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Wire System Ageing Assessment and Condition Monitoring (WASCO)

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Nuclear facilities rely on electrical wire systems to perform a variety of functions for successful operation. Many of these functions directly support the safe operation of the facility; therefore, the continued reliability of wire systems, even as they age, is critical. Condition Monitoring (CM) of installed wire systems is an important part of any aging program, both during the first 40 years of the qualified life and even more in anticipation of the license renewal for a nuclear power plant. This report contains the results of experiments performed in collaboration with Tecnatom SA, Spain, to compare several cable condition monitoring techniques including LIRA (LIne Resonance Analysis)

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Condition monitoring, cable ageing, transmission lines, hot spot detection, fault detection, frequency domain reflectometry, time domain reflectometry, standing wave reflectometry, LIRA.

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Abstract

Nuclear facilities rely on electrical wire systems to perform a variety of functions for successful operation. Many of these functions directly support the safe operation of the facility; therefore, the continued reliability of wire systems, even as they age, is critical. Condition Monitoring (CM) of installed wire systems is an important part of any aging program, both during the first 40 years of the qualified life and even more in anticipation of the license renewal for a nuclear power plant. This report contains the results of experiments performed in collaboration with Tecnatom SA, Spain, to compare several cable condition monitoring techniques including LIRA (LIne Resonance Analysis).

CONTENT

INTRODUCTION

The interest of safety aspects of wire systems aging (especially those wire systems used for control and instrumentation) is increasing worldwide because of their impact on several industrial fields, like power generation, transportation and defense. Although the environment conditions and degradation mechanisms of installed cables can be different from target to target, the negative consequences of wire failures, both from a safety and performance standpoint, are so important that almost all the countries in the industrialized world have some research project in progress in this area.
In the nuclear field, where cables are normally qualified before installation for an expected life of 40 years, there are a number of issues that are not completely solved today. These issues include:

- The effect of the particular adverse environment conditions (high radiation, humidity and temperature), especially during and after a Design Basis Accident (DBA).
- Extending the plant life after 40 years involves the requirement to assess and qualify the cable conditions for a longer time.
- Many cables condition monitoring techniques do exist today, but none of them is considered accurate and reliable enough for all the cable materials in use and conditions. In addition to that, only few of them are non-destructive techniques and are applicable in situ.
- Accelerated aging techniques, for qualification purposes under DBA conditions, are often not conservative and should be complemented with reliable condition monitoring methods.

A workshop on Wire System Ageing Assessment and Condition Monitoring was organized by the Halden Project at Zurzach, Switzerland, the 28-29 October 2004. This meeting was a good basis for the planning of the activities to be performed on this topic.

In 2005, the WASCO project has been focusing the development of a technique based on high frequency reflectometry and the development of a prototype software to test this technique. During 2005 the following 2 tests have been designed and performed:

- Norsk Hydro tests on long cables
- EPRI tests on thermally aged nuclear plant cables

A final report [5] was written and published with the achieved results

In 2006 the system was further developed and on-site tests at Barseback and Ringhals NPPs were performed and analyzed, as reported in the project final report [6].

Acknowledgement

NKS conveys its gratitude to all organizations and persons who by means of financial support or contributions in kind have made the work presented in this report possible.

Objective of the 2008 WASCO project

The main objective of this experiment is to evaluate and compare the capability of few popular CM techniques in the assessment of cable aging and failure as a consequence of thermal aging and mechanical damage. In particular, the detection and assessment of local hot spots, due to local higher environment temperature, will be evaluated. The techniques that will be tested in this experiment are:

- Elongation-At-Break (EAB). It will be used as a reference method to correlate the 3 other techniques to the widely accepted 50% absolute EAB as limiting value.
- The Indenter. It is a local mechanical test that is in use in several power plants. The Indenter has always shown a good correlation with EPR, EPDM and PVC insulation types, but less confidence with XLPE types.
- TDR and LIRA. Both these methods are based on electrical properties of the insulation. TDR is a time domain method used for many years to detect anomalies along electrical wires, while LIRA is supposed to be a more sophisticated and sensitive method that monitors cable impedance variations to detect and localise cable defects or degradations.

These methods were used to test EPR and XLPE insulated cables with thermal and mechanical degradations.

Figure 1 shows the experiment arrangement during the LIRA tests on the cable samples.

Figure 1 Testing facility for LIRA, at Tecnatom Lab

TEST DESCRIPTION

The cables used for the tests were two different cable types used for I & C in Nuclear Power Plants:

- EPR insulated cables

- XLPE insulated cables

Additional information about the type of the cables can be shown in table 1

Table 1. Properties of the cables.

Insulation	EPR	XLPE
Vendor	Prysmian (former Pirelli)	General Cable
Conductor	Cu/Sn class 2	Cu class 2
Cover	AFUMEX	HYPALON
Voltage	300 V	0,6/1 KV
Identification	2x2x16 AWG W-52	3x16 AWG 4D3

Nine samples of each cable were used to perform the measures and an additional reference cable is kept in case it was necessary to do some other measures in future sessions of tests. All the samples were measured using all the methods, later on, each specimen will suffer either a mechanical damage or a thermal aging.

The different tests to be done on each sample can be seen in table 2

Table 2: Identification of specimens

Test	**EPR Cable**		**XLPE Cable**	
	Id.	**Length (m)**	**Id.**	**Length (m)**
Reference sample	TEREF	10	TXREF	10
Cut	TEM2	27	TXM1	30
Gouge	TEM1	27	TXM2	30
Thermal global step 1	TEG1	17	TXG1	20
Thermal global step 2	TEG2	17	TXG2	17
Thermal global step 3	TEG3	17	TXG3	20
Thermal hot spot	TEL1	27	TXL1	30

severity 1				
Thermal hot spot severity 2	TEL2	27	TXL2	30
Thermal hot spot severity 3	TEL3	27	TXL3	30
Thermal hot spot severity 4	TEL4	27	TXL4	30

The thermal global step 3 and thermal hot spot severity 4 are related to a thermal aging equivalent to the total life of the power plant. According to this, thermal global steps 1, 2 and 3 will be equivalent to 20, 40 and 60 years and thermal hot spots severity 1, 2, 3 and 4 will be equivalent to 15, 30, 45 and 60 years. Thermal aging consist in keeping specimens in a dry oven to simulate the equivalent aging in a power plant. The exact conditions of the thermal aging performed will be explained in next report when the aging has been finished.

After measuring the undamaged samples, the mechanical damages were performed. Mechanical damages consist in a cut and a gouge. Both kind of damages are applied to 30-meter-long samples.

One sample must be cut down to the insulation at 10 m far from one of the ends. (See figures 1 and 3). The other sample must be gouged removing the jacket and the insulation for 2 cm, this can be made with a knife at the same distance from the end that the cut (figures 2 and 4)

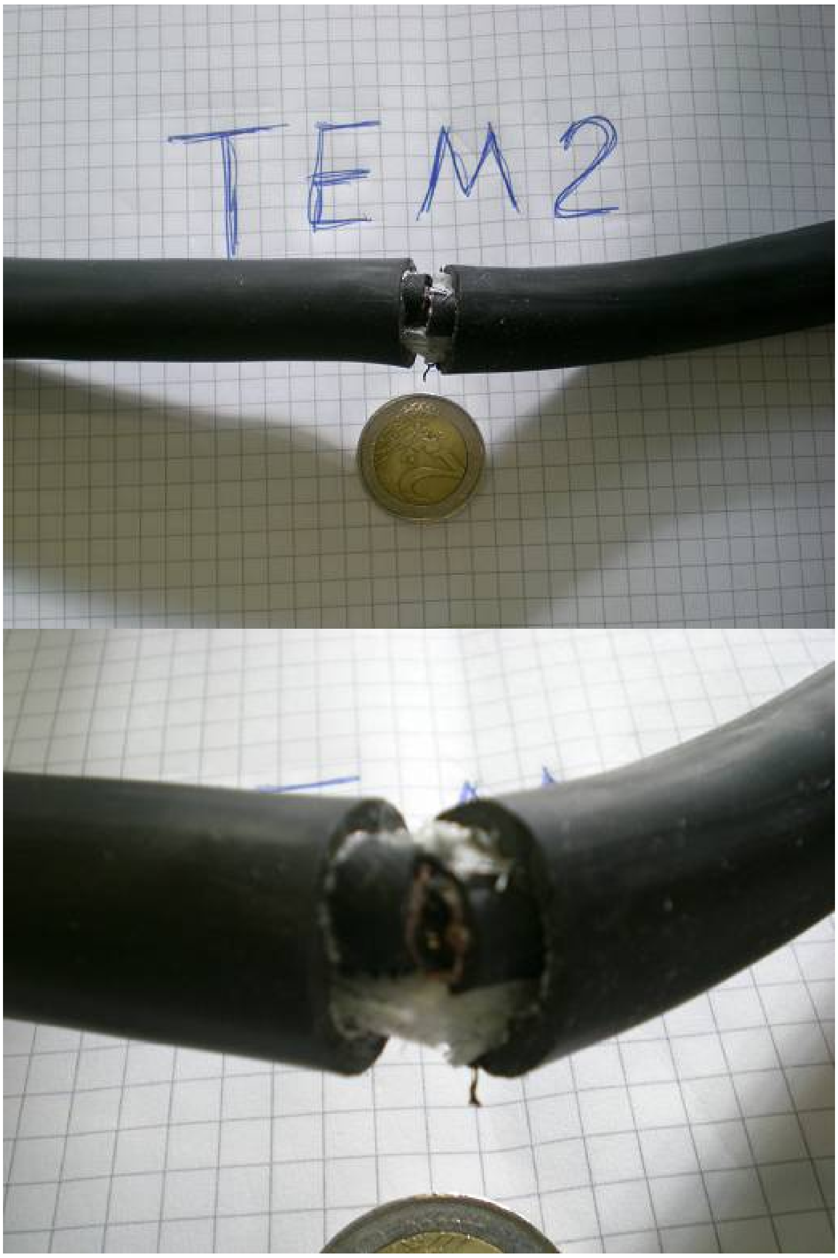

Figure 1: EPR cable cut

Figure 2: EPR cable gouged

Figure 3: XLPE cable cut

Figure 4: XLPE cable gouged

INDENTER

Indenter measurements are basically an indication of the compressive modulus of the polymer. Measurements are made by pressing a small probe (usually with a truncated cone shape) into the surface of the material under controlled conditions. The load-displacement curve is monitored and the slope of the curve is taken as an indication of the modulus.

Before starting the tests, the equipment has been checked to work properly according to indenter procedures. The parameters of the tests are reccomended by procedures to be the ones that shows table 3. Five measures were taken from both ends of each sample, as it is also recommended by indenter procedures.

Table 3. Indenter Parameters

Probe speed	0,6 cm/min
Maximum force	2 N
Máximum displacement	7 mm

The test can be done with the cable coiled and the necessary equipment is not very bulky so it does not need special conditions of space or environment. Later on, the results can be easily downloaded to a computer.

TDR

Applying a pulse voltage between the two conductors of an end of the samples and comparing the two outputs in an oscilloscope when the other end is close and when it is open, we can calculate the velocity of propagation of signals with this output and the length of the cable.

The velocity will be given by the next equation:

$$V = \frac{L}{\Delta t} \tag{1}$$

V: velocity of propagation

L: length of the cable

Δt: difference between the instant the rising side begins and the instant when the two waveforms start being different

In this case, equipment is a bit bigger than the indenter and the cable must be in a condition similar to the way it would be in the plant, this is, cable cannot be coiled so it is necessary to have much space for the cable, as can be seen in figure 5. According to the kind of oscilloscope used, the output can be saved in a memory card or downloaded to a computer at the same time they are being generated.

Figure 5: Cable disposition

EAB

As this part of the test will be performed on reference specimens, the results will be included in another report.

LIRA

The whole equipment for LIRA consists of several modules. These modules are: the LIRA Generator (Arbitrary Waveform Generator), the LIRA modulator and a computer with an special software (see figure 6).

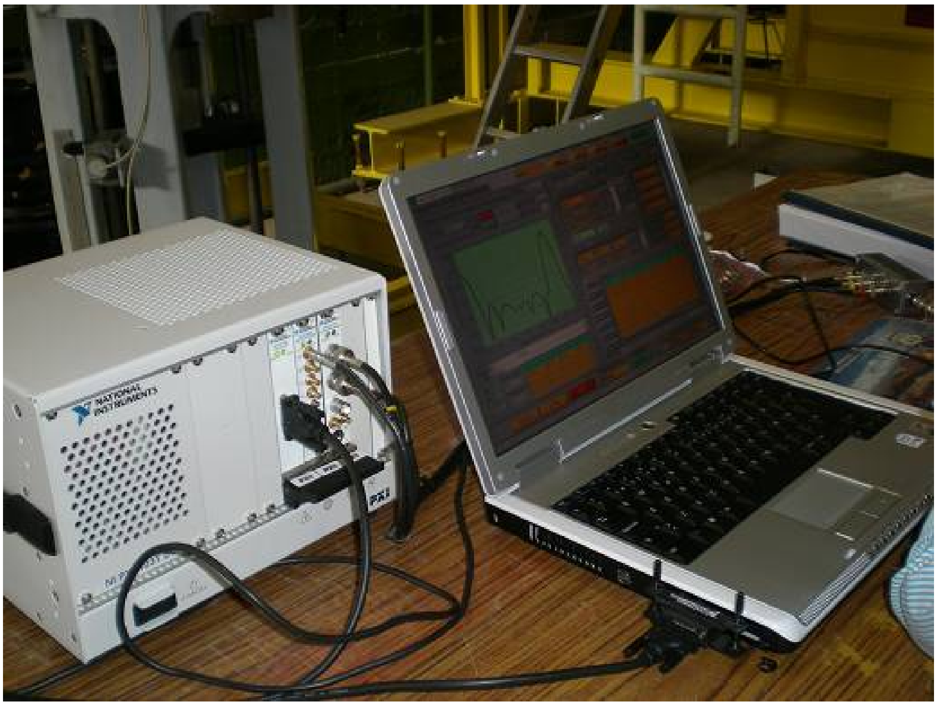

Figure 6: LIRA Generator, LIRA modulator and computer used in the tests

TEST PERFORMED AND ANALYSIS

As it can be seen in the results, the indenter has a big dispersion among the results obtained on each measure, these results are useful when comparing them with the ones obtained after a thermal aging. The reason for this is that compressive modulus varies a lot through years and a spoilt cable can be easily detected. The average values of the compressivity modulus for each test are shown in Table 4.

Table 4: Main results of the indenter

Test	Compressivity Modulus (N/mm)
XLPE Cover Side A	9,26204
XLPE Cover Side B	8,0025
XLPE Isolation Side A	59,63116
XLPE Isolation Side B	40,06522
EPR Cover Side A	8,69282
EPR Cover Side B	8,59436
EPR Isolation Side A	14,98683333
EPR Isolation Side B	14,84573333

The velocity of propagation calculated according to the equation (1) for the different samples are shown in tables 5 and 6. With this value, we could know if there is damage on cable insulation and roughly find out where it is. For the EPR cable, as it has two conductors, two measures, *a* and *b*, were performed.

Table 5: Results of the TDR for EPR cable

Sample	Frequency (MHz)	Δt (ns)	Length (m)	Velocity of propagation (m/s)
TEREFa	1,01485	134	10	7,46E+07
TEREFb	1,01483	140	10	7,14E+07
TEG3a	1,01486	216	17	7,87E+07
TEG3b	1,0149	216	17	7,87E+07
TEG2b	1,01496	220	17	7,73E+07
TEG1b	1,01486	224	17	7,59E+07
TEM1a	1,01493	340	27	7,94E+07
TEM1b	1,01494	326	27	8,28E+07
TEM2a	1,01494	326	27	8,28E+07
TEM2b	1,01493	340	27	7,94E+07
TEL3a	1,01501	344	27	7,85E+07
TEL3b	1,01504	344	27	7,85E+07
TEL1a	1,01497	342	27	7,89E+07
TEL1b	1,01498	346	27	7,80E+07
TEL2a	1,01496	344	27	7,85E+07
TEL2b	1,01492	344	27	7,85E+07

Table 6: Results of the TDR for the XLPE cable

Sample	Frequency (MHz)	Δt (ns)	Length (m)	Velocity of propagation (m/s)
TXG1	1,01636	226	20	8,85E+07
TXG2	1,01626	199	17	8.54E+08
TXG3	1,01636	232	20	8,62E+07
TXL1	1,01645	340	30	8,82E+07
TXL2	1,01639	340	30	8,82E+07
TXL3	1,01637	340	30	8,82E+07
TXL4	1,01633	340	30	8,82E+07
TXM1	1,01633	334	30	8,98E+07
TXREF	1,01624	117	10	8,55E+07

LIRA can save all the information in binary files and it also can create reports in an excel file. Appendix I shows all the tables and graphs as they were created by LIRA software.

The samples have been measured at 100 and 200 Ms/s. Some measures have been made between a conductor and a shield instead of the two conductors in case this information is needed when analyzing final results.

Table 1 Test specification

TAG	Length(m)	Ins. Type	Test description	Equiv. Years	Oven time (days)	Oven temp. (C)	Operating temp. (C)	Activation Energy (eV)
TEREF	10	EPR	Reference sample					
TEM1	27	EPR	Gouge					
TEM2	27	EPR	Cut					
TEG1	20	EPR	Thermal global step 1	20	10	140 ºC	45ºC	0.785
TEG2	20	EPR	Thermal global step 2	40	20	140 ºC	45ºC	0.785
TEG3	20	EPR	Thermal global step 3	60	30	140 ºC	45ºC	0.785
TEL1	27	EPR	Thermal hot spot severity 1	15	8	140 ºC	45ºC	0.785
TEL2	27	EPR	Thermal hot spot severity 2	30	15	140 ºC	45ºC	0.785
TEL3	27	EPR	Thermal hot spot severity 3	45	22.5	140 ºC	45ºC	0.785
TEL4	27	EPR	Thermal hot spot severity 4	60	30	140 ºC	45ºC	0.785
TXREF	10		Reference sample					
TXM1	30	XLPE	Cut					
TXM2	30	XLPE	Gouge					
TXG1	20	XLPE	Thermal global step 1	20	3	140 ºC	45ºC	0.9
TXG2	17.1	XLPE	Thermal global step 2	40	8	140 ºC	45ºC	0.9
TXG3	20	XLPE	Thermal global step 3	60	12	140 ºC	45ºC	0.9
TXL1	30	XLPE	Thermal hot spot severity 1	12	3	140 ºC	45ºC	0.9
TXL3	30	XLPE	Thermal hot spot severity 2	45	9	140 ºC	45ºC	0.9
TXL4	30	XLPE	Thermal hot spot severity 3	60	12	140 ºC	45ºC	0.9
TXL2	30	XLPE	Thermal hot spot severity 4	80	16	140 ºC	45ºC	0.9

Cable Specifications

Two sets of cable types were used in this experiment, the first one using EPR insulation and the other one XLPE insulation. The cable specs were as in the following table:

Table 2 Sample specifications

Material	EPR	XLPE
Manufacture	PRISMIAN	GENERAL CABLE
Model	RADIFLAM INSTRUMENTACION	XI ANTILLAMA
Insulation	EPDM FIREPROOF	XLPE FIREPROOF
Jacket	AFUMEX + flame screen	Hypalon

Thermal Aging Procedure and Facilities

Thermal ageing was carried out in a dry air oven at a temperature of 140 ºC. Using Arrhenius methodology and with the activation energies included in table 1, the equivalent times in oven are those indicated in the same table. For the cables globally aged the three steps were considered equivalent to 20, 40 and 60 years. For locally aged cables the four steps were considered equivalent to 15, 45, 60 and 80 years. For cables stressed with local heating a small portion of the cable at 10m from one end was inserted in the oven to simulate a hot spot.

EXPERIMENT RESULTS

Initial Conditions

Table 3 shows the LIRA initial estimated values of the cable samples electrical parameters, for the XLPE type. In this table Z0 is the Characteristic Impedance, VR is the Phase Velocity Ratio (the ratio between the velocity of the electric signal and the speed of light), Att is the cable attenuation, R the conductor resistance, L the conductor inductance, C the cable capacitance and Ref.freq the frequency at which all these values are estimated.

Each cable sample was measured from both sides (X and Y identify the two sides) with the far end open.

The measurements for all samples are in good agreement with a low standard deviation, as displayed in the last two rows of the table.

Figure 2 shows the estimated attenuation, in dB/km (LIRA), as a function of signal frequency.

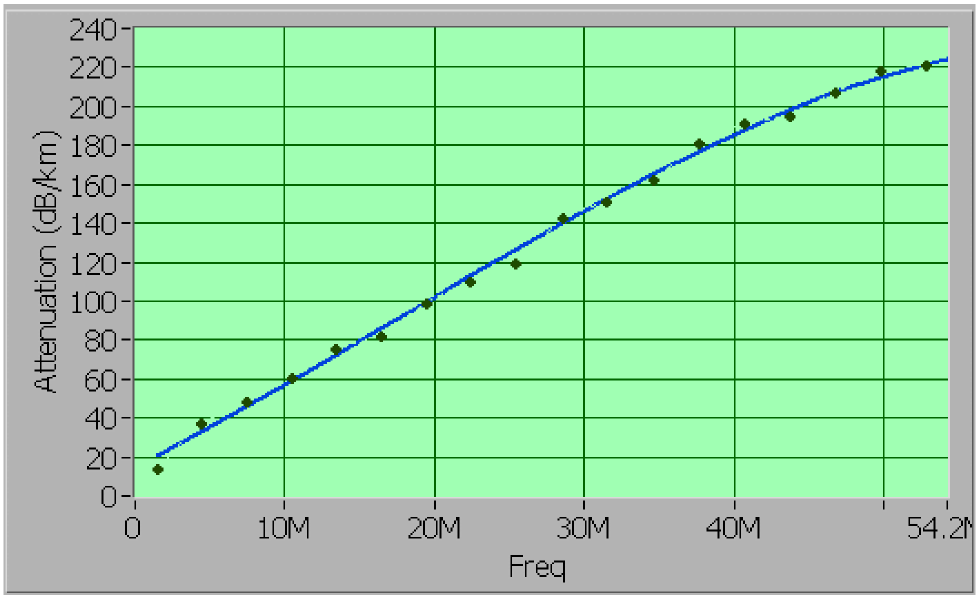

Figure 2 Attenuation vs. frequency in XLPE samples

Table 3 Electrical parameters for the XLPE samples as measured by LIRA

TAG	Z0(ohm)	VR	Att(dB/km)	R(ohm/km)	L(uH/m)	C(pF/m)	Ref.freq.(kHz)
TXL1-Y	112	0.6058	14	359	0.61	49	1435
TXL1-X	116	0.6059	13.7	364	0.64	47	1425
TXL2-X	117	0.6064	13.3	357	0.64	47	1429
TXL2-Y	112	0.6065	13.9	358	0.62	49	1436
TXL3-Y	111	0.6066	14.2	364	0.61	49	1430
TXL3-X	114	0.6067	13.6	355	0.63	48	1432
TXL4-X	117	0.6049	14.4	387	0.64	47	1430
TXL4-Y	115	0.6047	14.1	373	0.63	48	1426
TXM1-X	116	0.6049	14	375	0.64	48	1425
TXM2-Y	116	0.604	14.2	382	0.64	47	1421
TXM2-X	113	0.6048	14.9	388	0.63	48	1423
TXG1-X		0.6063					
TXG1-Y		0.6058					
TXG2-X		0.6053					
TXG2-Y		0.6041					
TXG3-X		0.605					

TXG3-Y		0.6052					
AVERAGE	**114**	**0.6056**	**14.0**	**369**	**0.63**	**48**	**1428**
STD	**2.16**	**0.0009**	**0.42**	**12.31**	**0.01**	**0.83**	**4.8**

Thermal Degradation Tests

Indenter Measurements

Table 4 includes the results of the indenter measurements in the aged samples. These measures were made on the jacket of the different samples.

Table 4 Indenter results on the sample jacket

CABLE SAMPLE	INDENTER (N/mm)
TX_REF	8.3
TXG1	10.11
TXG2	12.97
TXG3	24.9
TXL1	9.21
TXL2	27
TXL3	14.75
TXL4	23
TE_REF	16.69
TEG1	21.56
TEG2	25.6
TEG3	21.39
TEL1	14.27
TEL2	16.8
TEL3	22.38
TEL4	20.23

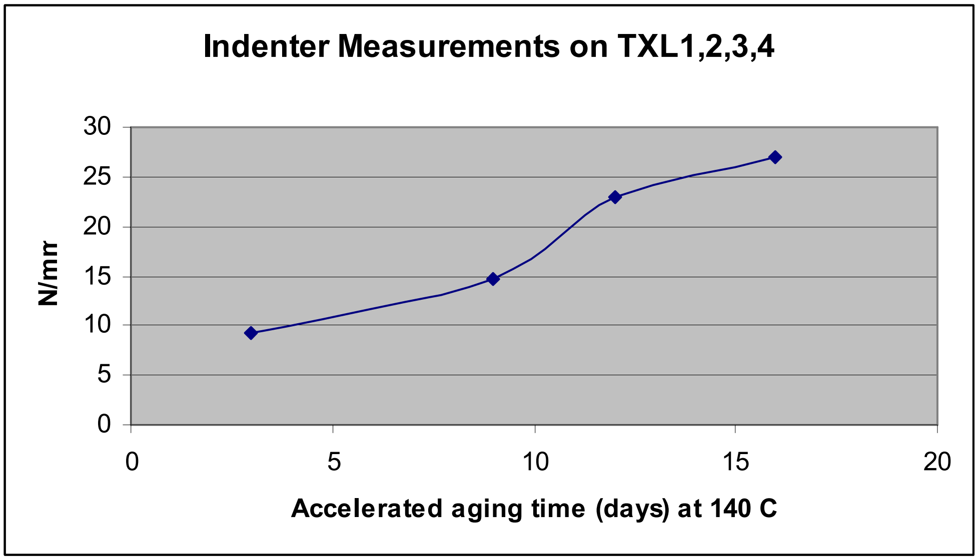

Figure 3 Indenter Measurements on local damaged samples

There is a quite good correlation between ageing and indenter. Of these two cable types the one with the XLPE insulation show the best correlation with ageing, the jacket of this cable is Hypalon (CSPE) which is a material with good hardness variation with thermal ageing. The EPR show variation with thermal ageing, but not so correlated as the XLPE cable. We have experienced similar behaviour in other tests with the same cable type and the evolution of hardness with thermal ageing is very slow.

