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Measurements and Calculations on Direct Electrical Heating of Duplex Steel Risers

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Measurements and Calculations on Direct Electrical Heating of Duplex Steel Risers

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RESULT (summary)

The objective of the test programme has been to:

- Study the effect of varying distances between neighbouring rigid Duplex steel risers on the electrical parameters and design criteria.
- To compare measured and calculated system impedances necessary for guidelines for electric rating.
- To calculate impedance and heat development based on two-dimensional electromagnetic finite element analyses.

The report describes the results from laboratory tests on magnetic characteristics of test pipe and field tests on heating of single, two and three Duplex steel risers at Orkanger. The tests were performed on a scaled model at 400 Hz.

The field tests include testing of parallel risers and risers with different individual spacing topside and subsea. Tests have been performed on single point grounded system, two point grounded system and several grounding electrodes (intermediate anodes) along the risers.

Measurements and calculation of the current distribution on parallel risers with OD = 99,8 mm and WT = 5,3 mm are in good accordance.

The results for multiple risers with increasing internal spacing confirm that the electrical system parameters and rating can be based on two-dimensional electromagnetic simulations.

The tests results give sufficient information for rating of direct electrical heating of Duplex risers.

KEYWORDS

SELECTED BY		
	Field tests	Neighbouring risers
	End connections	Grounding electrodes

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1 TEST PROGRAMME

The test programme comprised laboratory measurements and extensive measurements of electric characteristics for a simulated three-riser configuration at the Orkanger test field. The tests were performed on a scaled model at 400 Hz. In the laboratory the resistivity and relative effective permeability as a function of current was measured for a test sample of the same steel quality as used at Orkanger. The coil method was used to determine the relative effective permeability of the three Duplex risers at Orkanger.

The measured impedances for neighbouring risers with different spacing topside and subsea were compared with results from two-dimensional finite elements simulations. These results will be used to establish calculation methods for risers using modified two-dimensional finite elements simulations. This is a main objective of the DEO riser qualification programme.

2 ELECTRICAL AND MAGNETIC CHARACTERISTICS OF DUPLEX TEST PIPE

2.1 Laboratory measurements

A coil was fabricated to perform measurements on the Duplex test pipes for the installation at Orkanger. The coil measuring system was controlled in the laboratory at 400 Hz by the piggyback method on one of the test pipes from Orkanger.
The results from the laboratory tests on a piggyback configuration are shown in **Figure 2.1**. The effective permeability varies with the current in the pipe. Typical test current at the Orkanger test installation is in the range from 150 A – 400 A with a corresponding calculated relative effective permeability from 47 – 57.

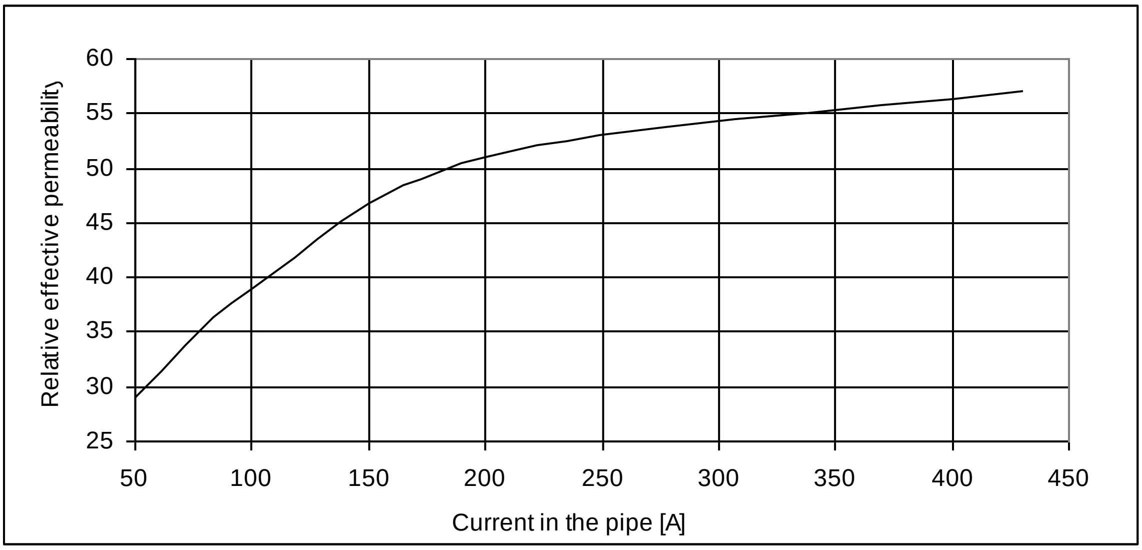


Figure 2.1: Relative effective permeability versus pipe current at 400 Hz for one of the pipes at Orkanger field test installation. Duplex pipe of OD = 99,8 mm, WT = 5,3 mm and 3 mm coating thickness (PE). Cable copper conductor cross section of 150 mm^2 and 10 mm thickness for the cable insulation system.

The resistivity of the Duplex steel pipe material was measured to 0,822 [Ω mm^2/m] at 20^oC.

2.2 Field tests on the three riser sections

The coil method was used to measure the effective relative permeability for the three riser sections, each of 70 m. The measurements were carried out at 4^{o}C with a magnetic field corresponding to a riser current of 200 A by the piggyback method. The results are shown in **Figure 2.2a**, **2.2b** and **2.2c**.

As seen from the test results in Figure 2.2b the relative effective permeability for one of the pipejoints is much higher than the average of 55. Similar variations have been observed in earlier measurements.

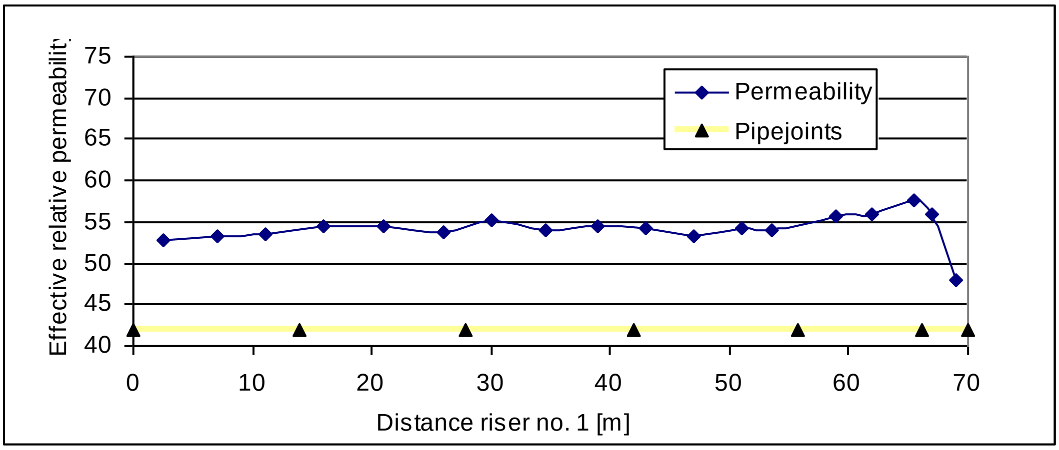


Figure 2.2a: Effective relative permeability for riser no. 1.

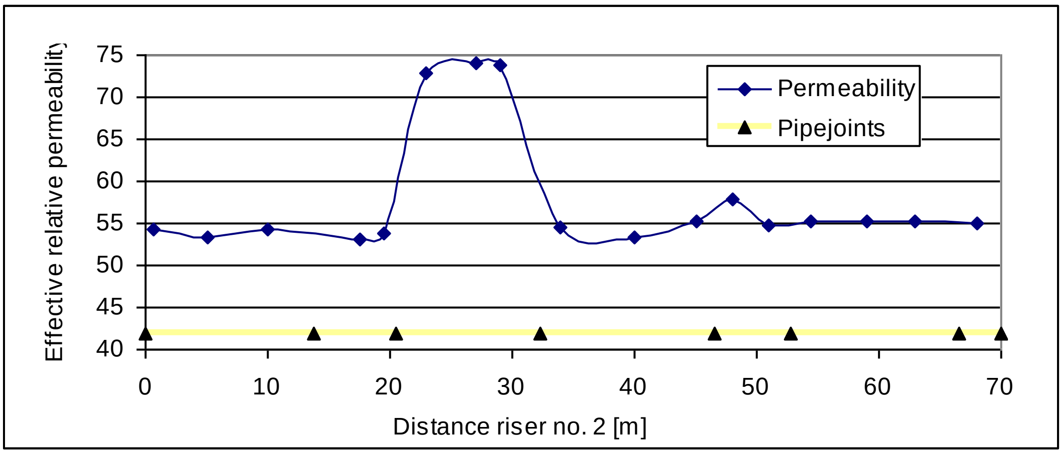


Figure 2.2b: Effective relative permeability for riser no. 2.

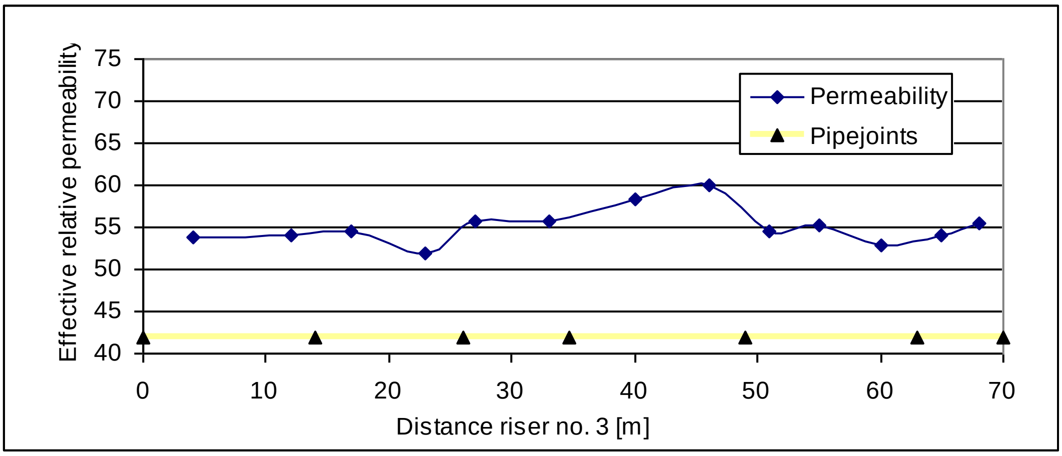


Figure 2.2c: Effective relative permeability for riser no. 3.

Figure 2.2: Results from field tests on the three test risers. Effective relative permeability measured by the coil method for the three risers. The magnetic field at the riser surface corresponds to a riser current of 200 A for the piggyback configuration. The tests were carried out at 4°C.

3 TEST RISER CONFIGURATIONS AT ORKANGER

3.1 Test site overview

The testing of electrical heating of risers was performed on a 400 Hz system. The main advantage for testing at 400 Hz compared to 50 Hz is a reduced dimension of the test set-up of 2,83 (ratio of the square root between the frequencies), [1].

A sketch of the test installation at Orkanger is shown in **Figure 3.1**. The riser currents were measured by Rogowski coils, which are located in between the grounding points along the risers. Steel riser temperature is measured on riser no. 2.

The 400 Hz power system consists of a three phase 20kVA generator, a transformer and capacitor banks for serial and parallel compensation.

Topside the risers were electrically insulated from the hang off structure [2], but can be grounded to the hang off structure by copper wires. At the subsea end flexible copper cables connect the risers. Each riser is connected to a 2 m bare 8” carbon steel pipe for grounding.

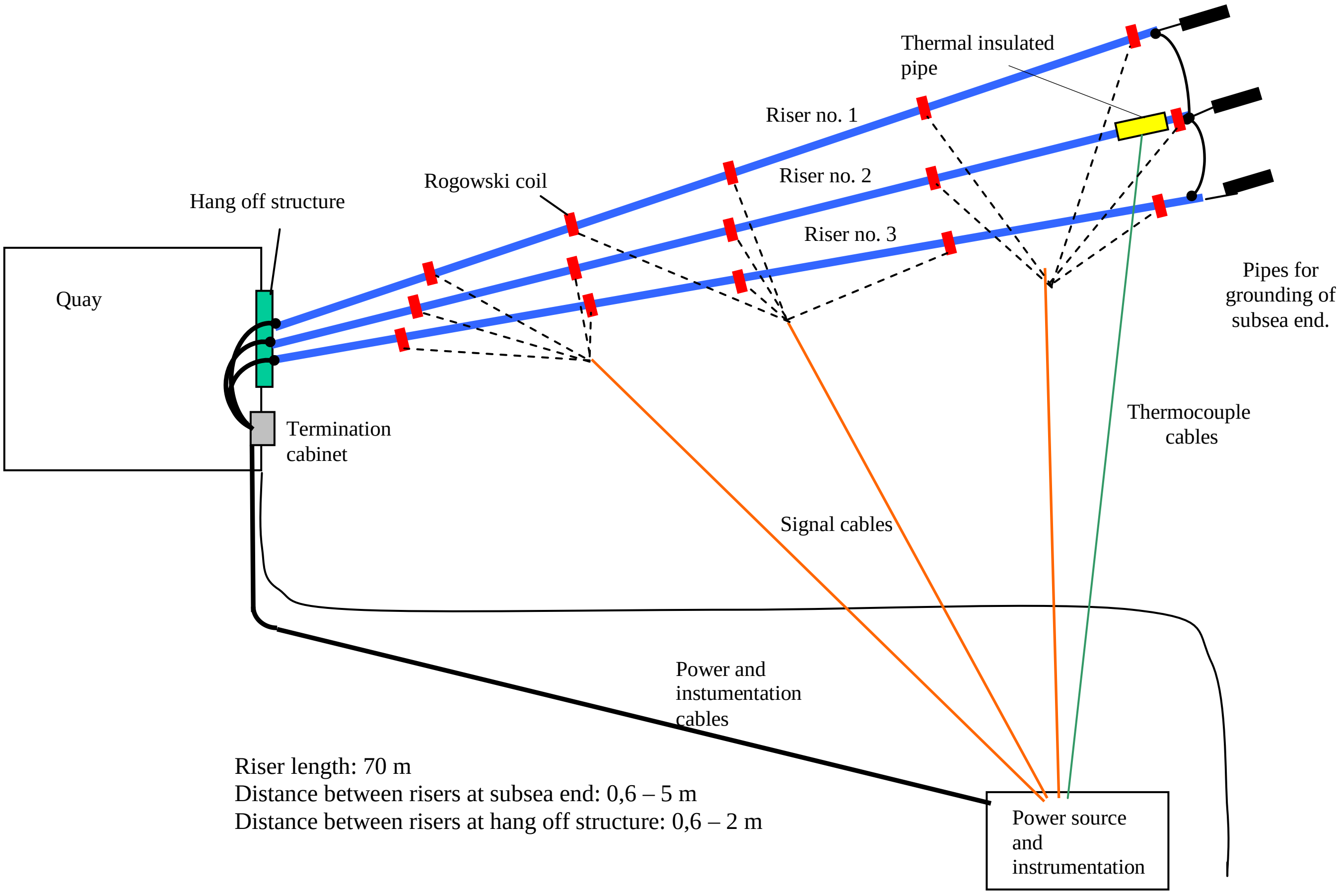


Figure 3.1: Sketch of test installation

Two of the risers were supplied with connection points (electrical insulated from seawater) distributed along the risers for connecting of intermediate anodes. Pictures and drawings are shown in **Appendix**.

