable Length Km 1166

① 3 failures due to trawls
2 failures in joints
2 failures due to mechanical damage during laying after repair

(1A) 30 km of new cable was laid in 0.75 meter depth sea bottom trench. One joint failed (75/76) but no difficulty lifting the cable for repair.

② The average failure rate for all cables, both solid paper and oil-filled is approximately 1 outage per 100 km transmission line year for the 1975-78 period.

③ Summary of Konti-Skan for 1970-78:
26 cable failures total
11 failures due to mechanical stress
15 failures due to joint failures.

④ Data reported for outage includes both OH and submarine sections.
1288 hours outage for 19 failures - may all be due to the 292 km of overhead lines

⑤ All data includes OH and UG transmission lines

⑥ 3 submarine failures in 1981 all due to faulty joints or mechanical damage near coast. 4 km of cable was replaced in 1982 with heavier armoured cable.

⑦ A total of 38 failures have occurred on the Konti-Skan circuit through mid 1985 — all related to anchors, fishing, or mecnanical damage during previous repairs.

⑧ Konti-Skan operated first 5 years without cable failures.

⑨ Changed fishing methods introduced about 1969. Heavy weights of 250-500 kg attached to trawls and dragged along the sea bed.

⑩ Nine cable failures have occurred from 1967 through 1970, most if not all due to anchors and trawling.

⑪ All Skagerak failures - total of 3 - were cuased by fishing trawls or tugboat dragging a howser along the sea bottom.

TA/ba

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TABLE 2 .2

HVDC SUBMARINE CABLE FAILURE SUMMARY

SOLID PAPER INSULATED CABLE

200 - 300 kV

Name	Distance km	Total Cable Length km	Rated Voltage kV	No.of Cables	Year of Commissioning	Total No. of Failures	No. of Years in Service	Kilo. Years	Failures/ 100 km/yr
Konti-Skan 1	60	60	250	1	1965	0 - 38	20	1200	3.2
Sardinia - Italy	121	242	200	2	1967	NA	-	-	-
Vancouver Pole 1	33	33	260	1	1968/69	0	16	528	0
Skagerak Pole 1	127	127	250	1	1976/77	0 - 3	9	2286	.13
Skagerak Pole 2	127	127	250	1					
Vancouver Pole 2	33	33	260	1	1977/79	0	9	297	0
Cross-Channel 2	68	544	270	8	1984	NA	-	-	-
			TOTAL			0 - 41		4311	0-.95

With improved repair techniques, the repeated joint failures and the mechanical damage during laying after repair have diminished substantially. Trenching the cable into the sea bottom has practically eliminated trawling and anchor failures, so the operating experiences have greatly improved during the last decade. For example, the Skagerak cable has experienced a total of 3 failures since installation in 1976 (.13 failures per 100km years), 10% of that reported for all submarine DC cables for the 1975-78 period. Appendix 1 details the equipment used for trenching the Skagerak cable.

Recognizing the improvements in design, operation, and repair occurring over the last ten years, it was felt that use of the average failure rate for the systems reported in Table 2-2 (.95 failures/100 km yr.) would be overly pessimistic. Consequently, the failure rate used during the reliability study was .5 failures per 100 km years.

On the subject of cable repair time, with a cable repair ship available, the repair time has been between 5 and 8 days, depending on the weather during the repair. For the proposed Belle Isle Strait cable where repair can be carried out from May 15 through December 15, and the repair vessel called in from Europe or Japan, the outage time can be quite long. Actual repair times were varied over a range of 1 to 4 months.

The preferred method for cable repair is to lift the cable onto the repair ship, splice in a new section of cable, e.g. make two joints, then lower the cable back onto the sea bottom. If the cable is trenched, a new trench needs to be made for the additional cable spliced into the circuit.

2.2 Estimation of Iceberg Scour

In estimating the expected number of iceberg scours per year for each of the three proposed cable crossings, the following information is necessary:

- the distribution of icebergs outside the Strait
- the probability of icebergs crossing the sill at the entrance to the Strait
- bathymetry data for the crossing alternatives
- the expected number of icebergs at each portion of the crossings.

References 8 through 12 provide sufficient information to permit reasonable estimates of iceberg scour.

The draft distribution of icebergs noted off the Labrador coast is based upon data reported in Ref. 8. Rather than using all 910 icebergs, only those icebergs whose drafts were actually measured are included in the data base. The frequency distribution of those icebergs having drafts of 80 meters or below are shown in Table 2-3.

TABLE 2-3
FREQUENCY DISTRIBUTION, ICEBERGS LESS THAN 80 METERS DRAFT (1)

Draft (M)	Number of Icebergs
26-30	4
31-35	3
36-40	5
41-45	6
46-50	10
51-55	6
56-60	15
61-65	6
66-70	21
71-75	6
76-80	21
TOTAL:	103

(1) From Ref. 8; only measured iceberg drafts included

The 70 meter sill at the entrance to the Strait will prevent many of the icebergs having substantially greater drafts from entering the Strait. Conservatively allowing for melting at the sill and during progression through the Strait would reduce the average iceberg draft by 10 meters, according to Refs. 8 and 9. Therefore, the distribution of iceberg drafts is assumed to be as given in Table 2-3, with the actual drafts reduced by 10 meters (e.g., the probability associated with the 80 meter draft given in Table 2-3 really refers to an iceberg that will have a draft of 70 meters at the crossing area).

The probability of an iceberg crossing the sill area was determined in Ref. 8, and is presented here in Table 2-4. The technique used in Ref. 8 accounts for the bathymetry of the sill area, recognizing the largest single width of a channel at various water depths.

TABLE 2-4
PROBABILITY OF ICEBERG CROSSING SILL (2)

Draft (M)	Prob. of Passing Through Sill
15-20	0.90
20-25	0.87
25-30	0.80
30-35	0.73
35-40	0.78
40-45	0.85
45-50	0.76 (3)
50-55	0.62
55-60	0.32
60-65	0.06
65-70	0.01

(2) From Ref. 8
(3) Combined prob. for both Newfoundland and Labrador channels, depths greater than 50 meters.

The distribution of drafts for icebergs reaching the crossings area is determined by multiplying the probability of iceberg draft of X meters and the probability of crossing the sill area. The resulting calculations are shown in Table 2-5.

TABLE 2-5
DRAFT DISTRIBUTION, ICEBERGS CROSSING SILL

Iceberg Draft (M)	A Prob. of Draft(4)	B Prob. of Iceberg Crossing Sill	Prob. of Iceberg Entering Strait(5)
16-20	0.0388	0.90	0.0349
21-25	0.0291	0.87	0.0253
26-30	0.0485	0.80	0.0388
31-35	0.0583	0.73	0.0426
36-40	0.0971	0.78	0.0757
41-45	0.0583	0.85	0.0496
46-50	0.1456	0.76	0.1107
51-55	0.0583	0.62	0.0361
56-60	0.2039	0.32	0.0652
61-65	0.0583	0.06	0.0035
66-70	0.2039	0.01	0.0020

(4) Calculated from Table 2-3
(5) A x B

Estimating the expected number of scours in the crossings area requires knowledge of the bathymetry of the three crossing alternatives. The plates contained in Ref. 12 were used to determine the probability of being in 5-meter increment water depths.

The annual expected number of scours is determined by calculating the probability of an iceberg having a draft of X meters encounter a section of the crossing area having a depth of X meters or less; how much less is an issue open to question. Given the bathymetric profile of the crossing areas, it seems reasonable to assume that an iceberg having a draft of X meters will not have the opportunity to ground in areas having water depths less than X-10 meters. Therefore, in place of the probability of water depth being X meters or less, the probability of water depths between X and X-10 meters was used. Distributions for various segments of the crossing routes (segments are defined by the test plow marks indicated in Plate 3 of Ref. 12) are presented in Tables 2-6a through 2-6c. Tables 2-7a through 2-7c summarize the calculation of scour probability for the three crossing alternatives.