TDR Measurements

It is difficult to extract conclusions with the results obtained from TDR tests. Figure 2 shows the results obtained with the TXL1, TXL2, TXL3 and TXL4 cables. Although some reflections are visible in all the traces, the spots at 10m are not easy to identify.

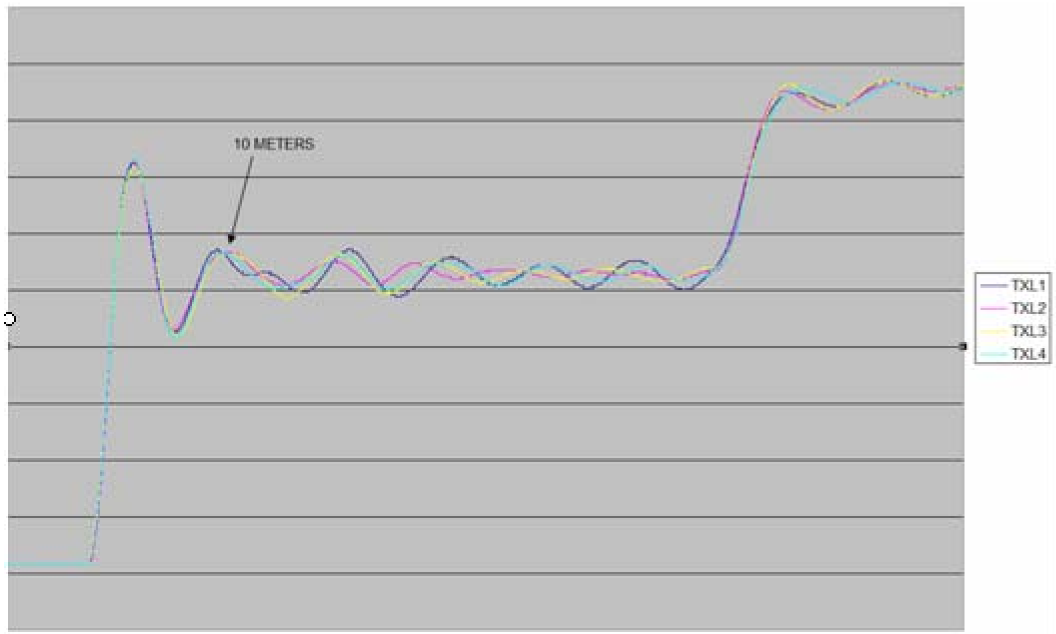

Figure 4 TDR representation of TXL cables

LIRA Measurements

The hot spots in the 4 aged samples were all clearly visible in LIRA. Figure 5 shows the signature for TXL1 from both sides. The shape of the spikes indicates that the size of this spot is close to 1.5m (the size at which the two spot ends start to be detected with a double peak) and the spot position is accurately detected. The large spike at 30m is the termination reflection.

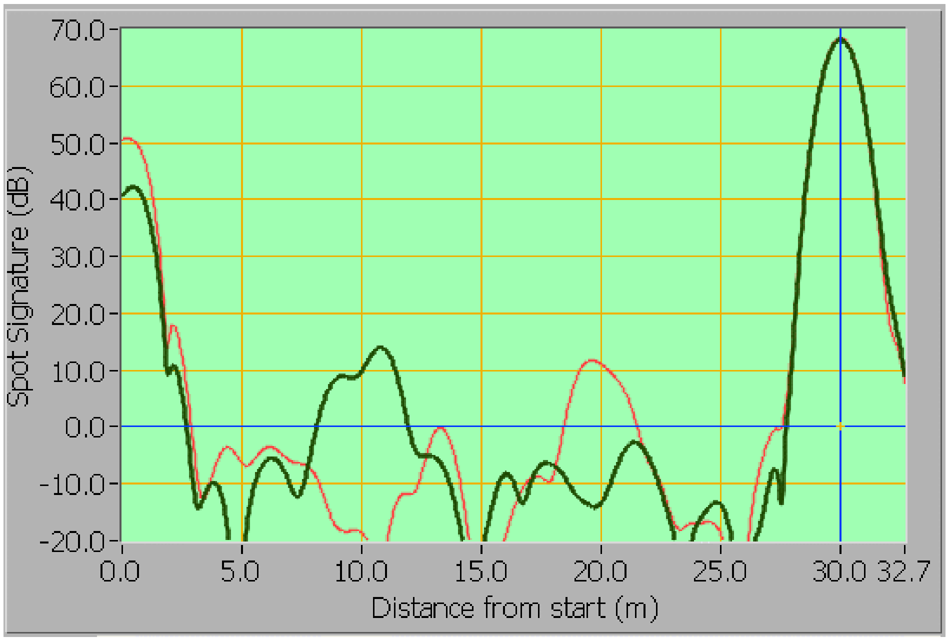

Figure 5 TXL1 spot at 10m (20m) measured from both sides (LIRA)

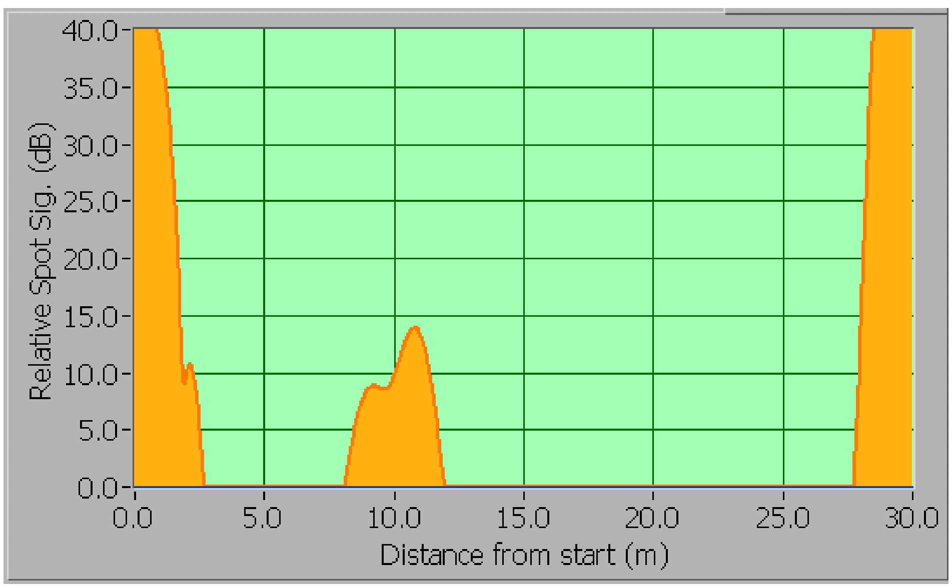

Figure 6 TXL1 spot in View Mode (LIRA)

Figure 6 shows the same signature (spot at 10m) in View Mode, where the low level noise is automatically removed.

Figure 7 shows the LIRA hot spot signature for sample TXL3. Note the clear double peak feature in the measurements from both sides, indicating a spot size of about 2m.

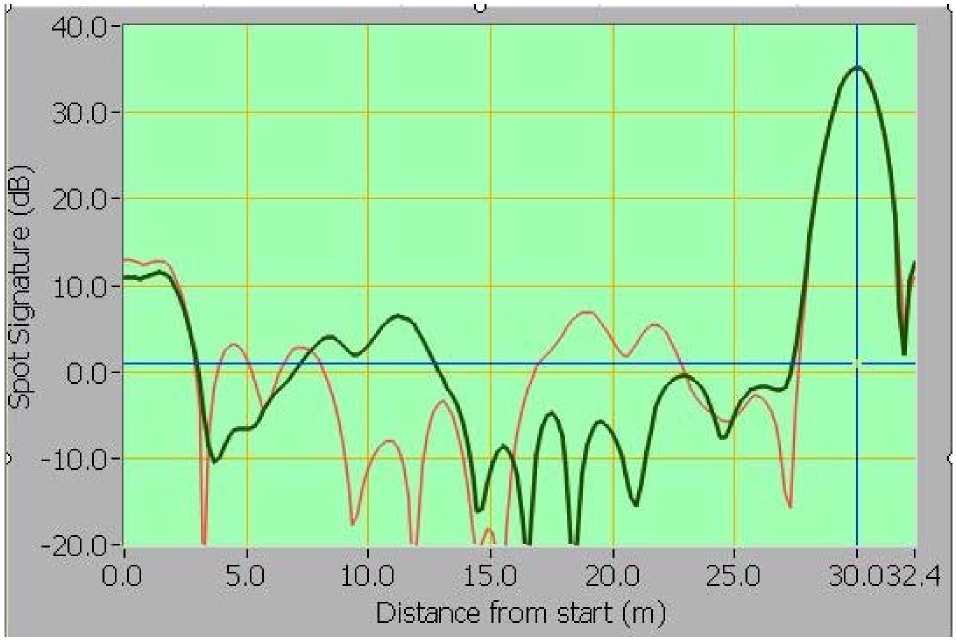

Figure 7 TXL3 long hot spot (3m) measured from both sides (LIRA)

Mechanical Faults Test

Two types of mechanical damage were tested: TXM1 had a cut down to the insulation of 2 conductors, see Figure 9, while TXM2 had a gouge as shown in Figure 8.

Figure 8 TXM2 gouge of 2 wires (dry)

Figure 9 TXM1 cut on the insulation of 2 wires (dry)

TDR Measurements

Figure 10 shows the traces for TXM1 and TXM2. Although some possible features are visible in the damaged areas, no clear diagnosis can be assessed.

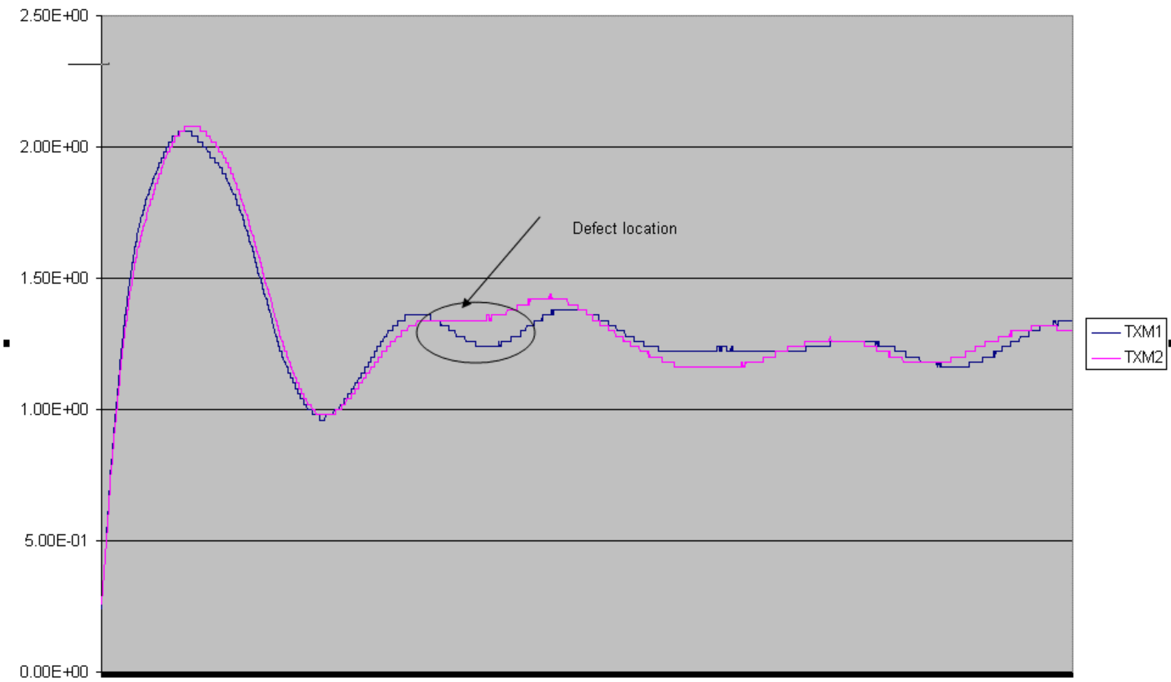

Figure 10 TDR trace for TXM1 and TXM2

LIRA Measurements

Figure 11 shows TXM2 before and after the mechanical damage at 20m. While the gouge feature is emerging at the right position, another feature is visible at about 22.5m in both signatures. The reason for this feature is not known.

The TXM1 signature is shown in Figure 12 from the short side (10m) and Figure 13 from the other side (20m). The spot feature is clearly visible in both signatures.

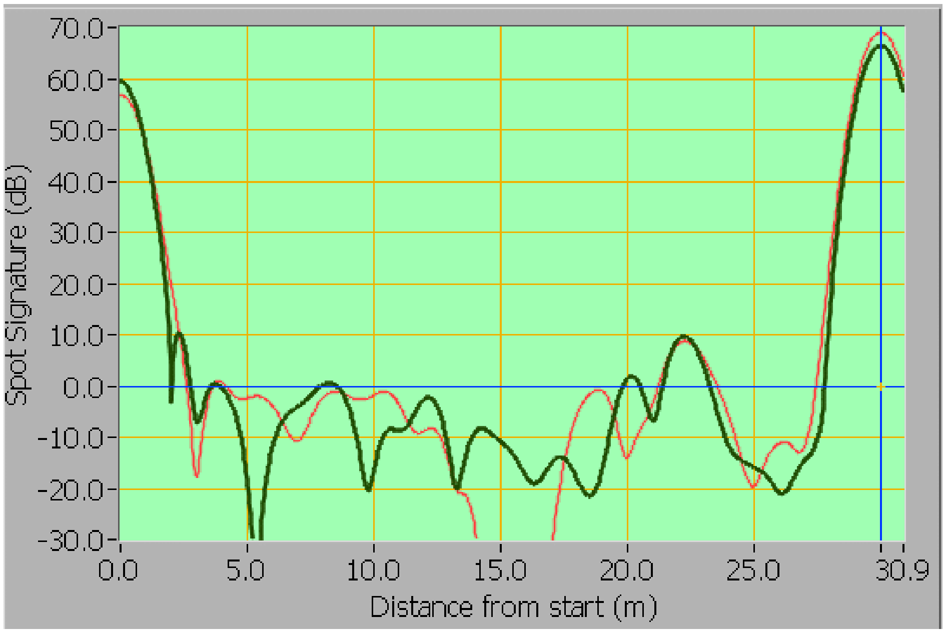

Figure 11 TXM2 gouge at 20m (dry)

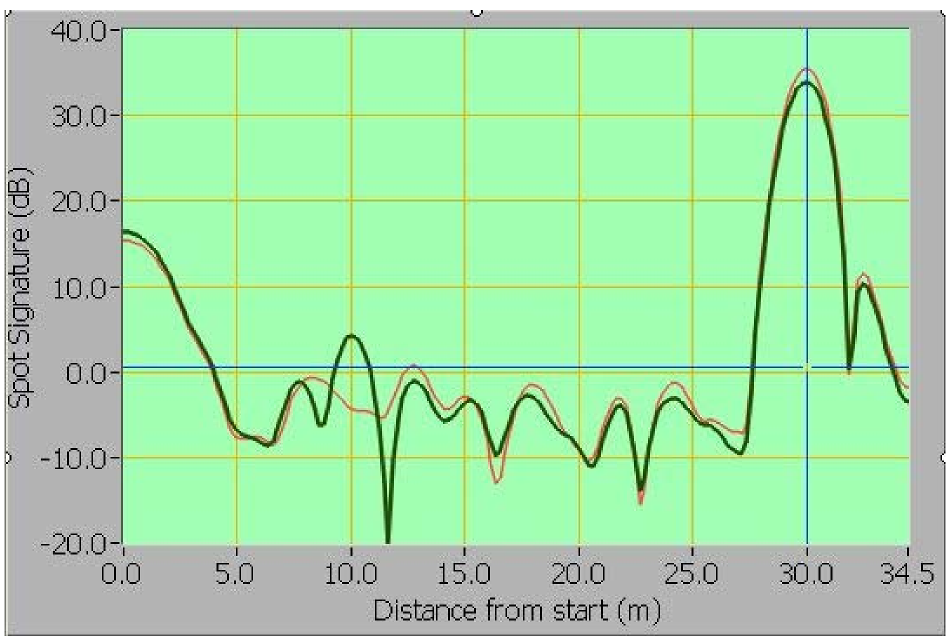

Figure 12 TXM1 cut at 10m (LIRA)

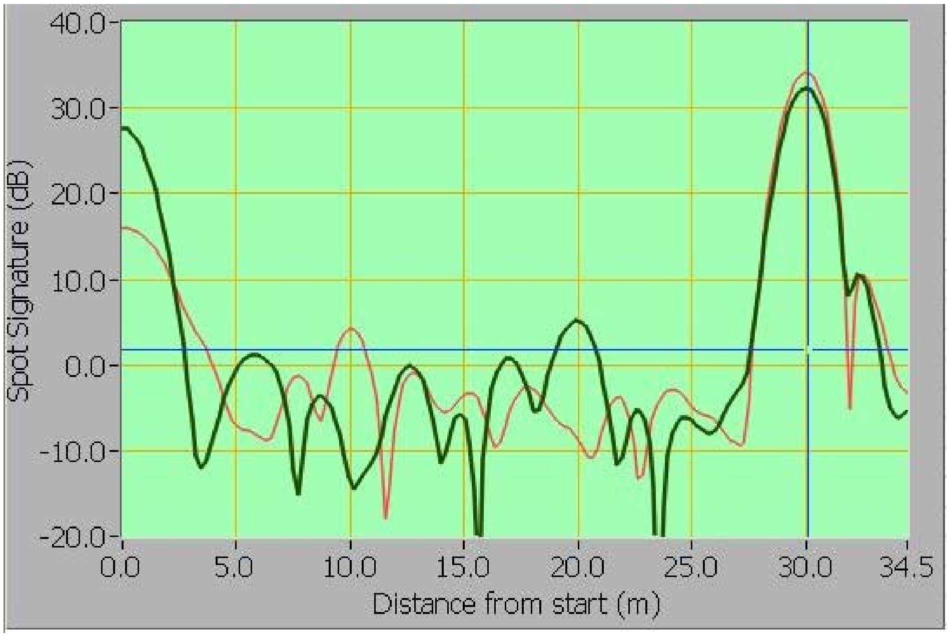

Figure 13 TXM1 cut from other side (20m)

Global Condition Assessment

Several tests [1, 3, 4, 6, 7, and 8] have shown that global degradation in a cable insulation results in changes in the dielectric capacitance and cable inductance, at some degree. These changes affect the cable attenuation, which can be expressed as:

(2) $$\alpha(dB/km) = Kf^{a}\sqrt{\frac{C}{L}}$$

Where *K* is constant for a particular cable type and geometry and depends on the DC resistance, *f* is the signal frequency and the exponent *a* takes into account the skin effect and ranges between 0.5 and 1. Figure 14 shows an example of LIRA calculated cable attenuation as a function of frequency.

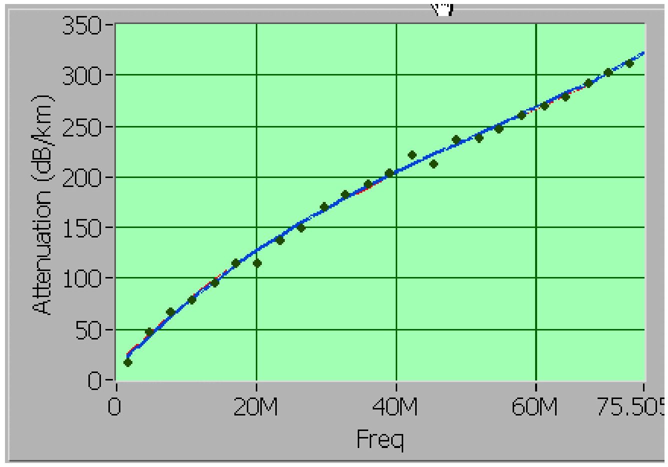

Figure 14 Cable attenuation (estimated by LIRA)

Eq. (2) shows that frequency acts as a gain factor in the relation between α and C/L and for this reason LIRA uses high frequency attenuation values as the basis for a global condition indicator. High frequency attenuation is estimated by LIRA through a proprietary method called 3rd-harmonic analysis [7].

However, the use of an attenuation figure as it is would not be enough for condition assessment, because of its dependence on the ratio C/L. Degradation affects C and L in a complex way and the shape of its ratio might be non monotonic through the entire cable life. For this reason, LIRA implements a method, sketched in Figure 15, where the contributions from C and L are isolated, resulting in an indicator sensitive only to C (CBAC[1]) and another indicator sensitive only to L (CBAL[2]). Since it has been demonstrated that degradation affects C at a higher degree than L [6, 7 and 8], CBAC is used as a global condition indicator. Note that no attempt is done to estimate directly C or L: CBAC is calculated through the estimation (using frequency analysis) of:

1. The high frequency attenuation (3rd harmonic analysis)
2. The cable characteristic impedance Z0
3. The signal phase velocity VR

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[1] CBAC: Central Band Attenuation for Capacitance
[2] CBAL: Central Band Attenuation for Inductance

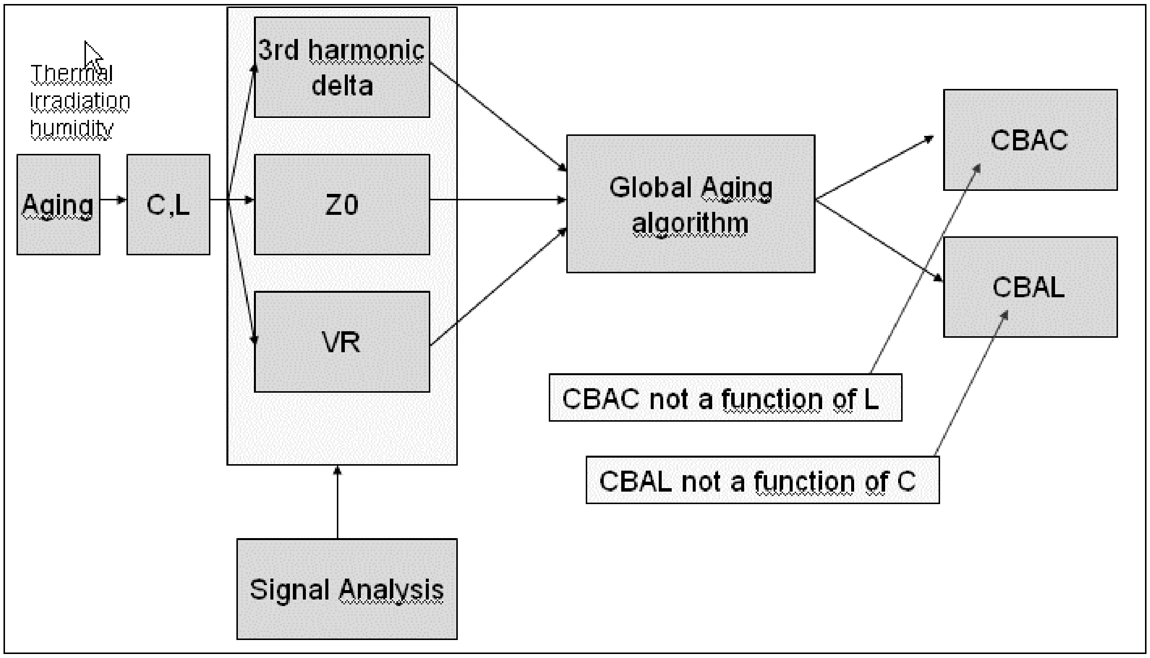


Figure 15 Global condition indicator (CBAC, CBAL) algorithm

3 EPR samples, 20 m long, were aged at 140 °C for 10, 20 and 30 days, producing a thermal degradation equivalent to 20, 40 and 60 years (based on the Arrhenius equation). Figure 16 shows the EAB (Elongation At Break) absolute on the insulation, for the 3 samples and the reference (new) sample.
Figure 17 shows the corresponding CBAC indications from LIRA, (CBAC is the global condition indicator sensitive to dielectric capacitance variations). The almost linear decreasing trend is due to the fact that thermal aging results in a slight **decrease** of the dielectric capacitance.
Figure 18 contains the correlation between the EAB indicator and CBAC on the 4 measured samples. It is interesting to see that this correlation is practically linear between 20 and 60 years, which makes easier interpolation and, more important, extrapolation to the end of life.