3.2 Test riser configurations

A cable with a conductor cross section of 150 mm^2 was piggybacked to each riser, see **Figure 3.2**, by straps at approx. 2 m spacing. The piggyback cables were connected to the subsea ends of the risers. The Duplex risers have a 3 mm electric insulation. 3 m of riser no. 2 is thermally insulated for direct measurement of temperature rise (**Figure 3.1** and **4.1**).

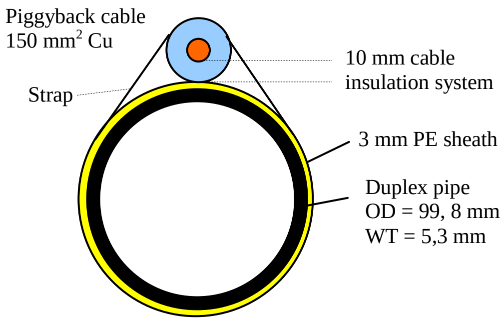


Figure 3.2: Piggyback configuration for the riser test.

The risers were equipped with a number of Rogowski coils to measure the riser current and control the state of the electrical riser insulation.

The tests have been performed at 400 Hz on the configurations shown in **Figure 3.3** with two and three risers. The reference configurations, **Figure 3.3a** and **3.3c** (parallel risers), are two-dimensional (in the main part of the risers) and can be analysed directly by two-dimensional calculation methods. These configurations are used as reference for the practical riser configurations in **Figure 3.3b** and **3.3d**. The comparison of measured and calculated characteristics for Figure **3.3a** and **3.3c,** which are performed at 0,6 m spacing between the risers, indicates the achievable accuracy in the calculations for the practical configurations of Figure **3.3b** and **3.3d**.

For the practical configurations in **Figure 3.3b** and **3.3d** the measurements were performed for following spacings between the risers in order to verify the calculation basis for a span of layouts:

- Topside: 0,6 and 2 m
- Subsea: 0,6 and 5 m.

The distances between risers in the scaled configuration corresponds to following spacing at 50 Hz:

- Topside: 1,7 and 5,6 m
- Subsea: 1,7 and 14 m.

The term “neighbouring risers” is used for two or more risers with different spacing topside and subsea.

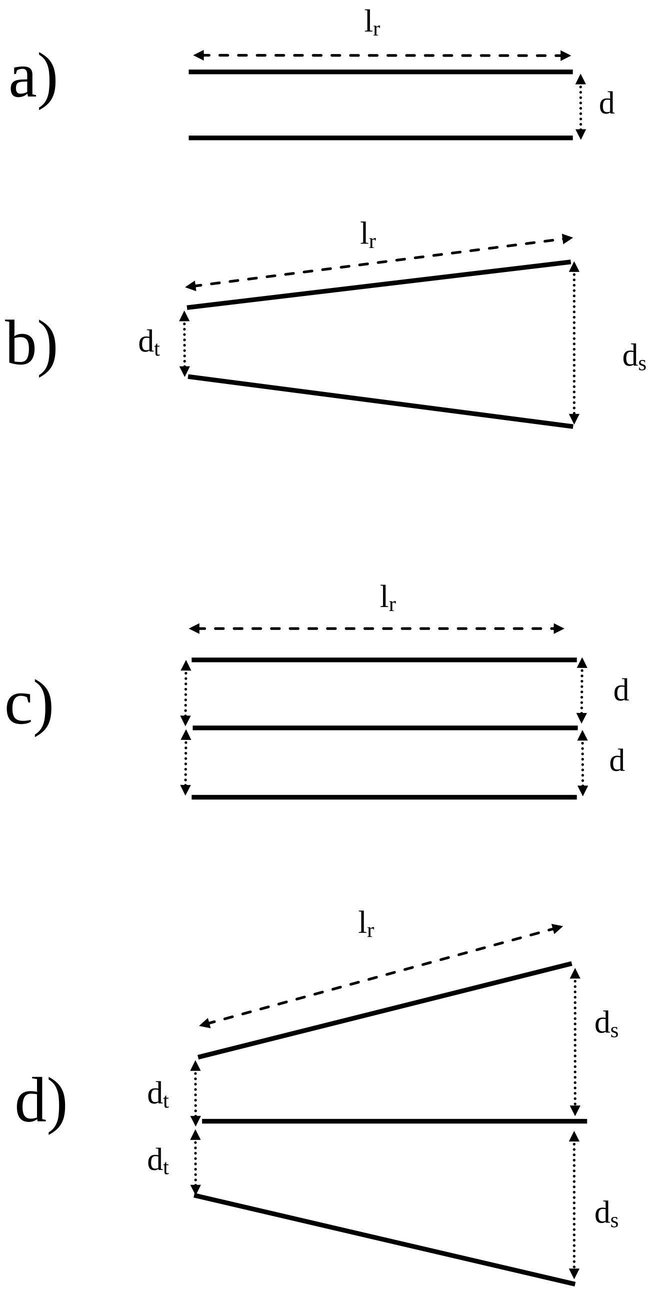


Figure 3.3: Test set-up for risers. Spacing topside (d_t): 0,6 m – 2 m and 0,6 m to 5 m subsea (d_s). Length of each riser (l_r) was 70 m.

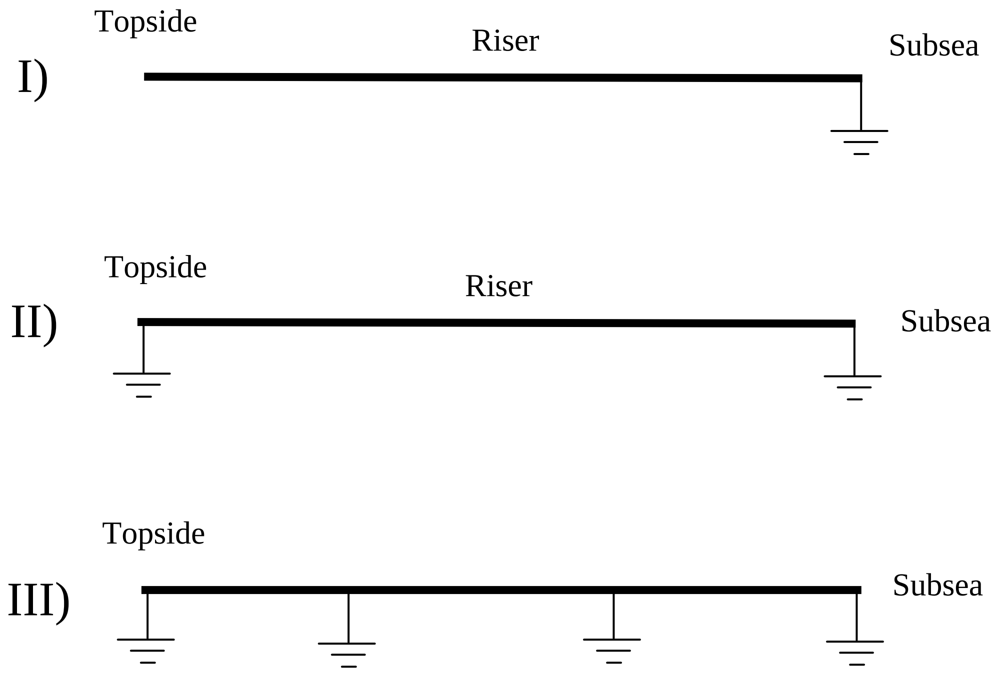


Figure 3.4: Grounding of risers – at subsea end without intermediate groundings and at both ends with and without intermediate groundings.

There are three principles for the heating concept of grounded risers as illustrated in **Figure 3.4**:

I) The risers are electrically grounded to seawater at the far end of the heated section. The risers have a combined thermal and electrical insulation and the risers is the only return conductors for the system current. The max. voltage between riser and ground is at the topside end.

II) The risers are electrically grounded to seawater at both ends of the heated section. The risers have a combined thermal and electrical insulation, i.e. in between the grounding points the currents in a riser is constant along the length and consequently the generated heat is constant.

III) Anodes to seawater at several locations along the length electrically ground the risers. In between the intermediate grounding points the risers have a combined thermal and electrical insulation, i.e. the current can vary along the riser, but is constant in between the intermediate grounding points.

The qualification tests included measurements of:

- Current distribution between risers and seawater along the risers.
- Transfer current between riser and seawater along the risers.
- Generated heat in the riser.
- Temperature rise.
- Impedance.
- Supply voltage.
- Induced voltage/current in neighbouring risers and signal cables.

The tests have been performed on risers with single point grounding, two point grounding and intermediate grounding i.e. alternatives I, II and III in **Figure 3.4** according to the test plan, [1]. For alternative III, with intermediate grounding, measurements were performed on two risers with a spacing of approx. 5 m between the intermediate anodes.

For each spacing measurements were performed for different coupling alternatives according to **Table 3.1** for two risers and **Table 3.2** for three risers for grounding alternative I and II. The test programme used to study the effect of number of anodes along the rises is shown in **Table 3.3**.

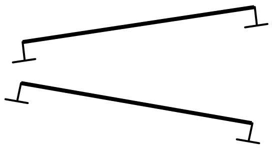
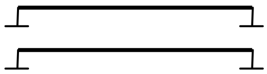
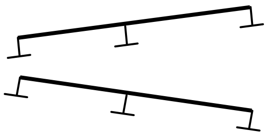
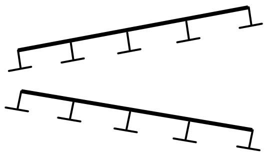
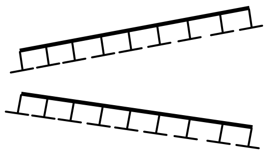
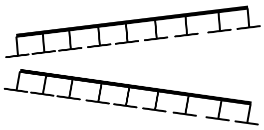
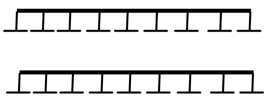
Table 3.1: Test configuration overview for two risers, grounding alternatives I and II. At each "Coupling no." the spacing between the risers were varied.

Coupling no.	Grounding alternative of riser, see **Figure 3.4**.		Power supply on riser no.
	Riser no. 1	Riser no. 2	
1	I	I	1
2	I	II	1
3	II	I	1
4	II	II	1
5	I	I	2
6	I	II	2
7	II	I	2
8	II	II	2
9	I	I	1 and 2
10	II	II	1 and 2

Table 3.2: Test configuration overview for three risers, grounding alternatives I and II. At each "Coupling no." the spacing between the risers were varied.

Coupling no.	Grounding alternative of riser, see **Figure 3.4**.			Power supply on riser no.
	Riser no. 1	Riser no. 2	Riser no. 3	
1	II	II	II	1
2	II	II	II	2
3	II	II	II	3
4	II	II	II	2 and 3
5	II	II	II	1 and 3
6	I	II	I	2
7	I	I	II	3
8	I	I	I	1, 2 and 3
9	II	II	II	1, 2 and 3

Table 3.3: Test configuration overview for two risers, grounding alternatives II and III for studying the effect of number of anodes along the risers.

Config	Min. distance [m]	Max. distance [m]	Number of intermediate anodes	Power supply on riser no.
	0,6	5	0	1, 2, 1 and 2
	0,6	0,6	0	1, 2, 1 and 2
	0,6	5	1	1, 2, 1 and 2
	0,6	5	3	1, 2, 1 and 2
	0,6	5	10	1, 2, 1 and 2
	0,6	2	10	1, 2, 1 and 2
	0,6	0,6	10	1, 2, 1 and 2

3.3 Test equipment and accuracy

The following test equipment was used for measurements topside:

Current probe	Fluke 80i-1000S	± 1,0 % of reading
Multimeter	Fluke 187/89	0,4 % of reading + 4mV
Transient recorder	HIOKI 8826	0,4 % of full scale
Power analyser	Norma D5235	± 1,5 % of reading

Subsea the riser currents were measured with Rogowski coils. Tests on the installation showed that the accuracy for the coils was ± 3,5 %.

The total accuracies referred to the measured values are:

Topside currents:	± 1,4 %
Subsea currents (Rogowski coils):	± 3,5 %
Voltage:	± 0,4 %
Power (generated heat):	± 2,5 %

3.4 Finite element calculations

Test results were compared with calculations by the programme FLUX2D, [3]. **Figure 3.5** shows the two-dimensional geometric model used in the calculations. The water depth along the risers varied between 6 m – 12 m. In the model a mean value of 8 m was used. Calculations showed that it was sufficient to include 50 m of the water volume to the right side of the risers in **Figure 3.5**. **Figure 3.6** shows the three risers located on the seabed, **Figure 3.7** shows the element graduation of the area close to a Duplex steel riser and **Figure 3.8** results from calculations with magnetic fluxlines close to the risers when all risers are heated.

