Q. Please provide all studies, expert opinions (including CESI of Italy) and any comparative statistics you have in Canada (outside NL) confirming the life expectancy of the Mass Impregnated (MI) cables for the SOBI Crossing.

A. The expert report attached as DD-NLH-067 Attachment 1 confirms the reasonableness of a 50 year design life for the Strait of Belle Isle cable system. In addition to providing a review of existing major DC submarine cable systems, the report discusses the factors that influence the working life of a mass impregnated cable.

The report concludes:

> *"In summary, results show that a 50 year design life is a reasonable expectation and is achievable."*

Cabletricity

Strait of Belle Isle

350 kV DC Submarine Cable System

Design Life

Submitted to: Nalcor Energy

By: Cabletricity Connections Ltd.

Date: April 9, 2012

Cabletricity Report 2012-3

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Acknowledgement

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Contents

1. Introduction

Nalcor's Request for Proposal No. LC-SB-003 was issued on August 11, 2012 for the design, supply and installation of a 350 kV dc submarine cable system across the Strait of Belle Isle (SOBI) between Labrador and Newfoundland. Exhibit 1B, section 4.2.6 Design Life, stated: "The HVDC cables shall have a design life of fifty (50) years continuous DC operation at rated capacity".

The purpose of this report is to describe why expectations of a 50 year cable system design life are realistic and to describe the process by which the EPC Contractor will demonstrate fulfillment. It is noteworthy that design, or technical lifetime, may be different than economic lifetime, which is based on commercial considerations compared to actual longevity.

This report begins with a review of global experience with similar cables, then examines the fundamental engineering determinants of longevity, discusses the factors that can influence lifetime and finally examines results of work by others on the subject.

2. Experience

One approach to demonstrating the validity of expectations for a 50 year design life is to review past installations of a similar nature. Table 1 provides a 58 year long list of major submarine cable projects using mass impregnated (MI) insulation, as planned for the SOBI crossing.

Cables with MI insulation were selected for SOBI because they have a long record of excellent field-proven performance for high voltage dc applications. They are manufactured by applying highly refined laminar insulating papers to a central conductor, drying and impregnating with high viscosity insulating fluid in a large vacuum tank, sealing with a lead alloy sheath, applying an anticorrosion jacket and finishing with external galvanized steel armour wires. Although manufacturing processes have not changed fundamentally during the last five decades, insulation materials have been refined. Modern computerized industrial process controls and advanced sensors, such as continuous ultrasonic and X-ray dimension measurements, have also been applied. This has ultimately led to improved production quality assurance. In addition, industry standards have been developed and improved, whereas they were absent before 1980[1]. It can therefore be expected that modern cables would have higher quality than early products, suggesting longer life.

The writer is unaware of any reports in the technical literature of MI cable internal failures due to spontaneous insulation breakdown. Most in-service failures have been due to third party damage by

[1] CIGRE WG 21.02, Recommendations for Tests on DC Cables for a Rated Voltage up to 600 KV, Electra No. 72, 1980.

vessel anchors and fishing activity, or due to cable damage arising from installation difficulties, which may not have been immediately apparent[2].