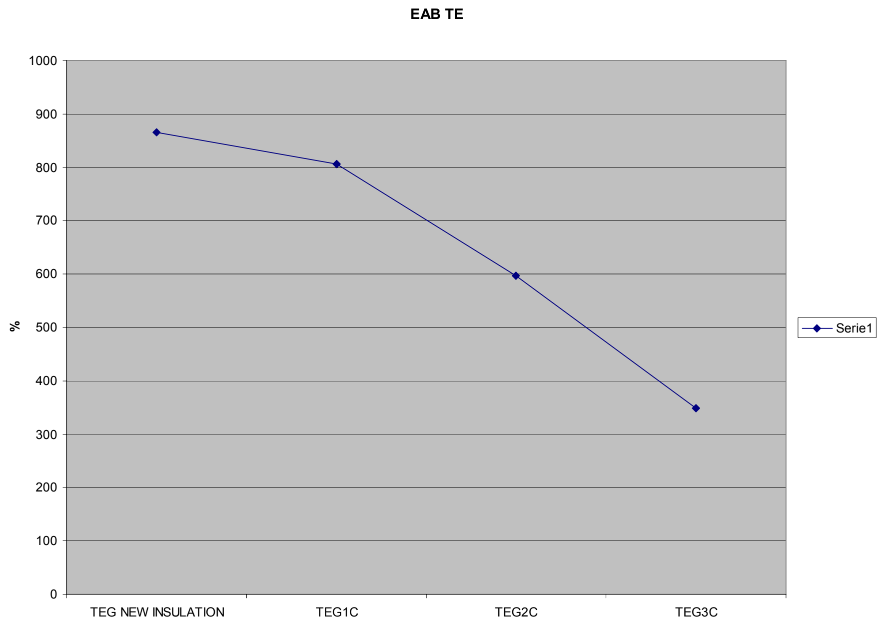


Figure 16 EAB measurement on EPR/EPDM samples (0,20,40 and 60 years)

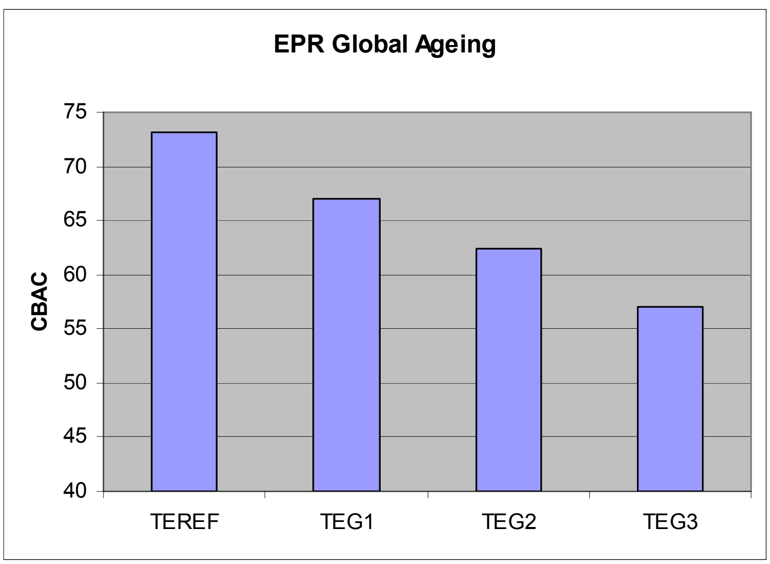


Figure 17 LIRA indicator CBAC vs. aging

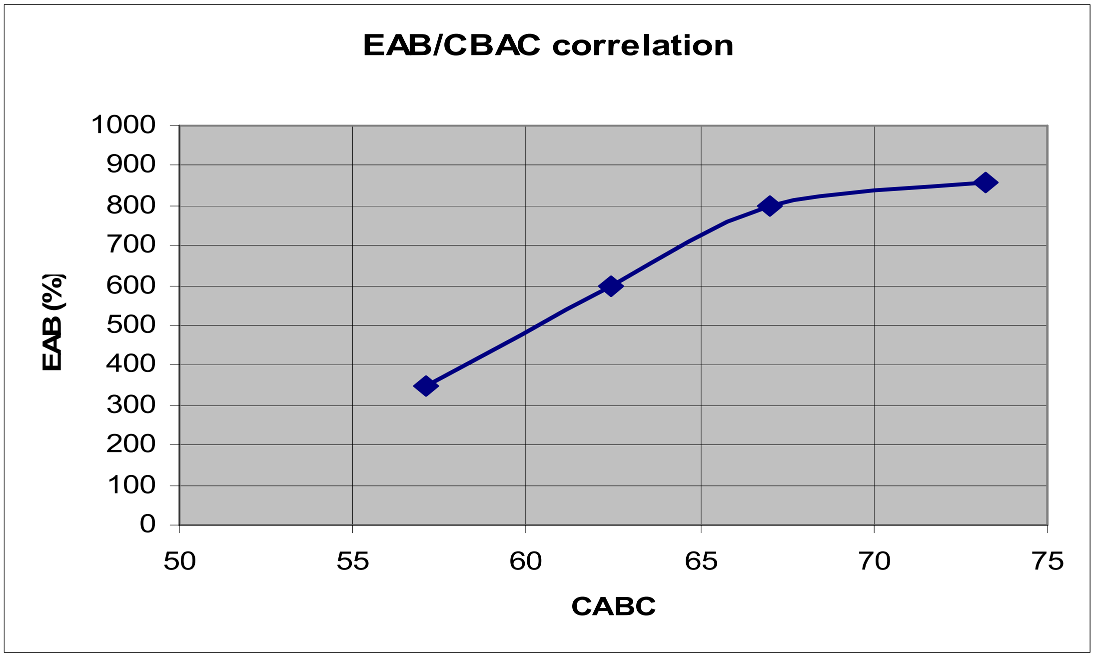


Figure 18 CBAC/EAB correlation for EPR/EPDM

CONCLUSIONS

This report presents the results from the tests performed in Madrid on EPR and XLPE insulated cables.

These results clearly indicate that the indenter is a good leading indicator of global aging degradation when used on Hypalon jacket materials. Hot Spot detection and localisation is somehow difficult and uncertain with TDR, while LIRA gives accurate and reliable indications, both for thermal aging and mechanical degradations.

APPENDIX A. LIRA Measurements on the samples before degradation

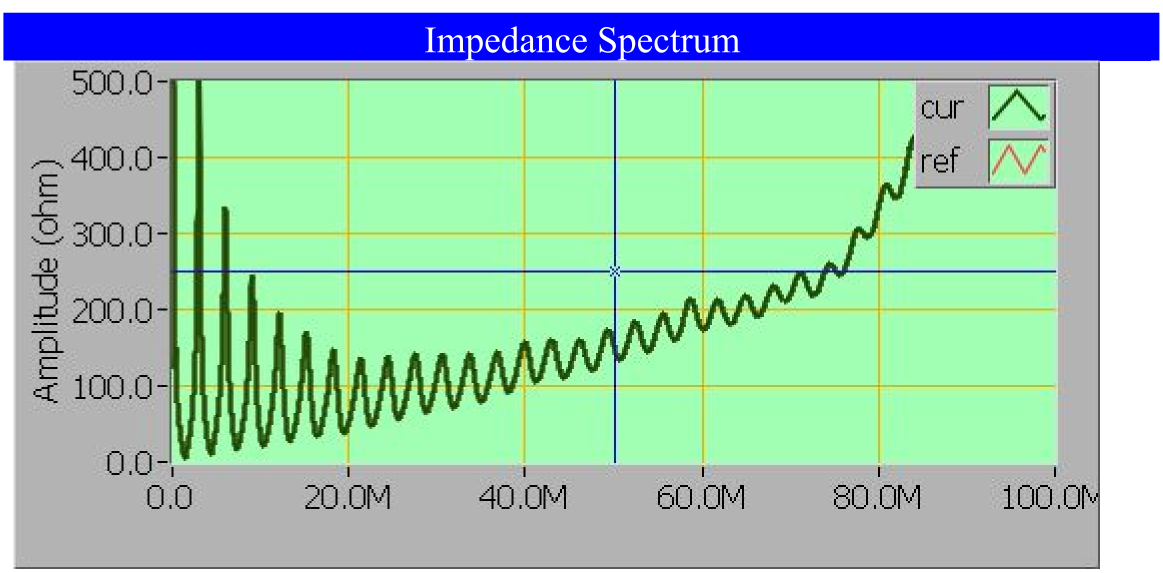
TEM1-200-AX-open Results

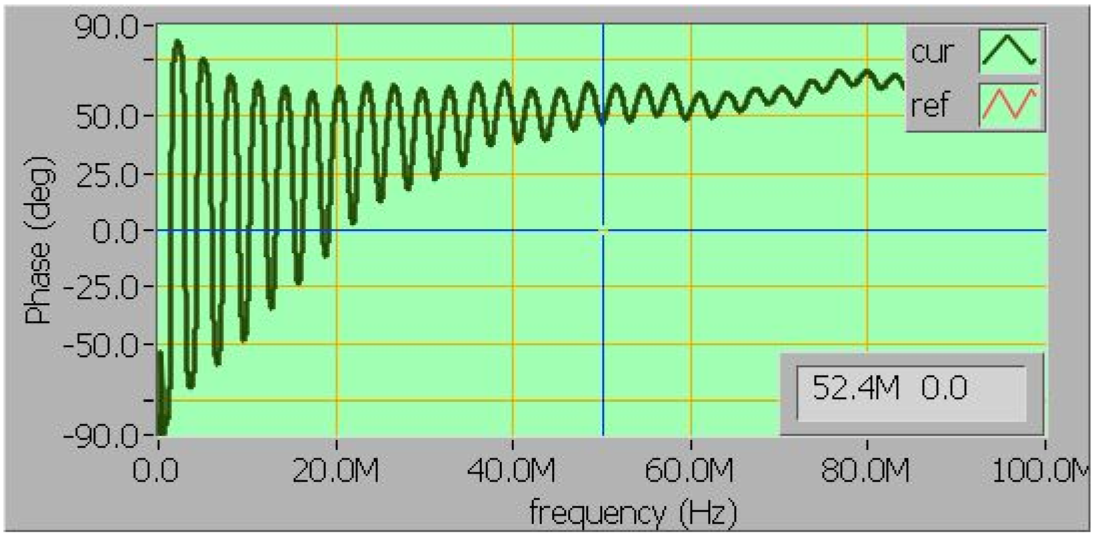
TestResults	
Avg. Velocity Ratio	0,628
CBA (dB/km)	303,5
Attenuation (dB/km)	54,2
Calc. Frequency (Hz)	3663292

Segment Results					
Segment	1	2	3	4	5
Length (m)	30,00				
Velocity Ratio	0,6280				
Char. Impedance (Ω)	62,8				
Inductance (μH/m)	0,3				
Capacitance (pF/m)	84,53				

Resonance Frequencies (Hz)					
1414225	10263443				
2986497	12216250				
4340088	13227664				
6020240	15354030				
7278632	16240626				
9091942	18519921				

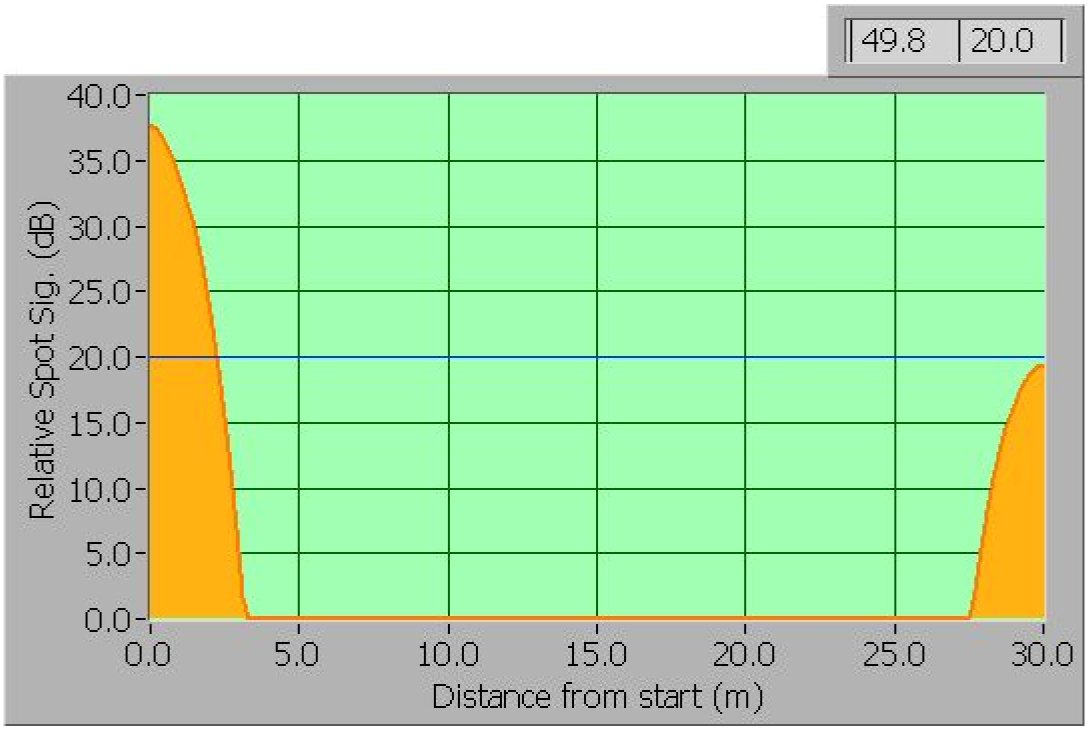
TEM1-200-AX-open Plots





Phase (deg)
90.0
50.0
25.0
0.0
-25.0
-50.0
-90.0
0.0
20.0M
40.0M
60.0M
80.0M
100.0M
frequency (Hz)
cur
ref
52.4M 0.0

HoTSpot Signature



TEM2-200-AX-open Parameters

TEM2-200-AX-open Results

TestResults	
Avg. Velocity Ratio	0,560
CBA (dB/km)	297,7
Attenuation (dB/km)	62,1
Calc. Frequency (Hz)	3629273

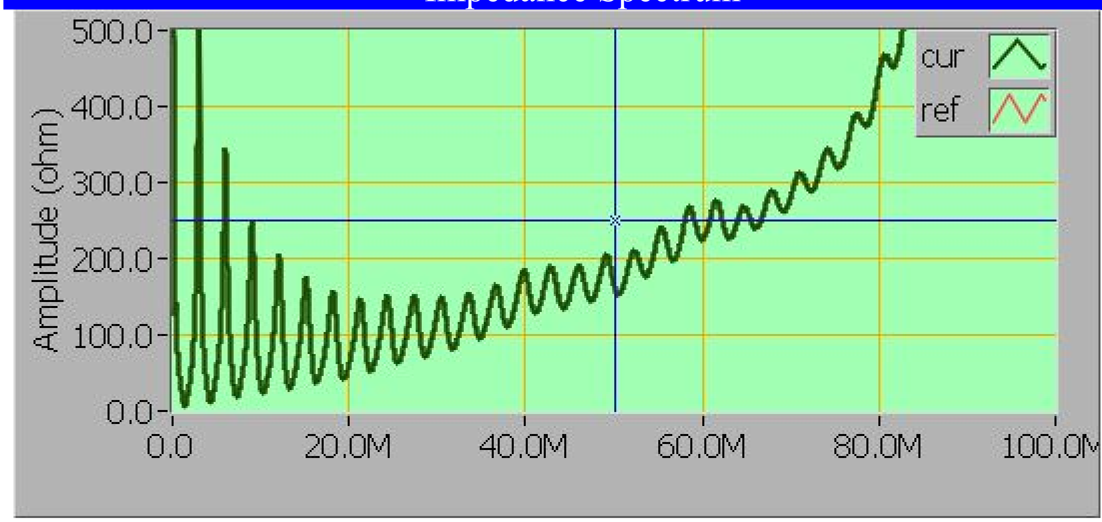
Segment Results					
Segment	1	2	3	4	5
Length (m)	27,00				

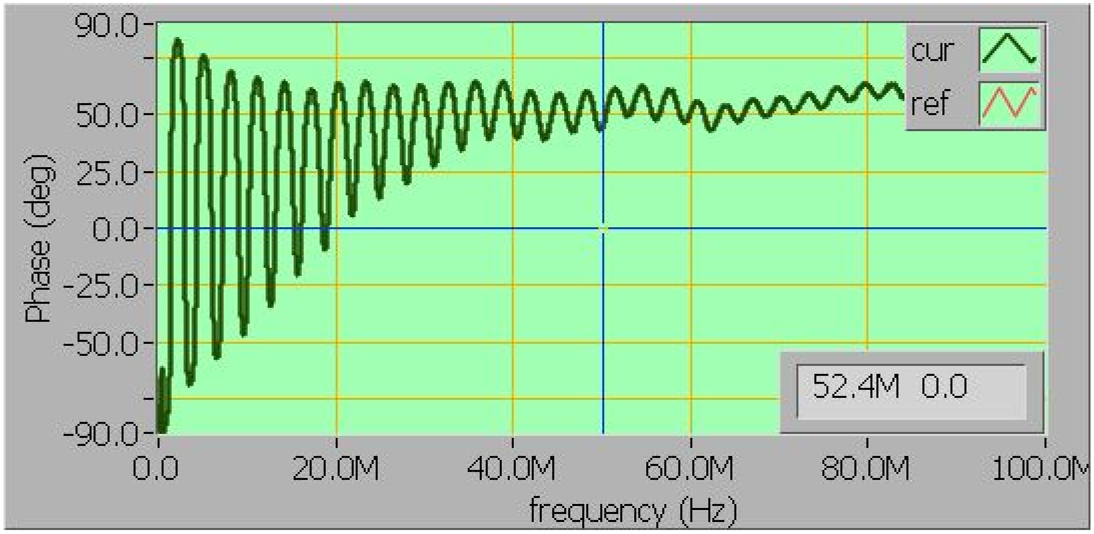
Velocity Ratio	0,5600				
Char. Impedance (Ω)	63,3				
Inductance (μH/m)	0,4				
Capacitance (pF/m)	94,05				

Resonance Frequencies (Hz)					
1397275	10179495				
2967412	12170349				
4291135	13150721				
6009116	15325466				
7232321	16113958				
9073371	18478926				

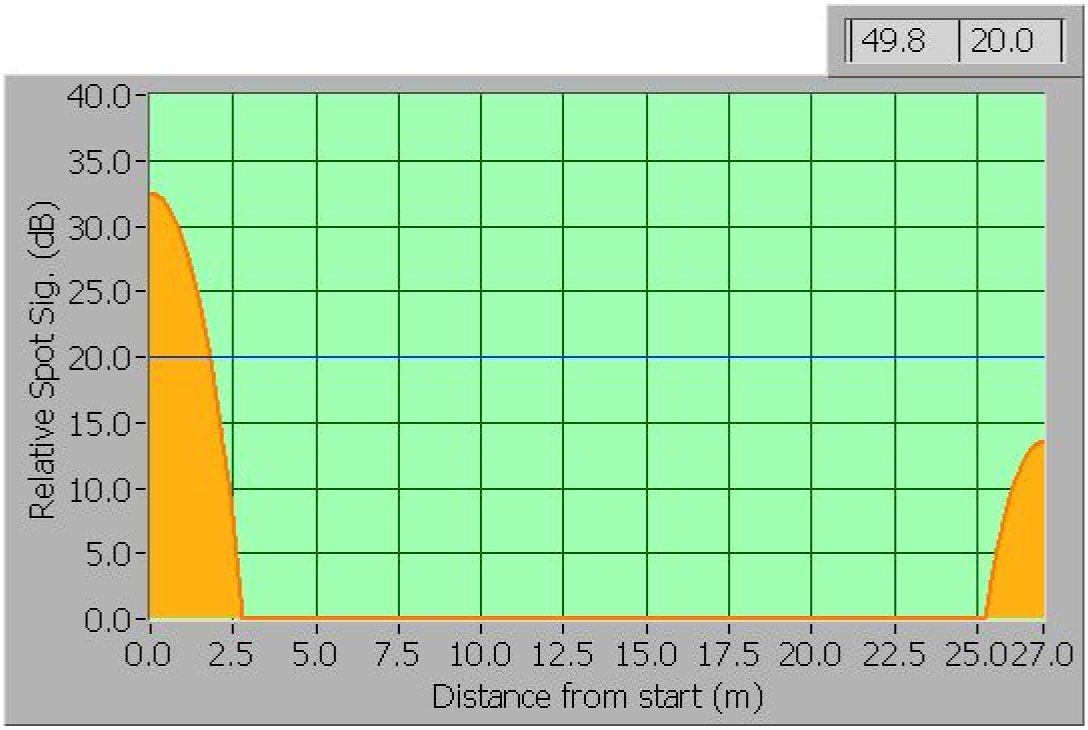
TEM2-200-AX-open Plots

Impedance Spectrum





HoTSpot Signature



TEG1-200-AX-open Parameters

TEG1-200-AX-open Results

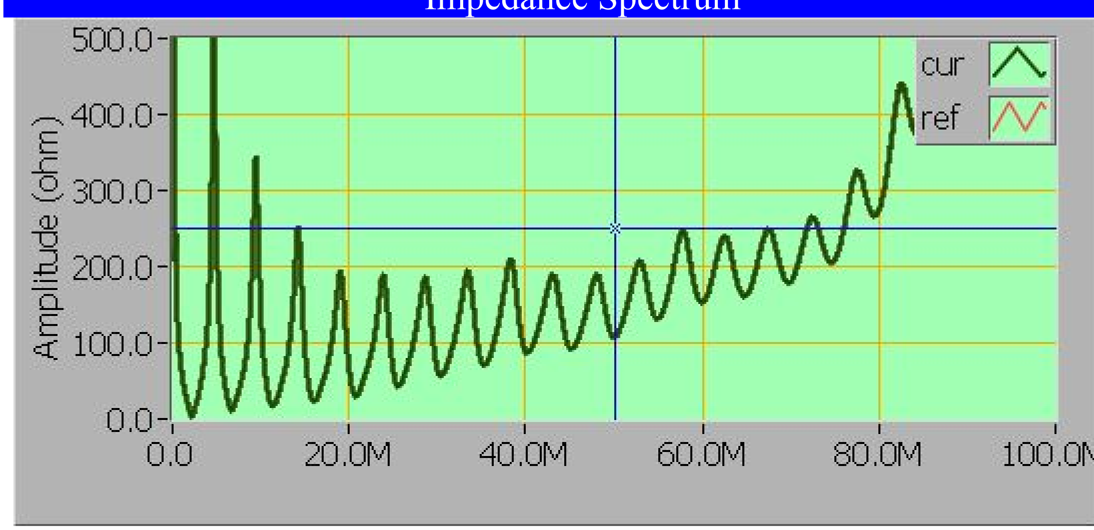
TestResults	
Avg. Velocity Ratio	0,552
CBA (dB/km)	446,5
Attenuation (dB/km)	88,5
Calc. Frequency (Hz)	5692222

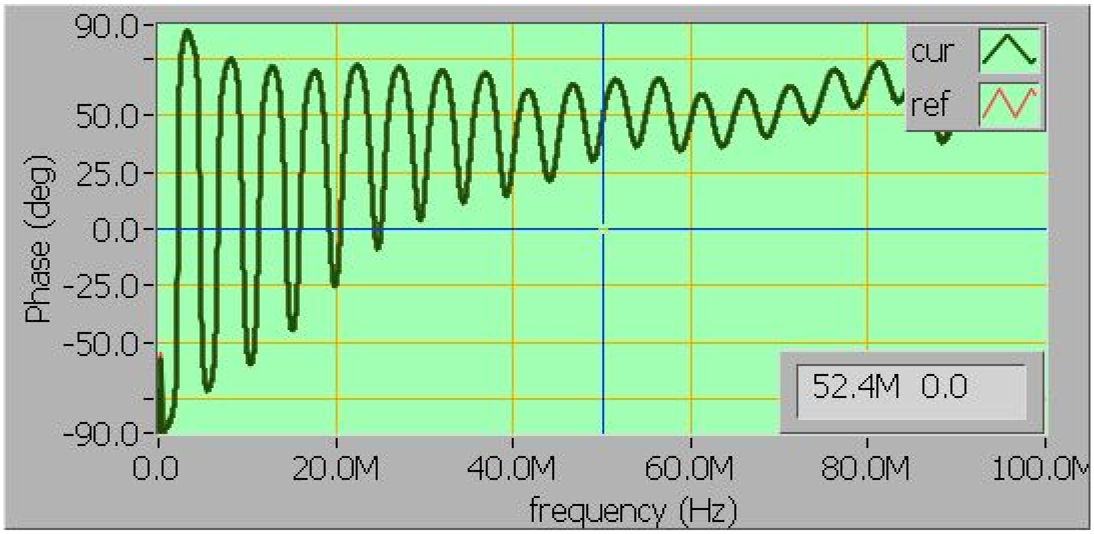
Segment Results					
Segment	1	2	3	4	5
Length (m)	17,00				
Velocity Ratio	0,5520				
Char. Impedance (Ω)	65,8				
Inductance (μH/m)	0,4				
Capacitance (pF/m)	91,87				

Resonance Frequencies (Hz)					
2178754	15924037				
4695363	19288332				
6689081	20514693				
9484560	24372976				
11310432	25119412				
14335818	0				