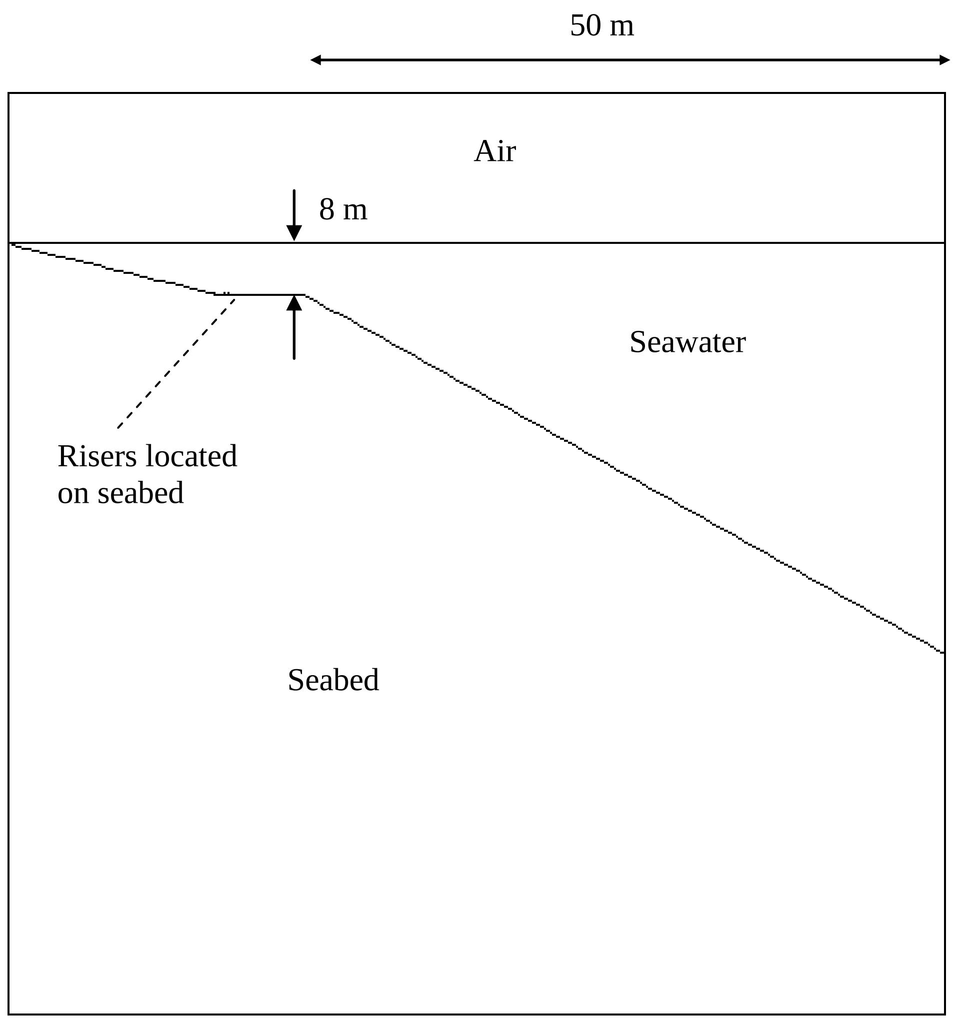


Figure 3.5: Two-dimensional model used in simulations by FLUX2D.

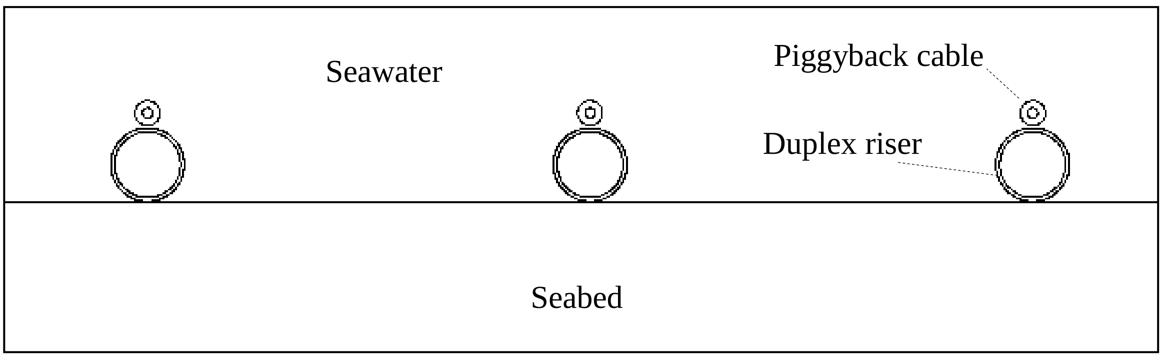


Figure 3.6: Duplex steel risers located on the seabed.

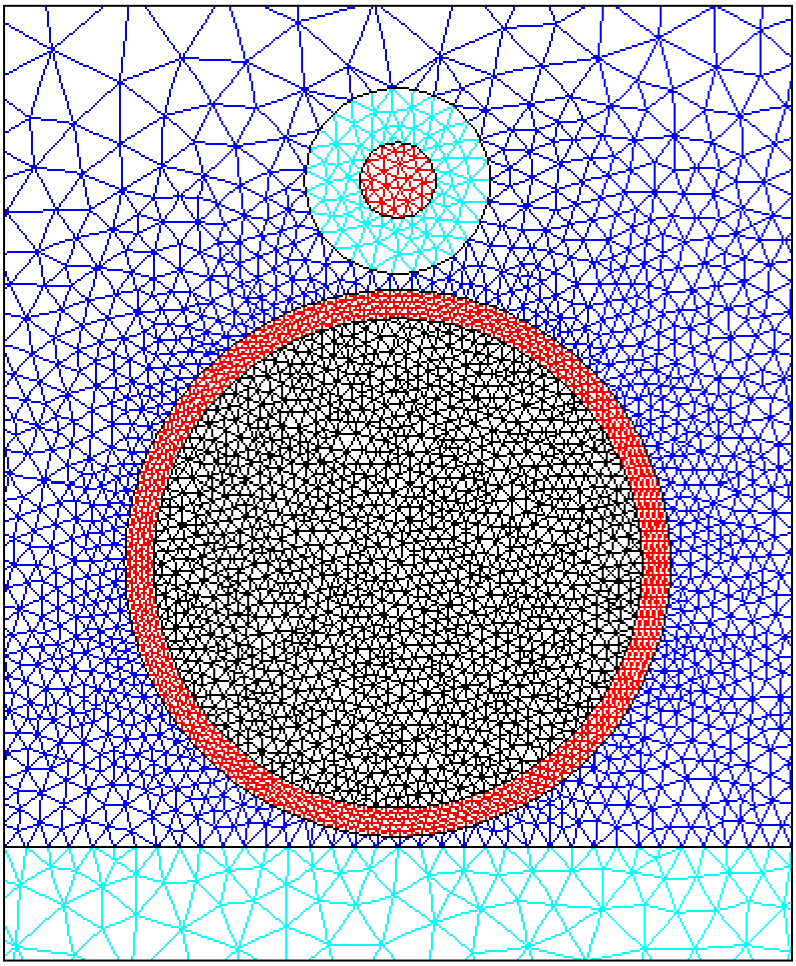


Figure 3.7: Element graduation of the Duplex steel riser.

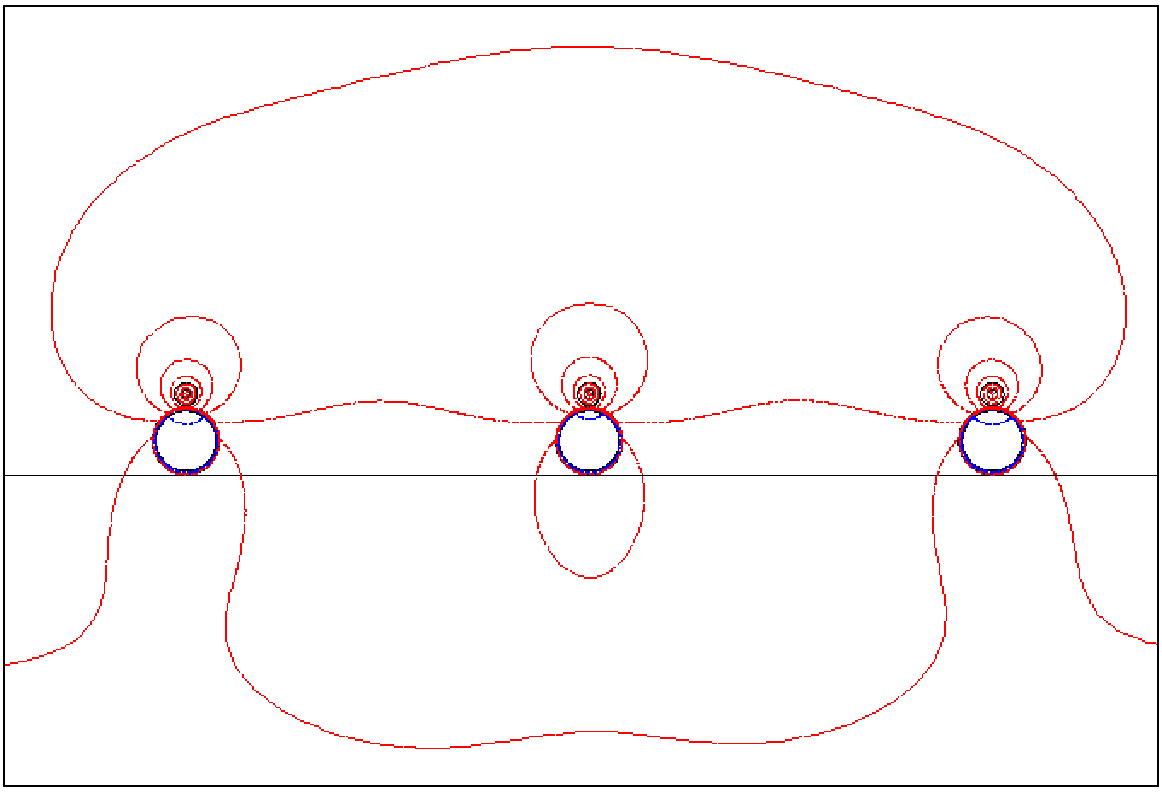


Figure 3.8: Magnetic flux lines when heating three risers simultaneously.

4 TEST RESULTS AND CALCULATIONS ON THE RISER CONFIGURATIONS

4.1 Introduction

Measurements and calculations of voltage drop (impedance), current distribution and generated heat have been performed for parallel (constant spacing) and neighbouring risers. The term “neighbouring risers” is used for two or three risers with different spacing topside and at the subsea end. The measured characteristics for risers are compared with two-dimensional simulations. Simulations by the finite element method, [12], have been performed for the same spacing between individual risers as the tests, i.e. spacing at 0,6, 2 and 5 m. For the case of neighbouring risers the calculated values presented in the tables are arithmetic means of the simulations for parallel risers at different spacing.

The relative permeability given in **Figure 2.1** is used in the comparative calculations in the report. At a piggyback current of 200 A the relative permeability is approx. 52. The max. deviation from this value is in a part of test riser no. 2 (from approx. 20-32 m in **Figure 2.2b**) having a relative permeability of approx. 75. Risers with two point grounding without heating carries induced currents considerably less than the heated risers and hence the relative permeability for these risers are less than for the heated risers.

The test installation (**Figure 3.1**) comprises three risers. Measurements were performed on:

Heating of a single riser.
In this case only one of the three risers is heated. The two other risers are grounded only at the subsea end. A voltage is induced in these risers, but there is no current. Therefore these two risers have no effect on the impedance for the heated riser.

Heating of one of two neighbouring risers.
One riser is heated (i.e. connected to the power source). The second riser has two point grounding and a circulating current is induced. There is some heat development due to this current, and it affects the impedance of the heated riser. The third riser is grounded only at one point and could be removed without consequence for the impedance.

Heating of one of three neighbouring risers.
One riser is heated (connected to the power source). The two other risers are two point (or multiple) grounded, and carry induced currents.

Heating of two of three neighbouring risers.
Two risers are heated. The third riser has two point (or multiple) grounding and carries an induced current.

4.2 Temperature measurements

Measurements of steel riser temperature for the 3 m pipelength with thermal insulation were carried out at a risercurrent of 290 A, i.e. approx. 76 W/m generated heat in the riser. The positions of the thermocouples are shown in **Figure 4.1**. The results from the test are shown in **Figure 4.2**.

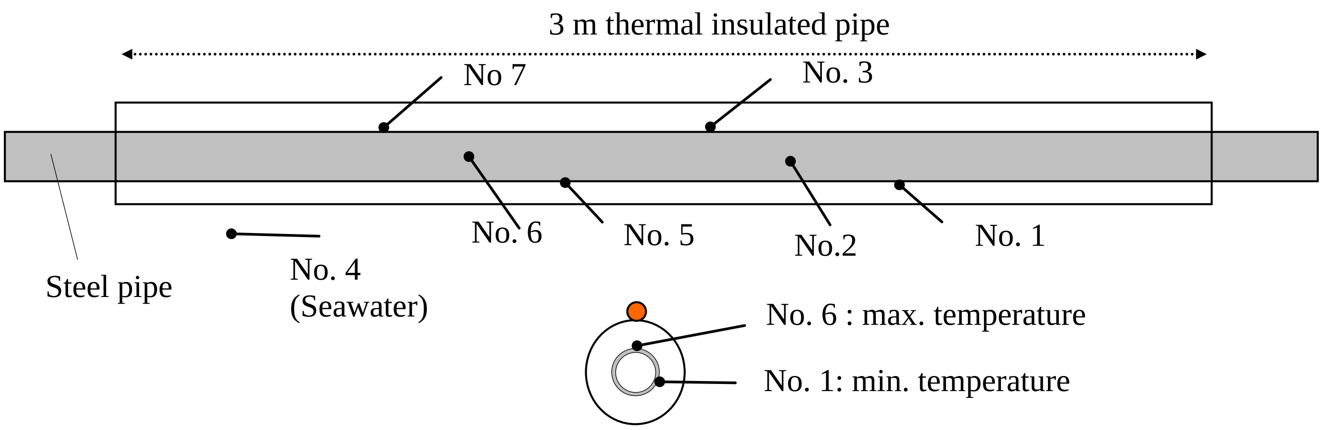


Figure 4.1: Location of thermocouples on the insulated section of riser no. 2.