Table 1: Listing of the World's Major DC Submarine Cable Links using MI Cables

Name of Link	Date	Voltage (kV)	Power (MW)	Cable Length (km)	Supplier
Gotland I (Denmark)	1954-1986	100	20	100	ABB
England-France I	1961-1981	100	160	130	Nexans
Italy-Sardinia-Corsica	1965	200	200	119	Prysmian
Vancouver Island I (Canada)	1969	300	156	81	Nexans
Skagerrak I (Norway-Denmark)	1975	250	250	130	ABB/Nexans
Skagerrak II (Norway-Denmark)	1977	250	250	130	ABB/Nexans
Gotland II (Denmark)	1983	150	130	95	ABB
England-France II	1984	270	2000	200	Nexans/Prysmian
Gotland III (Denmark)	1986	150	260	97	ABB
Konti-Skan I (Denmark-Sweden)	1988	285	300	66	ABB
Fenno-Skan I (Sweden-Finland)	1989	400	500	200	ABB/Nexans
Konti-Skan II (Denmark-Sweden)	1991	285	250	64	ABB
Cook Strait II (New Zealand)	1991	350	500	120	ABB/Nexans
Skagerrak III (Nor-Den)	1993	350	500	125	Nexans
Baltic Cable (Sweden)	1994	450	600	250	ABB
Haenam-Jeju I (S Korea)	1997	180	300	101	Nexans
Swepol (Sweden-Poland)	1999	450	600	253	ABB
Greta (Italy-Greece)	2001	400	500	160	Prysmian
Moyle (Scotland-Ireland)	2001	250	500	126	Nexans
BassLink (Australia)	2006	400	500	283	Prysmian
Neptune (USA)	2007	500	660	102	Prysmian
Norned (Norway-Netherlands)	2007	450	700	1200	ABB/Nexans
Sapei (Sardinia-Italy)	2009	500	1000	420	Prysmian
Stora Balt (Denmark)	2009	400	600	61	ABB
Britned (UK-Netherlands)	2011	450	1000	520	ABB
Cometa	2011	250	400	480	Nexans
Fenno-Skan II	2012	500	800	200	Nexans
Jindo-Jeju (S Korea)	2012	250	400	119	LS Cable

Referring to Table 1, experience with the 300 kV dc Vancouver Island cables appears to be most representative of Strait of Belle Isle application and lifetime expectations[3]. Since commissioning in 1969 they have only experienced failures due to external hazards. Two of the original three cables remain in service but the third was abandoned in 2008 as a result of external third party damage. Estimated costs to repair were determined to be excessive, considering declining converter availability and alternative transmission with a newly installed 242 kV ac submarine cable system. Following a 1991 cable repair due

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[2] CIGRE WG B1.21, Third-Party Damage to Underground and Submarine Cables, Technical Brochure 398, Dec. 2009.

[3] The 300 kV Direct Current Submarine Cables Transmission between British Columbia and Vancouver Island, I Eyraud, L R Horne, CIGRE 1970 Session, Paper 21-07.

to external damage, condition assessment testing was done on samples, and concluded that the insulation was in near original condition after 23 years of service[4].

The long list of later submarine cable projects in Table 1 runs from 1954 to the present, demonstrating steadily increasing voltages and transmission capacities enabled by advancing technology. If the Vancouver Island cables have performed well using 1960's manufacturing technology, it is reasonable to expect that modern manufacturing technologies will produce cables with even greater longevity.

The oldest project in Table 1 is the 1954 vintage 100 kV Gotland 1 link. The original cables were uprated to 150 kV in 1983 and then replaced in 1986 by the Gotland 3 expansion, not due to poor performance, but because of load growth[5]. After 32 years of service, tests were done on the removed cable, showing it to be in almost as-new condition.[6] This included 16 years of elevated voltage operation at 150 kV, a level for which it was not originally designed.

Cables for the second oldest 100 kV England-France link were replaced in 1981 to meet higher capacity requirements, not because of aging.

The third oldest 200 kV Italy-Sardinia-Corsica cables remain in service after 47 years, as do all the later cables in Table 1.

3. Fundamentals

MI submarine cables experience several different forms of aging, as summarized below. If properly managed during execution of the EPC contract, none should threaten a 50 year design lifetime.

3.1 Electrical Aging

The main cable component affected by electrical aging is the central 350 kV insulation. Type tests described in Electra No. 189[7] prescribe application of a test voltage 1.8 times the normal operating voltage, for a total of 30 days. Based on the rather inexact voltage power law, this is apparently equivalent to about 40 years of in-service aging at the normal operating voltage.

$$V^n \cdot t = constant, \text{ where}$$

[4] J Jue, Discussions on Questions 6-10 re State of Art of Submarine Cables, Special Report for Group 21, CIGRE 1994 Session.