TEG1-200-AX-open Plots

Impedance Spectrum





Phase (deg)
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25.0
0.0
-25.0
-50.0
-90.0
0.0
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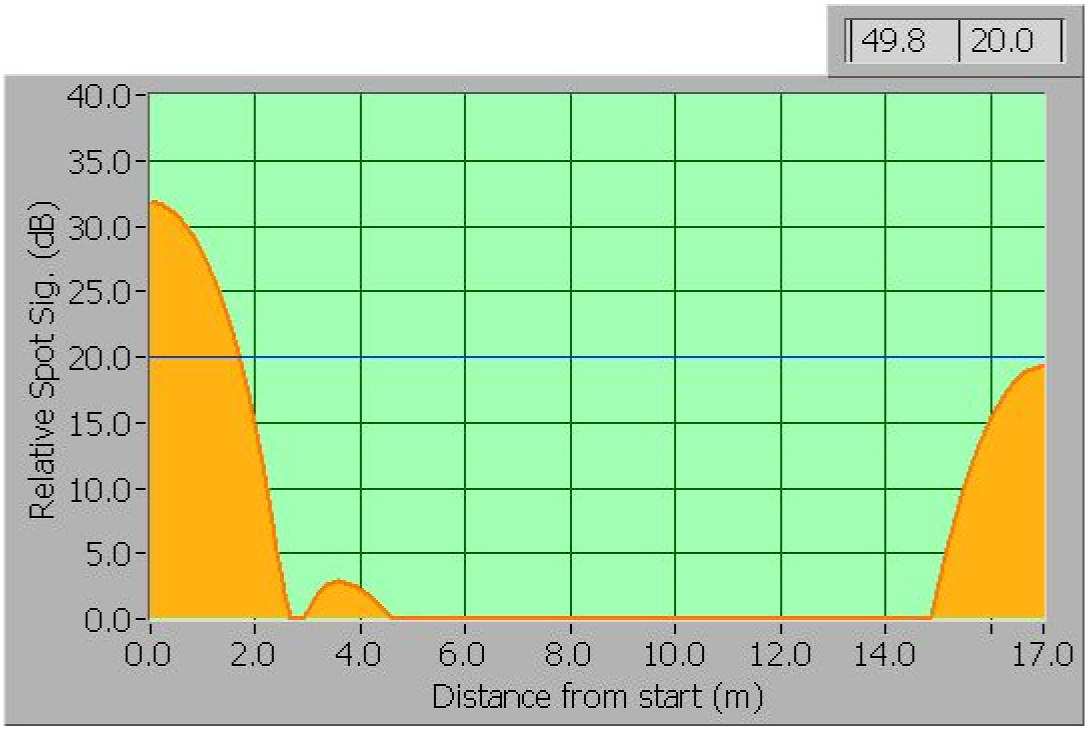
40.0M
60.0M
80.0M
100.0M
frequency (Hz)
cur
ref
52.4M 0.0

HoTSpot Signature



TEG1-200-AY-open Results

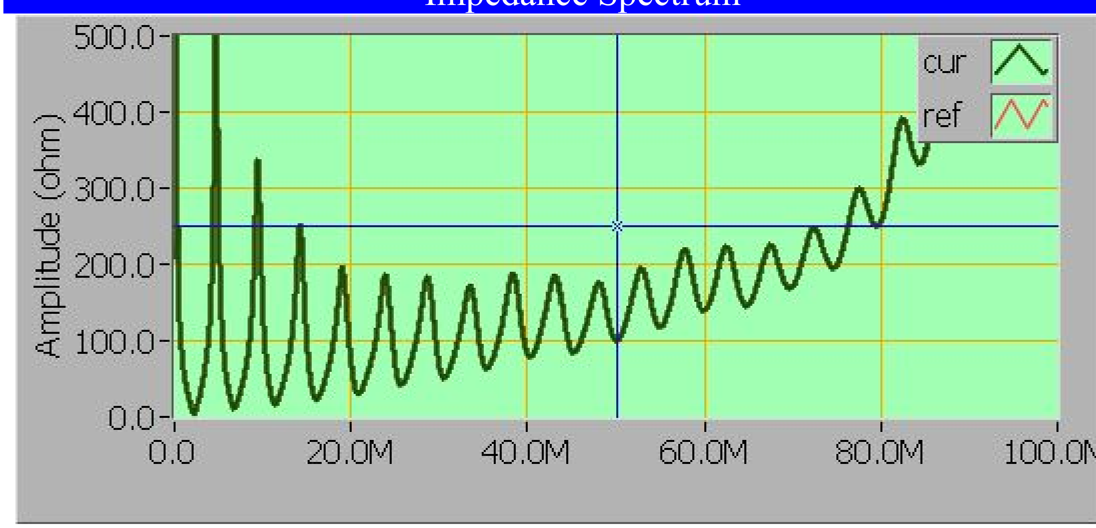
TestResults	
Avg. Velocity Ratio	0,554
CBA (dB/km)	471,7
Attenuation (dB/km)	90,1
Calc. Frequency (Hz)	5713735

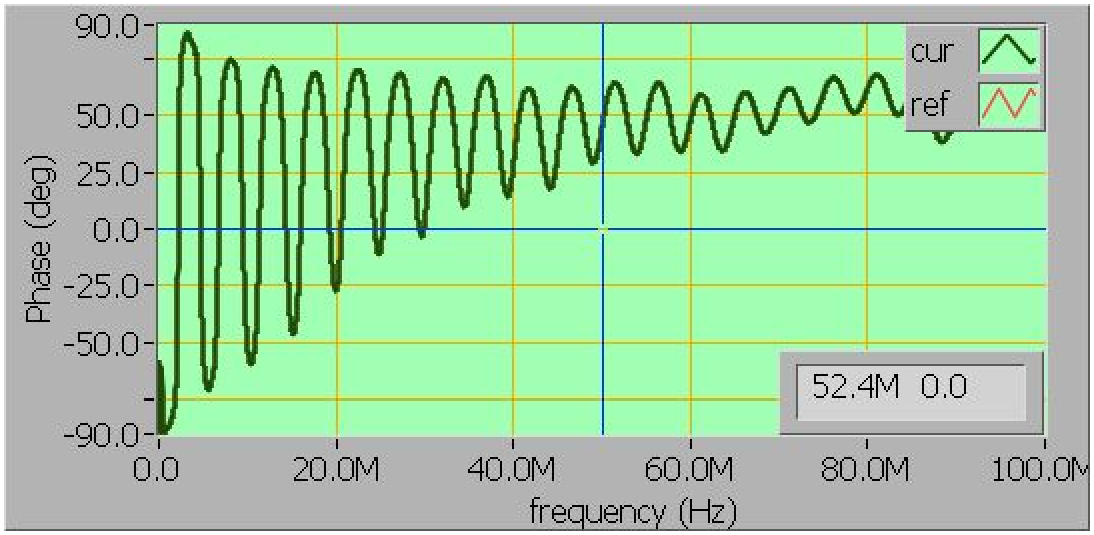
Segment Results					
Segment	1	2	3	4	5
Length (m)	17,00				
Velocity Ratio	0,5540				
Char. Impedance (Ω)	65,5				
Inductance (µH/m)	0,4				
Capacitance (pF/m)	91,89				

Resonance Frequencies (Hz)					
2180556	15975647				
4703193	19279839				
6724277	20610595				
9482237	24357287				
11338123	25257222				
14336131	29392696				

TEG1-200-AY-open Plots

Impedance Spectrum





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25.0
0.0
-25.0
-50.0
-90.0
Phase (deg)
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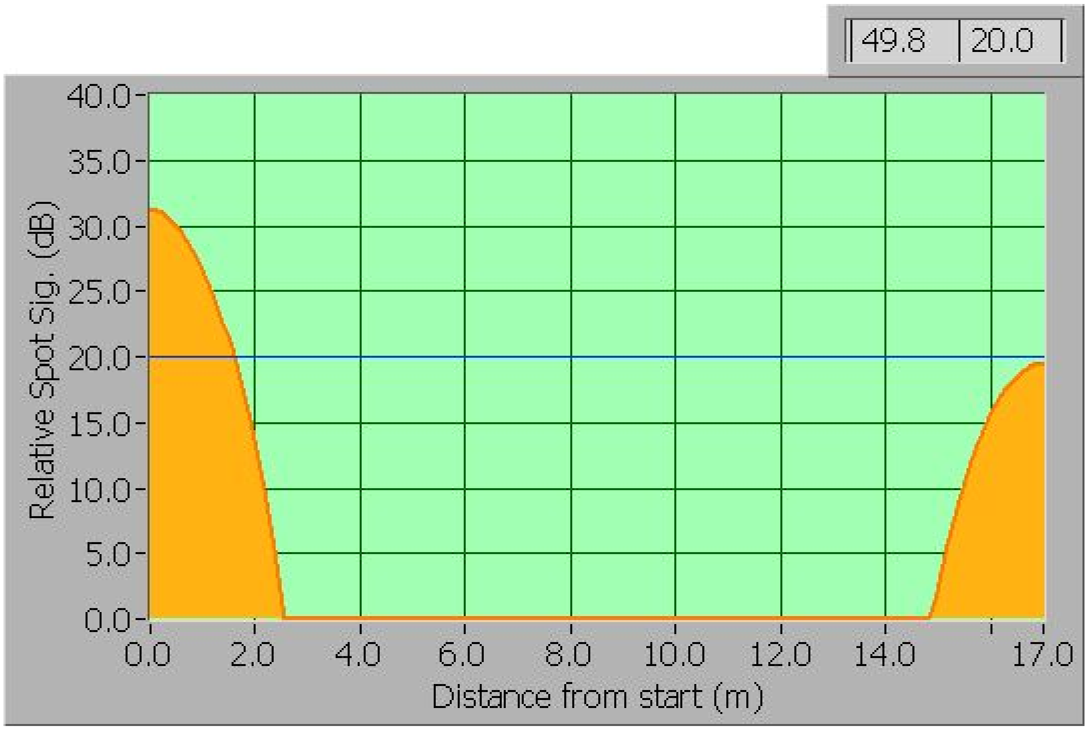
60.0M
80.0M
100.0M
frequency (Hz)
cur
ref
52.4M 0.0

HoTSpot Signature



TEG2-200-AX-open Results

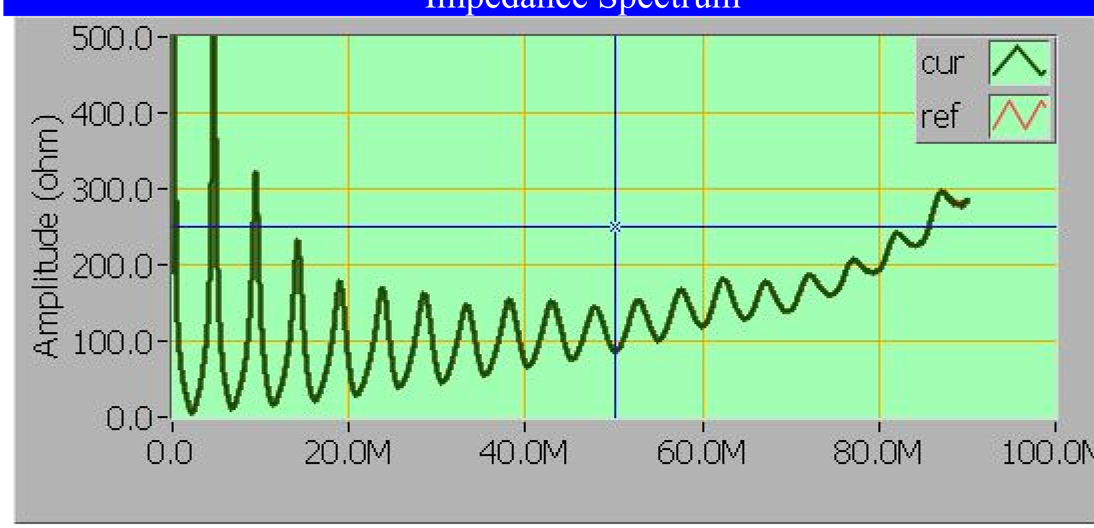
TestResults	
Avg. Velocity Ratio	0,554
CBA (dB/km)	339,6
Attenuation (dB/km)	88,6
Calc. Frequency (Hz)	5734803

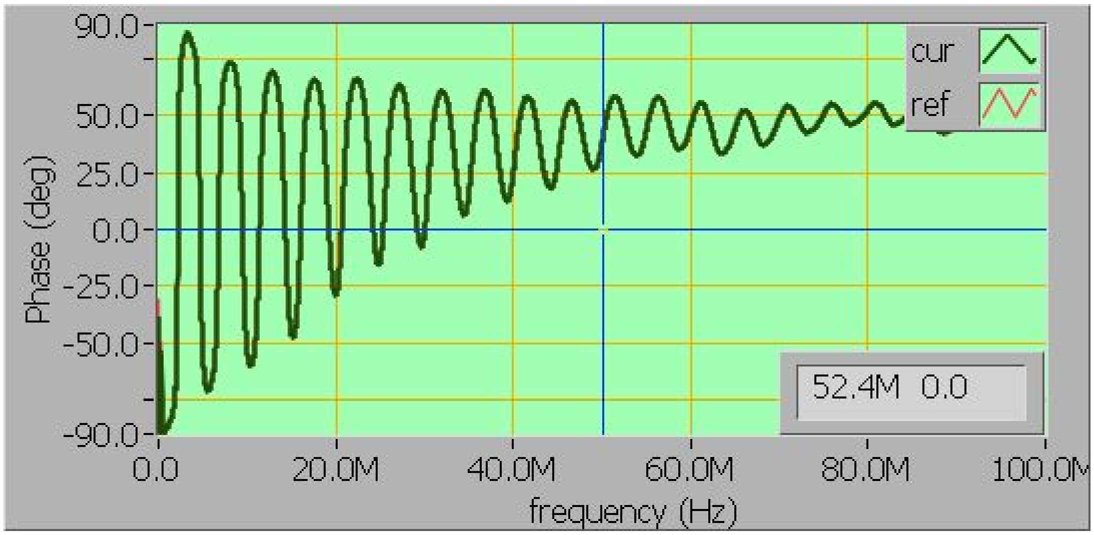
Segment Results					
Segment	1	2	3	4	5
Length (m)	17,00				
Velocity Ratio	0,5540				
Char. Impedance (Ω)	63,5				
Inductance (µH/m)	0,4				
Capacitance (pF/m)	94,86				

Resonance Frequencies (Hz)					
2189299	16039144				
4696485	19229656				
6773120	20663793				
9466169	24235085				
11391229	25345894				
14293267	29191999				

TEG2-200-AX-open Plots

Impedance Spectrum





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25.0
0.0
-25.0
-50.0
-90.0
Phase (deg)
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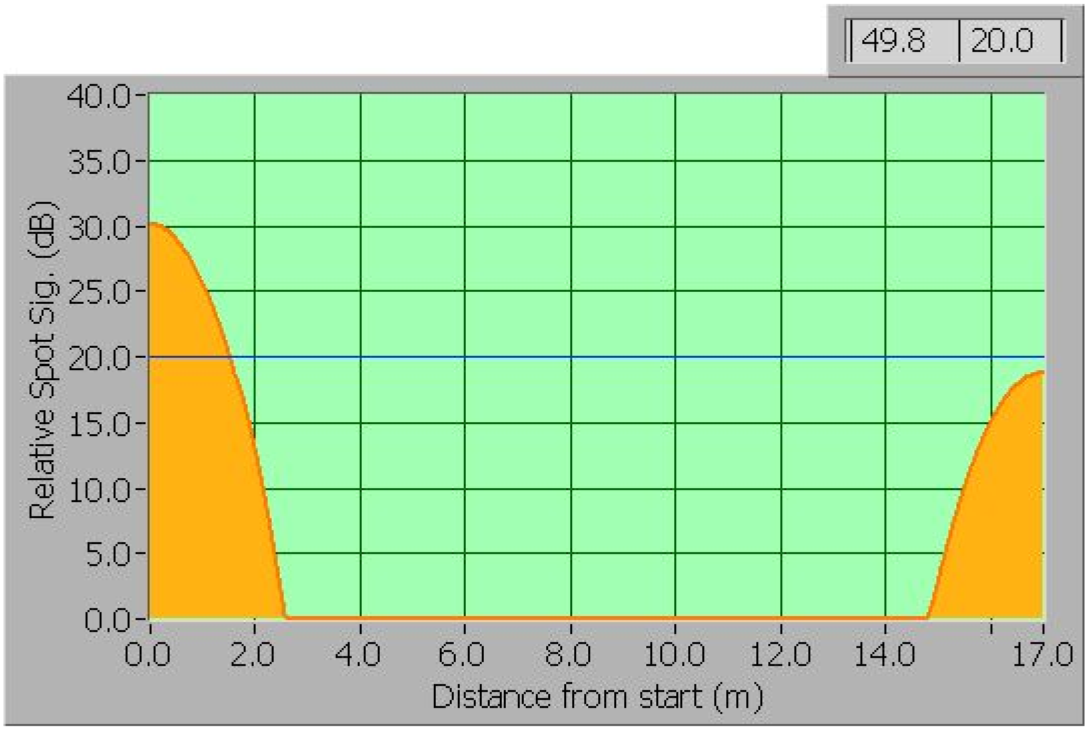
60.0M
80.0M
100.0M
frequency (Hz)
cur
ref
52.4M 0.0

HoTSpot Signature



TEG3-200-AX-open Results

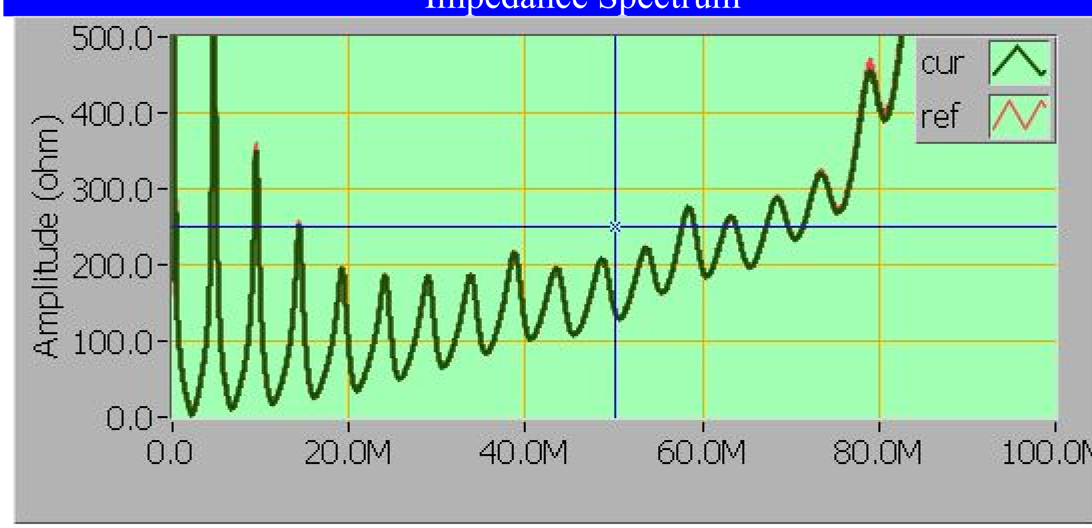
TestResults	
Avg. Velocity Ratio	0,563
CBA (dB/km)	327,6
Attenuation (dB/km)	86,2
Calc. Frequency (Hz)	5710418

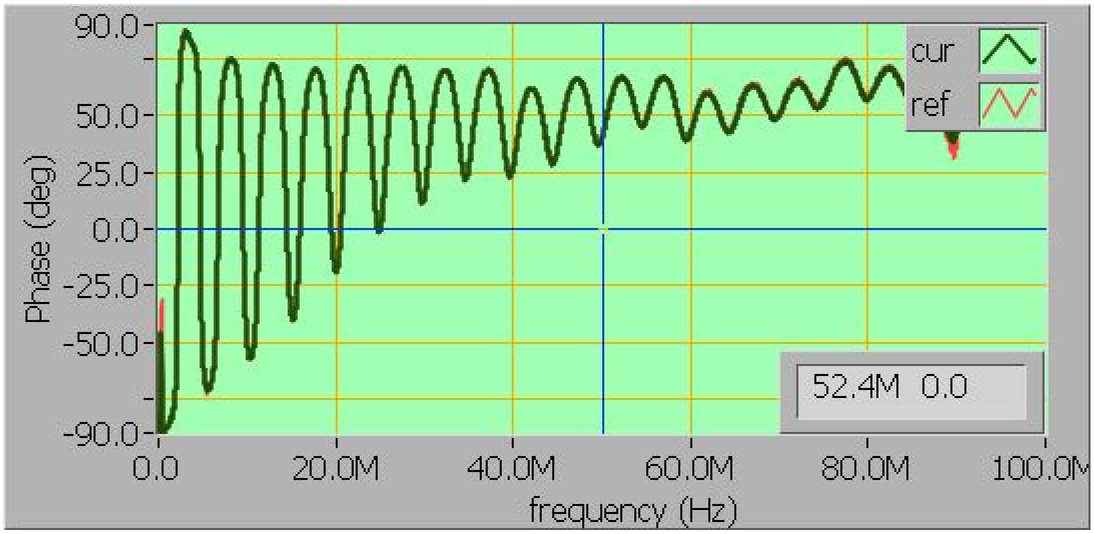
Segment Results					
Segment	1	2	3	4	5
Length (m)	17,00				
Velocity Ratio	0,5630				
Char. Impedance (Ω)	66,7				
Inductance (μH/m)	0,4				
Capacitance (pF/m)	88,87				

Resonance Frequencies (Hz)					
2185919	15938188				
4708648	19500563				
6712188	20565882				
9547047	24731839				
11301003	25040992				
14470958	0				

TEG3-200-AX-open Plots

Impedance Spectrum





90.0
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0.0
-25.0
-50.0
-90.0
Phase (deg)
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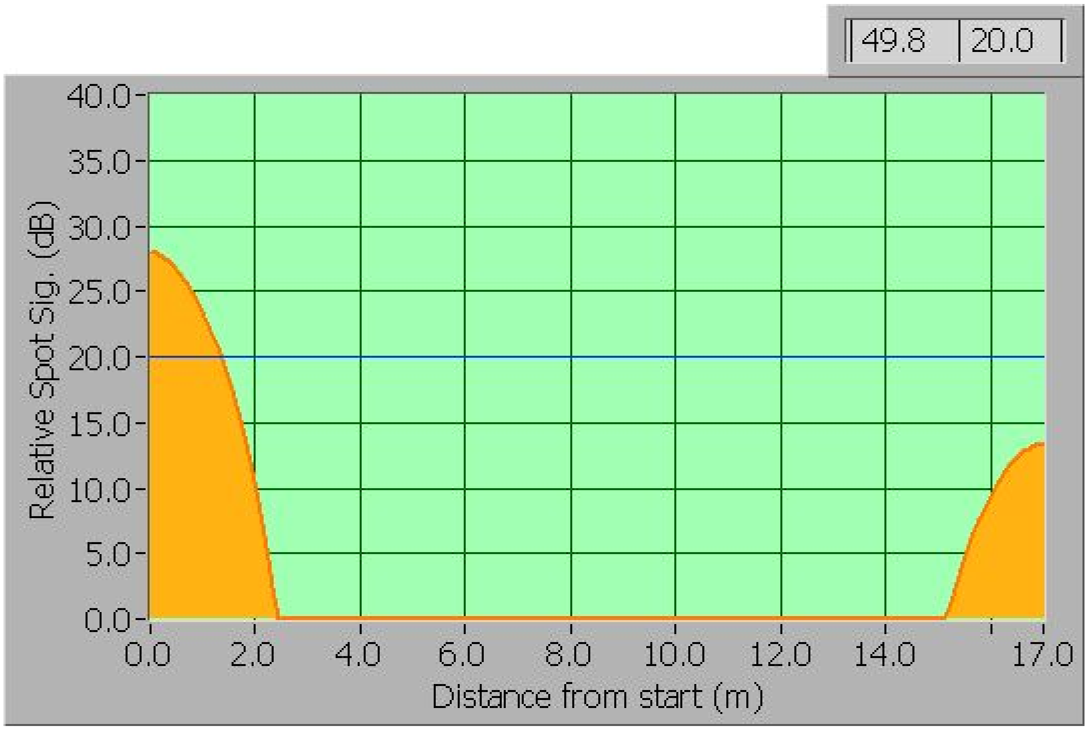
60.0M
80.0M
100.0M
frequency (Hz)
cur
ref
52.4M 0.0

HoTSpot Signature



TEL1-200-AX-open Results

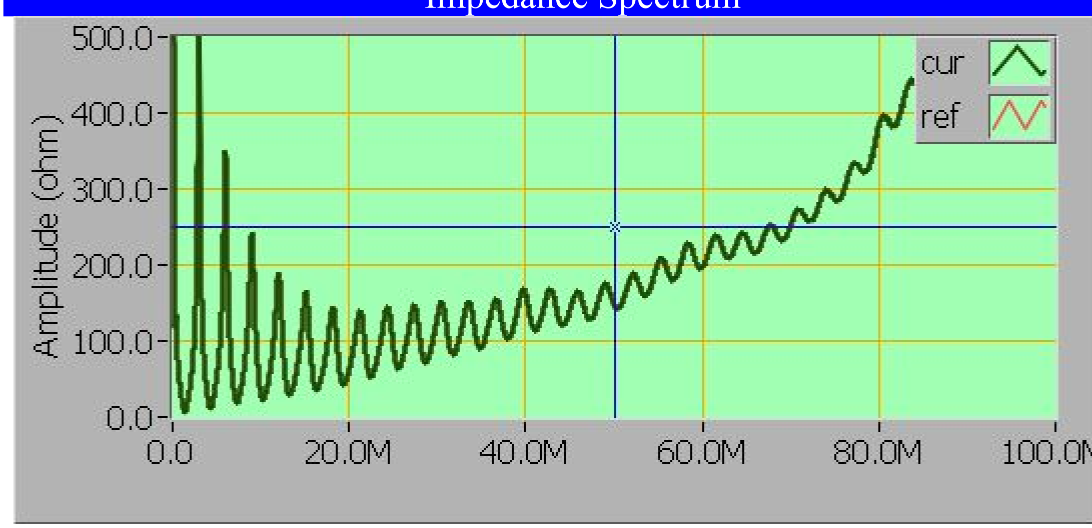
TestResults	
Avg. Velocity Ratio	0,562
CBA (dB/km)	364,8
Attenuation (dB/km)	65,8
Calc. Frequency (Hz)	3624966