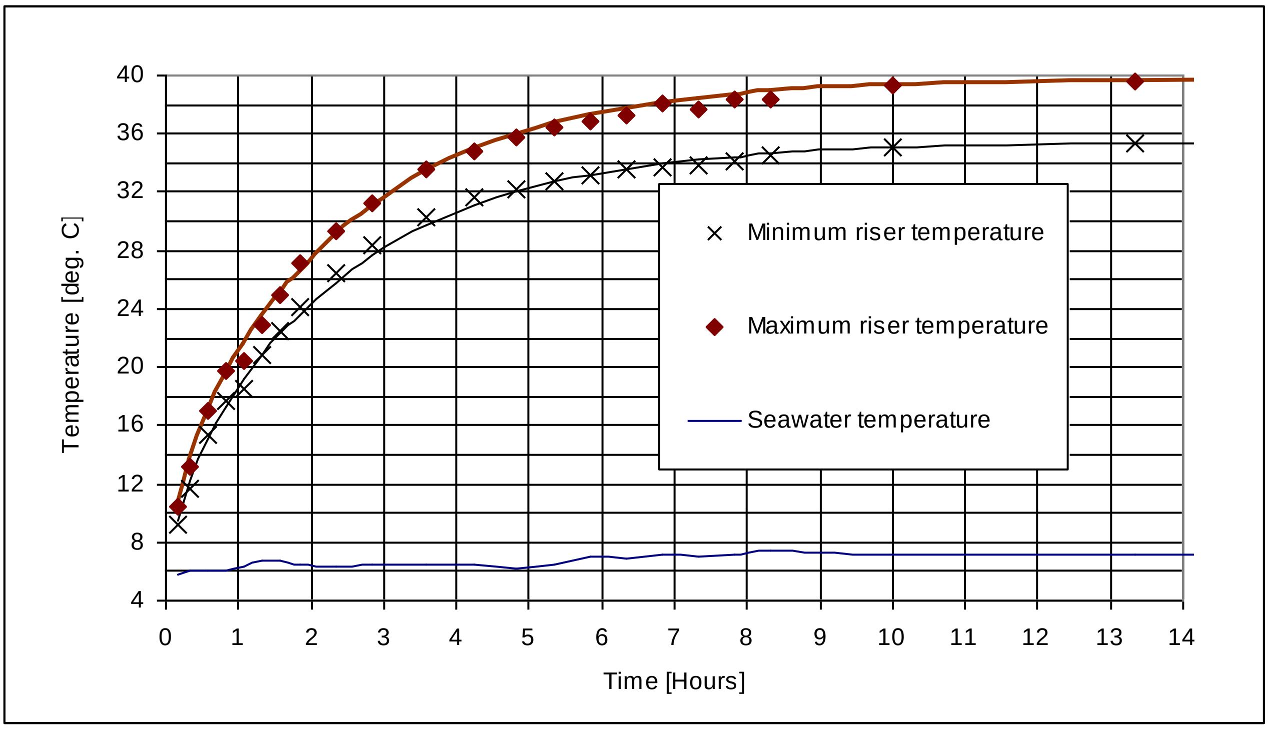


Figure 4.2: Results from temperature measurements on the thermal insulated riser at a current of 290 A in the riser. The diagram shows the max. temperature at "position 6" and minimum temperature at "position 1" on the riser. Air filled riser.

The maximum and minimum temperature of the steel riser is shown in **Figure 4.2**. At stationary conditions, which are obtained after 14 hours the temperature rise was approx. 33^{o}C and 29^{o}C for these two points. The accuracy for the temperature measurements is approx. 2^{o}C.

Then thermal resistance for the insulated riser, R_p, is given by:

$R_p = \rho/2\pi \ln(d_2/ d_1)$

ρ - thermal resistivity of riser insulation
d_2 = outer diameter of riser insulation (180 mm)
d_1 = internal diameter of riser insulation (100 mm)

The thermal resistivity of the riser insulation is estimated to 4,6 m^{o}C/W by Thermotite. The thermal resistance is:

R_p = 0,43 m^{o}C/W

For a heat generation in the riser of 76 W/m the temperature rise of the riser is calculated to **33^{o}C**, which is in good accordance with the measurements (temperature rise is: $\Delta\upsilon = R_p * P$).

4.3 Test circuit formed by two parallel insulated risers in a loop

This test set-up was used to verify the theoretical modeling of the risers. Comparative measurements and calculations of the impedance and generated heat were performed. In the calculations a relative permeability of 52 was used according to the test results in **Figure 2.2**.

Table 4.1: Test circuit formed by two parallel insulated risers in a loop with a separation of 0,6 m. In this case the risers are grounded only at the subsea end and disconnected from ground "topside". Deviation between measurements and calculations in % is also given in the table.

	Current in the risers [A]	Impedance [mΩ]	Generated heat [W]
Measured	219	308	5 462
Calculated	219	305	5 176
Deviation between measurements and calculations [%]	-	1,0	5,5

The calculations and measurements are in good accordance.

4.4 Heating of a single riser

Tests on single riser were performed for coupling alternatives 2, 3, 6 and 7 in **Table 3.1**. The results are shown in **Table 4.2** for grounding alternative I (insulated), and **Table 4.3** for grounding alternative II. The results are compared with calculations. In the calculations a relative permeability of 50 was used according to the test results in **Figure 2.2.**

The voltage drop and generated power for coupling cables between the termination cabinet and connections on the risers are included in the measurements. For each riser the impedance in these cables is approx. 4 mΩ. The measured supply voltage is corrected for the voltage drop in the connecting (supply) cables (at 300 A system current the voltage drop is approx. 1,2 V). The measurements are corrected for power loss in connecting cables (8 m - 150 mm^2 copper conductor) of 80 W and in connecting busbars (0,3 m stainless steel - 200 mm^2) of 100 W at 300 A.

Table 4.2: Measurements compared with calculations for heating of a single insulated riser. Heated riser is only grounded at the subsea end. Neighbouring risers are grounded at the subsea end and disconnected topside. (*System current is the current in piggyback cable). Max. deviation between measurements and calculations in % is also given in the table.

	Riser no	System current* [A]	Impedance [mΩ]	Generated heat [W]
Measured	1	228	188	3 716
Calculated	1	228	186	3 783
Measured	2	231	180	3 768
Calculated	2	231	186	3 866
Measured	3	235	180	3 956
Calculated	3	235	186	4 008
Max. deviation between measurements and calculations [%]	-	-	3,3	2,6

Table 4.3: Measurements compared with calculations for heating of a single two point grounded riser. The heated riser is grounded at both ends. The non heated risers are grounded only at the subsea end and disconnected topside. (*System current is the current in piggyback cable for the heated riser). Max. deviation between measurements and calculations in % is also given in the table.

	Current [A]				Impedance [mΩ]	Generated heat [W]
	System current*	Riser no 1	Riser no 2	Riser no 3		
Measured	228	167	0	0	173	2 791
Calculated	228	166	0	0	160	2 590
Measured	227	0	162	0	171	2 668
Calculated	227	0	165	0	160	2 568
Measured	241	0	0	177	168	3 164
Calculated	241	0	0	174	160	2 895
Max. deviation [%]	-	0,6	1,9	1,7	7,5	8,5

Table 4.2 and **4.3** indicates good accordance between measurements and calculations.

4.5 Simultaneous heating of parallel risers

Calculations have been performed with different spacing between parallel risers. The results from calculations for simultaneous heating of two and three risers are shown in **Table 4.4** and **Table 4.5**. Two point grounding is applied (grounding alternative II).

Table 4.4: Results from calculations of simultaneous heating of two parallel risers. The configuration is shown in **Figure 3.3a**. Riser length: 70 m.

Spacing [m]	System current [A]	Supply voltage [V]	Current in riser no. 1 [A]	Current in riser no. 2 [A]	Current in seawater [A]	Generated heat [W]	Z [mΩ]	X [mΩ]	R [mΩ]
0,6	300	25,3	126	126	56,0	2 588	84,3	79,2	28,8
2	300	24,8	123	122	61,7	2 532	82,7	77,8	28,1
5	300	24,6	118	118	67,6	2 485	82,0	77,2	27,6

Table 4.5: Results from calculations of simultaneous heating of three parallel risers. The configuration is shown in **Figure 3.3c**. Riser length: 70 m.

Spacing [m]	System current [A]	Supply voltage [V]	Current in riser no. 1 [A]	Current in riser no. 2 [A]	Current in riser no. 3 [A]	Current in seawater [A]	Generated heat [W]	Z [mΩ]	X [mΩ]	R [mΩ]
0,6	450	25,7	131	133	130	65,5	4 098	57,1	34,5	45,5
2	450	25,2	127	129	126	77,3	3 992	56,0	34,1	44,4
5	450	24,8	122	123	121	90,1	3 886	55,1	34,2	43,2

Comparison between measurements and calculation for two parallel risers is shown **Table 4.6** (configuration in **Figure 3.3a** grounding alternative II in **Figure 3.4**) and for three parallel risers in **Table 4.7** (configuration in **Figure 3.3c** grounding alternative II in **Figure 3.4**)

Table 4.6: Measurements compared with calculations for simultaneous heating of two parallel risers (configuration in **Figure 3.3a** and grounding alternative II in **Figure 3.4**). Spacing between risers: 0,6 m.

	Current [A]			Impedance [mΩ]	Generated heat [W]
	Total supply current	Riser no 1	Riser no 2		
Calculated	267	112	112	84,3	2 031
Measured	267	114	107	85,8	2 055
Max. deviation [%]	-	1,8	4,7	1,8	1,2

Table 4.7: Measurements compared with calculations for simultaneous heating of three parallel risers (configuration in **Figure 3.3c** and grounding alternative II in **Figure 3.4**). Spacing between risers: 0,6 m.

	Current [A]				Impedance [mΩ]	Generated heat [W]
	Total supply current	Riser no 1	Riser no 2	Riser no 3		
Calculated	445	130	132	129	57,1	4 007
Measured	445	124	128	131	59,3	4 013
Max. deviation [%]	-	4,8	3,1	1,6	3,7	0,2

The results from calculations and measurements of the riser currents are in good accordance for the heated risers. Results from measurements and calculations of impedance and generated heat are also in good accordance.

4.6 Simultaneous heating of two neighbouring risers

Calculations have been performed with different spacing between neighbouring risers. The results from calculations of the current in one riser for simultaneous heating of two risers are shown in **Figure 4.4**.

As seen from the results the riser current is reduced by 2% and the impedance by 2% when the distance between the parallel risers increases from 0,6 to 5 m.

The results from measurements of the current distribution for simultaneous heating of two risers at a total current of 250 A, see **Table 4.8,** indicate a negligible reduction of the riser current when the distances increase for the configurations in **Figure 3.3b**. The variation of the measured current distribution is less than the accuracy by the measuring method, which in this case is approx 3,5%.

Table 4.8: Measurements compared with calculations of the current distribution for simultaneous heating of two risers. The configuration is shown in **Figure 3.3b**. Grounding alternative II in **Figure 3.4**.

	Spacing topside-subsea [m]	Current [A]			Impedance [mΩ]	Generated heat [W]
		System current	Riser no 1	Riser no 2		
Calculated	0,6 - 2	251	102	102	83,7	1 792
Measured	0,6 – 2	251	97,8	104	86,5	1 819
Calculated	0,6 – 5	247	101	101	83,4	1 720
Measured	0,6 – 5	247	95,4	100	85,8	1 764
Calculated	2 – 5	250	100	100	82,4	1 742
Measured	2 – 5	250	101	100	85,2	1 799
Max. deviation [%]	-	-	4,9	3,0	3,3	3,2

The results from calculations and measurements of the riser currents are in good accordance for the heated risers. Results from measurements and calculations of impedance and generated heat are also in good accordance.

4.7 Heating one of two neighbouring risers

Calculations have been performed with different spacing between parallel risers by heating one of two risers for the configuration shown in **Figure 3.3a** and grounding alternative II in **Figure 3.4**. The results are shown in **Table 4.9**.

Table 4.9: The results from calculations of the current distribution for heating one of two parallel risers. Riser no 1 is the heated riser. The configuration is shown in **Figure 3.3b**. Grounding alternative II in **Figure 3.4**.

Spacing [m]	Heating riser number	System current [A]	Supply voltage [V]	Current in riser no. 1 [A]	Current in riser no. 2 [A]	Current in seawater [A]	Generated heat [W]	Z [mΩ]	X [mΩ]	R [mΩ]
0,6	1	300	46,9	201	51,0	57	4 006	156	150	44,5
2	1	300	48,0	217	32,0	61	4 275	160	153	47,5
5	1	300	48,4	224	21,6	67	4 433	161	153	49,3

The results from measurements of the current distribution in the risers by heating one of two risers are shown in **Table 4.10** for the configuration shown in **Figure 3.3b** and grounding alternative II in **Figure 3.4**.

Table 4.10: Measurements compared with calculations of the current distribution for heating one of two neighbouring risers. Riser no 1 is the heated riser. The configuration is shown in **Figure 3.3b**. Grounding alternative II in **Figure 3.4**.

	Spacing topside-subsea [m]	Current [A]			Impedance [mΩ]	Generated heat [W]
		System current	Riser no 1	Riser no 2		
Calculated	0,6 – 0,6	230	155	39,1	156	2 355
Measured	0,6 – 0,6	230	151	41,1	170	2 484
Calculated	0,6 – 5	239	173	26,2	159	2 678
Measured	0,6 – 5	239	171	23,5	173	2 937
Calculated	2 – 5	238	175	21,3	161	2 763
Measured	2 – 5	238	171	22,2	171	2 925
Max. deviation [%]	-	-	2,7	-	8,1	8,8

The results from calculations and measurements of the riser currents for the heated risers in **Table 4.10** are in good accordance. For the non-heated risers the currents are relative small and have little effect on the system impedance. This is confirmed both by measurements and calculations. Results from measurements and calculations of impedance and generated heat are also in good accordance.

4.8 Simultaneous heating of three neighbouring risers

Calculations have been performed with different spacing between parallel risers for flat formation of the risers. The results from calculations of the current distribution for simultaneous heating of three risers are shown in **Figure 4.5** for the riser in the middle. The current in the other two risers is approx. 0,5% less than in the middle riser. The system impedance is shown in **Figure 4.4.**

The results from measurements of the current distribution for simultaneous heating of three neighbouring risers at a total current of 445 A, see **Table 4.11**, indicate a negligible reduction of the riser current, when the distances increase for the configurations in **Figure 3.3d**. The variation of the measured current distribution is less than the accuracy by the measuring method, which in this case is approx 2%.

Table 4.11: Measurements compared with calculations of the current distribution for simultaneous heating of three risers. The configuration is shown in **Figure 3.3d**. Grounding alternative II in **Figure 3.4**.

	Spacing topside-subsea [m]	Current [A]				Impedance [mΩ]	Generated heat [W]
		System current	Riser no 1	Riser no 2	Riser no 3		
Calculated	0,6 - 2	460	131	133	131	56,7	4 227
Measured	0,6 – 2	460	127	134	129	60,2	4 311
Calculated	0,6 – 5	411	115	116	114	56,2	3 330
Measured	0,6 – 5	411	111	119	115	58,4	3 351
Calculated	2 – 5	387	106	108	106	55,6	2 913
Measured	2 – 5	387	108	103	107	58,4	3 173
Max. deviation [%]	-	-	3,6	4,9	1,6	5,8	8,2

The results from calculations and measurements of the riser currents are in good accordance for the heated risers. For the non-heated risers the currents are relative small and have little effect on the system impedance. This is confirmed both by measurements and calculations. Results from measurements and calculations of impedance and generated heat are also in good accordance.