[5] The Gotland HVDC Link; http://www.abb.com/industries/ap/db0003db004333/8e63373c2cdc1cdac125774a0032c5ed.aspx (retrieved March 2012)

[6] G Hjalmarsson, J Thoren, et al, After-service analysis of the 32-year-old HVDC cable Gotland 1; CIGRE 1992 session paper 21-302.

[7] CIGRE WG 21.02, Recommendations for Tests on DC Cables for a Rated Voltage up to 800 KV, Electra No. 189, April 2000.

V : *voltage*

t : *time (days)*

n : *life exponent from voltage versus time-to-breakdown tests*

Vdc : *test voltage*

$Vdc = V_0 \cdot K_1$ *, where*

V_0 *:* *system voltage*

K_1 *:* *deterioration coefficient*

$K_1 = (t_0 / t_1)^{1/n}$ *, where*

t_0 *:* *design life (days)*

t_1 *:* *test duration (days)*

Assuming K_1 = 1.8, a 30 day Type Test period, as in the preceding paragraph, and a 40 year life, yields an inferred value of n = 10.5.

In order to provide electrical equivalency to a 50 year design life, a deterioration coefficient K_1 would be revised to 1.85, indicating a test voltage about 2.7% higher than the Electra 189 recommended value.

It's noteworthy that the initial 1980 Electra 72 testing document (footnote 1) called for a K_1 value of 2.0, which would indicate an equivalent life of over 100 years, if n = 10.5 was also assumed.

It can be concluded that relating test values to expected electrical life is inaccurate based on the above criteria, considering a lack of information in the technical literature describing appropriate values of n to use. In addition, long-time service-aged cables subjected to lab tests have shown little sign of electrical aging, casting suspicions on what values of n should be used for such analysis. However, to be conservative, it is recommended that if new Type Tests are done for the SOBI cables, they be done with a test voltage equal to 1.85 times 350 kV, or 547.5 kV, which would approximately confirm 50 year electrical life equivalency in accordance with the criteria outlined in Electra No. 189.

3.2 Thermal Aging

Thermal aging of insulation is caused by chemical reactions within it, which are temperature dependent. The classical Arrhenius aging model describes the life of a material exposed to thermal aging as:

$$\tau = A \cdot e^{(U/T)}$$

τ *:* *relative life time*

A : *constant, depending on material*

U : *activation energy for the applicable chemical process*

T : absolute temperature (K)

Lifetime versus temperature data obtained for key mechanical characteristics of the cellulose tapes used for the insulation have shown that their properties conform to Arrhenius' theory[8]. There is general agreement that the rate of deterioration of impregnated paper insulation doubles with each 8 °C increase in temperature above 85 °C and halves for each 10 °C decrease below 85 °C[9]. Insulation life of approximately 40 years is predicted for continuous operation at 85 °C, which corresponds with standards for high voltage ac laminar insulation cables. Applying the "8 °C rule" would infer an approximate 10 year life if operated at 100 °C. Conversely a "10 °C rule" would infer an approximate 300 year life if operated at 50 to 55 °C, which is the maximum conductor temperature anticipated for SOBI cables. Clearly, the thermal life of SOBI cable insulation would be much greater than 50 years.

Temperature cycling due to a fluctuating electrical load can also cause thermal-mechanical aging of cable components, which is covered in the next section.

3.3 Mechanical Aging

Cable mechanical aging can be caused by long term load cycling. A key aging factor is cyclic fatigue cracking of lead alloy sheaths. Potential areas of susceptibility could be where cables would otherwise be free to move with thermal expansion/contraction, such as beneath cable terminations and at the top and bottom of HDD casings, as well as at mechanical discontinuities, for example near the armour clamp at land/sea transition joints.