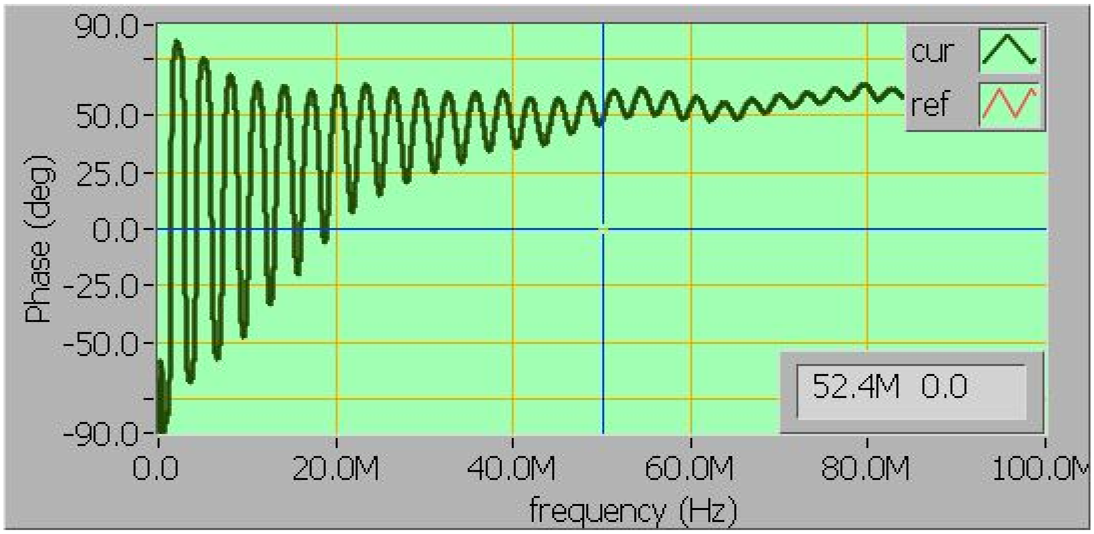
Segment Results					
Segment	1	2	3	4	5
Length (m)	27,00				
Velocity Ratio	0,5620				
Char. Impedance (Ω)	63,9				
Inductance (µH/m)	0,4				
Capacitance (pF/m)	92,78				

Resonance Frequencies (Hz)					
1397459	10193602				
2972007	12122549				
4277925	13127175				
6002971	15301486				
7257395	16100331				
9041911	18522907				

TEL1-200-AX-open Plots

Impedance Spectrum

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-90.0
Phase (deg)
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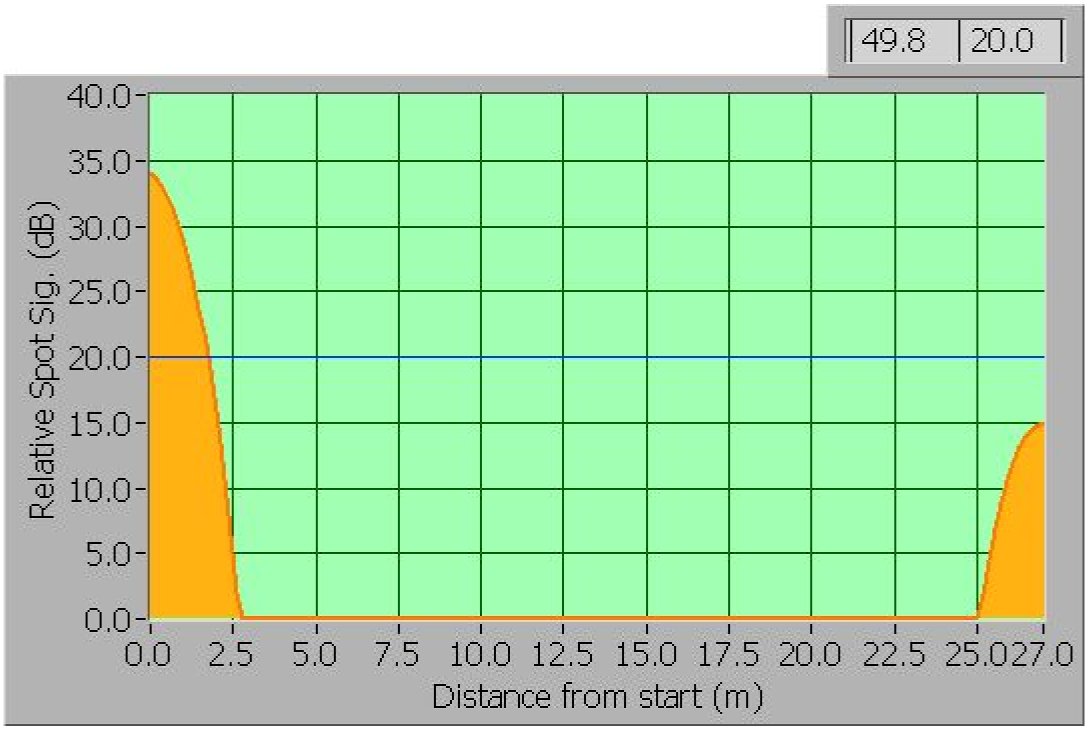
40.0M
60.0M
80.0M
100.0M
frequency (Hz)
cur
ref
52.4M 0.0

HoTSpot Signature



TEL2-200-AX Results

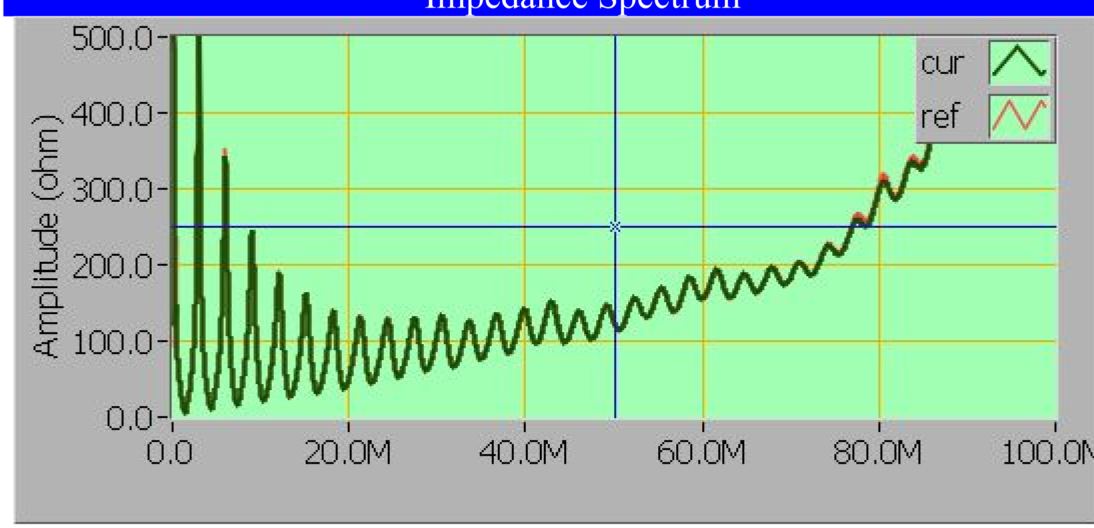
TestResults	
Avg. Velocity Ratio	0,560
CBA (dB/km)	369,9
Attenuation (dB/km)	61,1
Calc. Frequency (Hz)	3658044

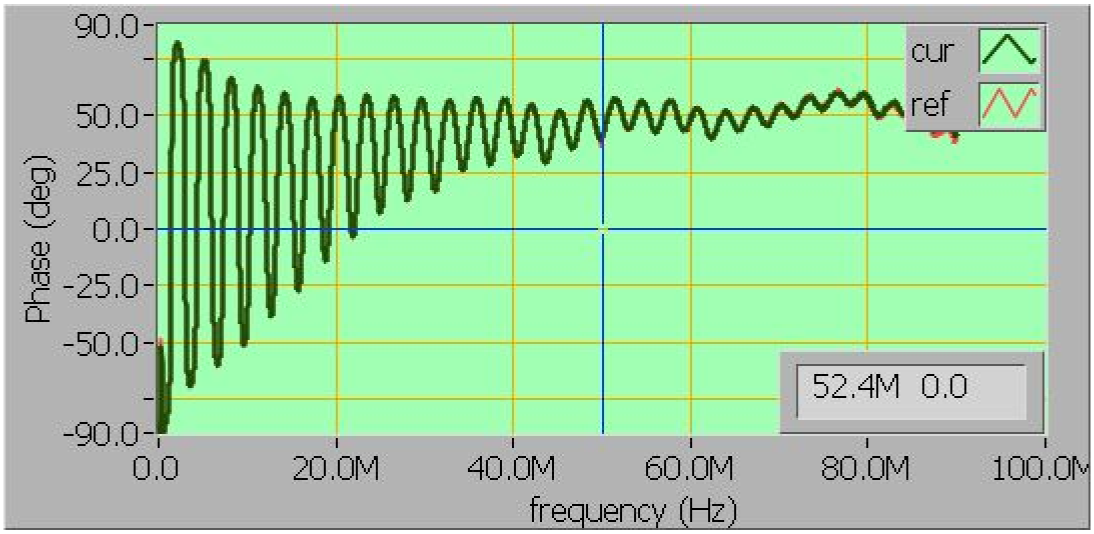
Segment Results					
Segment	1	2	3	4	5
Length (m)	27,00				
Velocity Ratio	0,5600				
Char. Impedance (Ω)	62,7				
Inductance (μH/m)	0,4				
Capacitance (pF/m)	95,14				

Resonance Frequencies (Hz)					
1407929	10290635				
2967823	12152476				
4348264	13261338				
6003361	15268777				
7312201	16249819				
9052668	18455232				

TEL2-200-AX-open Plots

Impedance Spectrum





90.0
50.0
25.0
0.0
-25.0
-50.0
-90.0
Phase (deg)
0.0
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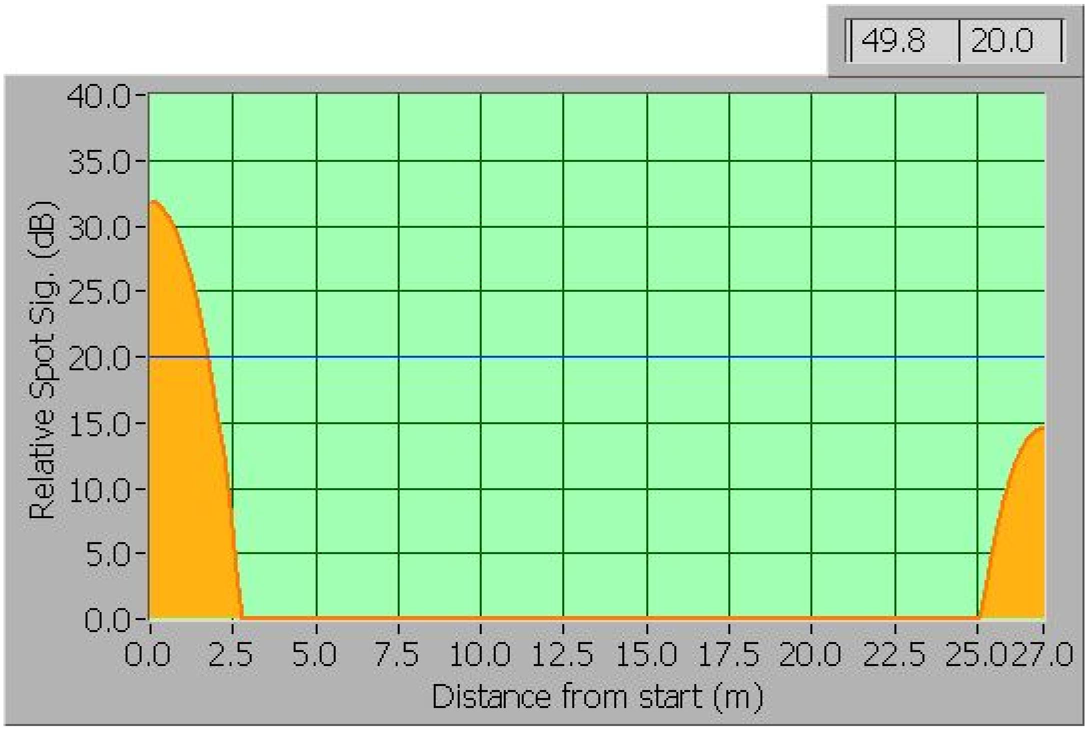
40.0M
60.0M
80.0M
100.0M
frequency (Hz)
cur
ref
52.4M 0.0

HoTSpot Signature



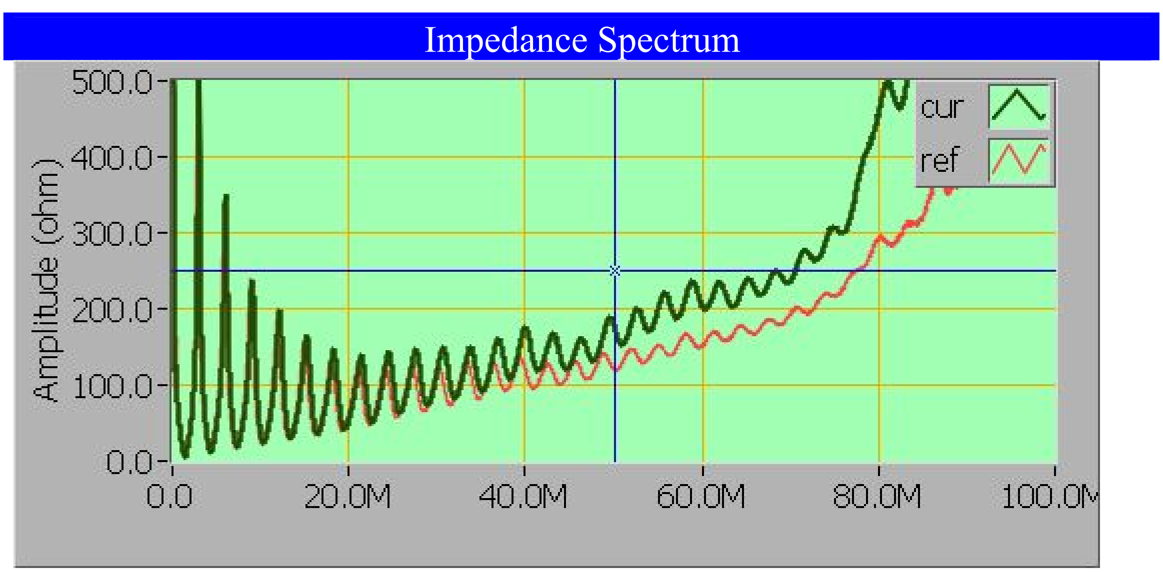
TEL3-200-AX-open Results

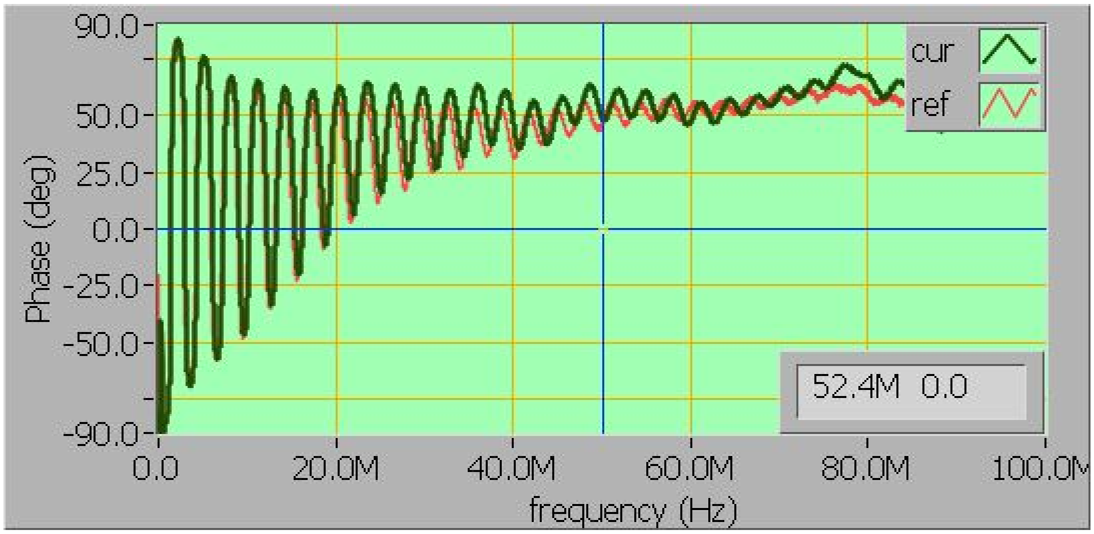
TestResults	
Avg. Velocity Ratio	0,568
CBA (dB/km)	337,1
Attenuation (dB/km)	61,1
Calc. Frequency (Hz)	3654451

Segment Results					
Segment	1	2	3	4	5
Length (m)	27,00				
Velocity Ratio	0,5680				
Char. Impedance (Ω)	62,9				
Inductance (µH/m)	0,4				
Capacitance (pF/m)	93,38				

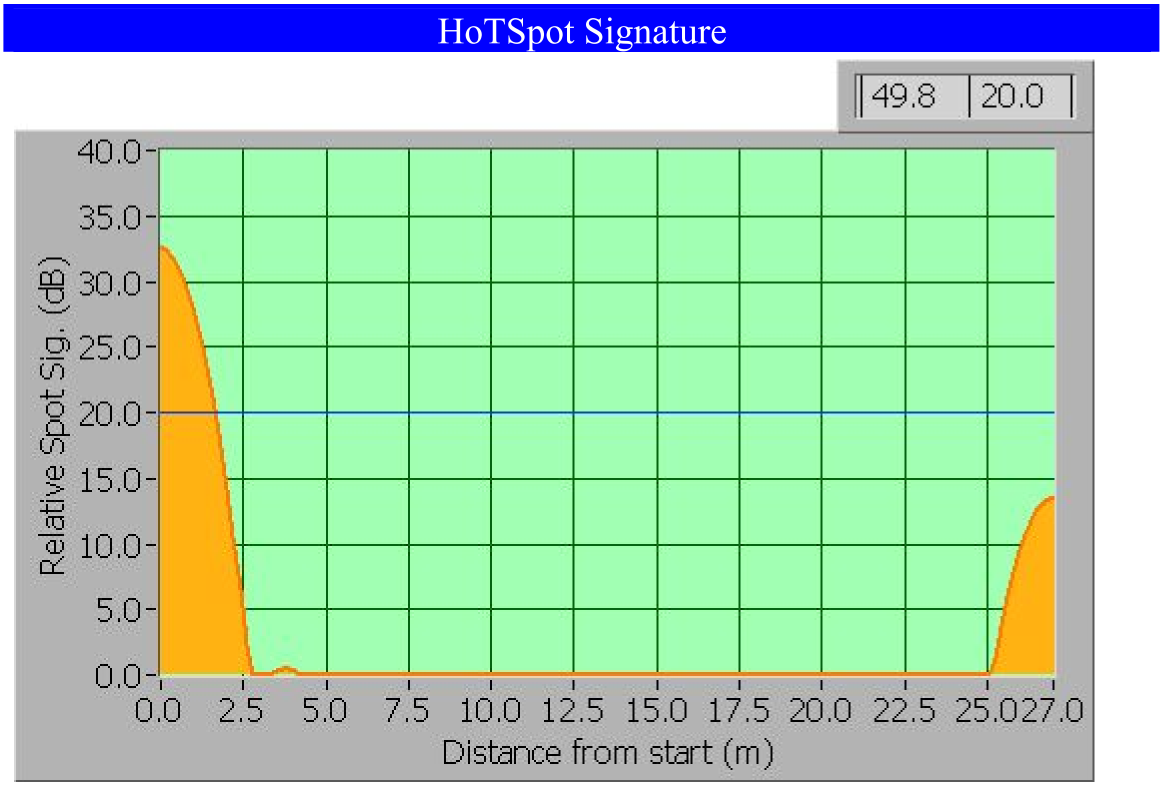
Resonance Frequencies (Hz)					
1409972	10265873				
2987444	12247378				
4321457	13263882				
6059294	15409526				
7291283	16236137				
9121735	18642376				

TEL3-200-AX-open Plots





90.0
50.0
25.0
0.0
-25.0
-50.0
-90.0
Phase (deg)
0.0
20.0M
40.0M
60.0M
80.0M
100.0M
frequency (Hz)
cur
ref
52.4M 0.0



HoTSpot Signature
49.8
20.0
Relative Spot Sig. (dB)
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
25.0
27.0
Distance from start (m)

TEL4-200-AX-open Results

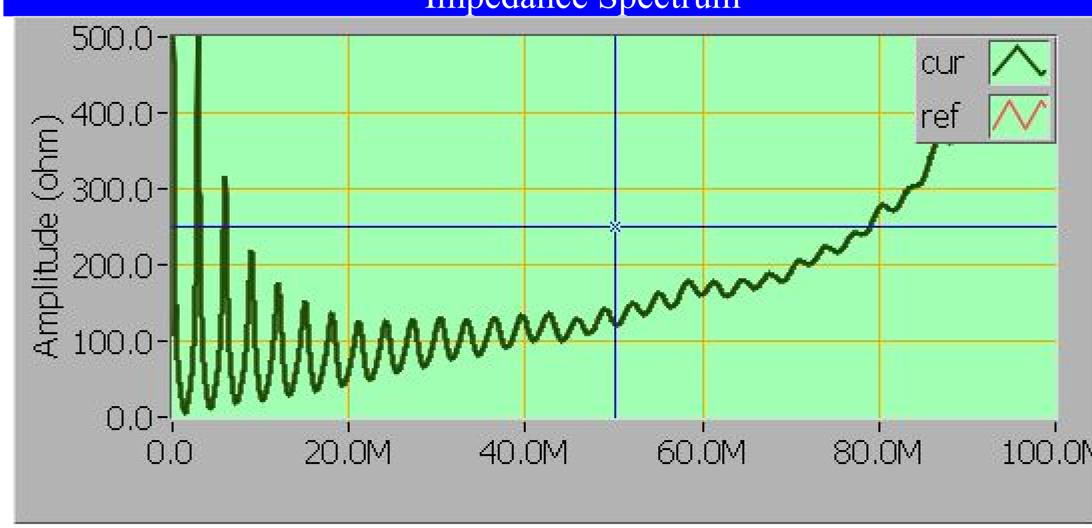
TestResults	
Avg. Velocity Ratio	0,558
CBA (dB/km)	336,4
Attenuation (dB/km)	59,9
Calc. Frequency (Hz)	3598288

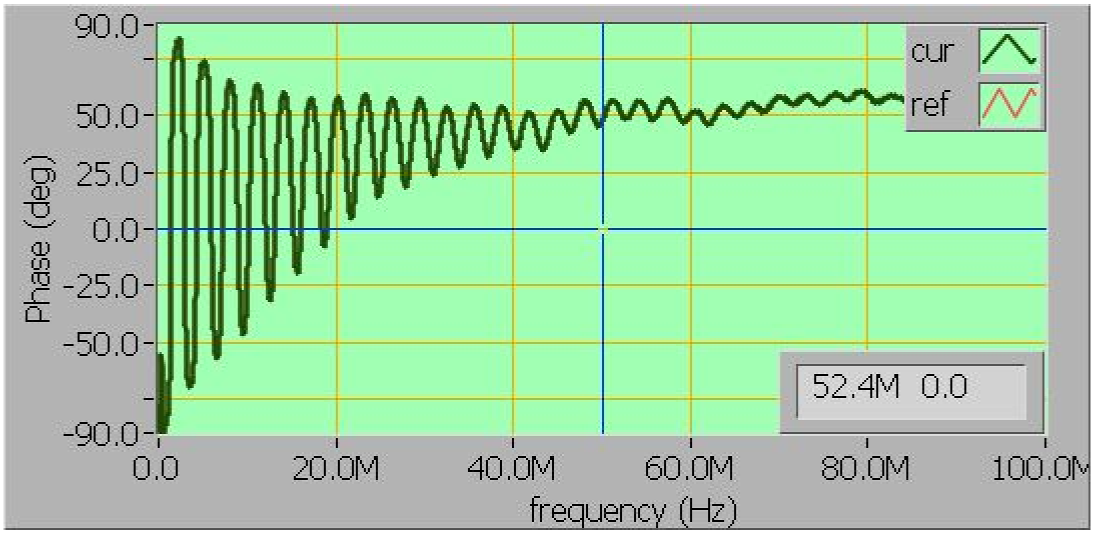
Segment Results					
Segment	1	2	3	4	5
Length (m)	27,00				
Velocity Ratio	0,5580				
Char. Impedance (Ω)	60,4				
Inductance (µH/m)	0,4				
Capacitance (pF/m)	98,96				

Resonance Frequencies (Hz)					
1400399	10152833				
2924346	12089319				
4272230	13088030				
5961211	15200199				
7205806	16043961				
8974382	18387155				

TEL4-200-AX-open Plots

Impedance Spectrum




Phase (deg)
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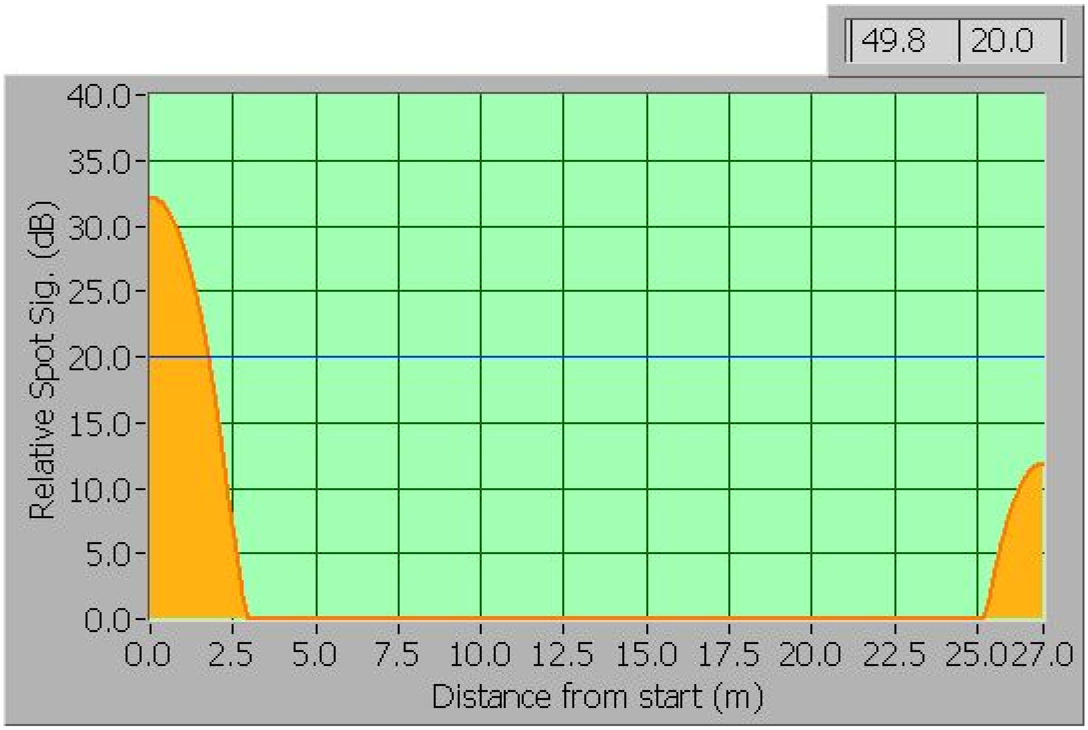
50.0
25.0
0.0
-25.0
-50.0
-90.0
0.0
20.0M
40.0M
60.0M
80.0M
100.0M
frequency (Hz)
cur
ref
52.4M 0.0