4.9 Heating one of three neighbouring risers

Calculations have been performed with different spacing between parallel risers in flat formation by heating one of three risers for the configuration shown in **Figure 3.3c** and grounding alternative II in **Figure 3.4**. The results are shown in **Table 4.12**.

Table 4.12: The results from calculations of the current distribution for heating one of three parallel risers in flat formation. Riser no 1 is the heated riser. The configuration is shown in **Figure 3.3c**. Grounding alternative II in **Figure 3.4**.

Spacing [m]	Heating riser number	System current [A]	Supply voltage [V]	Current in riser no. 1 [A]	Current in riser no. 2 [A]	Current in riser no. 3 [A]	Current in seawater [A]	Generated heat [W]	Z [mΩ]	X [mΩ]	R [mΩ]
0,6	1	300	46,7	199	41,3	25,1	45,6	3860	156	150	42,9
2	1	300	47,9	216	27,5	16,5	52,7	4203	160	153	46,7
5	1	300	48,4	224	19,7	11,0	60,8	4409	161	154	49,0

Table 4.13: The results from calculations of the current distribution for heating one of three parallel risers in flat formation. Riser no 2 is the heated riser. The configuration is shown in **Figure 3.3c**. Grounding alternative II in **Figure 3.4**.

Spacing [m]	Heating riser number	System current [A]	Supply voltage [V]	Current in riser no. 1 [A]	Current in riser no. 2 [A]	Current in riser no. 3 [A]	Current in seawater [A]	Generated heat [W]	Z [mΩ]	X [mΩ]	R [mΩ]
0,6	2	300	45,9	41,5	186	41,5	38,7	3 663	153	147	40,7
2	2	300	47,6	27,4	210	27,4	47,1	4 056	159	152	45,1
5	2	300	48,3	18,9	219	18,9	56,6	4 275	161	154	47,5

The results from measurements of the current distribution in the risers by heating one of three risers are shown in **Table 4.14** (heating riser no. 1) and **4.15** (heating riser no. 2) for the configuration shown in **Figure 3.3d** and grounding alternative II in **Figure 3.4**.

Table 4.14: Measurements compared with calculations of the current distribution for heating one of two neighbouring risers. Riser no 1 is the heated riser. The configuration is shown in **Figure 3.3d**. Grounding alternative II in **Figure 3.4**.

	Spacing topside-subsea [m]	Current [A]				Impedance [mΩ]	Generated heat [W]
		System current	Riser no 1	Riser no 2	Riser no 3		
Calculated	0,6 – 0,6	239	159	32,9	20,0	156	2 450
Measured	0,6 – 0,6	239	153	35,3	17,5	170	2 600
Calculated	0,6 – 2	333	230	38,8	25,0	158	4 968
Measured	0,6 – 2	333	221	42,3	18,8	174	5 403
Calculated	0,6 – 5	304	214	28,6	16,5	159	4 246
Measured	0,6 – 5	304	210	28,7	13,2	175	4 720
Calculated	2 – 5	239	175	18,8	11,3	161	2 733
Measured	2 – 5	239	172	18,2	9,7	173	2 962
Max. deviation [%]	-	-	4,1	-	-	9,2	10

Table 4.15: Measurements compared with calculations of the current distribution for heating one of two risers. Riser no 2 is the heated riser. The configuration is shown in **Figure 3.3d**. Grounding alternative II in **Figure 3.4**.

	Spacing topside-subsea [m]	Current [A]				Impedance [mΩ]	Generated heat [W]
		System current	Riser no 1	Riser no 2	Riser no 3		
Calculated	0,6 – 0,6	260	35,9	162	35,8	153	2 751
Measured	0,6 – 0,6	260	36,8	157	37,5	165	3 007
Calculated	0,6 – 2	338	38,7	224	38,5	156	4 900
Measured	0,6 – 2	338	39,3	219	37,9	169	5 329
Calculated	0,6 – 5	313	28,9	212	28,3	157	4 320
Measured	0,6 – 5	313	26,2	213	30,1	172	4 820
Calculated	2 – 5	239	18,7	170	18,1	160	2 644
Measured	2 – 5	239	17,9	167	21,3	173	2 831
Max. deviation [%]	-	-	-	3,2	-	8,7	10

The results from calculations and measurements of the riser currents in **Table 4.14** and **4.15** are in good accordance for the heated risers. For the non-heated risers the currents are relative small and have little effect on the system impedance. This is confirmed both by measurements and calculations. Results from measurements and calculations of impedance and generated heat are also in good accordance.

4.10 Heating two of three neighbouring risers

Calculations have been performed with different spacing between parallel risers in flat formation by simultaneous heating two of three risers for the configuration shown in **Figure 3.3c** and grounding alternative II in **Figure 3.4**. The results are shown in **Table 4.16** for heating riser no 1 and 2 (or no. 2 and 3) and in **Table 4.17** for heating risers no. 1 and 3.

Table 4.16: The results from calculations of the current distribution for heating two of three parallel risers in flat formation. Riser no 1 and 2 is the heated risers. The configuration is shown in **Figure 3.3c**. Grounding alternative II in **Figure 3.4**.

Spacing [m]	Heating riser number	System current [A]	Supply voltage [V]	Current in riser no. 1 [A]	Current in riser no. 2 [A]	Current in riser no. 3 [A]	Current in seawater [A]	Generated heat [W]	Z [mΩ]	X [mΩ]	R [mΩ]
0,6	1 and 2	300	24,6	118	114	33,0	42,3	2352	82,0	26,1	77,8
2	1 and 2	300	24,7	119	117	21,5	49,9	2404	82,2	26,7	77,7
5	1 and 2	300	24,6	118	117	14,3	58,6	2429	81,9	27,0	77,3

Table 4.17: The results from calculations of the current distribution for heating two of three parallel risers in flat formation. Riser no 1 and 3 is the heated risers. The configuration is shown in **Figure 3.3c**. Grounding alternative II in **Figure 3.4**.

Spacing [m]	Heating riser number	System current [A]	Supply voltage [V]	Current in riser no. 1 [A]	Current in riser no. 2 [A]	Current in riser no. 3 [A]	Current in seawater [A]	Generated heat [W]	Z [mΩ]	X [mΩ]	R [mΩ]
0,6	1 and 3	300	24,0	109	41,3	109	46,0	2242	80,1	24,9	76,1
2	1 and 3	300	24,3	113	27,2	113	53,7	2308	80,9	25,6	76,7
5	1 and 3	300	24,2	114	18,9	113	62,9	2323	80,8	25,8	76,5

The results from measurements compared with calculations of the current distribution in the risers by simultaneous heating two of three risers are shown in **Table 4.18** (heating riser no. 2 and 3) and **4.19** (heating riser no. 1 and 3) for the configuration shown in **Figure 3.3d** and grounding alternative II in **Figure 3.4**.

Table 4.18: Measurements compared with calculations of the current distribution for heating two of three neighbouring risers. Riser no 2 and 3 are the heated risers. The configuration is shown in **Figure 3.3d**. Grounding alternative II in **Figure 3.4**.

	Spacing topside-subsea [m]	Current [A]				Impedance [mΩ]	Generated heat [W]
		System current	Riser no 1	Riser no 2	Riser no 3		
Calculated	0,6 – 0,6	421	46,3	160	166	82,0	4 632
Measured	0,6 – 0,6	421	44,5	151	171	86,2	5 208
Calculated	0,6 – 2	339	30,8	131	135	82,0	3 036
Measured	0,6 – 2	339	26,8	129	136	87,3	3 179
Calculated	0,6 – 5	323	23,1	125	128	82,0	2 771
Measured	0,6 – 5	323	18,7	126	130	87,3	2 940
Max. deviation [%]	-	-	-	6,0	2,9	6,1	11

Table 4.19: Measurements compared with calculations of the current distribution for heating two of three neighbouring risers. Riser no 1 and 3 are the heated risers. The configuration is shown in **Figure 3.3d**. Grounding alternative II in **Figure 3.4**.

	Spacing topside-subsea [m]	Current [A]				Impedance [mΩ]	Generated heat [W]
		System current	Riser no 1	Riser no 2	Riser no 3		
Calculated	0,6 – 0,6	426	156	60	156	80,1	4 521
Measured	0,6 – 0,6	426	145	58,1	161	86,4	4 971
Calculated	0,6 – 2	349	130	39,8	130	80,2	3 079
Measured	0,6 – 2	349	124	39,3	131	86,8	3 230
Calculated	0,6 – 5	334	124	30,4	124	80,2	2 830
Measured	0,6 – 5	334	121	30,4	126	86,8	2 977
Max. deviation [%]	-	-	7,6	-	3,1	7,6	9,1

The results from calculations and measurements of the riser currents are in good accordance for the heated risers. For the non-heated risers the currents are relative small and have only slightly affect on the system impedance. This is confirmed both by measurements and calculations. Results from measurements and calculations of impedance and generated heat are also in good accordance.

4.11 Results from 50 Hz tests and simulations

Tests were carried out for the case with heating of three parallel risers with a spacing of 0,6 m. The risers were grounded at both ends. **Table 4.20** shows the results from simultaneous heating and **Table 4.21** comparison between calculations and measurements.

Table 4.20: Results from calculations of simultaneous heating of three parallel risers. The configuration is shown in **Figure 3.3c**. Riser length: 70 m.

Spacing [m]	System current [A]	Supply voltage [V]	Current in riser no. 1 [A]	Current in riser no. 2 [A]	Current in riser no. 3 [A]	Current in seawater [A]	Generated heat [W]	Z [mΩ]	X [mΩ]	R [mΩ]
0,6	800	11,4	208	212	207	250	6957	14,3	9,26	10,9
5	800	10,8	191	193	187	295	6430	13,5	9,07	10,0

Table 4.21: Measurements compared with calculations for simultaneous heating of three parallel risers (configuration in **Figure 3.3c** and grounding alternative II in **Figure 3.4**). Spacing between risers: 0,6 m.

	Current [A]				Impedance [mΩ]	Generated heat [W]
	Total supply current	Riser no 1	Riser no 2	Riser no 3		
Calculated	803	209	213	208	14,3	7 009
Measured	803	215	214	212	15,1	7 795
Max. deviation [%]	-	2,9	0,5	1,9	5,6	11

The results show good accordance between calculations and simulations also at 50 Hz.

5 THE EFFECT OF NUMBER OF ANODES ALONG THE RISER

5.1 Results from measurements of current distribution and impedance

The objective for the measurements is to investigate the effect of the distance between two risers at the subsea end and the number of intermediate anodes on the system impedance and riser current. The heat development in the riser is proportional with the square of the riser current. Both heating of one of two risers and simultaneous heating are investigated. For measurements on one riser the grounding of the second riser will affect the results. This effect is negligible in case of single point grounding. In case of two point and multiple grounding a current will be flowing in this second riser. For the case of simultaneous heating the system impedance is referred to the total supply current (supply voltage divided by the total supply current). All tests were performed on **58 m** length. The tests with no intermediate anodes (**Section 4**) were performed on 70 m riser length.

The tests are performed for different number of anodes along the risers, and with different spacing between the two risers subsea. At topside the spacing between the risers was constant (0,6 m). Anodes were mounted at several locations along the length of the two point grounded risers as grounding alternative III shown in **Figure 3.4**. In between the intermediate anodes the risers have a combined thermal and electrical insulation, i.e. the current can vary along the riser, but is constant in between two neighbouring anodes. The risers can have maximum 10 intermediate anodes with 5 m spacing.
In the measurements of the impedance in the supply cables (approx. 20 m) is included and is considered when comparing test results with calculations.
In these measurements the connection cables were different from the cables used in the measurements in **Section 3**. The voltage drop in the supply cables is approx. 9 V at a system current of 300 A. At 300 A the total voltage is approx. 60 V.

Table 5.1 shows the results of the measurements when heating one of two risers on two point grounded system with and without intermediate anodes. The measured values are referred to a system current of 300 A and a riser length of 58 m.

Table 5.1: Results from measurements of heating one of two neighbouring risers. Results are referred to a system current of 300 A. Spacing topside: 0,6 m. Riser length: 58 m.

Distance between risers at subsea end. [m]	Number of intermediate anodes.	Minimum current of riser referred to current in piggyback cable. [%]	P [W]	Z [mΩ]	R [mΩ]	X [mΩ]
0,6	0	69,6	4 304	145	47,8	137
5	0	74,2	4 434	149	49,3	140
5	1	73,1	4 465	148	49,6	139
5	3	72,9	4 443	148	49,4	140
0,6	10	66,1	4 194	147	46,6	140
2	10	69,4	4 342	149	48,2	141
5	10	71,8	4 396	149	48,8	141

For parallel risers the number of intermediate anodes has no significant effect on both the riser current and system impedance. The variations are within the expected measuring accuracy. Some difference of riser current may occur due to different magnetic properties in the riser along the length depending on the number of the intermediate anodes.

Table 5.2 shows the results of the measurements where two risers were heated on a two point grounded system with intermediate anodes.

Table 5.2: Results from measurements of simultaneous heating of two neighbouring risers. Results are referred to a system current of 300 A. Spacing topside: 0,6 m. Riser length: 58 m.

Distance between risers at subsea end. [m]	Number of intermediate anodes.	Minimum current of riser referred to current in piggyback cable. [%]	P [W]	Z [mΩ]	R [mΩ]	X [mΩ]
0,6	0	87,2	2 373	74,9	26,4	70,1
5	0	85,4	2 332	74,0	25,9	69,3
5	1	84,8	2 357	73,9	26,2	69,1
5	3	84,2	2 343	73,7	26,0	69,0
0,6	10	84,4	2 353	75,0	26,1	70,3
2	10	82,8	2 327	74,4	25,9	69,8
5	10	82,8	2 312	73,3	25,7	68,6

Comparison of **Table 5.1** and **Table 5.2** shows that the riser current is increased, from 72% to 83% of the piggyback current, when two risers (0,6 m spacing topside and 5 m spacing subsea) are simultaneously heated. The reason is that the seawater current for both risers partly flow in the same water volume. Consequently the "voltage drop" in seawater is increased and part of the return current is shifted from water to the riser. This means that the target riser heat development in case of simultaneous heating is obtained for a lower system voltage. These results are only valid if the two system currents have the same phase angle, i.e. each riser is supplied from the same system voltage.

5.2 Results from calculations of steady state current distribution, power loss and impedance for parallel risers

Table 5.3 shows results from calculations on heating of a single riser, a single riser with parallel riser and simultaneous heating of two parallel risers. For all cases the risers are two point grounded.
The calculations are performed at the same current values as the measurements and effective relative permeability given in **Figure 5.1**. For heating of one riser with a piggyback current of 300 A an effective permeability for Duplex steel of 50 is used.