TABLE 2-6a

PROBABILITY OF WATER DEPTH CROSSING 2/A (6)

Water Depth (M)	Test Plow TPM-TPD	Test Plow TPD-TPX
10-20	0	0.0442
15-25	0	0.0629
20-30	0.0017	0.0221
25-35	0.0034	0.0051
30-40	0.0034	0.0034
35-45	0.0051	0.0034
40-50	0.0102	0.0034
45-55	0.0102	0.0034
50-60	0.0068	0.0068
55-65	0.0068	0.0102
60-70	0.0068	0.0136

(6) Probabilities based on total length of crossing; only depths to 70 meters reported.

TABLE 2-6b

PROBABILITY OF WATER DEPTH CROSSING B (7)

Water Depth (M)	Test Plow TP14-TP9	Test Plow TPD-TPX
10-20	0.0130	0.0282
15-25	0.0184	0.0401
20-30	0.0076	0.0141
25-35	0.0055	0.0033
30-40	0.0076	0.0022
35-45	0.0130	0.0022
40-50	0.0130	0.0022
45-55	0.0173	0.0022
50-60	0.0282	0.0044
55-65	0.0510	0.0066
60-70	0.0586	0.0087

(7) Probabilities based on total length of crossing; only depths to 70 meters reported.

TABLE 2-6c

PROBABILITY OF WATER DEPTH CROSSING C (8)

Water Depth (M)	Test Plow TP14-TP9	Test Plow TP9-TP6	Test Plow TP6-TP1
10-20	0.0137	0	0.0364
15-25	0.0194	0	0.0592
20-30	0.0080	0	0.0615
25-35	0.0057	0	0.0478
30-40	0.0080	0	0.0250
35-45	0.0137	0	0.0478
40-50	0.0137	0	0.0740
45-55	0.0183	0.0524	0.0478
50-60	0.0296	0.1242	0.0160
55-65	0.0535	0.0775	0.0262
60-70	0.0615	0.0490	0.0159

(8) Probabilities based on total length of crossing; only depths to 70 meters reported.

TABLE 2-7a

PROBABILITY OF ICEBERG SCOUR CROSSING 2/A (9)

Iceberg Draft (M)	Section TPM-TPD	Section TPD-TPX
20	0	1.54E-3
25	0	1.59E-3
30	0.07E-3	0.86E-3
35	0.14E-3	0.22E-3
40	0.26E-3	0.26E-3
45	0.25E-3	0.17E-3
50	1.13E-3	0.38E-3
55	0.37E-3	0.12E-3
60	0.44E-3	0.44E-3
65	0.02E-3	0.04E-3
70	0.01E-3	0.03E-3
TOTAL:	2.69E-3	5.65E-3

(9) Calculated on the basis of an iceberg of draft X meters encountering a water depth of between X-10 and X meters.

TABLE 2-7b

PROBABILITY OF ICEBERG SCOUR CROSSING B (10)

Iceberg Draft (M)	Section TP14-TP9	Section TPD-TPX
20	0.45E-3	0.98E-3
25	0.47E-3	1.01E-3
30	0.29E-3	0.55E-3
35	0.23E-3	0.14E-3
40	0.58E-3	0.17E-3
45	0.64E-3	0.11E-3
50	1.44E-3	0.24E-3
55	0.62E-3	0.08E-3
60	1.84E-3	0.29E-3
65	0.18E-3	0.02E-3
70	0.12E-3	0.02E-3
TOTAL:	6.86E-3	3.61E-3

(10) Calculated on the basis of an iceberg of draft X meters encountering a water depth of between X-10 and X meters.

TABLE 2-7c

PROBABILITY OF ICEBERG SCOUR CROSSING C (11)

Iceberg Draft (M)	Section TP14-TP9	Section TP9-TP6	Section TP6-TP1
20	0.48E-3	0	1.27E-3
25	0.49E-3	0	1.50E-3
30	0.31E-3	0	2.39E-3
35	0.24E-3	0	2.04E-3
40	0.61E-3	0	1.89E-3
45	0.68E-3	0	2.37E-3
50	1.52E-3	0	8.19E-3
55	0.66E-3	1.89E-3	1.73E-3
60	1.93E-3	8.10E-3	1.04E-3
65	0.19E-3	0.27E-3	0.09E-3
70	0.12E-3	0.10E-3	0.03E-3
TOTAL:	7.23E-3	1.04E-2	2.25E-2

(11) Calculated on the basis of an iceberg of draft X meters encountering a water depth of between X-10 and X meters.

To obtain the annual expected number of scours, it is necessary to estimate the average number of icebergs reaching the crossings area. From Refs. 8 and 11, a conservative figure for the number of icebergs passing over the sill and entering the Strait would be roughly 75 per year. From Ref. 10, iceberg sightings tend to divide between the Labrador and Newfoundland portions of the Strait in roughly a 5:2 proportion. Also from Ref. 10, the east-west run of the Strait in the vicinity of the crossings area can be broken down into three areas of iceberg activity, with the proportion of sightings given in Table 2-8. Table 2-9 gives the average annual number of icebergs expected at each of the crossing sites, based on 75 icebergs per year entering the Strait. In all cases, the distribution of iceberg drafts is assumed to be identical to the distribution shown in Table 2-5. The annual expected number of scours is shown in Table 2-10 for the three crossing alternatives.

TABLE 2-8

PROPORTION OF ICEBERGS IN STRAIT
REACHING CROSSING SECTIONS (12)

Coordinates	Crossing Sections (13)	Proportion of Icebergs in Strait Reaching Crossing
56:20W - 56:37W	-----	1.0
56:37W - 56:54W	TP6-TP1 (Route C) TPD-TPX (Routes 2/A,B)	0.5
56:54W - 57:10W	TP14-TP9 (Routes B,C) TP9-TP6 (Route C) TP9-TPD (Route B) TPM-TPD (Route 2/A)	0.25

(12) From Ref. 10
(13) Approximate section location

TABLE 2-9

AVERAGE ANNUAL NUMBER OF ICEBERGS EXPECTED AT EACH CROSSING (14)

Route	Segment	#Icebergs (15)
2/A	TPM-TPD	13
	TPD-TPX	11
B	TP14-TP9	13
	TP9-TPD	13
	TPD-TPX	11
C	TP14-TP9	13
	TP9-TP6	5
	TP6-TP1	11

(14) Based on an average of 75 icebergs entering the Strait
(15) East-West division of icebergs according to Table 2-8; North-South division in 5:2 ratio (Ref. 10), with sections TP14-TP9, TP9-TPD, and TPM-TPD in northern half.

TABLE 2-10

ANNUAL EXPECTED NUMBER OF SCOURS FOR CROSSING ALTERNATIVES

Crossing	Segment	Prob. of Scour(16)	#Icebergs(17)	Expected # Scours (18)
2/A	TPM-TPD	2.69E-3	13	0.1
	TPD-TPX	5.65E-3	11	
B	TP14-TP9	6.86E-3	13	0.13
	TP9-TPD	0	13	
	TPD-TPX	3.61E-3	11	
C	TP14-TP9	7.23E-3	13	0.39
	TP9-TP6	1.04E-2	5	
	TP6-TP1	2.25E-2	11	

(16) From Tables 2-7a through 2-7c
(17) From Table 2-9
(18) Calculated as prob. of scour multiplied by the number of icebergs

3.0 SYSTEM AND CABLE RELIABILITY MODELS, TEST CASE RESULTS

The reliability model used to represent the HVDC connection from Churchill Falls to Newfoundland is similar to that chosen in Ref. 13, with the exception of the undersea cable segment. To facilitate the reliability calculations for alternative cable schemes, it is useful to divide the reliability model into an undersea cable model and a model of the remainder of the HVDC system. Sections 3.1 and 3.2 present the models and test case results for the remainder of the HVDC system; cable reliability models and test case results can be found in sections 3.3 and 3.4. The procedure used to merge the MW transfer-probability tables to reflect the entire HVDC system is given in section 3.5. Section 3.6 discusses how to reduce the composite MW transfer-probability tables to a single generating unit capacity and forced outage rate model.