HoTSpot Signature



TXM1-200-X-open Results

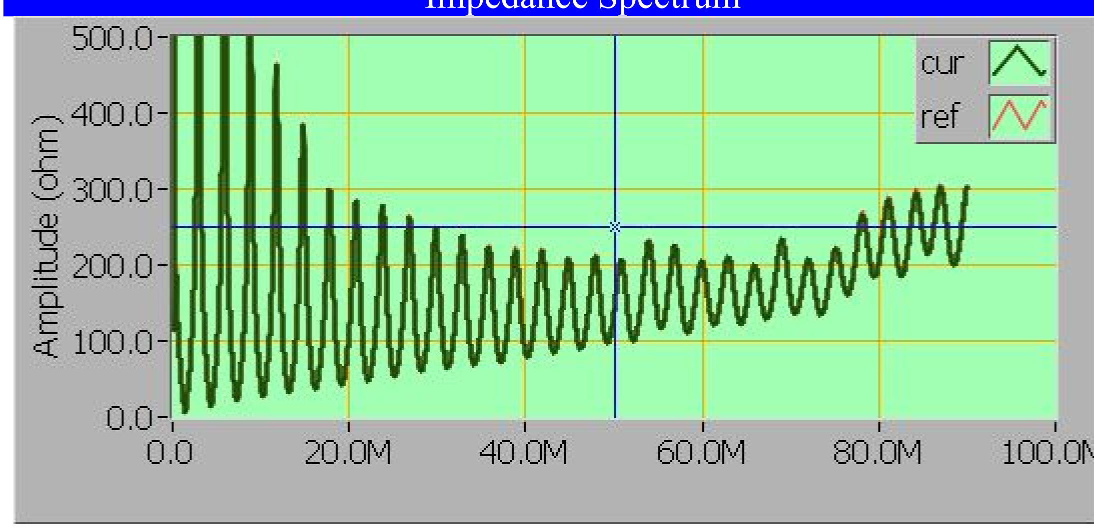
TestResults	
Avg. Velocity Ratio	0,607
CBA (dB/km)	189,8
Attenuation (dB/km)	37,3
Calc. Frequency (Hz)	3621929

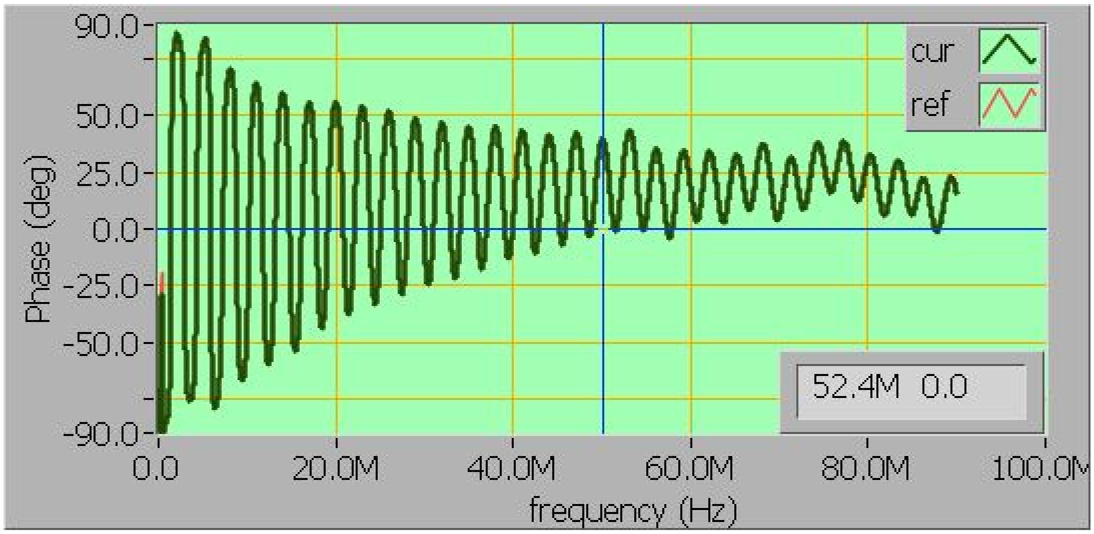
Segment Results					
Segment	1	2	3	4	5
Length (m)	30,00				
Velocity Ratio	0,6070				
Char. Impedance (Ω)	107,6				
Inductance (μH/m)	0,6				
Capacitance (pF/m)	51,08				

Resonance Frequencies (Hz)					
1403666	10230867	19086111	28038663	36972963	45863046
2927255	11773347	20853773	29923747	39074947	48317461
4316604	13177980	22063460	31012426	39938400	48798358
5872088	14772295	23876513	32929428	42103764	51374510
7267248	16156504	25039876	34002208	42909535	51627750
8799962	17826475	26913422	35983473	45182435	54537865

TXM1-200-X-open Plots

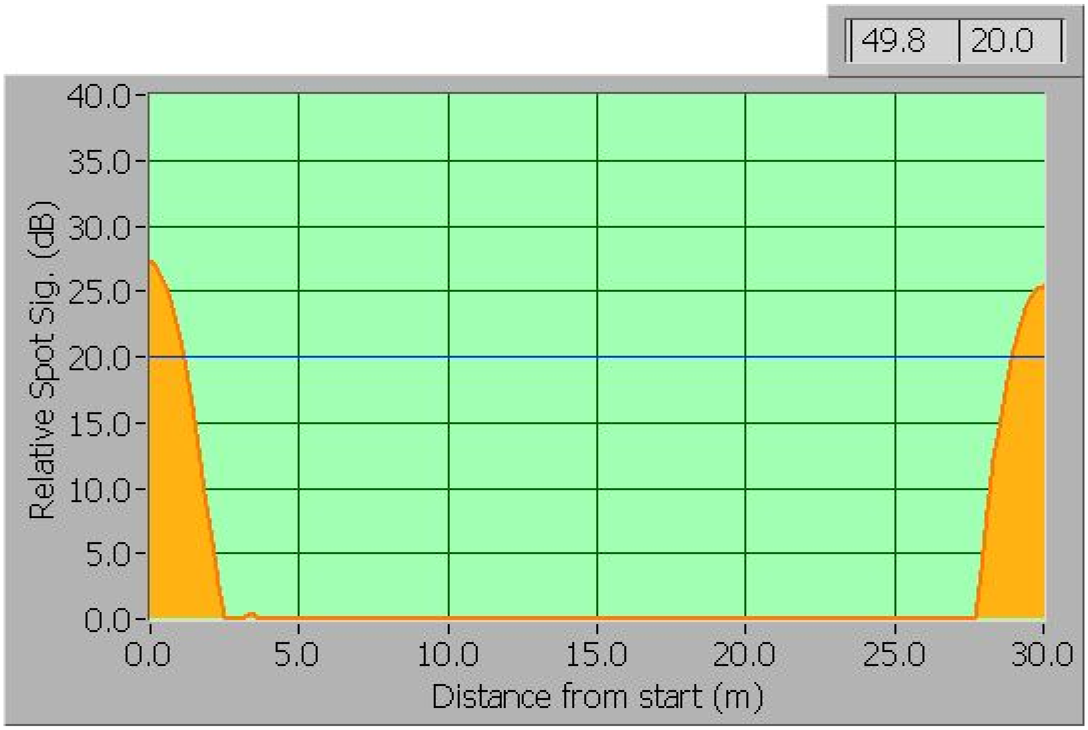
Impedance Spectrum





90.0
50.0
25.0
0.0
-25.0
-50.0
-90.0
Phase (deg)
0.0
20.0M
40.0M
60.0M
80.0M
100.0M
frequency (Hz)
cur
ref
52.4M 0.0

HoTSpot Signature



TXM1-200-X-open-cut10mWET Results

TestResults	
Avg. Velocity Ratio	0,601
CBA (dB/km)	217,5
Attenuation (dB/km)	44,5
Calc. Frequency (Hz)	3602417

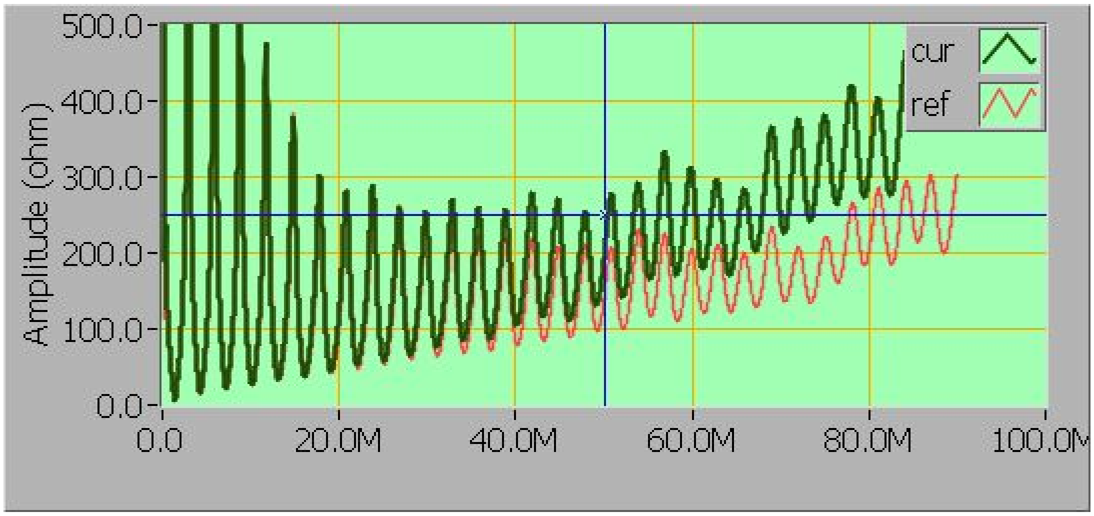
Segment Results					
Segment	1	2	3	4	5
Length (m)	30,00				
Velocity Ratio	0,6010				
Char. Impedance (Ω)	110,1				
Inductance (μH/m)	0,6				
Capacitance (pF/m)	50,40				

Resonance Frequencies (Hz)					
1395902	10156616	18936485	27766532		
2929014	11794199	20921611	30134058		
4275820	13066471	21869471	30642929		
5888561	14793238	23939085	33207110		
7225576	16027679	24847276	33651286		
8807733	17847707	27001550	36263673		

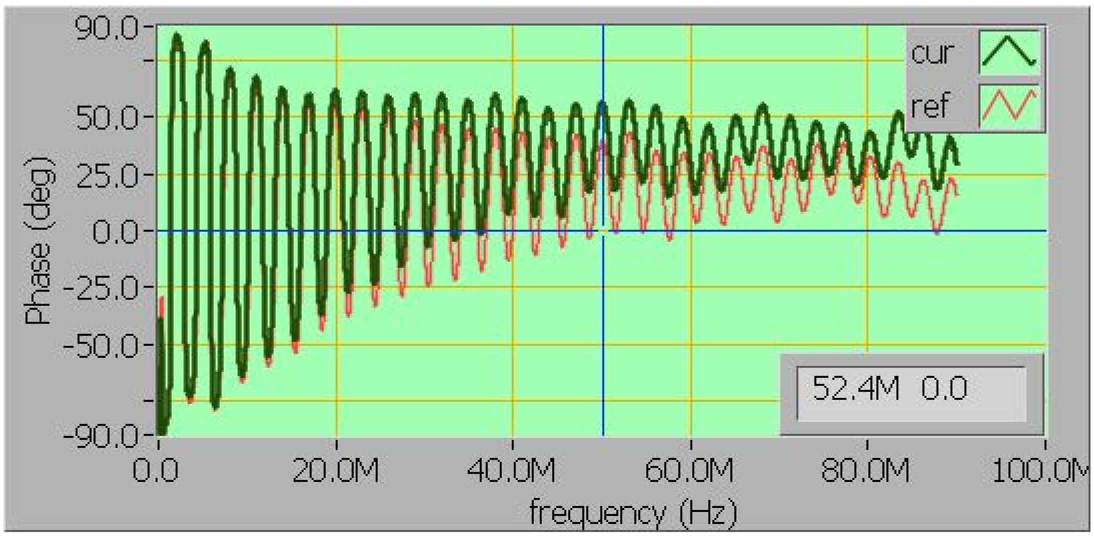
HotSpot			
Loc(m)	**Peak(dB)**	**Delta**	**DNORM**
5,97	-1,3	-33,5	33,0
10,04	-0,9	-33,1	32,8
30,00	32,2	0,0	0,0

TXM1-200-X-open-cut10mWET Plots

Impedance Spectrum

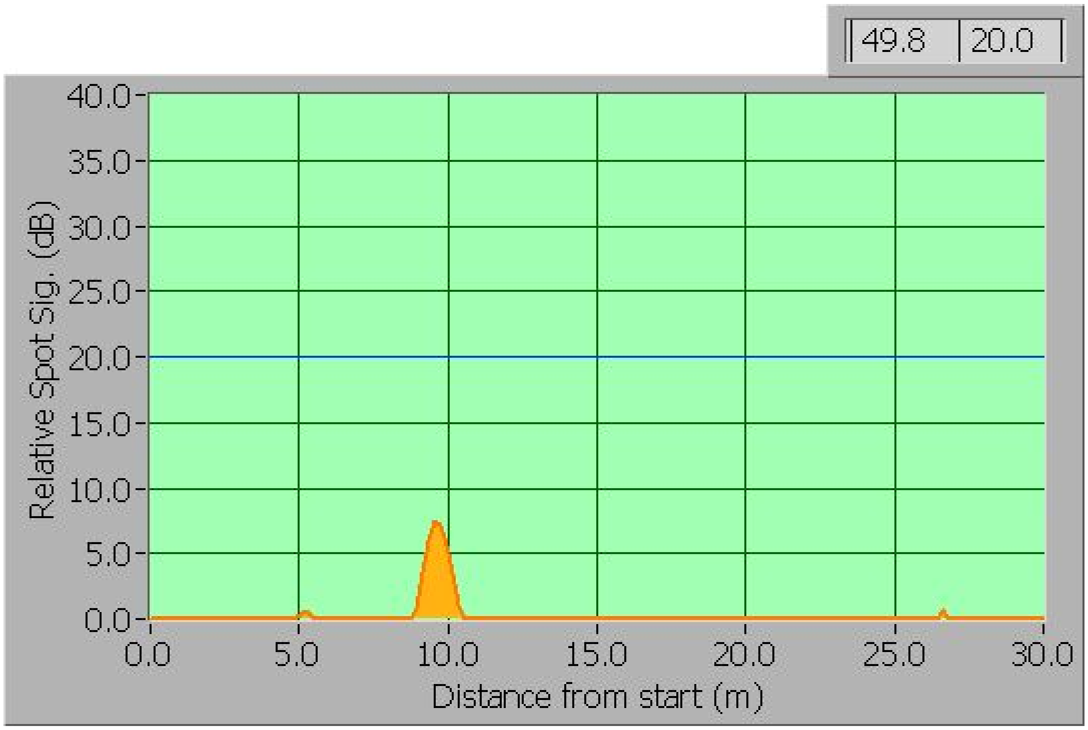


Amplitude (ohm)
500.0
400.0
300.0
200.0
100.0
0.0
0.0
20.0M
40.0M
60.0M
80.0M
100.0M
cur
ref



Phase (deg)
90.0
50.0
25.0
0.0
-25.0
-50.0
-90.0
0.0
20.0M
40.0M
60.0M
80.0M
100.0M
frequency (Hz)
cur
ref
52.4M 0.0

HoTSpot Signature



TXM2-200-X-open Results

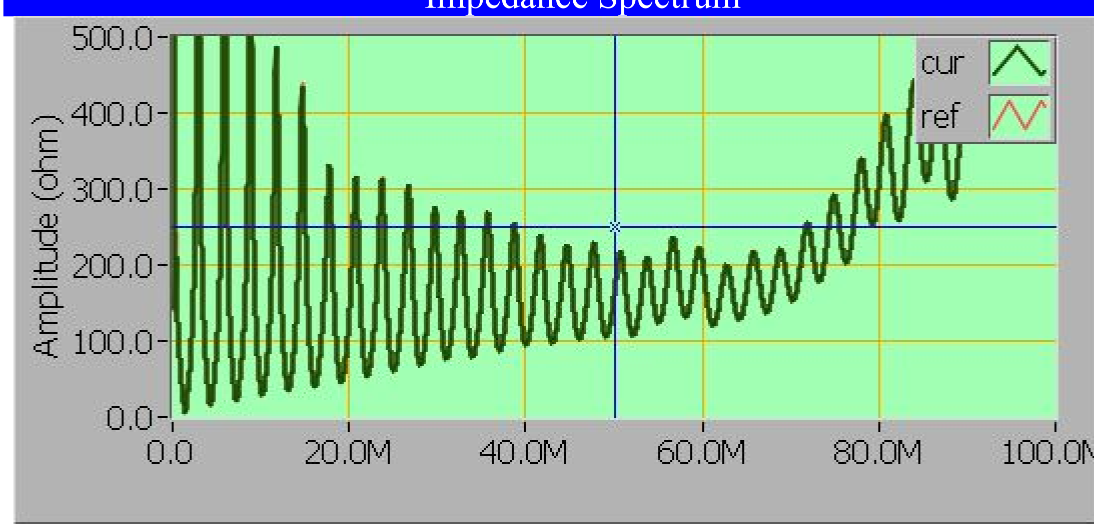
TestResults	
Avg. Velocity Ratio	0,605
CBA (dB/km)	192,2
Attenuation (dB/km)	45,5
Calc. Frequency (Hz)	3597290

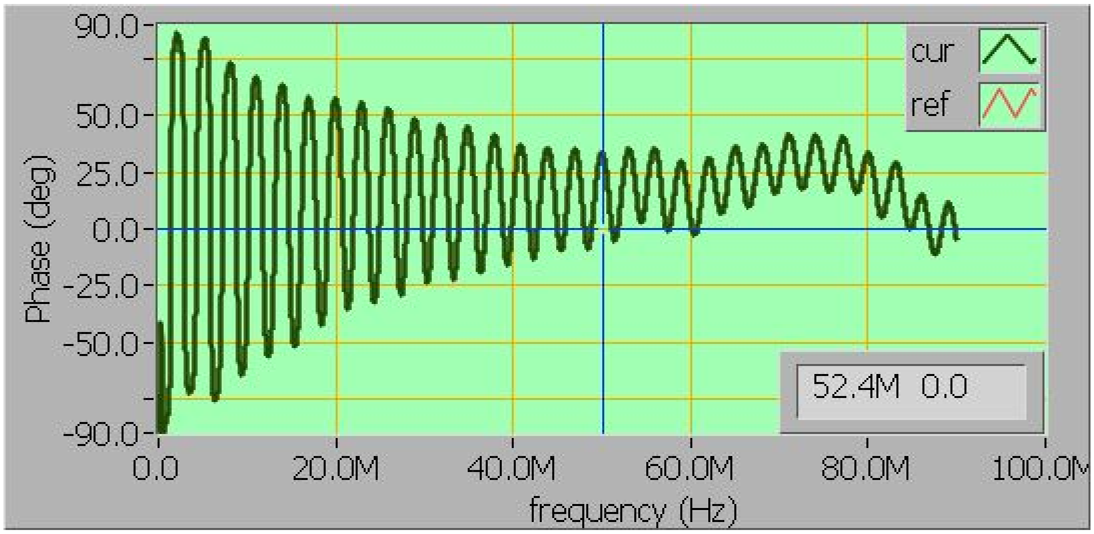
Segment Results					
Segment	1	2	3	4	5
Length (m)	30,00				
Velocity Ratio	0,6050				
Char. Impedance (Ω)	106,3				
Inductance (μH/m)	0,6				
Capacitance (pF/m)	51,85				

Resonance Frequencies (Hz)					
1403386	10148658	19040271	27952582	36872960	45785936
2909875	11771033	20820398	29840996	38881874	47987792
4284706	13090670	21954427	30859795	39823688	48808134
5856934	14746777	23801597	32781374	41855913	51094738
7219519	16081052	24934120	33823238	42786094	51766459
8822509	17808882	26843188	35858605	44939765	57261957

TXM2-200-X-open Plots

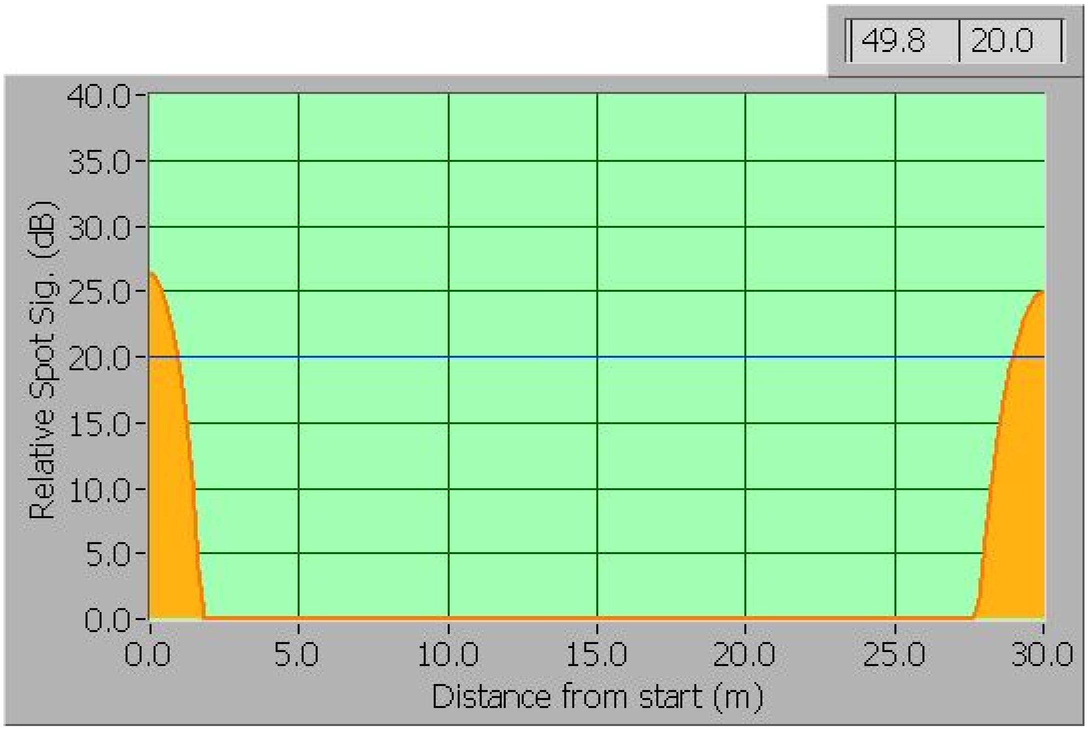
Impedance Spectrum





90.0
50.0
25.0
0.0
-25.0
-50.0
-90.0
Phase (deg)
0.0
20.0M
40.0M
60.0M
80.0M
100.0M
frequency (Hz)
cur
ref
52.4M 0.0

HoTSpot Signature



TXG1-200-Y-open Results

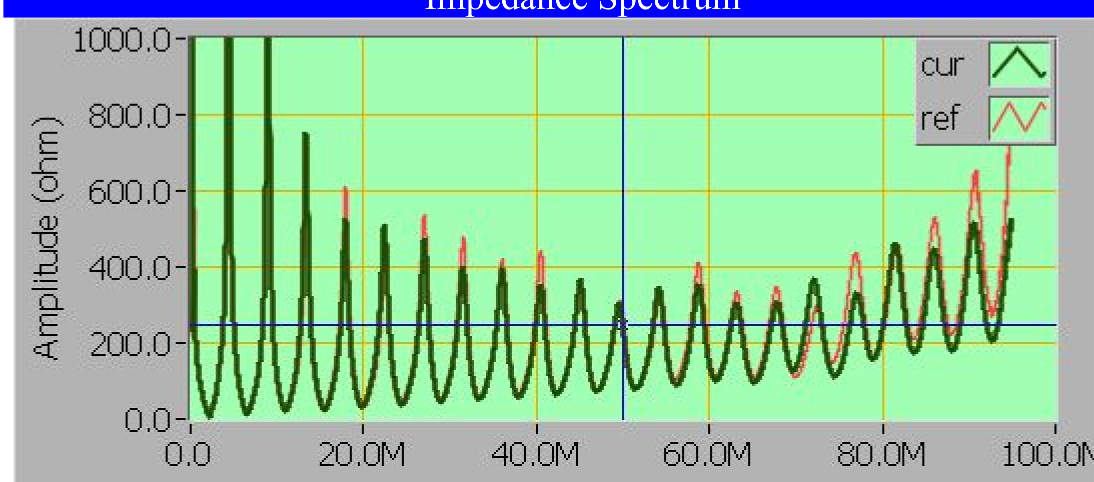
TestResults	
Avg. Velocity Ratio	0,605
CBA (dB/km)	219,2
Attenuation (dB/km)	34,7
Calc. Frequency (Hz)	5454566