Table 5.3: Results from calculations of heating parallel risers. Results are referred to a piggyback cable current of 300 A for heating of a single riser and 150 A for simultaneous heating of two risers. Riser length: 58 m. (*Single two point grounded riser with parallel riser single point grounded).

Spacing [m]	Heating riser number	Piggyback cable current [A]	Supply voltage [V]	Current in riser no. 1 [%]	Current in riser no. 2 [%]	Generated heat [W]	Z [mΩ]	R [mΩ]	X [mΩ]
* 0,6	1	300	39,7	70,7	0	3 719	132	41,3	125
0,6	1	300	38,9	65,3	17,9	3 319	130	36,9	125
2	1	300	39,7	70,3	11,3	3 542	132	39,4	126
5	1	300	40,1	72,3	7,60	3 673	134	40,8	128
0,6	1 and 2	150	20,9	81,3	81,3	2 124	69,7	23,6	65,6
2	1 and 2	150	20,6	79,3	79,3	2 099	68,7	23,3	64,6
5	1 and 2	150	20,4	77,3	77,3	2 059	68,0	22,9	64,0

5.3 Presentation of test results for current distribution and generated heat

Figure 5.1 shows an example of the current distribution along the heated riser for two parallel risers with a spacing of 0,6 m. The number of intermediate anodes (anodes between the grounding points at each end) is 10 and consequently 11 currents are measured between the grounding points at the ends.

Curves are drawn for heating of one riser and simultaneous heating of two risers. In these tests the power supply is connected to the riser at the first anode, i.e. the anode at 11,5 m from the riser end close to the structure.

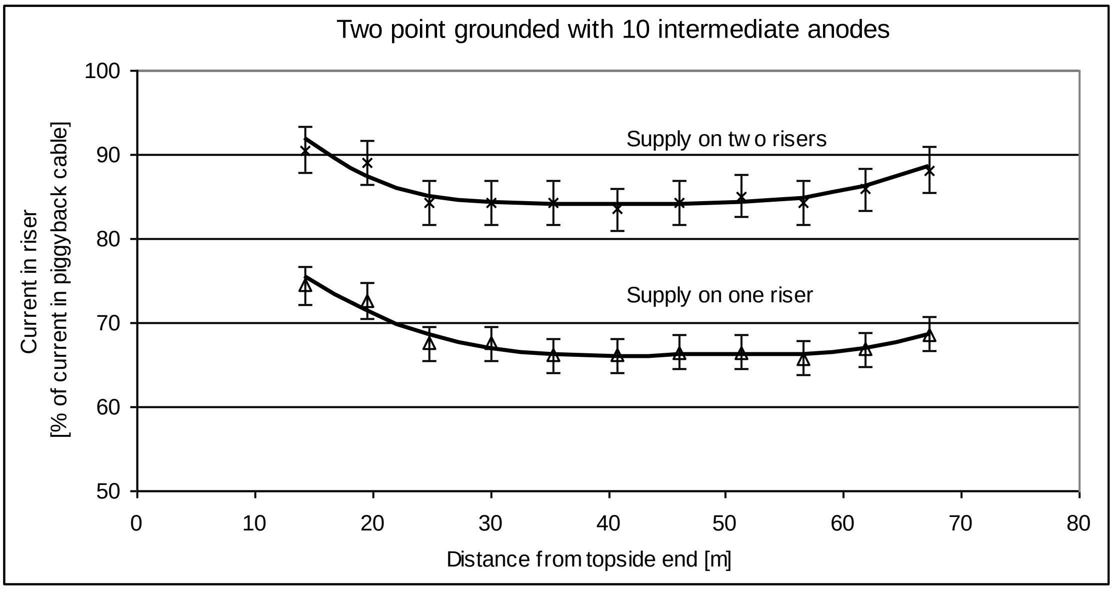


Figure 5.1: Current in the heated riser as a function of distance from the topside end for heating of one of two risers and simultaneous heating of two risers. Parallel risers with a spacing of 0,6 m.

Figure 5.1 shows that minimum riser current is approximately 84% of the current in the piggyback cable when heating two risers simultaneously and 66% when only one riser is heated.

Figure 5.2 shows the power development along the risers for the same configuration as in **Figure 5.1**. The power development is referred to the current in the piggyback cable for the heated riser.

The generated heat is proportional with the square of the current in the riser. The reference value for the power development in the riser is the value obtained for the riser current equal to the piggyback current.

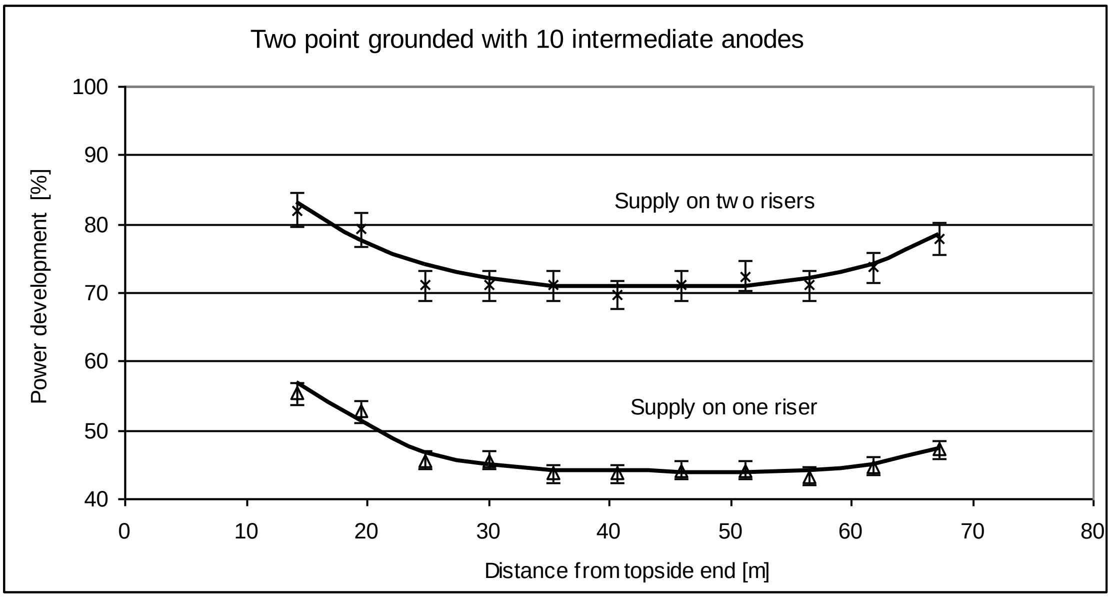


Figure 5.2: Relative power development along the riser referred to the piggyback current. Both heating of one of two risers and simultaneous heating of two risers are shown. Parallel risers with a spacing of 0,6 m.

Measurements have been performed with different spacing topside and subsea for heating of a single riser and simultaneous heating of two risers. The number of anodes has been varied between 3 and 10 along the test risers. **Figure 5.3** shows the minimum current in the riser as function of number of intermediate anodes. The spacing is 0,6 m topside and 5 m subsea in all tests.

The minimum current in the riser appears in the middle part (section 5-7 in **Figure 5.4.c**) of the riser for 10 intermediate anodes.

For 1 intermediate anode the minimum current appears at the part of the riser closest to the neighbouring riser, section 1 in **Figure 5.4.a**, when heating one riser and for the part at maximum spacing for simultaneous heating.

For 3 intermediate anodes with heating of one riser the minimum riser current appears in section 2 in **Figure 5.4.b** and for simultaneous heating in section 3 in the same figure.

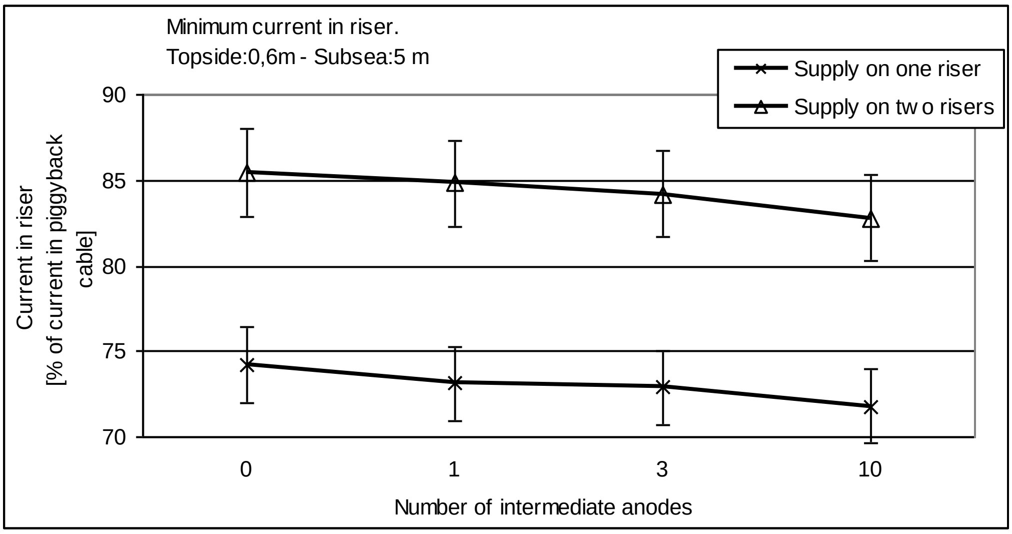


Figure 5.3: Minimum value of the current in the riser referred to the current in the piggyback cable as a function of number intermediate anodes. Both heating of one of two risers and simultaneous heating are shown. Spacing between risers topside is 0,6 m and 5 m subsea.

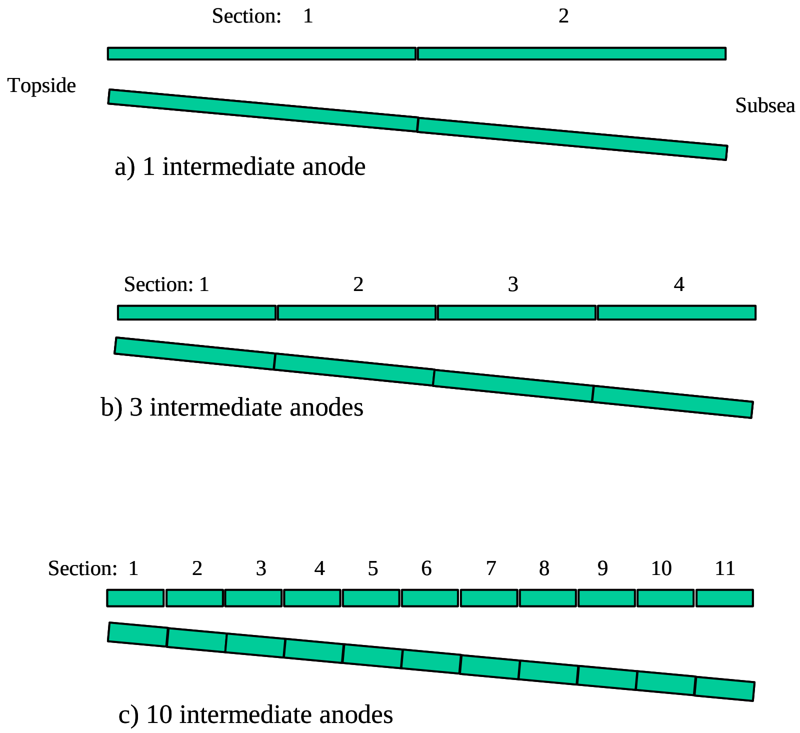


Figure 5.4: Illustration of risers (58 m test length) with intermediate anodes.

Figure 5.5 shows the minimum current in the riser as function of distance between risers when the number of intermediate anodes is constant.

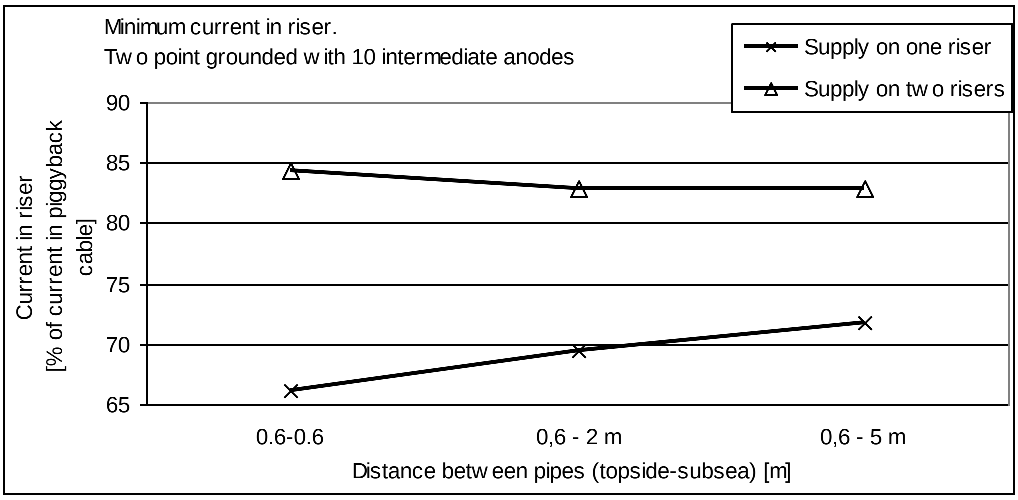


Figure 5.5: Minimum value of the current in the riser referred to the current in the piggyback cable as a function of distance between risers at subsea end between 0,6 and 5 m. The spacing topside is 0, 6 m. Both heating of one of two risers and simultaneous heating of two risers are shown.

The results in **Figure 5.5** shows that:

- When heating one riser the minimum current in the riser increases with increasing spacing between risers.
- When heating two risers simultaneously, the current in the risers decreases with increasing spacing between risers.

5.4 Presentation of test results for impedances

As defined in **Section 5.1** the impedance (reactance and resistance) is the ratio between the supply voltage and total supply current.

All measurements were performed with two point grounding of two neighbouring risers. The impedances are referred to the test length for the risers of 58 m and a supply current of approximately 300 A. The effect of different number of intermediate anodes were investigated.

Impedances, reactances and resistances for two point grounded risers with 10 anodes are shown in **Figure 5.6 and 5.7** when heating one riser and in **Figure 5.8 and 5.9** for simultaneous heating of two risers. The figures show the results for a constant distance between the risers of 0,6 m topside and different spacing subsea between 0,6 and 5 m.