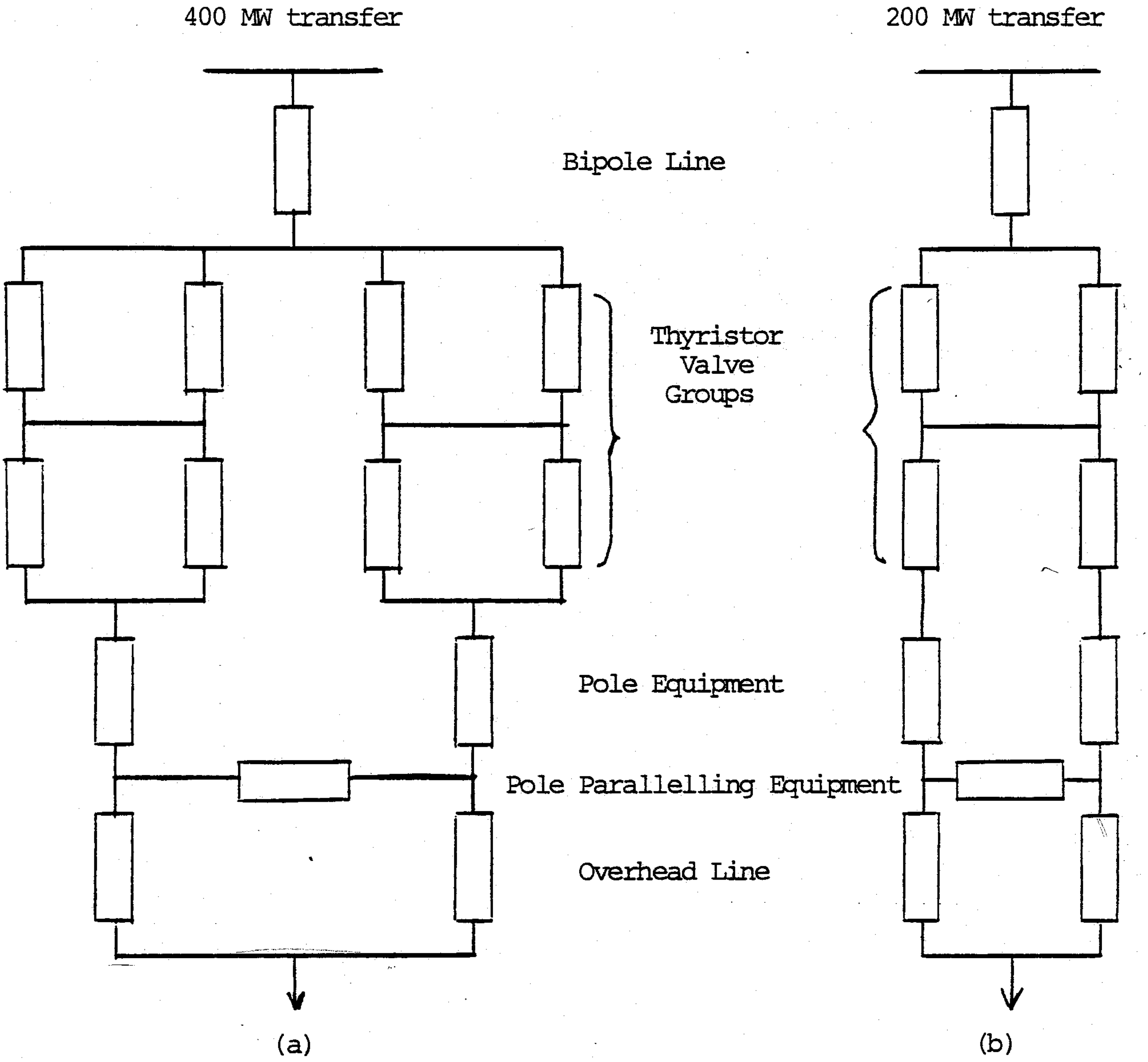
In analyzing the reliability of the entire system, three base cases were used, reflecting various loading and maintenance conditions:

1) 200 MW transfer
2) 400 MW transfer
3) 400 MW transfer, 1 valve group on maintenance

The uncertainty in cable failure rates and repair times suggests use of sensitivity studies on certain key parameters, resulting in several variations on the three test cases.

3.1 HVDC System Reliability Model

Figure 3-1 presents the reliability block diagrams for the overhead line, bipole line, and terminal equipment for both 200 and 400 MW transfer conditions. Figure 3-1a is similar to that presented in Section 3.1.1 of Reference 13, the difference being that no cables are shown in Figure 3-1.



(a)

(b)

<u>Figure 3-1</u>

Reliability Block Diagram
for
Overhead Line, Bipole, and Terminal Equipment

Since the primary concern of the present study is the reliability of the various undersea cable alternatives, it is possible to factor out the remainder of the HVDC system from the reliability studies. Reliability calculations for the three base cases described above were computed using PTI's Substation Reliability Program (SRPE). The resulting indices represent the reliability of the remainder of the HVDC system, and can be combined with the results of the cable reliability analyses using the technique described in section 3.5.

3.2 Reliability of Overhead Line, Bipole, and Terminal Equipment

Tables 3-1 through 3-3 present the results of the SRPE studies for the 200 MW and 400 MW transfer cases. The reliability of the HVDC system is presented in terms of the probability and frequency of various transfer levels; results do not include the effects of cable outages. For the 400 MW transfer condition with 1 valve group on maintenance, the maximum transfer that can be accommodated is 300 MW. As in the earlier studies reported in Ref. 13, the main contributor (not considering cable effects) to system unreliability was the bipole line section.

TABLE 3-1
200 MW Transfer Condition
HVDC System (w/o Cable Effects)

MW Transfer	Freq. (1/yr)	Prob.
200	---	.9918
100	13.58	.6427E-2
0	0.1624	.1790E-2

TABLE 3-2
400 MW Transfer Condition
HVDC System (w/o Cable Effects)

MW Transfer	Freq. (1/yr)	Prob.
400	---	.9875
300	18.95	.8477E-2
200	4.141	.2197E-2
100	.0357	.8750E-5
0	.1435	.1775E-2

TABLE 3-3
400 MW Transfer, 1 Valve Group on Maint.
HVDC System (w/o Cable Effects)

MW Transfer	Freq. (1/yr)	Prob.
300	---	.9907
200	13.93	.6394E-2
100	2.078	.1101E-2
0	.1481	.1786E-2

3.3 Submarine Cable Reliability Model

The primary focus of the present reliability study centered around the location and configuration of the undersea cables crossing the Strait of Belle Isle. Three alternative cable crossings were considered:

- Route 2/A (Forteau Point - Yankee Point)
- Route B (L'anse au Clair - Yankee Point)
- Route C (L'anse au Clair - Winter Cove)

For each of the locations, configurations of two and three cables were considered. In the latter case, the third cable was assumed to function as a spare cable, energized only in the event of loss of one or both of the remaining cables.

The reliability analysis of the various cable configurations is accomplished using Markov state space techniques. The state space diagrams for the two- and three-cable configurations are given in Figures 3-2a and 3-2b, respectively. Repairs are made only during the open season on the Strait; cable failures may occur throughout the year, although failures due to iceberg scour are assumed to occur only during the open season.