Sheath fatigue failure can also occur where submarine cables free-span between two high points on the sea bottom. The lateral force from tidal currents can cause displacement and abrasion of suspended cables, and in the worst case result in vortex induced vibration[10]. Susceptibility to vibration and fatigue failure is dependent on water velocity, direction, cable mass, cable bending stiffness, cable diameter, cable tension and characteristics of the bottom contact points. However, for the SOBI project, plans are to carefully place imported fill over the cables for the whole route, including at free spans, which would eliminate any possibility of vortex induced vibration and cable abrasion.

The maximum conductor temperatures for the SOBI cables would be limited to 50 to 55 °C, whereas 85 °C is permitted for self-contained fluid filled cables with lead alloy sheaths, which experience 40 to 50 year longevity. Therefore the SOBI cables would experience a lower temperature operating range above ambient temperature leading to less thermal-mechanical expansion/contraction effects. The result would suggest lower risks of fatigue problems due to cyclic loading of SOBI cables. Regardless, the contract requires the cable supplier to provide design submittal documentation confirming 50 year lead

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[8] Underground Systems Reference Book, Electric Power Research Institute, 1992 Edition, Chapter 2, Page 28.

[9] E M Allam, J H Cooper, J F Shimshock, Development and Long Term Testing of a Low-Loss 765 kV High Pressure Oil-Filled Pipe Type Cable, CIGRE 1986 Paper 21-06.

[10] G E Balog, K Bjorlow-Larsen, A Ericsson, B Dellby, Vortex Induced Vibration on Submarine Cables, CIGRE 2006 Paper B1-208.

alloy sheath fatigue life. An option for a Special Test to analyze lead sheath fatigue properties has been provided in the RFP documents.

3.4 Chemical Aging

The main chemical aging threat is corrosion of the galvanized steel armour wires and the steel HDD casing. There are many types of corrosion that could apply, but following are the main varieties applicable to submarine cables.

3.4.1 Armour wire corrosion

Armour corrosion is typically affected by the following main in-situ seawater parameters.

- dissolved oxygen content
- sea currents
- temperature
- salinity
- marine growth and decaying organic matter

Submarine cable armour wires are susceptible to five main corrosion mechanisms.

General chemical corrosion

Chemical corrosion occurs where cables are directly exposed to salty, oxygen-rich sea water. Primary protection is by the zinc galvanizing layer. Secondary protection is provided by the hot bitumen coating and polypropylene serving applied during manufacturing. The bitumen and serving layer can be degraded during installation, by external impacts and due to sand-blasting abrasion from high water currents.

Since the submarine sections will be covered with backfill, oxygen levels and abrasion effects should be low, so general chemical corrosion rates are also anticipated to be low.

AC corrosion

AC cables are subject to corrosion in areas of mutual impedance change, notably where the inter-phase spacing of single-core cables converges/diverges near the landings. Here induced ‘transverse’ AC currents in the armour can pass into the sea or sea bottom, and if ac current densities are sufficiently high, ac corrosion can occur.

Although the SOBI cables do not carry ac power, a relatively small (max 3%) ac ripple is expected to be superimposed on the dc voltage. However, it is not anticipated to result in any ac corrosion.

Differential aeration corrosion

This occurs where cables transition from buried, where oxygen levels are low, to unburied, where concentrations are higher. The equilibrium potential of the iron corrosion cathodic reaction at constant pH depends on dissolved oxygen concentrations as follows:

$$E_0 = constant + 0.0148*log(p(O_2)) \quad (Volts)$$

Where $p(O_2)$ is the partial pressure of oxygen in equilibrium with the quantity of the same gas dissolved in water.

As a consequence, if a part of an iron wire is prevented from being reached by dissolved oxygen due to burial, while another part is not because it is unburied, a longitudinal potential difference will develop in the armour wires. The exposed part will behave cathodically with respect to the buried part, which will corrode. The corrosion rate is determined by the ratio between buried and unburied lengths, and the relative amount of dissolved oxygen in water.

This phenomenon has been observed when recovering old ac and dc submarine cables, as well as guy anchor rods passing through soil materials with differing oxygen content.