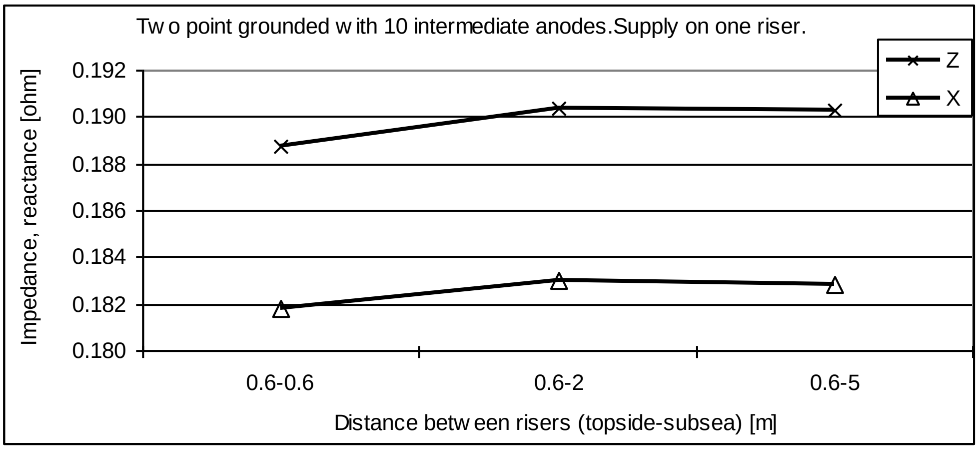


Figure 5.6: Impedance and reactance for heating one of two risers. Spacing between risers topside: 0,6 m. Spacing subsea between 0,6 and 5 m.

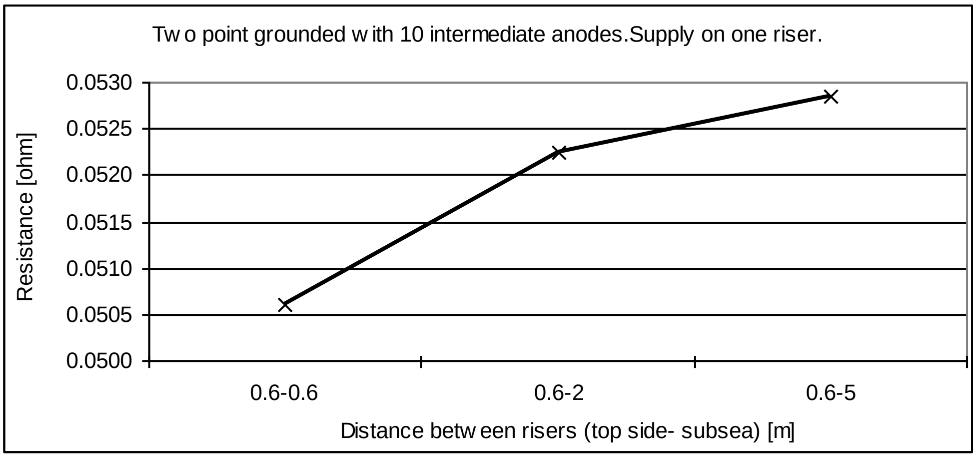


Figure 5.7: Resistance for heating one of two risers. Spacing between risers topside: 0,6 m. Spacing subsea between 0,6 and 5 m.

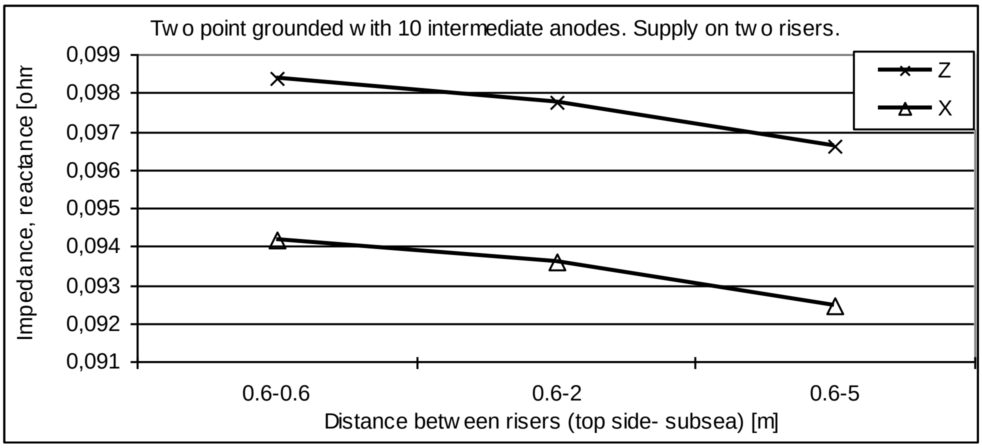


Figure 5.8: Impedance and reactance for simultaneous heating of two risers. Spacing between risers topside: 0,6 m. Spacing subsea between 0,6 and 5 m.

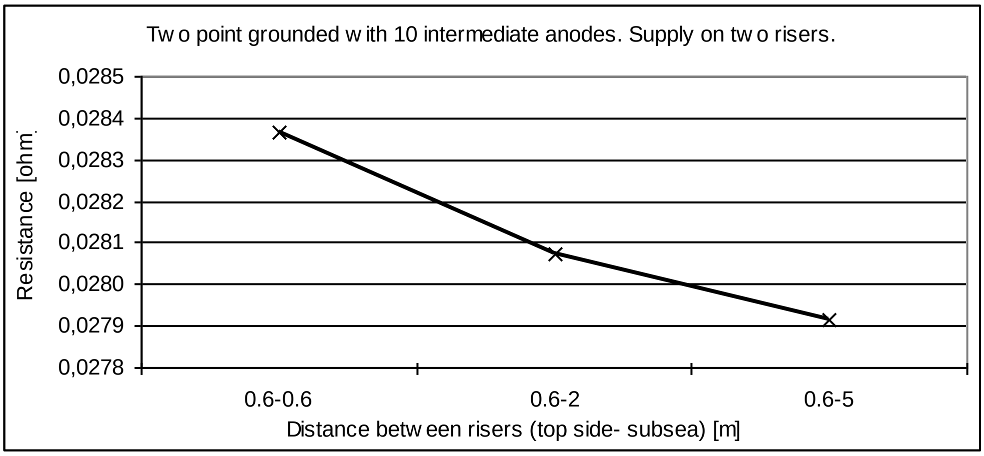


Figure 5.9: Resistance for simultaneous heating of two risers. Spacing between risers topside: 0,6 m. Spacing subsea between 0,6 and 5 m.

The results show relative small variation of the impedance when the spacing subsea is increased from 0,6 to 5 m:

- For heating of one riser an increase of less than 1 % in the impedance and approx. 4% in the resistance are observed.
- For simultaneous heating the impedance decreases by less than 2 % and the resistance decreases by 2%.

The results from measurements on impedances, reactances and resistances for two point grounded risers as a function of number of intermediate anodes are shown in **Figure 5.10 and 5.11** when heating one riser and in **Figure 5.12 and 5.13** when heating two risers simultaneously. The figures show the results for a constant distance between the risers of 0,6 m topside and 5 m subsea.

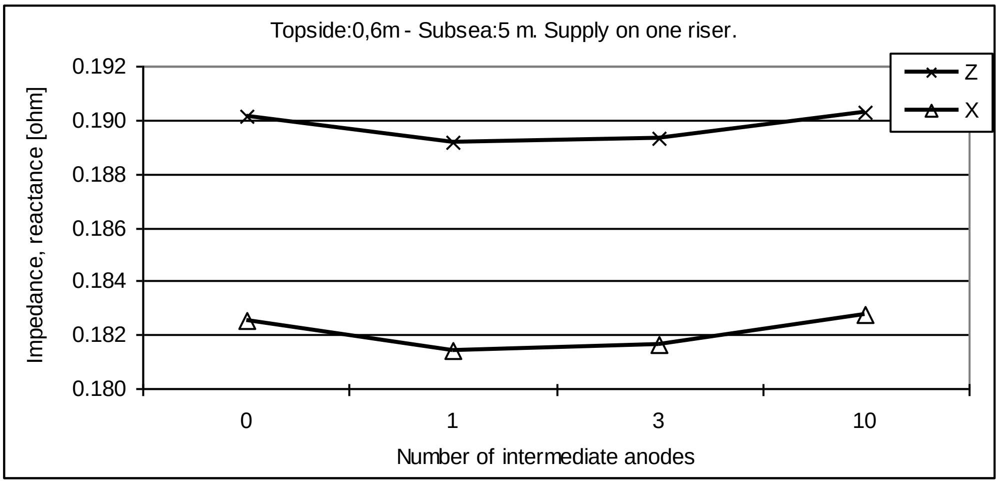


Figure 5.10: Impedance and reactance for heating one of two risers as a function of number of intermediate anodes. Spacing between risers topside is 0,6 m and 5 m subsea.

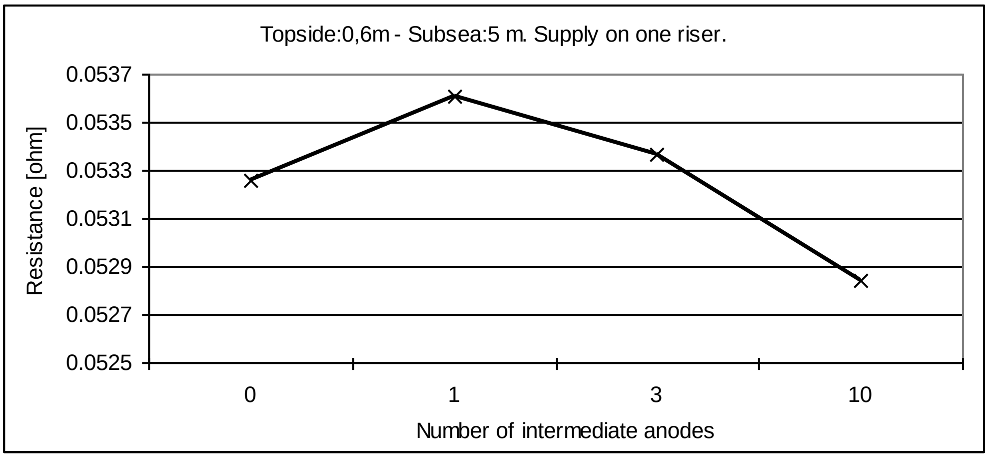


Figure 5.11: Resistance for heating one of two risers as a function of number of intermediate anodes. Spacing between risers topside is 0,6 m and 5 m subsea.

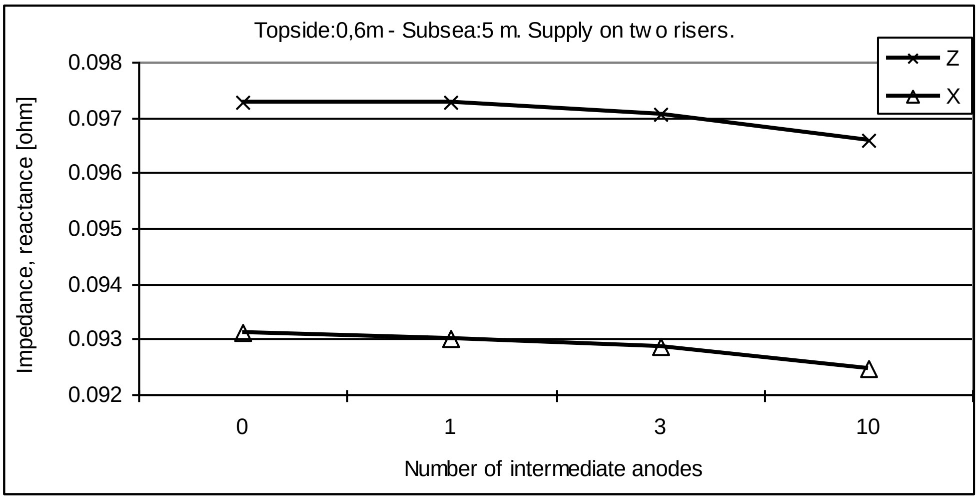


Figure 5.12: Impedance and reactance for simultaneous heating of two risers as a function of number of intermediate anodes. Spacing between risers topside is 0,6 m and 5 m subsea.

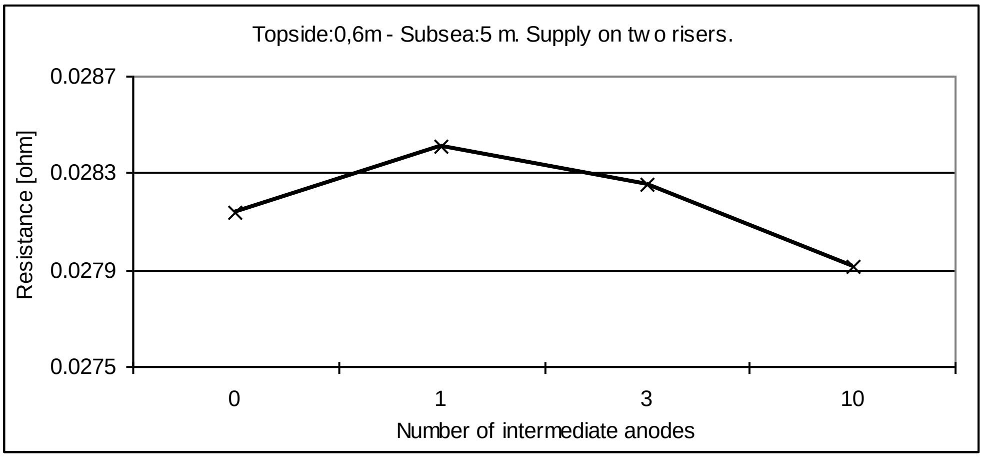


Figure 5.13: Resistance for simultaneous heating of two risers as a function of number of intermediate anodes. Spacing between risers topside is 0,6 m and 5 m subsea.

The results show relative small variation of the impedance when the number of intermediate anodes is increased from 0 to 10:

- For heating of one riser the impedance decreases by less than 1 % and the resistance decreases by 1%.
- For simultaneous heating the impedance decreases by less than 1 % and the resistance decreases by 1%.

6 POTENTIALS IN SEAWATER.

The highest voltage gradients in seawater occur in the current transfer zones at the riser ends. The corresponding resistive voltage is the maximum “touch” voltage that can occur at the other end of an otherwise isolated conductor and indicates the voltage as an example may be imposed on a ROV operating in the active transfer zone.

The resistive voltage is determined by the size and shape of anodes and is proportional with the seawater resistivity and current leaving the current transfer zone.

At some distance from the transfer zone, there is electromagnetic determined current distribution. For a single riser and parallel risers the seawater current is parallel to the riser and there is no “touch” voltage radially.