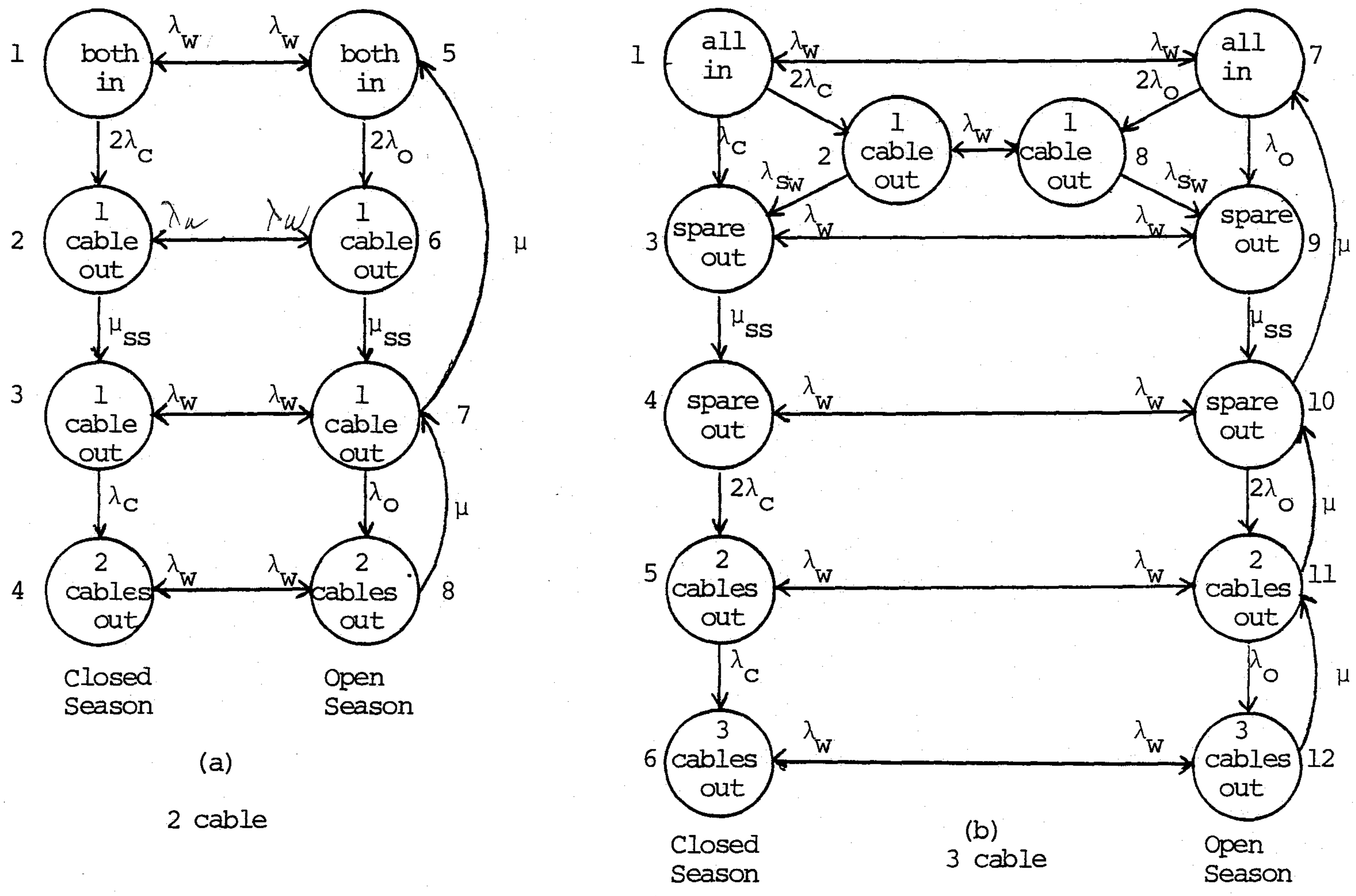


Figure 3-2

State Space Diagrams
for
2 and 3 cable configurations

Transition rates between states are given in Table 3-4. Sensitivity studies were performed on both the single cable failure rate and the cable repair time, as indicated by the ranges presented in the tables. The lower limit on cable failures assumed that no mechanical or electrical failures (apart from iceberg scour) would occur; an upper limit on the mechanical and electrical failure rate was set at 0.5 failures/100km-yr, as discussed in Section 2.1. Cable repair times were varied from 1 to 4 months, to take into account weather conditions and repair procedures.

TABLE 3-4

State Space Diagram Transition Rates

Rate	Crossing 2/A	Crossing B	Crossing C
λ_w	2	2	2
μ_{ss}	4	4	4
μ	$12 \rightarrow 3$ (1 mo.) (4 mos.)	$12 \rightarrow 3$ (1 mo.) (4 mos.)	$12 \rightarrow 3$ (1 mo.) (4 mos.)
λ_c	$0 \rightarrow .117$	$0 \rightarrow .186$	$0 \rightarrow .180$
λ_o	$.10 \rightarrow .217$	$.13 \rightarrow .316$	$.39 \rightarrow .570$
exposure	.234 100 km-yr	.372 100 km-yr	.359 100 km-yr

Note: all rates in units of yr^{-1}

λ_w = transition rate between closed and open season (and vice versa)

μ_{ss} = rate of outfitting supply ship (3 months required)

μ = repair time once supply ship is in place (1 month → 4 months)

λ_c = cable failure rate during closed season; does not consider failures due to iceberg scour; calculated as:

$$0.5 \frac{\text{faults}}{100\ \text{km-yr}} \times \text{cable exposure}$$

λ_o = cable failure rate during open season; considers all cable failure modes; calculated as:

$$\lambda_c + \text{failure rate due to iceberg scour}$$

3.4 Cable Reliability Test Case Results

A series of six cases were run for each of the three cable crossing sites:

1) Case 1 - cable failures due to iceberg scour only, 1 month repair time, two cable/two trench scheme.
2) Case 2 - cable failures due to iceberg scour only, 4 month repair time, two cable/two tranch scheme.
3) Case 3 - mechanical and electrical cable failures considered, 1 month repair time, two cable/two trench scheme.
4) Case 4 - mechanical and electrical cable failures considered, 4 month repair time, two cable/two trench scheme.
5) Case 5 - cable failures due to iceberg scour only, 1 month repair time, three cable/three trench scheme.
6) Case 6 - mechanical and electrical cable failures considered, 4 month repair time, three cable/three trench scheme.

Comparative results for the three crossing locations are given in Tables 3-5 through 3-10. In each table, the probability and frequency of entering each state is shown. Each state corresponds to a specific transfer capability, dependent upon the number of cables remaining in service. For the two cable configuration, the probability and frequency of individual transfer states are as follows:

0 MW: prob. $= p_4 + p_8$

freq. $= p_8\mu$

200 MW: prob. $= p_2 + p_3 + p_6 + p_7$

freq. $= 2(p_1\lambda_c + p_5\lambda_o)$

For the three cable configuration, the probability and frequency of individual transfer states are as follows:

0 MW: prob. $= p_6 + p_{12}$

freq. $= p_{12}\mu$

300 MW: prob. $= p_2 + p_5 + p_8 + p_{11}$

freq. $= 2(\lambda_c(p_1 + p_4) + \lambda_o(p_7 + p_{10}))$

TABLE 3-5

Case 1 Results
Crossing 2/A

STATE	PROB	FREQ(1/YR)
1	0.474246	0.948492
2	0.592807E-02	0.355684E-01
3	0.197602E-01	0.395205E-01
4	0.658675E-04	0.131735E-03
5	0.474246	1.04334
6	0.177842E-01	0.106705
7	0.790410E-02	0.111448
8	0.658675E-04	0.922145E-03

Crossing B

STATE	PROB	FREQ(1/YR)
1	0.467005	0.934011
2	0.758884E-02	0.455330E-01
3	0.252961E-01	0.505923E-01
4	0.109617E-03	0.219233E-03
5	0.467005	1.05543
6	0.227665E-01	0.136599
7	0.101185E-01	0.142974
8	0.109617E-03	0.153463E-02

Crossing C

STATE	PROB	FREQ(1/YR)
1	0.412078	0.824156
2	0.200888E-01	0.120533
3	0.669627E-01	0.133925
4	0.870515E-03	0.174103E-02
5	0.412078	1.14558
6	0.602664E-01	0.361598
7	0.267851E-01	0.385437
8	0.870515E-03	0.121872E-01

TABLE 3-6

Case 2 Results
Crossing 2/A

STATE	PROB	FREQ(1/YR)
1	0.451921	0.903841
2	0.564901E-02	0.338940E-01
3	0.414261E-01	0.828521E-01
4	0.100427E-02	0.200854E-02
5	0.451921	0.994225
6	0.169470E-01	0.101682
7	0.301280E-01	0.153653
8	0.100427E-02	0.502134E-02