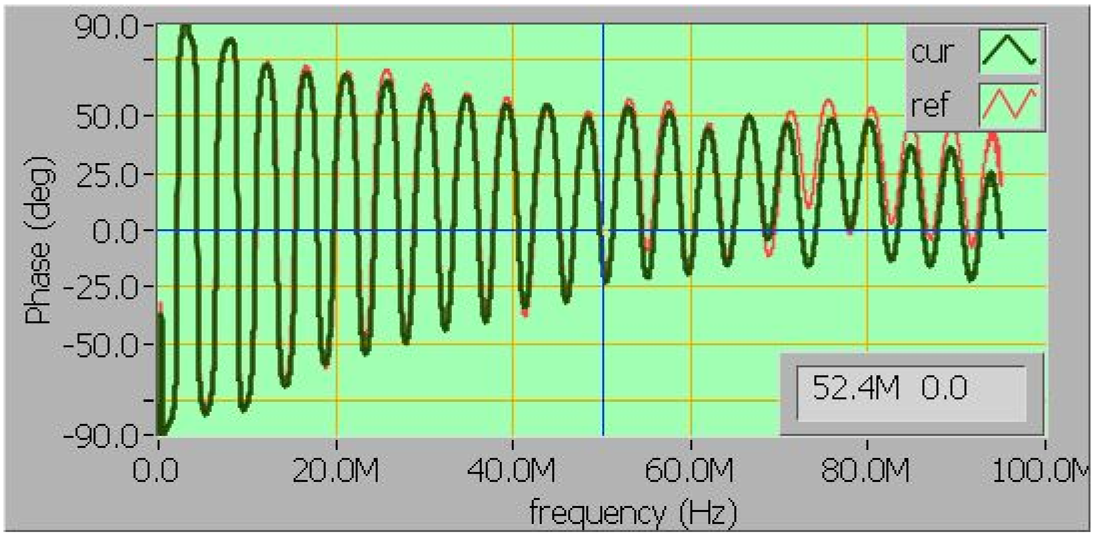
Segment Results					
Segment	1	2	3	4	5
Length (m)	20,00				
Velocity Ratio	0,6050				
Char. Impedance (Ω)	111,8				
Inductance (μH/m)	0,6				
Capacitance (pF/m)	49,31				

Resonance Frequencies (Hz)					
2118244	15465392	28855638	42180509	55855175	69078942
4389457	17908224	31526969	45199954	58994078	72451158
6519675	19754858	33277276	46819798	60443729	74117362
8939324	22450937	36087938	49733484	63389584	81861959
10943916	24371084	37810451	51190889	64841520	83351538
13329172	27076114	40589929	54381288	68384549	86220105

TXG1-200-Y-open Plots

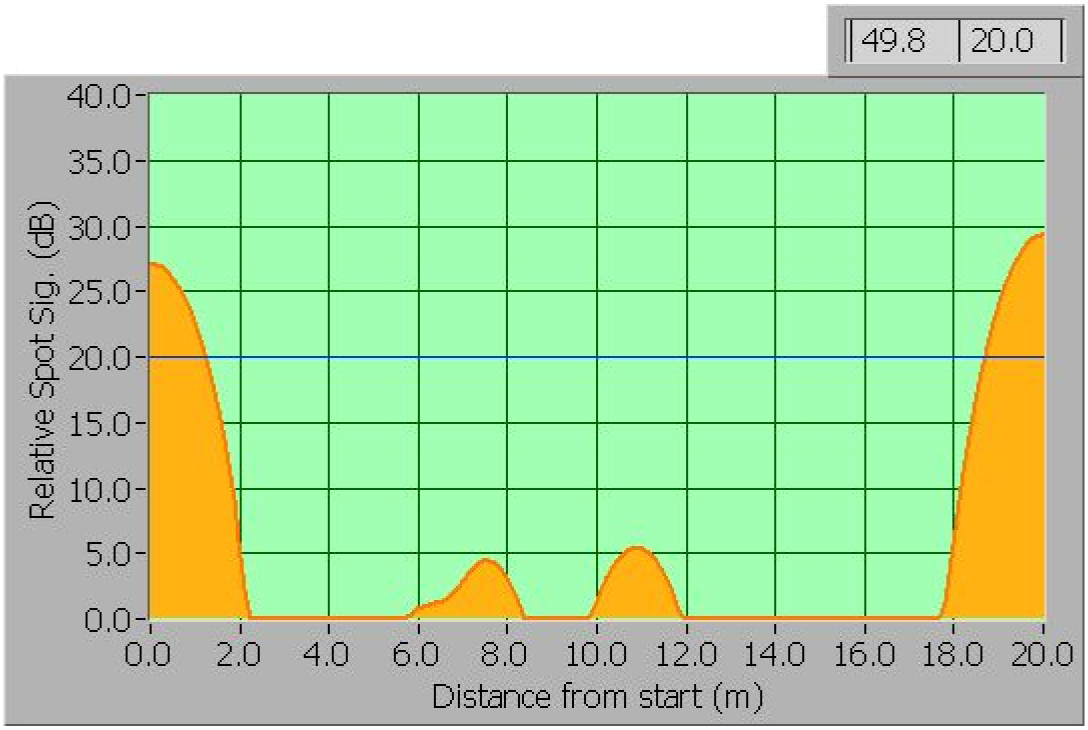
Impedance Spectrum





90.0
50.0
25.0
0.0
-25.0
-50.0
-90.0
Phase (deg)
0.0
20.0M
40.0M
60.0M
80.0M
100.0M
frequency (Hz)
cur
ref
52.4M 0.0

HoTSpot Signature



TXG2-200-X-open Results

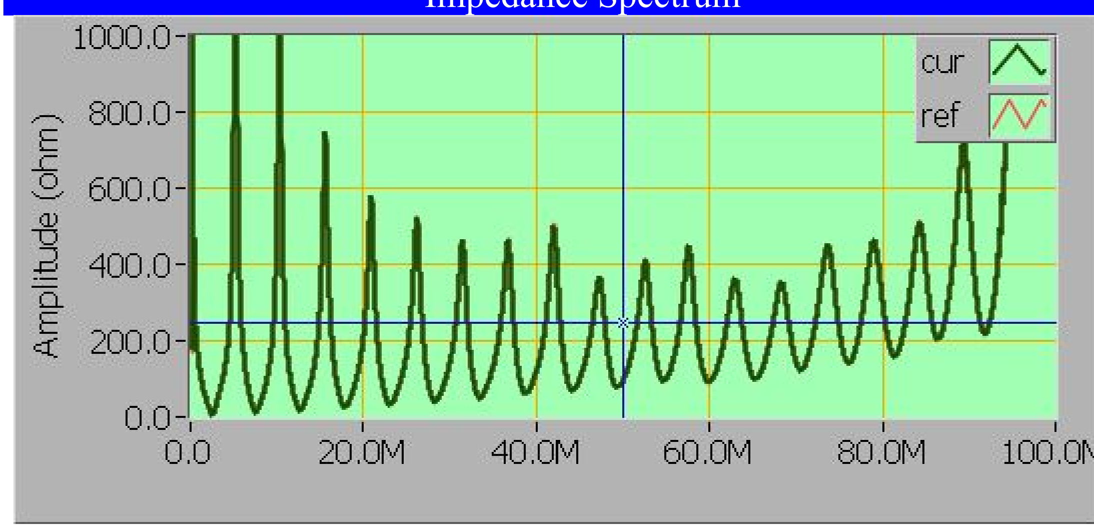
TestResults	
Avg. Velocity Ratio	0,601
CBA (dB/km)	260,8
Attenuation (dB/km)	26,4
Calc. Frequency (Hz)	6372753

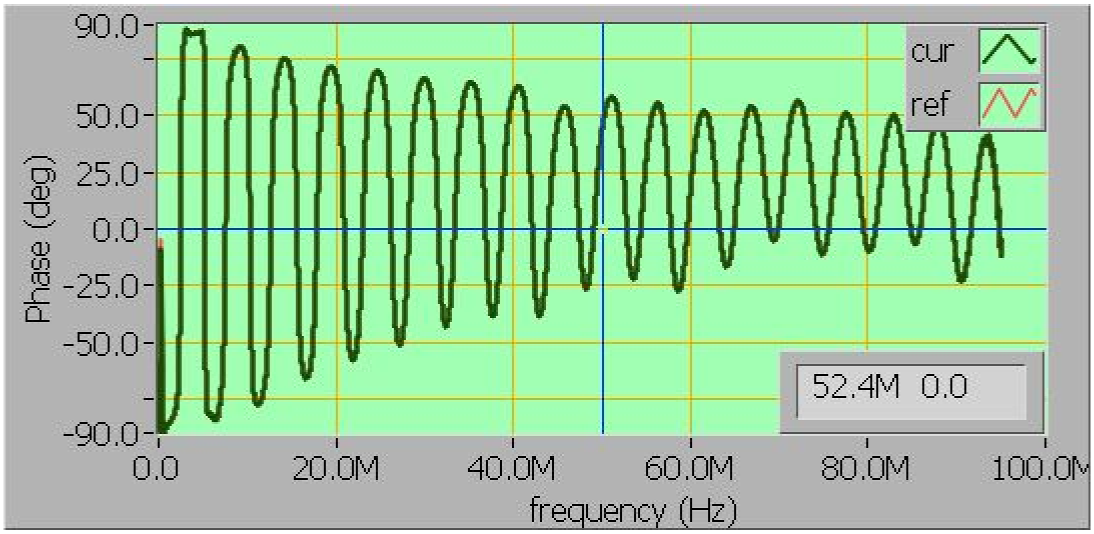
Segment Results					
Segment	1	2	3	4	5
Length (m)	17,10				
Velocity Ratio	0,6010				
Char. Impedance (Ω)	117,5				
Inductance (µH/m)	0,7				
Capacitance (pF/m)	47,22				

Resonance Frequencies (Hz)					
2472421	17843202	33353209	49072463	64881785	80854932
5188522	20911335	36856898	52800024	68920503	84829830
7556985	23015262	38620575	54353738	69868513	85846645
10309354	26238631	42122752	57769865	74184594	89619929
12655992	28213761	43981630	59642626	75563652	91619305
15599946	31556336	47429284	63272851	79495003	94804070

TXG2-200-X-open Plots

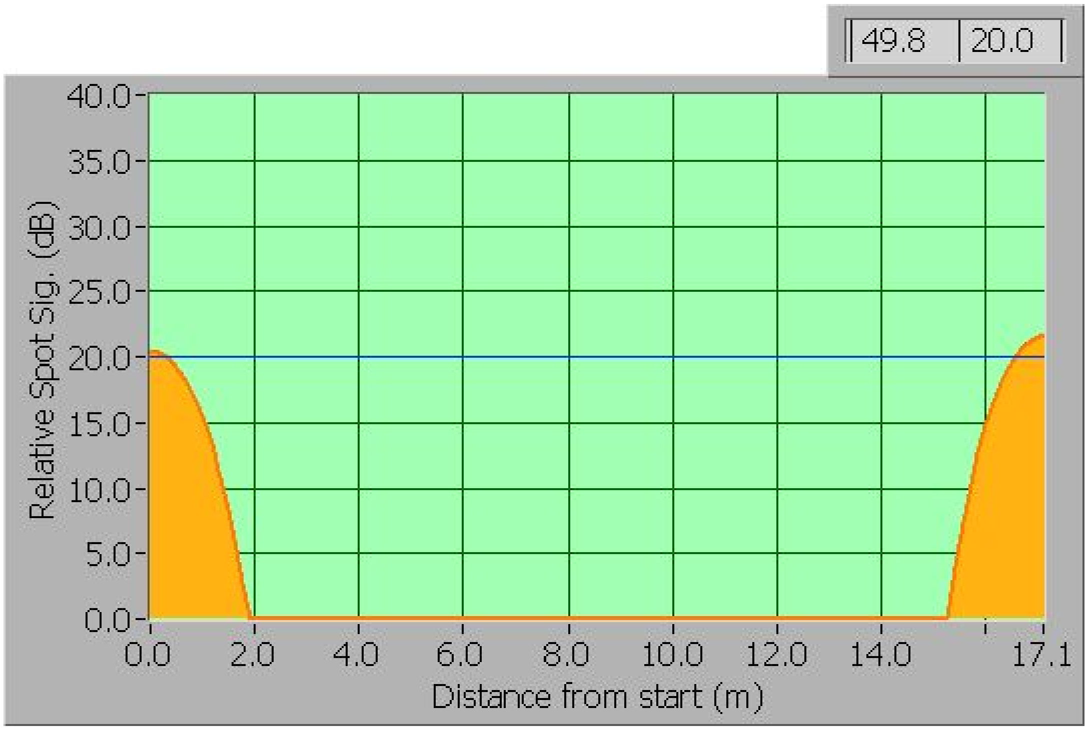
Impedance Spectrum





cur
ref
Phase (deg)
90.0
50.0
25.0
0.0
-25.0
-50.0
-90.0
52.4M 0.0
0.0
20.0M
40.0M
60.0M
80.0M
100.0M
frequency (Hz)

HoTSpot Signature



TXG3-200-X-open Results

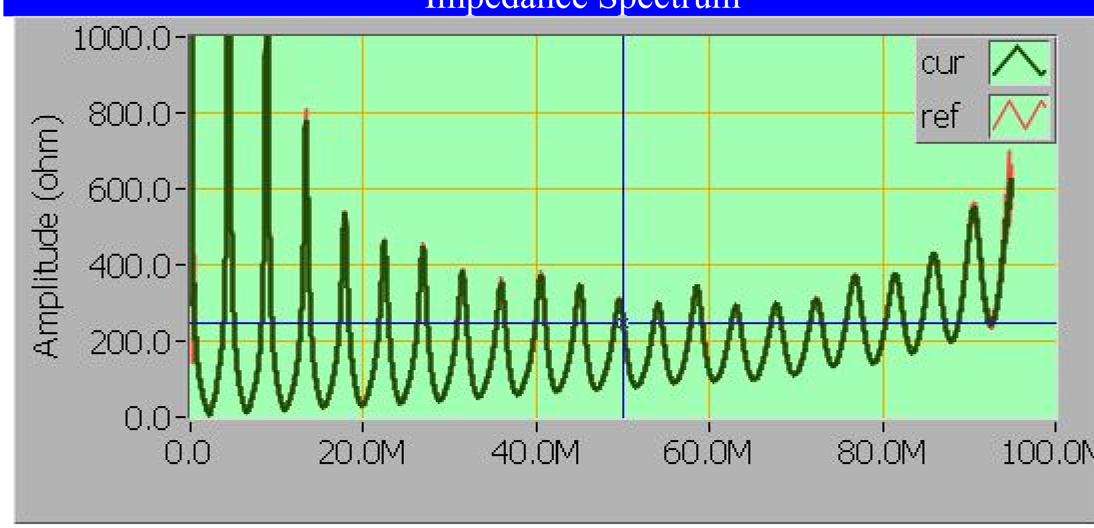
TestResults	
Avg. Velocity Ratio	0,604
CBA (dB/km)	230,8
Attenuation (dB/km)	29,7
Calc. Frequency (Hz)	5464521

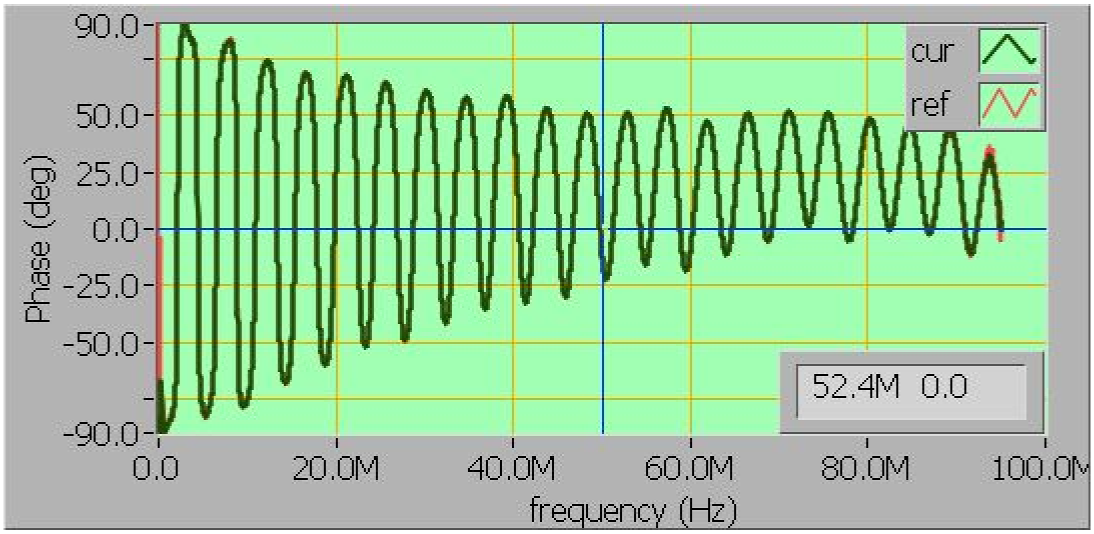
Segment Results					
Segment	1	2	3	4	5
Length (m)	20,00				
Velocity Ratio	0,6040				
Char. Impedance (Ω)	114,0				
Inductance (µH/m)	0,6				
Capacitance (pF/m)	48,44				

Resonance Frequencies (Hz)					
2118068	15374724	28750435	42211925	55539586	69157567
4416266	17841179	31553776	45123468	58792723	77434558
6512776	19799234	33232416	46721189	60222946	78321006
8832967	22471810	36063912	49772479	63441549	82341106
10931995	24255149	37657670	51237983	64648559	82575681
13377107	26942919	40673692	54316865	68293115	86673202

TXG3-200-X-open Plots

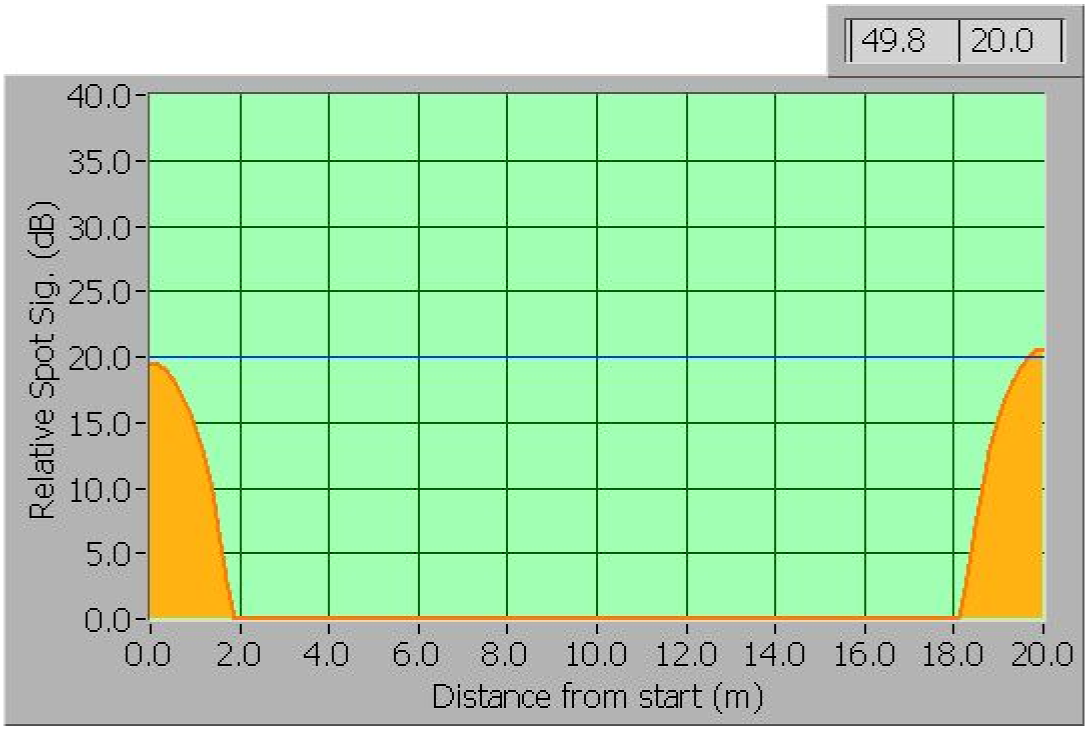
Impedance Spectrum





cur
ref
52.4M 0.0
Phase (deg)
90.0
50.0
25.0
0.0
-25.0
-50.0
-90.0
0.0
20.0M
40.0M
60.0M
80.0M
100.0M
frequency (Hz)

HoTSpot Signature



TXL1-200-X-open Results

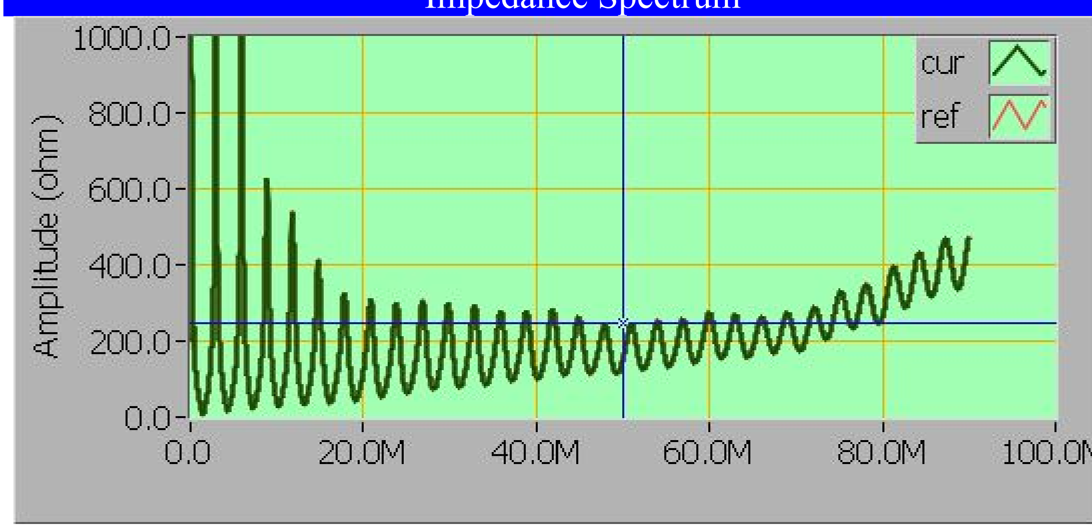
TestResults	
Avg. Velocity Ratio	0,603
CBA (dB/km)	215,3
Attenuation (dB/km)	46,0
Calc. Frequency (Hz)	3616342

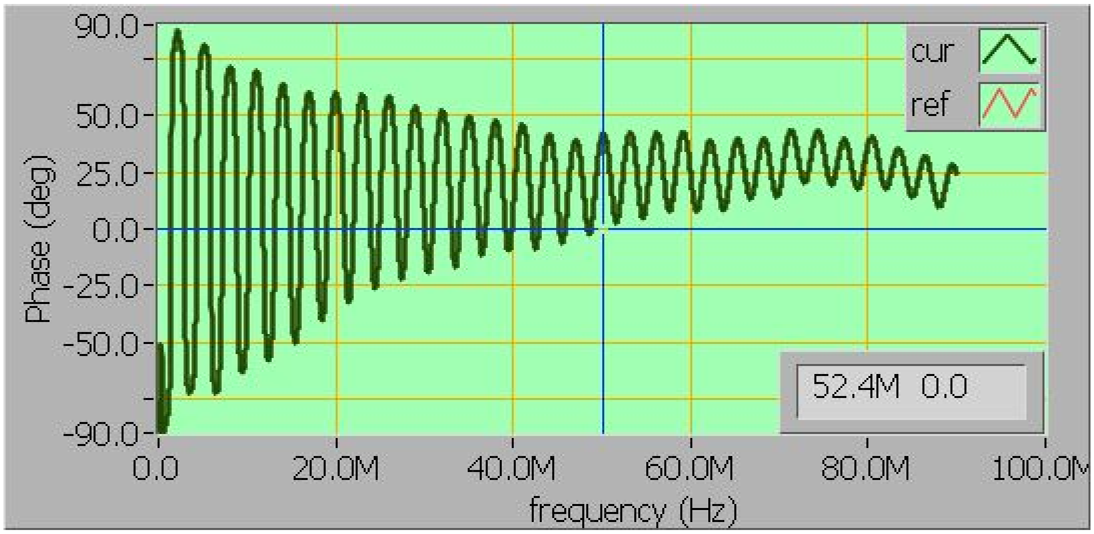
Segment Results					
Segment	1	2	3	4	5
Length (m)	30,00				
Velocity Ratio	0,6030				
Char. Impedance (Ω)	106,7				
Inductance (µH/m)	0,6				
Capacitance (pF/m)	51,83				

Resonance Frequencies (Hz)					
1406664	10174709	19031565	27924587	36873702	
2937262	11819099	20938117	30006217	39144508	
4295422	13132118	21984337	30904484	39861244	
5910217	14835010	23957416	33067000	42185986	
7223361	16095926	24919631	33916193	42880786	
8846302	17879294	27022293	36154201	45185540	