Since plans are to backfill over the submarine cables for the whole underwater route, it is anticipated that oxygen concentrations would be relatively homogenous and therefore corrosion rates due to differential aeration corrosion low. A possible exception could be in the vicinity of the bottom of the HDD casing, where oxygen levels could be higher inside than outside. However in this zone cable armour would be protected by a PE jacket, mainly intended to reduce friction during pull-in to the casing.

Geo-magnetically induced leakage current corrosion

Another explanation for advanced corrosion at the transitions between buried and unburied sections is due to geo-magnetically induced dc currents in the armour wires[11] [12]. The potential difference between two locations, which is generated by tidal flow of electrically conductive seawater in the presence of the earth's magnetic field, can be calculated as follows.

$$E = B \cdot V \cdot L$$

Where E = induced electromotive force

B = vertical component of earth's magnetic field

L = width of water crossing

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[11] M. Furugen, et al, 'Completion of Submarine Cable Lines Combining Low Environmental Impact with Low Cost', Furukawa Review No. 21, 2002.

[12] M. Fujii, T. Uematsu, et al, 'Steel Armour Corrosion of Submarine Cable', IEEE PES Summer Meeting, Los Angeles, CA, July 16-21, 1978.

V = velocity of water flow, assumed perpendicular to cables

Dc leakage current from the armour is dependent on leakage resistance. Where buried, the resistance is higher and the leakage current lower. Where current leaves the armour wires, they become anodic, resulting in corrosion. The maximum corrosion rates occur at discontinuities between buried and unburied sections, at locations where the water depth changes rapidly and near the landings.

It appears that burying the cables will eliminate this corrosion threat.

Microbiologically influenced corrosion (MIC)

Sea bottoms comprised of decomposing organic matter can result in sulphide reducing bacteria creating acids that corrode cable armour[13] [14]. These conditions do not appear to be present in the Strait of Belle Isle, however, they could exist in stagnant water within the HDD casing.

Use of dissimilar metals

Many corrosion problems associated with submarine cable armour can be alleviated if the use of different metals in the electrical system is avoided. Consideration should be given not only to materials in the immediate vicinity of the area of concern, but also to the surrounding area. Depending upon the resistance in the electrical circuit, corrosion currents can travel long distances, such that bare copper grounding wire at relatively remote land sites could contribute to galvanic corrosion of galvanized steel armoured cables in the Strait of Belle Isle.

Corrosion protection measures

Most of the above corrosion hazards can be mitigated by applying an impressed current cathodic protection system. Typically they place a potential of about -0.8 to -1.1 Volts (relative to a Ag/AgCl half-cell) onto the armour wires. Detailed application descriptions are provided in the footnote[15] .

Use of a cathodic protection system would help provide assurances of 50 year design life for submarine cable armour.

3.4.2 HDD Casing Corrosion

The steel HDD casing could be susceptible to all of the corrosion types described in the foregoing for cable armour, except for ac corrosion.

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[13] H. A. Flores, 'Submarine Cables to 34.5 kV of the Carmen Beach to Cozumel Island in Mexico. Corrosion Specification and Operational Experience', Paper B1-115, CIGRE 2010, Paris.

[14] M. Eashwar et al, 'Microbiologically Influenced Corrosion of Steel During Putrefaction of Seawater: Evidence for a New Mechanism', NACE, Corrosion 49, 108, 1993.

[15] Det Norske Veritas, 'Recommended Practice RP-401, Cathodic Protection Design', Det Norske Veritas www.dnv.com, January 2005.

Mitigation methods would be to apply a cathodic protection system to the steel casing, which would also be coupled onto cable armour wires if the PE jacket wore through during pull-in operations. Periodic application of a biocide and oxygen scavengers to the inside of the casing would help reduce differential aeration and microbiological influence corrosion, providing the bottom of the casing was sealed. It could also reduce fouling of the casing with marine growth, which could prevent later removal of a cable in the event of damage.