Crossing B

STATE	PROB	FREQ(1/YR)
1	0.438915	0.877830
2	0.713237E-02	0.427942E-01
3	0.523041E-01	0.104608
4	0.164837E-02	0.329674E-02
5	0.438915	0.991948
6	0.213971E-01	0.128383
7	0.380393E-01	0.195142
8	0.164837E-02	0.824185E-02

Crossing C

STATE	PROB	FREQ(1/YR)
1	0.347210	0.694420
2	0.169265E-01	0.101559
3	0.124128	0.248255
4	0.117357E-01	0.234714E-01
5	0.347210	0.965244
6	0.507795E-01	0.304677
7	0.902746E-01	0.486580
8	0.117357E-01	0.586785E-01

TABLE 3-7

Case 3 Results
Crossing 2/A

STATE	PROB	FREQ(1/YR)
1	0.388978	0.868976
2	0.288519E-01	0.173111
3	0.765261E-01	0.162006
4	0.564423E-02	0.112885E-01
5	0.434488	1.05754
6	0.410453E-01	0.246272
7	0.232991E-01	0.331243
8	0.116745E-02	0.163444E-01

Crossing B

STATE	PROB	FREQ(1/YR)
1	0.344745	0.817735
2	0.401962E-01	0.241177
3	0.103031	0.225227
4	0.120274E-01	0.240548E-01
5	0.408868	1.07614
6	0.564661E-01	0.338797
7	0.322208E-01	0.461273
8	0.244547E-02	0.342365E-01

Crossing C

STATE	PROB	FREQ(1/YR)
1	0.310616	0.733055
2	0.470817E-01	0.282490
3	0.126883	0.276604
4	0.154193E-01	0.308385E-01
5	0.366527	1.15090
6	0.853341E-01	0.512005
7	0.441386E-01	0.643099
8	0.399982E-02	0.559975E-01

TABLE 3-8

Case 4 Results

Crossing 2/A

STATE	PROB	FREQ(1/YR)
1	0.334731	0.747789
2	0.248282E-01	0.148969
3	0.122679	0.259711
4	0.177622E-01	0.355245E-01
5	0.373894	0.910059
6	0.353211E-01	0.211927
7	0.801990E-01	0.418398
8	0.105855E-01	0.529277E-01

Crossing B

STATE	PROB	FREQ(1/YR)
1	0.278171	0.659822
2	0.324339E-01	0.194603
3	0.154494	0.337725
4	0.349007E-01	0.698014E-01
5	0.329911	0.868326
6	0.455619E-01	0.273372
7	0.103994	0.552834
8	0.205327E-01	0.102664

Crossing C

STATE	PROB	FREQ(1/YR)
1	0.229453	0.541509
2	0.347793E-01	0.208676
3	0.183468	0.399959
4	0.523001E-01	0.104600
5	0.270754	0.850169
6	0.630365E-01	0.378219
7	0.130421	0.726445
8	0.357881E-01	0.178940

TABLE 3-9

Case 5 Results
Crossing 2/A

STATE	PROB	FREQ(1/YR)
1	0.462241	0.924482
2	0.240836E-08	0.211021E-04
3	0.866965E-02	0.520179E-01
4	0.288953E-01	0.577907E-01
5	0.192600E-03	0.385201E-03
6	0.160500E-05	0.321001E-05
7	0.462241	1.06315
8	0.105510E-04	0.924482E-01
9	0.259984E-01	0.155990
10	0.115560E-01	0.164095
11	0.192600E-03	0.271566E-02
12	0.160500E-05	0.224700E-04

Crossing B

STATE	PROB	FREQ(1/YR)
1	0.451933	0.903866
2	0.306105E-08	0.268209E-04
3	0.110192E-01	0.661153E-01
4	0.367262E-01	0.734525E-01
5	0.318236E-03	0.636472E-03
6	0.344756E-05	0.689511E-05
7	0.451933	1.08012
8	0.134105E-04	0.117503
9	0.330442E-01	0.198265
10	0.146878E-01	0.209448
11	0.318236E-03	0.449668E-02
12	0.344756E-05	0.482658E-04

Crossing C

STATE	PROB	FREQ(1/YR)
1	0.377790	0.755581
2	0.767660E-08	0.672624E-04
3	0.276343E-01	0.165806
4	0.921032E-01	0.184206
5	0.239425E-02	0.478849E-02
6	0.778130E-04	0.155626E-03
7	0.377790	1.19760
8	0.336312E-04	0.294677
9	0.828694E-01	0.497216
10	0.368346E-01	0.544415
11	0.239425E-02	0.344532E-01
12	0.778130E-04	0.108938E-02

TABLE 3-10

Case 6 Results

Crossing 2/A

STATE	PROB	FREQ(1/YR)
1	0.274499	0.645348
2	0.733449E-05	0.642648E-01
3	0.311964E-01	0.187179
4	0.147296	0.329059
5	0.410945E-01	0.869970E-01
6	0.590653E-02	0.118131E-01
7	0.322674	0.855409
8	0.159844E-04	0.140055
9	0.454061E-01	0.272436
10	0.102137	0.555011
11	0.262649E-01	0.137024
12	0.350251E-02	0.175125E-01

Crossing B

STATE	PROB	FREQ(1/YR)
1	0.208338	0.532930
2	0.884962E-05	0.775404E-01
3	0.375880E-01	0.225528
4	0.167057	0.396260
5	0.710796E-01	0.155380
6	0.159277E-01	0.318554E-01
7	0.266465	0.785538
8	0.192220E-04	0.168424
9	0.546273E-01	0.327764
10	0.122954	0.692476
11	0.466174E-01	0.247818
12	0.931730E-02	0.465865E-01

Crossing C

STATE	PROB	FREQ(1/YR)
1	0.154863	0.393351
2	0.636861E-05	0.558018E-01
3	0.367044E-01	0.220226
4	0.180838	0.426778
5	0.985725E-01	0.214888
6	0.290156E-01	0.580312E-01
7	0.196676	0.729667
8	0.255904E-04	0.224223
9	0.682810E-01	0.409686
10	0.139980	0.859480
11	0.748932E-01	0.417155
12	0.201441E-01	0.100720

3.5 Merging of Cable and System Reliability Indices

The MW transfer-probability tables for the remainder of the HVDC system presented in Tables 3-1 through 3-3 can be modified to include the effects of cable outages using the results obtained in the previous section. To include the effects of cable outages, the following adjustments are made to the base case MW transfer-probability tables:

- Add the probability (or frequency) of all cables out to the 0 MW transfer state.
- In the 400 MW transfer case (no maintenance), add the probability (or frequency) of 1 cable out (2 cables in the three cable configuration) to the 300 MW transfer state.
- For all cases, the probability of maximum transfer is given as one minus the sum of all lower transfer probabilities.

The above calculations are approximate in that the system transfer probabilities are not multiplied by the availability of the cables, giving a slight overestimate of the probability and frequency of the reduced transfer states. The error is primarily in the third significant digit of each transfer state probability and frequency, and is ignored in the interests of simplified calculations.

Tables 3-11 through 3-16 present the results of the various cases studied, after merging the MW transfer-probability tables for the cables and the remainder of the HVDC system. Several observations can be made concerning the various cable alternatives:

- Cable crossing locations 2/A and B have essentially the same probability and frequency of partial transfer, with location C being somewhat less reliable; the principal cause of the difference in reliability can be attributed to the increased risk of iceberg scour at crossing C.
- For 400 MW loading conditions, the ability to achieve full transfer is somewhat degraded due to single cable outages.
- The reliability of the various cable alternatives is quite sensitive to both the cable failure rate and the repair time.