TXL1-200-X-open Plots

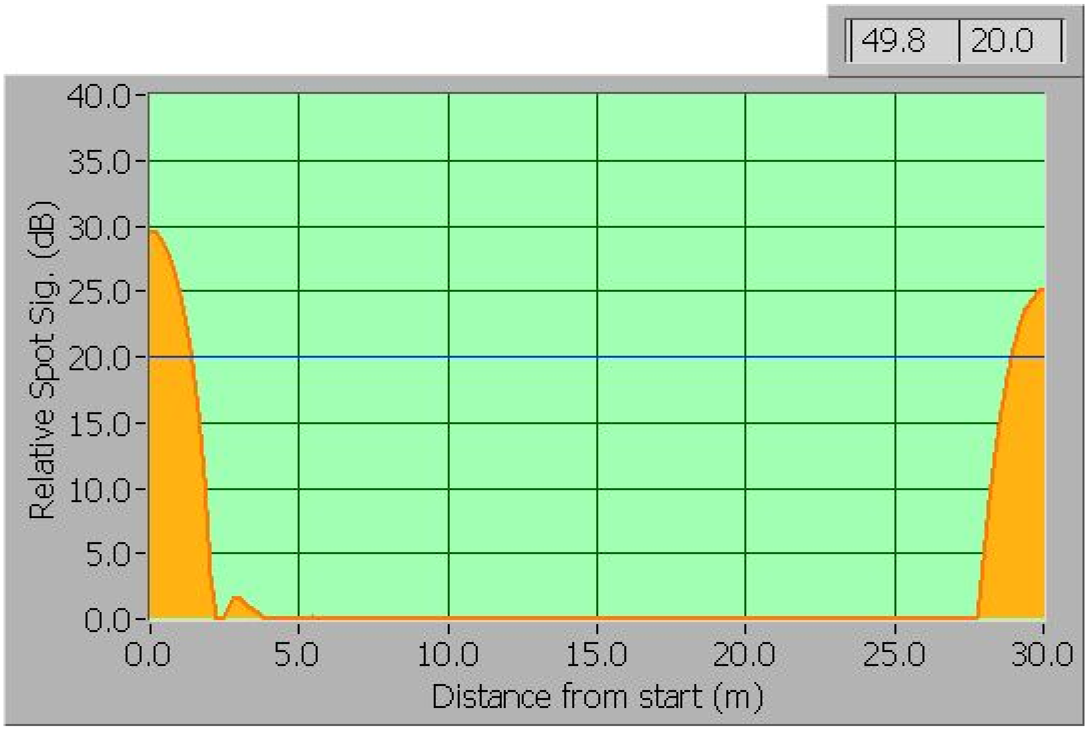
Impedance Spectrum





Phase (deg)
90.0
50.0
25.0
0.0
-25.0
-50.0
-90.0
cur
ref
52.4M 0.0
0.0
20.0M
40.0M
60.0M
80.0M
100.0M
frequency (Hz)

HoTSpot Signature



TXL2-200-X-open Results

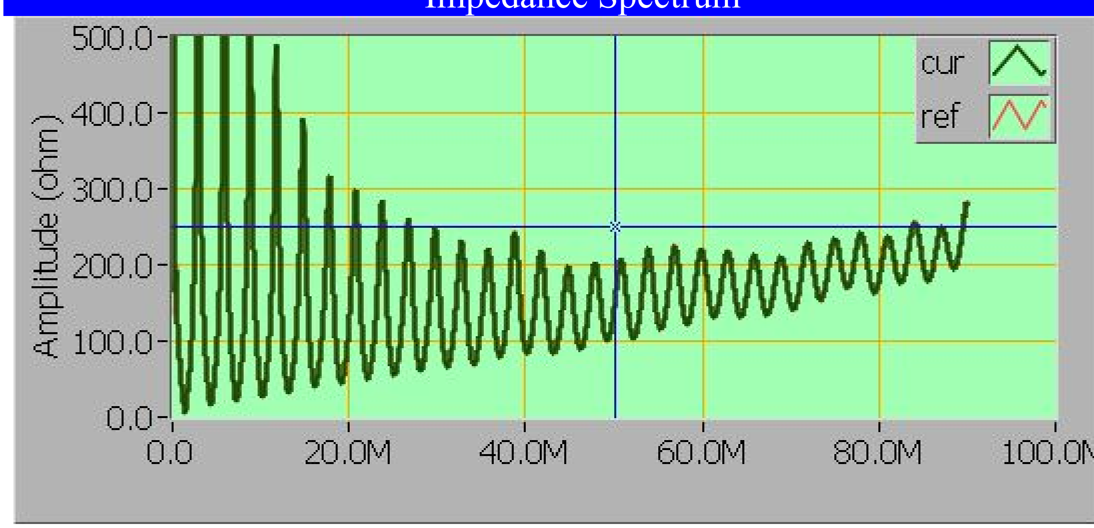
TestResults	
Avg. Velocity Ratio	0,602
CBA (dB/km)	209,1
Attenuation (dB/km)	40,7
Calc. Frequency (Hz)	3613053

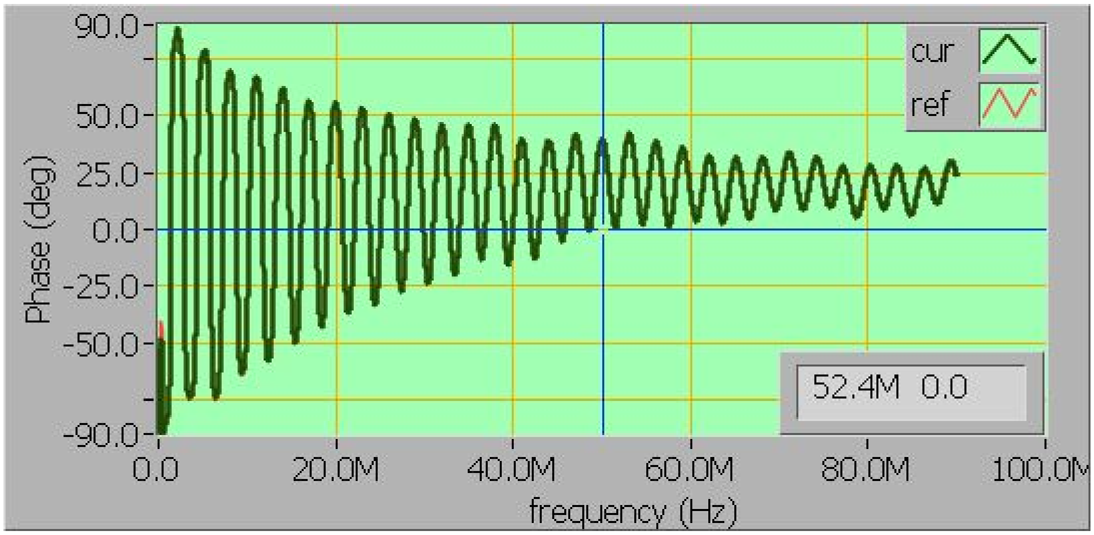
Segment Results					
Segment	1	2	3	4	5
Length (m)	30,00				
Velocity Ratio	0,6020				
Char. Impedance (Ω)	108,4				
Inductance (μH/m)	0,6				
Capacitance (pF/m)	51,10				

Resonance Frequencies (Hz)					
1400284	10194407	19065933	27990845	36861054	
2910108	11782675	20830019	29893617	38990005	
4315997	13137220	22057075	30994383	39962263	
5881042	14829089	23829870	32913733	41994756	
7252114	16116815	25034784	33950708	42920522	
8812760	17815451	26874348	36014190	45182139	

TXL2-200-X-open Plots

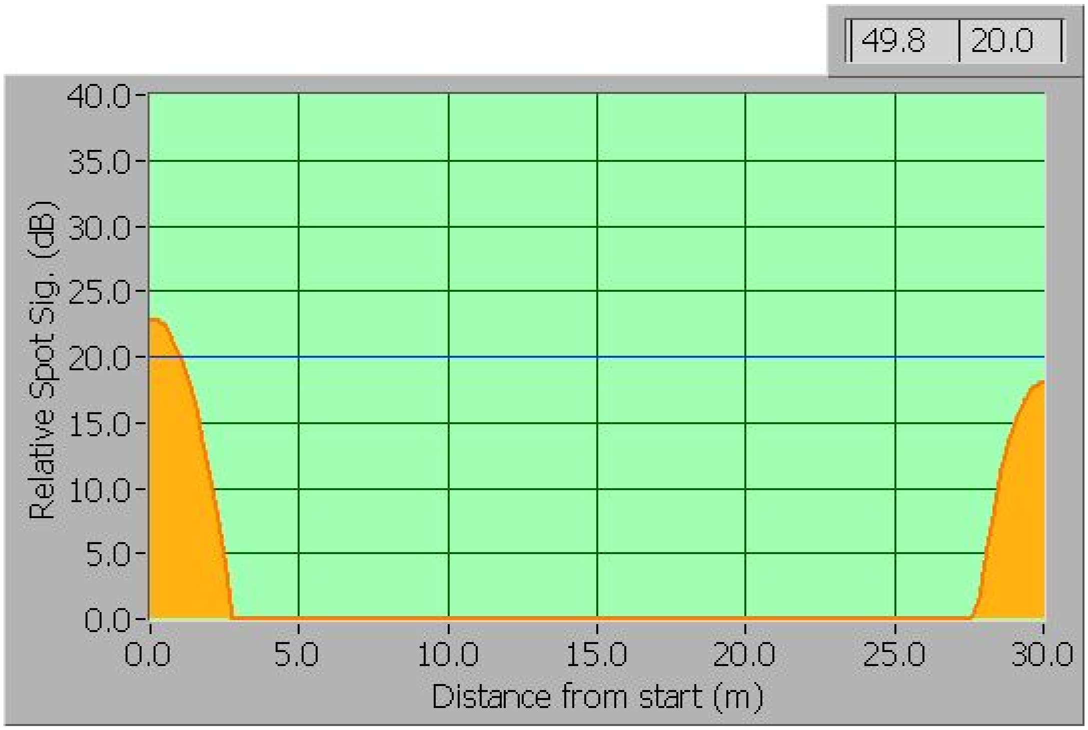
Impedance Spectrum





90.0
50.0
25.0
0.0
-25.0
-50.0
-90.0
Phase (deg)
0.0
20.0M
40.0M
60.0M
80.0M
100.0M
frequency (Hz)
cur
ref
52.4M 0.0

HoTSpot Signature



TXL3-200-X-open Results

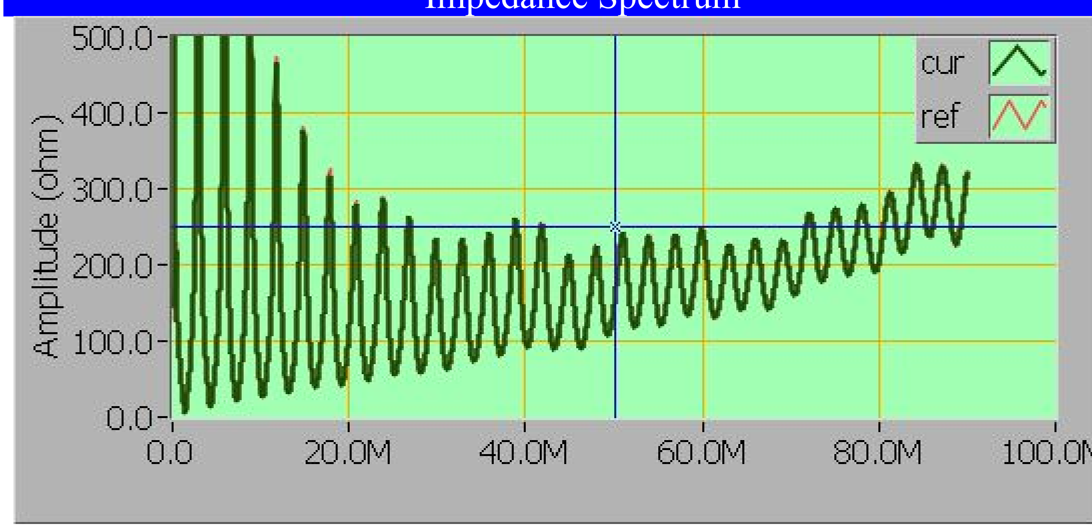
TestResults	
Avg. Velocity Ratio	0,603
CBA (dB/km)	222,5
Attenuation (dB/km)	40,9
Calc. Frequency (Hz)	3611665

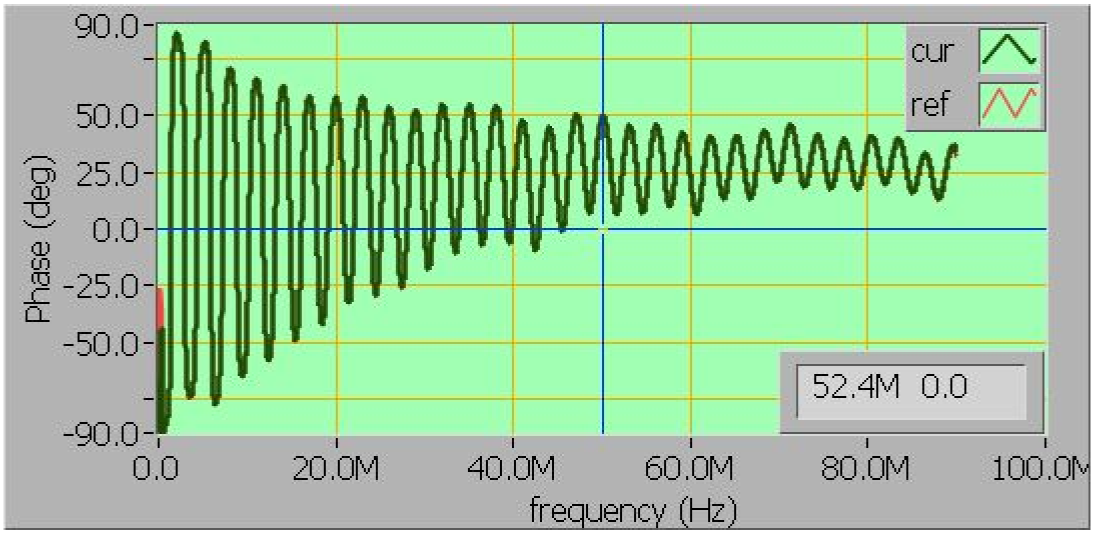
Segment Results					
Segment	1	2	3	4	5
Length (m)	30,00				
Velocity Ratio	0,6030				
Char. Impedance (Ω)	107,0				
Inductance (µH/m)	0,6				
Capacitance (pF/m)	51,65				

Resonance Frequencies (Hz)					
1407610	10205416	19084510	28006090	36795436	
2925110	11799376	20903724	30008404	39259060	
4298220	13147935	22000046	30892248	39826628	
5886902	14849425	23962261	33143597	42142226	
7259621	16111560	25049434	33832565	42885441	
8827682	17860615	26933837	36213244	45411757	

TXL3-200-X-open Plots

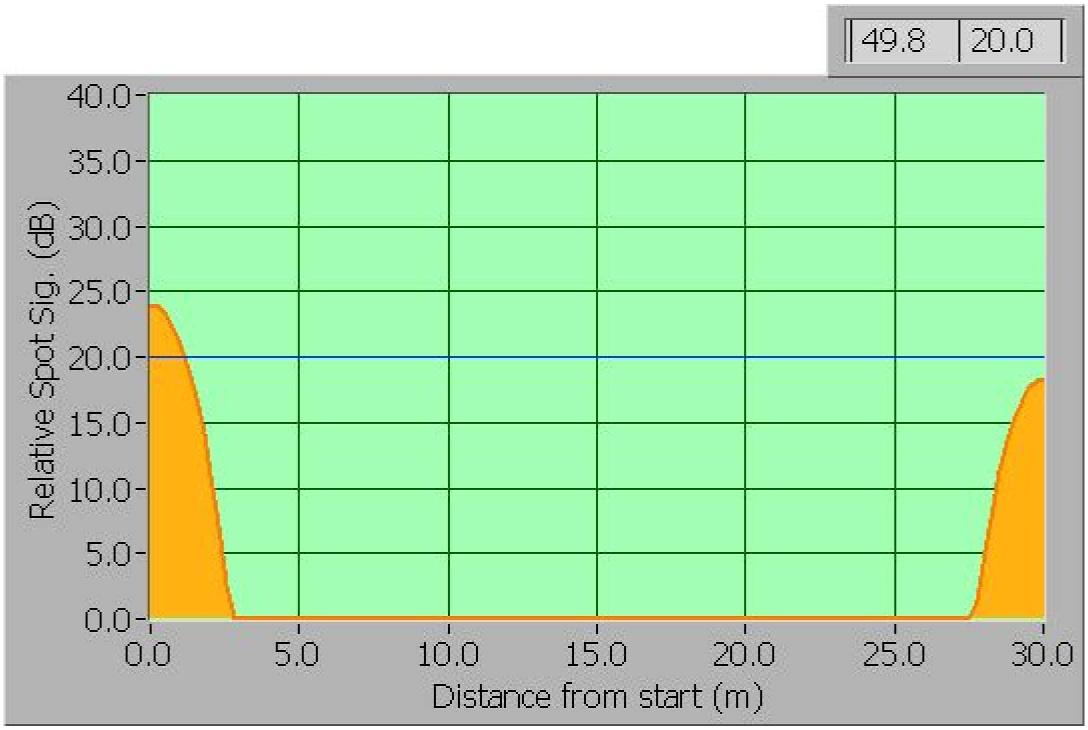
Impedance Spectrum





90.0
50.0
25.0
0.0
-25.0
-50.0
-90.0
Phase (deg)
cur
ref
52.4M 0.0
0.0
20.0M
40.0M
60.0M
80.0M
100.0M
frequency (Hz)

HoTSpot Signature



TXL4-200-X-open Results

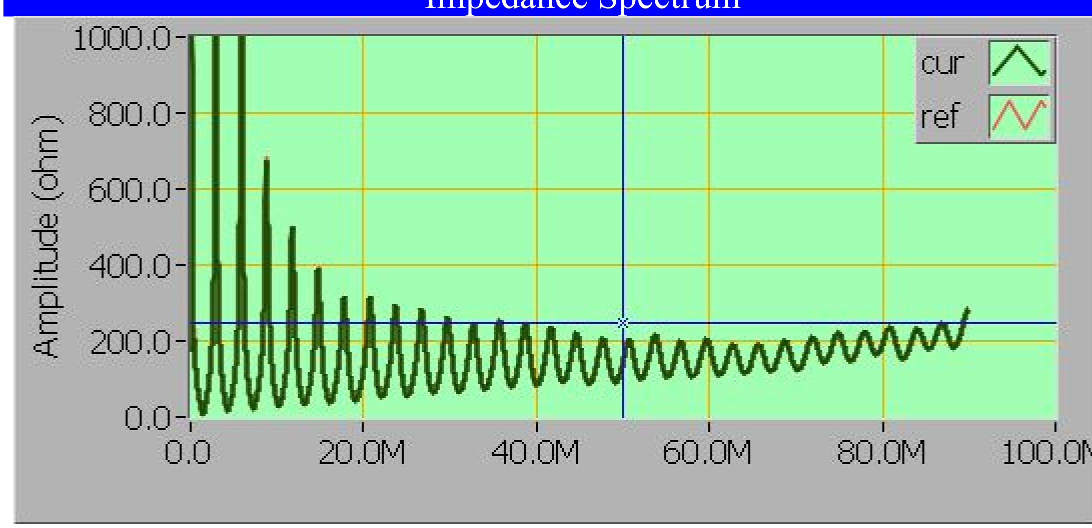
TestResults	
Avg. Velocity Ratio	0,601
CBA (dB/km)	197,2
Attenuation (dB/km)	41,0
Calc. Frequency (Hz)	3602051

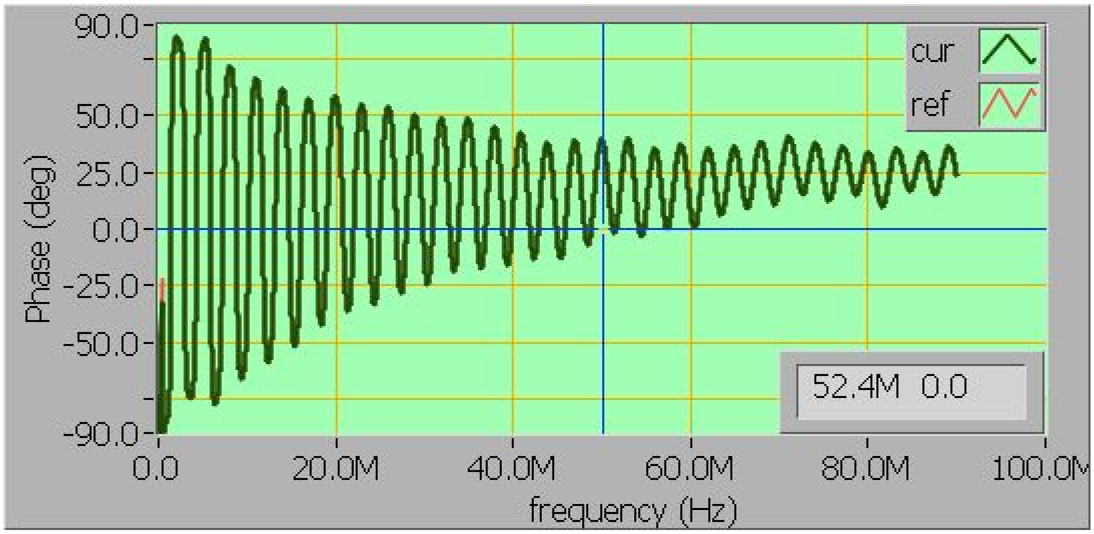
Segment Results					
Segment	1	2	3	4	5
Length (m)	30,00				
Velocity Ratio	0,6010				
Char. Impedance (Ω)	107,1				
Inductance (µH/m)	0,6				
Capacitance (pF/m)	51,87				

Resonance Frequencies (Hz)					
1405972	10184457	19002037	27943221	36889085	45823037
2914729	11767341	20821672	29826387	38891366	48012629
4289374	13138126	22004058	30913433	39847665	48749732
5875837	14753890	23782998	32863413	41903187	51186934
7236211	16073098	24952353	33829858	42831406	51577328
8784969	17776189	26828449	35907944	44826356	54161575

TXL4-200-X-open Plots

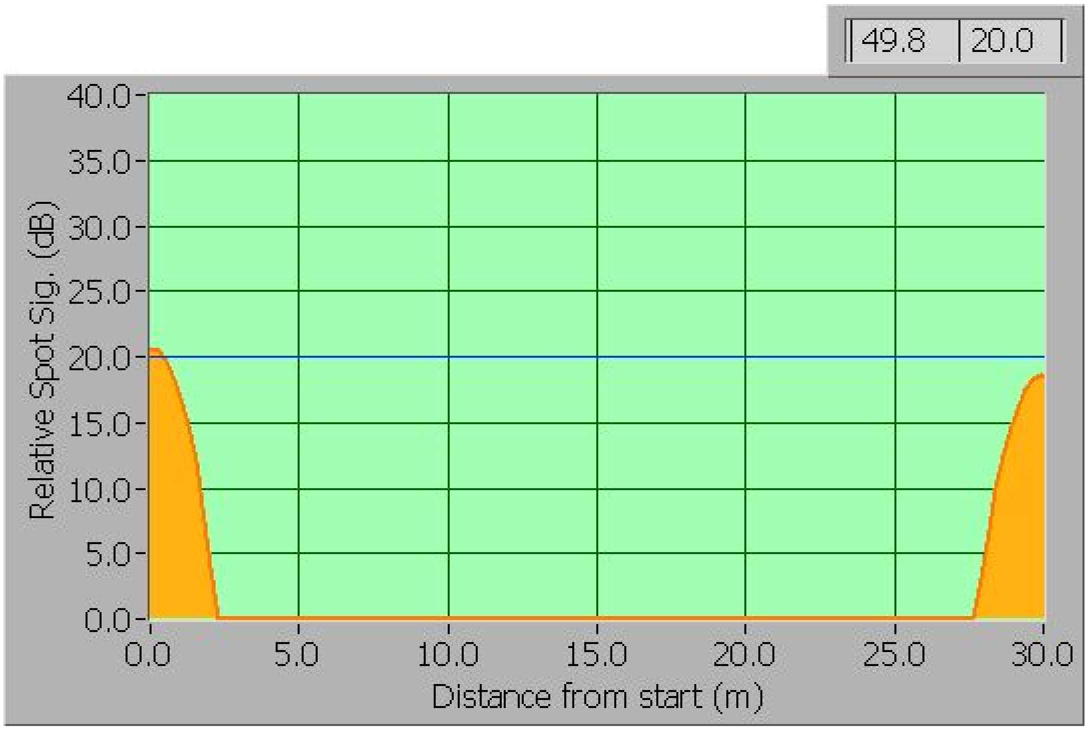
Impedance Spectrum





90.0
50.0
25.0
0.0
-25.0
-50.0
-90.0
Phase (deg)
0.0
20.0M
40.0M
60.0M
80.0M
100.0M
frequency (Hz)
cur
ref
52.4M 0.0

HoTSpot Signature



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Title	Wire System Ageing Assessment and Condition Monitoring (WASCO)
Author(s)	Paolo F. Fantoni
Affiliation(s)	Institute for Energy Technology (IFE), Norway
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No. of illustrations	37
No. of references	13

Abstract

Nuclear facilities rely on electrical wire systems to perform a variety of functions for successful operation. Many of these functions directly support the safe operation of the facility; therefore, the continued reliability of wire systems, even as they age, is critical. Condition Monitoring (CM) of installed wire systems is an important part of any aging program, both during the first 40 years of the qualified life and even more in anticipation of the license renewal for a nuclear power plant. This report contains the results of experiments performed in collaboration with Tecnatom SA, Spain, to compare several cable condition monitoring techniques including LIRA (LIne Resonance Analysis)

Key words: Condition monitoring, cable aging, transmission lines, hot spot detection, fault detection, frequency domain reflectometry, time domain reflectometry, standing wave reflectometry, LIRA

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