Applying the above measures would provide assurances of 50 year design life for the HDD casings.

4. Dependencies

Expectations about design life assume that the complete cable system will be operated and maintained in accordance with the EPC Contractor's instructions and specifications.

With respect to operation, it is assumed that external influences such as control of dc converters and adherence to Operating Orders would prevent inadvertent application of over-currents and over-voltages higher than those for which the cable system was designed. This could include use of Remedial Action Schemes to prevent such events from happening. Otherwise, actual cable system life could be shortened.

Similarly, it is assumed that the EPC Contractor's recommendations regarding scheduled maintenance will be followed, supplemented with appropriate condition based maintenance tools, such as continuous cable temperature monitoring systems.

5. Investigations by Others

In June 2004, Statnett and Tennet completed an internal investigation of life expectancy for HVDC systems, as part of preparations for the 450 kV NorNed project.[16] It concluded:

"Service experience has demonstrated that paper tape insulated cables in general have much longer lifetime than the 30 years lifetime expectancy frequently used earlier. The probability that the technical lifetime will be more than 50 years is high. Thus, 40 years can be justified as economic lifetime as far as the submarine cable is concerned."

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[16] HVDC Transmission and Life Expectancy; http://www.tennet.org/images/19-B7-HVDC_Transmission_and_Lifetime_Expectancy_tcm41-12302.pdf (retrieved March 2012)

Since completion of the Statnett/Tennet report, another 8 years of successful experience has been gained with existing installations, adding even more validity to their conclusion of a 50 year technical lifetime.

In response to the SOBI RFP, three proposals were received. None objected to the specified 50 year design life requirement.

6. Conclusions

A review has been done of expectations for a 50 year design life for the SOBI 350 kV dc submarine cable system. The performance history of similar cable systems has been investigated, as well as the factors influencing actual achievement of expected life, including good design, installation, operation and maintenance practices. Consideration has also been given to investigations by others into longevity of MI cables, as well as RFP responses. Key conclusions were:

- A ‘first generation’ 300 kV dc MI submarine cable system connecting mainland British Columbia to Vancouver Island has been operating since 1969 without internal cable failures.
- If the Vancouver Island 300 kV dc cables have performed well using 1960’s manufacturing technology, it is reasonable to expect that modern manufacturing technologies will produce cables with even greater longevity.
- All installed MI dc submarine cables remain in service, except for those strategically replaced due to increased transmission capacity requirements, or abandoned as not economic to repair following damage by third parties.
- The thermal life of SOBI cable insulation would be much greater than 50 years.
- 50 year electrical life equivalency can be approximated by performing new Type Tests on SOBI cables (an RFP requirement) with a test voltage equal to 1.85 times 350 kV, or 547.5 kV, in accordance with the criteria outlined in Electra No. 189.
- The main mechanical aging factors would be: i) lead sheath fatigue due to cyclic loading, ii) lead sheath fatigue due to tidal current-driven vortex induced vibration at free spans, and iii) tidal current-driven abrasion at free span touch down points. Plans are to eliminate the second and third factors by placing backfill around the submarine cables for the entire route. Plans are to assure the first factor by an RFP requirement for cable supplier design submittals and Special Tests to confirm adequate sheath fatigue life for 50 years.
- The main chemical aging factor is corrosion of steel wire armour and HDD steel casings. The RFP calls for provision of adequate corrosion protection measures for 50 year longevity.
- Investigations by two major power utilities (Statnett and Tennet) planning a new 450 kV dc submarine MI cable system, concluded that there is a high probability the technical lifetime would be more than 50 years.

- In response to the SOBI RFP, three proposals were received. None objected to the specified 50 year design life requirement.
- Expectations about design life assume that the complete cable system will be operated and maintained in accordance with the EPC Contractor's instructions and specifications.

In summary, results show that a 50 year design life is a reasonable expectation and is achievable.