TABLE 3-11
CASE 1
ONLY CABLE OUTAGES DUE TO ICEBERG SCOUR
1 MONTH CABLE REPAIR TIME

Crossing 2/A			Crossing B			Crossing C		
200 MW Transfer			200 MW Transfer			200 MW Transfer		
MW	Freq	Prob	MW	Freq	Prob	MW	Freq	Prob
200	---	.9917	200	---	.9916	200	---	.9900
100	13.58	.6427E-2	100	13.58	.6427E-2	100	13.58	.6427E-2
0	.1632	.1922E-2	0	.1637	.2009E-2	0	.1729	.3531E-2
400 MW Transfer			400 MW Transfer			400 MW Transfer		
MW	Freq	Prob	MW	Freq	Prob	MW	Freq	Prob
400	---	.9360	400	---	.9216	400	---	.8117
300	19.04	.5986E-1	300	19.07	.7425E-1	300	19.27	.1826
200	4.141	.2197E-2	200	4.141	.2197E-2	200	4.141	.2197E-2
100	.0357	.8750E-5	100	.0357	.8750E-5	100	.0357	.8750E-5
0	.1443	.1907E-2	0	.1448	.1994E-2	0	.1540	.3516E-2
400 MW (w/maint)			400 MW (w/maint)			400 MW (w/maint)		
MW	Freq	Prob	MW	Freq	Prob	MW	Freq	Prob
300	---	.9906	300	---	.9905	300	---	.9890
200	13.93	.6394E-2	200	13.93	.6394E-2	200	13.93	.6394E-2
100	2.078	.1101E-2	100	2.078	.1101E-2	100	2.078	.1101E-2

TABLE 3-12
CASE 2
ONLY CABLE OUTAGES DUE TO ICEBERG SCOUR
4 MONTH CABLE REPAIR TIME

Crossing 2/A			Crossing B			Crossing C		
200 MW Transfer			200 MW Transfer			200 MW Transfer		
MW	Freq	Prob	MW	Freq	Prob	MW	Freq	Prob
200	---	.9898	200	---	.9885	200	---	.9683
100	13.58	.6427E-2	100	13.58	.6427E-2	100	13.58	.6427E-2
0	.1654	.3798E-2	0	.1673	.5087E-2	0	.1976	.2526E-1
400 MW Transfer			400 MW Transfer			400 MW Transfer		
MW	Freq	Prob	MW	Freq	Prob	MW	Freq	Prob
400	---	.8914	400	---	.8654	400	---	.6819
300	19.04	.1026	300	19.06	.1273	300	19.29	.2906
200	4.141	.2197E-2	200	4.141	.2197E-2	200	4.141	.2197E-2
100	.0357	.8750E-5	100	.0357	.8750E-5	100	.0357	.8750E-5
0	.1465	.3784E-2	0	.1484	.5072E-2	0	.1787	.2529E-1
400 MW (w/maint)			400 MW (w/maint)			400 MW (w/maint)		
MW	Freq	Prob	MW	Freq	Prob	MW	Freq	Prob
300	---	.9887	300	---	.9875	300	---	.9672
200	13.93	.6394E-2	200	13.93	.6394E-2	200	13.93	.6394E-2
100	2.078	.1101E-2	100	2.078	.1101E-2	100	2.078	.1101E-2
0	.1511	.3795E-2	0	.1530	.5083E-2	0	.1833	.2526E-1

TABLE 3-13
CASE 3
ALL TYPES OF CABLE OUTAGES CONSIDERED
1 MONTH CABLE REPAIR TIME

Crossing 2/A			Crossing B			Crossing C		
200 MW Transfer			200 MW Transfer			200 MW Transfer		
MW	Freq	Prob	MW	Freq	Prob	MW	Freq	Prob
200	---	.9850	200	---	.9773	200	---	.9724
00	13.58	.6427E-2	100	13.58	.6427E-2	100	13.58	.6427E-2
0	.1764	.8602E-2	0	.1918	.1626E-1	0	.2104	.2121E-1
400 MW Transfer			400 MW Transfer			400 MW Transfer		
MW	Freq	Prob	MW	Freq	Prob	MW	Freq	Prob
400	---	.8110	400	---	.7412	400	---	.6648
300	19.23	.1782	300	19.34	.2403	300	19.48	.3118
200	4.141	.2197E-2	200	4.141	.2197E-2	200	4.141	.2197E-2
100	.0357	.8750E-5	100	.0357	.8750E-5	100	.0357	.8750E-5
0	.1575	.8587E-2	0	.1729	.1625E-1	0	.1915	.2119E-1
400 MW (w/maint)			400 MW (w/maint)			400 MW (w/maint)		
MW	Freq	Prob	MW	Freq	Prob	MW	Freq	Prob
300	---	.9839	300	---	.9762	300	---	.9713
200	13.93	.6394E-2	200	13.93	.6394E-2	200	13.93	.6394E-2
100	2.078	.1101E-2	100	2.078	.1101E-2	100	2.078	.1101E-2
0	.1621	.8598E-2	0	.1775	.1626E-1	0	.1961	.2121E-1

TABLE 3-14
CASE 4
ALL TYPES OF CABLE FAILURES CONSIDERED
4 MONTH CABLE REPAIR TIME

Crossing 2/A			Crossing B			Crossing C		
200 MW Transfer			200 MW Transfer			200 MW Transfer		
MW	Freq	Prob	MW	Freq	Prob	MW	Freq	Prob
200	---	.9634	200	---	.9364	200	---	.9037
100	13.58	.6427E-2	100	13.58	.6427E-2	100	13.58	.6427E-2
0	.1942	.3014E-1	0	.2240	.5722E-1	0	.2698	.8988E-1

Crossing 2/A			Crossing B			Crossing C		
400 MW Transfer			400 MW Transfer			400 MW Transfer		
MW	Freq	Prob	MW	Freq	Prob	MW	Freq	Prob
400	---	.6962	400	---	.5956	400	---	.4877
300	19.19	.2715	300	19.26	.3450	300	19.34	.4202
200	4.141	.2197E-2	200	4.141	.2197E-2	200	4.141	.2197E-2
100	.0357	.8750E-5	100	.0357	.8750E-5	100	.0357	.8750E-5
0	.1753	.3013E-1	0	.2051	.5721E-1	0	.2509	.8987E-1

Crossing 2/A			Crossing B			Crossing C		
400 MW (w/maint)			400 MW (w/maint)			400 MW (w/maint)		
MW	Freq	Prob	MW	Freq	Prob	MW	Freq	Prob
300	---	.9624	300	---	.9353	300	---	.9026
200	13.93	.6394E-2	200	13.93	.6394E-2	200	13.93	.6394E-2
100	2.078	.1101E-2	100	2.078	.1101E-2	100	2.078	.1101E-2
0	.1799	.3014E-1	0	.2097	.5722E-1	0	.2555	.8988E-1

TABLE 3-15
CASE 5
ONLY CABLE OUTAGES DUE TO ICEBERG SCOUR
1 MONTH CABLE REPAIR TIME (3 CABLES)

CROSSING 2/A 400 MW Transfer			CROSSING B 400 MW Transfer			CROSSING C 400 MW Transfer		
MW	Freq	Prob	MW	Freq	Prob	MW	Freq	Prob
400	---	.9871	400	---	.9869	400	---	.9826
300	19.04	.8873E-2	300	19.07	.9127E-2	300	19.27	.1330E-1
200	4.141	.2197E-2	200	4.141	.2197E-2	200	4.141	.2197E-2
100	.0357	.8750E-5	100	.0357	.8750E-5	100	.0357	.8750E-5
0	.1435	.1778E-2	0	.1435	.1782E-2	0	.1444	.1931E-2

TABLE 3-16
CASE 6
ALL TYPES OF CABLE OUTAGES CONSIDERED
4 MONTH CABLE REPAIR TIME (3 CABLES)

CROSSING 2/A			CROSSING B			CROSSING C		
400 MW Transfer			400 MW Transfer			400 MW Transfer		
MW	Freq	Prob	MW	Freq	Prob	MW	Freq	Prob
400	---	.9107	400	---	.8446	400	---	.7650
300	19.23	.7586E-1	300	19.34	.1262	300	19.45	.1819
200	4.141	.2197E-2	200	4.141	.2197E-2	200	4.141	.2197E-2
100	.0357	.8750E-5	100	.0357	.8750E-5	100	.0357	.8750E-5
0	.1540	.1118E-1	0	.1715	.2703E-1	0	.2039	.5094E-1

3.6 Single Unit Equivalent Models

The MW transfer-probability tables computed in the previous section can be reduced to equivalent single generating unit reliability models for inclusion in a generation reliability program. The reduced model consists of a single unit equivalent forced outage rate and maximum unit capacity. The technique for creating single unit models recognizes the reduced energy capability of the partial outage states by reducing the maximum unit capacity (representing the maximum unit transfer capability).

Given a MW transfer-probability table as shown below:

MW Transfer	Probability	
C_0	p_0	C_0 = full transfer
C_1	p_1	
C_2	2	
.	.	
.	.	
C_n	p_n	C_n = 0 MW transfer

The single unit equivalent MW size is:

$$\begin{aligned} C_{eq} = C_0 - ((C_0 - C_1) * p_1 &+ \\ (C_0 - C_2) * p_2 &+ \\ \ldots + (C_0 - C_{n-1}) * p_{n-1}) & \end{aligned}$$

The single unit equivalent forced outage rate is given as:

$$F.O.R.\ (\%) = p_n * 100\%$$

Table 3-17 summarizes the single unit equivalent forced outage models for the cases reported in the previous section.

TABLE 3-17
SINGLE UNIT EQUIVALENT MODELS

	200 MW		400 MW		400 MW (w/maint)	
Case	MW	FOR	MW	FOR	MW	FOR
1A	199.4	.192	393.6	.191	299.1	.192
1B	199.4	.201	392.1	.199	299.1	.201
1C	199.4	.353	381.3	.352	299.1	.353
2A	199.4	.380	389.3	.378	299.1	.380
2B	199.4	.509	386.4	.507	299.1	.509
2C	199.4	2.53	370.5	2.52	299.1	2.53
3A	199.4	.860	381.7	.859	299.1	.860
3B	199.4	1.63	375.5	1.63	299.1	1.63
3C	199.4	2.12	368.4	2.12	299.1	2.12
4A	199.4	3.01	372.4	3.01	299.1	3.01
4B	199.4	5.72	365.1	5.72	299.1	5.72
4C	199.4	8.99	357.5	8.99	299.1	8.99
5A			398.7	.178		
5B			398.6	.178		
5C			398.2	.193		
6A			391.9	1.12		
6B			386.9	2.70		
6C			381.4	5.10		

Note: All forced outage rates in percent.
Case subscripts: A = Crossing 2/A
B = Crossing B
C = Crossing C

4.0 REFERENCES

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6) "A Survey of the Reliability of HVDC Systems Throughout the World During 1981-1982," J. Knudsen, O. Skogheim, P.F. Albrecht, CIGRE 14-06, 1984.

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8) "Strait of Belle Isle Iceberg Scour Risk Study," report prepared by Lemberg Consultants (Canada) Inc., February, 1982.

9) Memorandum Report on the "Analysis of the Risk of Iceberg Scour to a Power Cable Across the Strait of Belle Isle," D.H. Wagner Associates, February 2, 1982.

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Belle Isle," Department of Transport, Ice Forecasting Central, June 10, 1968.

11) "Estimates of Iceberg Scour Probabilities in the Strait of Belle Isle Using the Monte Carlo Technique," H.G. Miller, October, 1981.

12) Final Report on "Strait of Belle Isle Crossing HVDC Transmission Submarine Cable Scheme 1984 Program," Volume III (Plates), Lower Churchill Development Corporation Limited, December, 1984.

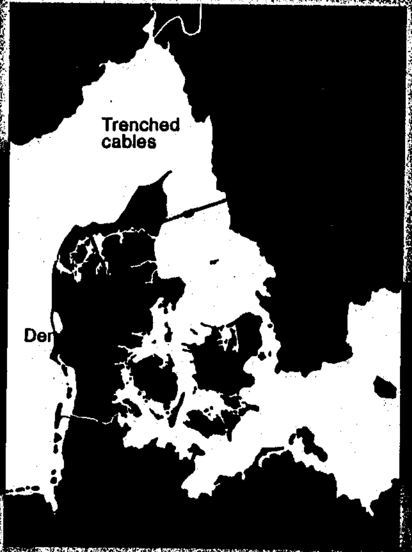
13) "Newfoundland and Labrador Hydro HVDC Project: HVDC Link Reliability Studies," prepared by Power Technologies, Inc., Report No. R64-81, November, 1981.

APPENDIX 1

Trenching Cables

For further information concerning the Danish trenching system, please contact:

ELSAM
Transmission Line Department
DK-7000 Fredericia
Telephone: +45 5 562500
Telex: DK 51151

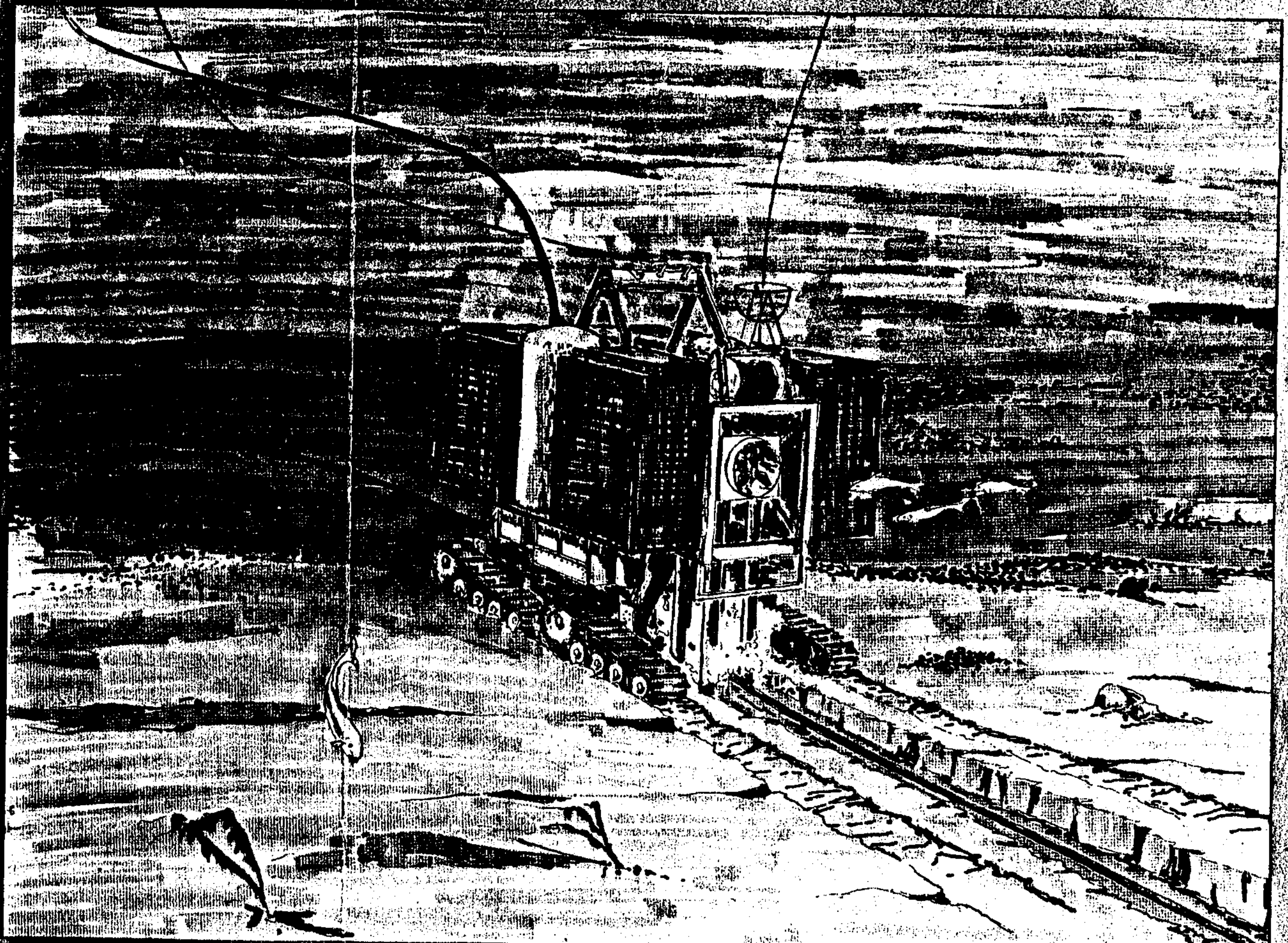


The trenching system has been developed by engineers employed by ELSAM, the Jutland-Funen Power Pool. ELSAM supplies the electricity consumed in the western part of Denmark (approx. 3 million inhabitants). ELSAM was founded in 1956 by the seven power companies in Jutland and on Funen. Operation and development of the generating and main transmission system are coordinated by ELSAM. Power station engineering assistance is made available to the Partners of ELSAM, the seven Jutland-Funen power companies. ELSAM is responsible for financing and fuel purchasing, and for interconnections and agreements with power supply undertakings outside Jutland-Funen.

The power stations are owned by local electricity companies, which are either municipal, co-operatives or partnerships.

TRENCHING

Cables and Pipes



ELSAM · Denmark

During recent years Danish engineers have developed an efficient, quick and inexpensive remote-controlled unit for trenching cables and pipes into the sea bed in order to protect these against damage. The unit has been modified concurrently with the performance of a number of practical tasks.

After trenching 300 km of cable it can be documented:

- that the unit is very suitable for trenching telecommunication as well as high voltage transmission cables
- that the remote control is so efficient that there is no risk of damaging the cables during trenching
- that it is also possible to work even if the sea bed is very soft or stony
- that the unit can carry out 120 m of trenching per hour.

It was the laying of two 250 kV cables in the Skagerrak between Denmark and Norway in 1976 and 1977 which started the Danish development. The cables were soon damaged by the heavy fishing tackle of the trawlers. No suitable trenching equipment existed on the market. Danish engineers therefore started to develop a trenching unit.

Trenching Unit

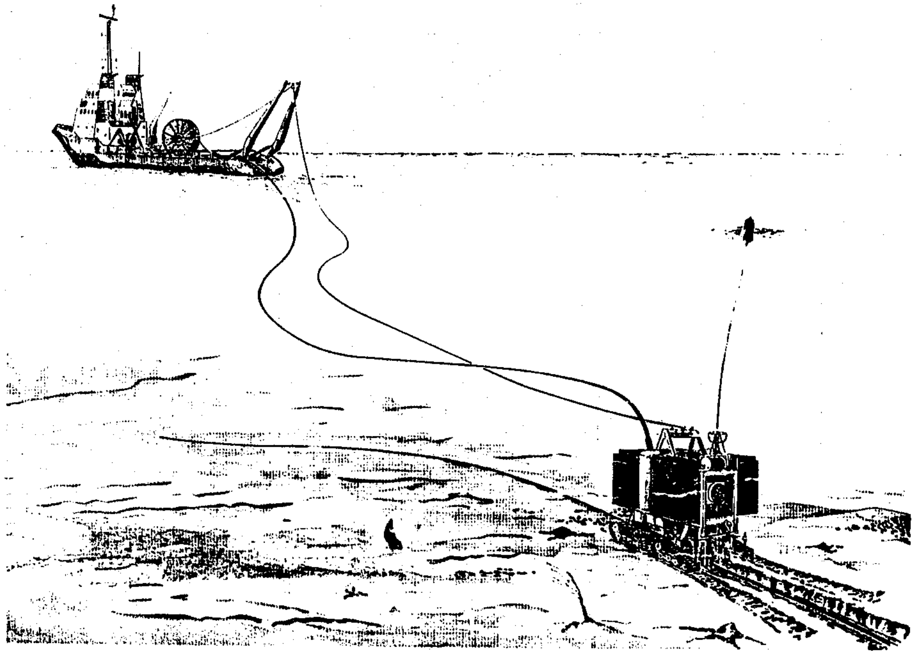
Their efforts led to the development of a remote controlled, hydraulically driven excavator. The excavator is lowered onto the sea bed by means of an A-frame on the support vessel.

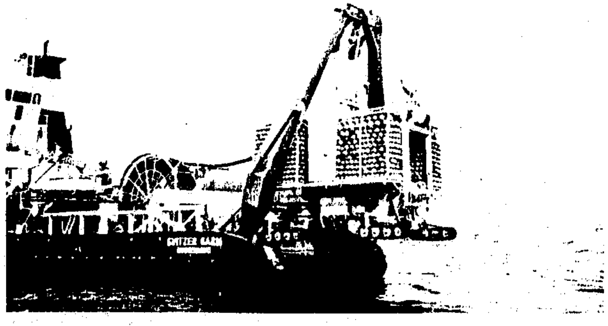
On the sea bed the excavator moves on four tracks powered and steered by hydraulic motors.

The excavator is positioned over the cable by means of electric sensors. The excavator is steered by remote control via the sensor system and underwater video camera. Control of the trench is made in the same way. All signals from the sensor and video systems are transmitted back to the technicians on board the support vessel. From here also the weight of the excavator is adjusted by means of buoyancy tanks in accordance with the prevailing bottom conditions.

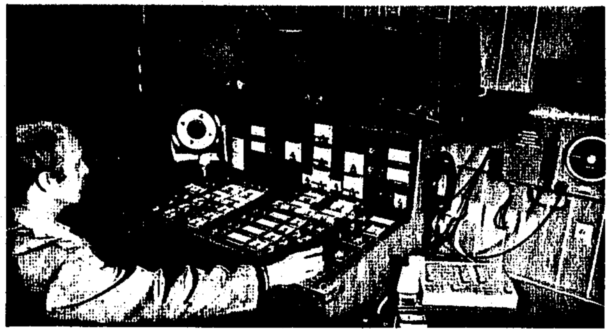
The trenching is carried out by a combination of water jets and propeller pumps or air-lift-pumps whereby the sea bed material is pumped away from under the cable, and a ditch is made into which the cable will fall by its own weight. The excavator is able to work in almost every type of sea bed.

The trenching unit is handled by a 40 tons A-frame mounted on the support vessel. The support ship furthermore carries 20' containers holding a complete power pack, a furnished control room for operating the unit, workshops, etc., and an umbilical reel. The support vessel must furthermore be equipped with a joystick control system to make it possible to hold the ship in position during the operation. 6-8 men are necessary for operating the trenching unit.

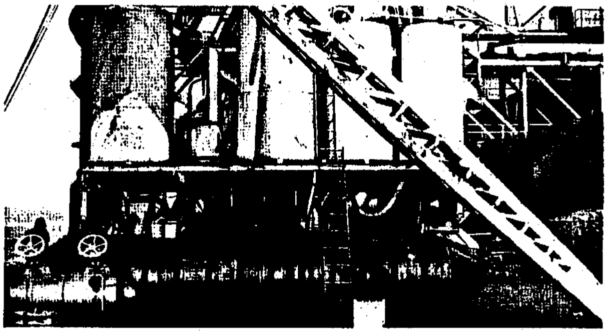




The trenching unit during launching
Displacement: 35 tons
Max. working depth: Performed 160 m. Designed for 350 m
Sea state: 4-5
Buoyancy: + 1 ton to – 5 tons
Guiding system: Electric sensors, underwater television
Size of trench: Approx. 1 m wide 1 m deep
Production rate: 2 metres per minute depending on sea bed condition
The trenching is normally carried out on a 24-hour-a-day basis.



From the control room the trenching unit is followed by means of signals from sensors placed at both ends of the unit. Pictures are transmitted by two cameras on the unit. All functions are controlled from the control panel.



The trenching unit normally moves on tracks. On soft sea bed the tracks are replaced by two large Archimedean screws. The change-over takes 24 hours in habour. The suction pipes are available in different sizes. They can also be replaced within 24 hours.

References:

The trenching unit has carried out the following operations.

Skagerrak cables (2 × 250 kV - HVDC):
1977: 2.5 km
1978: 70 km at water depths 10-80 m (air-lift-pumps)
1979: 20 km at water depths 80-160 m (propeller pumps)

Due to migrating sand waves the cables have had to be retrenched. This has been done in sections of 25 km each year during the period 1979-1982.

Bornholm cables (3 × 60 kV - AC)
1980: 120 km

Miscellaneous:

Various sections of telecommunication cables in the North Sea.