Figure 6.1 shows the measured voltage in seawater as a function of vertical distance above the cable connection point for a single Duplex riser with two points grounding without intermediate anodes. The steady state current is divided with 73% in the riser and 27% in seawater. The measurements were performed with a system current of 260 A and the current leaving the anode is 70 A. **Figure 6.1** indicates a maximum voltage drop of 6 V referred to 70 A at 400 Hz. The voltage drop is proportional to the current. It differs only slightly from 400 to 50 Hz.

The max. “touch voltage” in seawater with reference in seawater close to the riser measured vertically at location 5 m from the cable connection point, see **Figure 6.2**,was approx. 0,5% of the value in **Figure 6.1** and at 10 m only 0,2%. This confirms that in this case there is no significant voltage difference in seawater in a cut at right angle to the riser, except at the two termination points.

Figure 6.3 shows the results from similar measurements for the two point grounded Duplex riser with intermediate anodes of approximately 5 m spacing and surface area for each aluminum anode of 0,3 m^2 (anodes of rectangular shape with both sides exposed to seawater). The maximum voltage difference measured vertically above the termination point in this case is reduced to about 10% compared to the case with the electrically insulated riser without intermediate anodes. This indicates that the resistance for the special current transfer anode is relatively high and that the neighboring distributed anodes are active in the current transfer. The total current leaving the anodes towards seawater was 70 A in this case. As indicated in **Figure 6.4** the “touch voltage” vertically in seawater with reference in seawater close to the riser is reduced with the distance from the connection. At 10 m the vertically voltage is close to zero and stationary current distribution is achieved at this position.

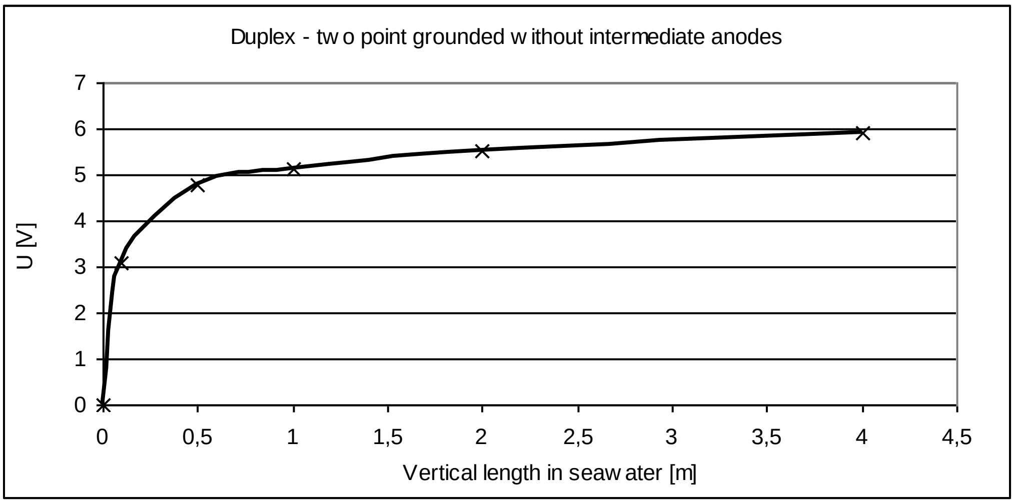


Figure 6.1: The measured voltage in seawater referred to the cable connection point as a function of vertical distance above the cable connection point. A single Duplex riser with two point grounding without intermediate anodes. Curves are shown for position "0 m cable connection at end of riser". System current: 260 A, stationary seawater current: 70 A.

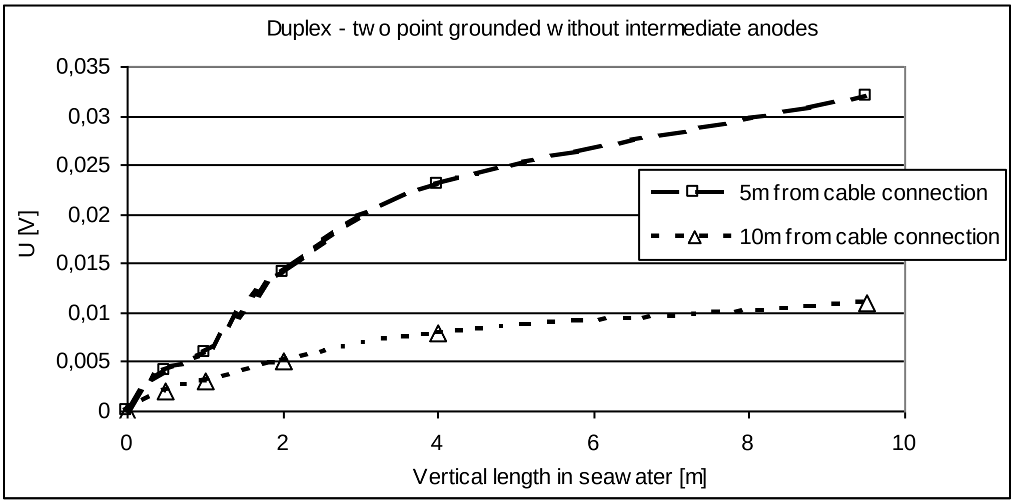


Figure 6.2: The measured voltage in seawater with reference in seawater close to the riser as a function of vertical distance above the riser. Single Duplex riser with two point grounding without intermediate anodes. Curves are shown at position3 5 and 10 m. System current: 260 A, stationary seawater current: 70 A.

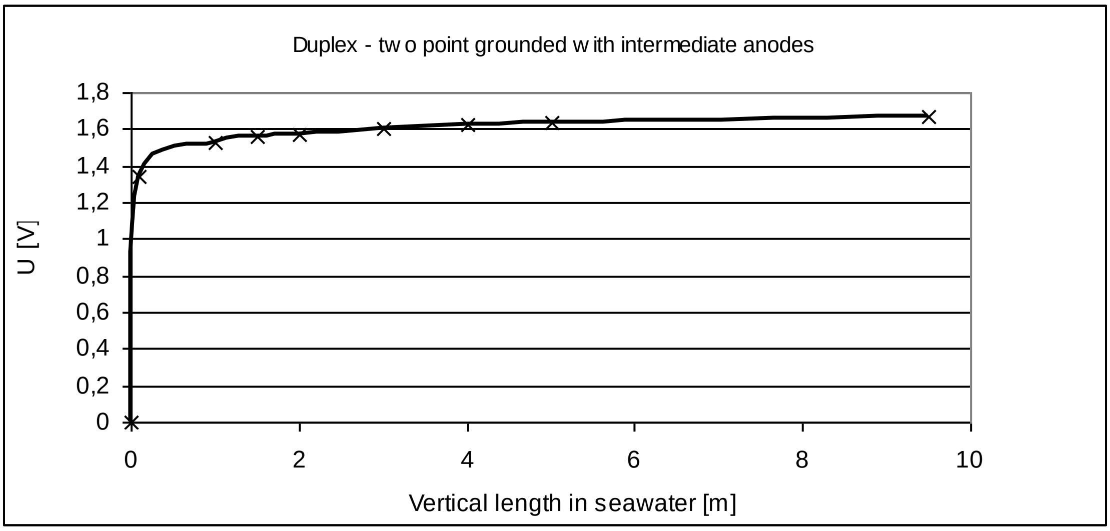


Figure 6.3: The measured voltage in seawater referred to the cable connection point as a function of vertical distance above the cable connection point. A single Duplex riser with two point grounding and with intermediate anodes. Curves are shown at position "0m cable connection at end of riser". System current: 262 A, stationary seawater current: 76 A.

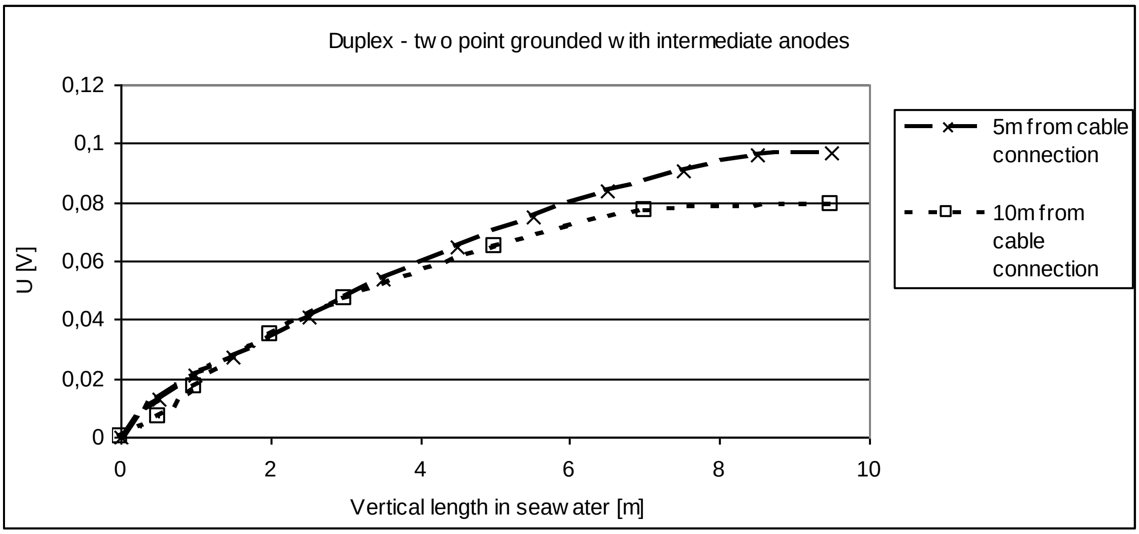


Figure 6.4: The measured voltage in seawater with reference in seawater close to the riser as a function of vertical distance above the riser. Single Duplex riser with two point grounding with intermediate anodes. Curves are shown at positions 5 and 10 m. System current: 262 A, stationary seawater current: 76 A.

The potential in seawater at the hang off is measured as a function of the distance from the hang-off structure. In this case one riser was heated with a second riser in parallel with a distance of 0,6m. The risers were two point grounded with intermediate anodes with approximately 5 m spacing. The total current leaving the anodes towards seawater was 80 A. **Figure 6.5** shows the measured voltage in seawater as a function of horizontal distance from the hang off structure.

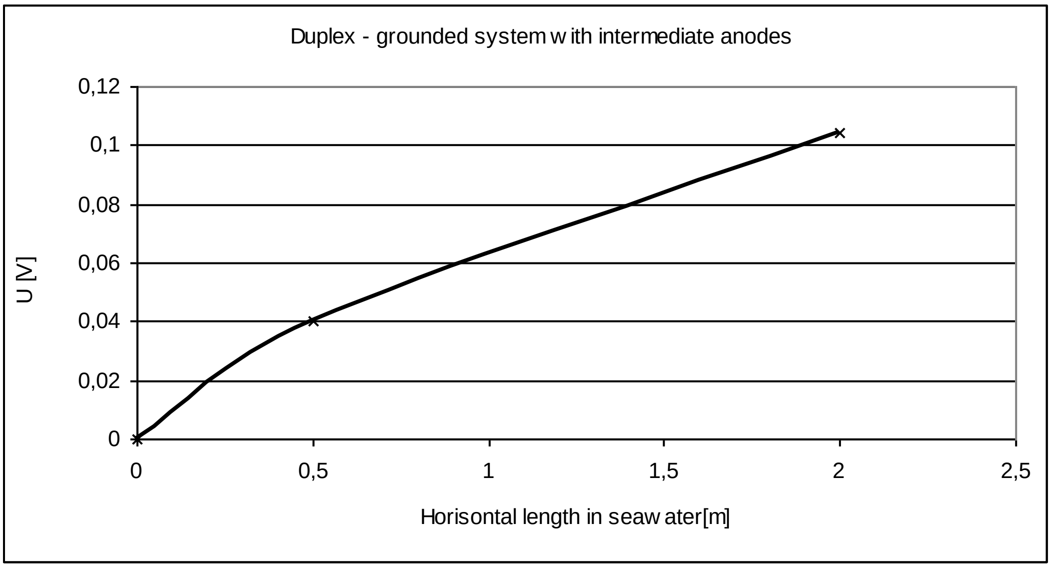


Figure 6.5: The measured voltage in seawater referred to the hang off structure as a function of horizontal distance. Two point grounding with intermediate anodes. One of the risers heated with the second riser in parallel with a distance of 0,6m. System current: 232 A, stationary seawater current: 80 A.

Measurements of potentials at the riser end have also been performed on Carbon steel riser with intermediate anodes [4] indicating similar results as for Duplex risers.

7 INDUCED VOLTAGE IN NEIGHBOURING CABLES AND INSULATED RISERS.

Because of the magnetic field surrounding a heated riser a voltage will be induced in parallel insulated conductors. Measurements have been performed of the common mode (longitudinal) induced voltage in an insulated conductor (piggyback cable conductor) at a constant distance of 0,6 m and 1,2 m from the heated riser. For comparison the voltage is also calculated as a function of separation. The magnitude depends on:

- The cable (system) current for the heated riser
- The return current in the riser
- The distance from the heated riser
- The frequency
- The grounding configuration for the risers.

Similar measurements have been performed on Carbon steel risers in this project [4]. On Carbon steel risers measurements have also been performed for different spacing between risers topside and subsea.

The **Table 7.1** shows the results from measurements on Duplex risers for the cases of single and two point grounding of the heated riser for individual distances as shown in the table. The induced voltages are referred to system current of 300 A and length of 100 m.

Table 7.1: Induced voltage in piggyback cable conductor of the neighboring a parallel Duplex riser to a heated Duplex riser (riser no. 2) with two point and single point grounding of the non heated riser. The distance between riser and conductor (neighbor riser and cable) is 0,6 m and 1,2 m. The voltages are referred to system current of 300 A and length of 100 m.

Grounded/electrical insulated risers from seawater for riser no		Distance between risers [m]		Induced voltage in cable on unheated riser [V]		Supply current on piggyback cable no. [A]	
1	2	“topside”	“subsea”	Measured	Calculated	1	2
Insulated	Grounded	0,6	0,6	15,1	14,3	-	300
Insulated	Grounded	1,2	1,2	12,1	11,3	-	300
Grounded	Grounded	0,6	0,6	5,6	6,5	-	300
Grounded	Grounded	1,2	1,2	3,7	4,9	-	300
Grounded	Grounded	2	2	-	4,0	-	300
Grounded	Grounded	5	5	-	2,7	-	300

The calculation of induced voltage is based on **Equation 7.1** (Carson [3]):

$U_{ind} = 0{,}063 * (f /50) * \ln (1{,}31*\delta_s / g_{12}) * s * I_s$ (Equation 7.1)

f – frequency [Hz]
δ_s – depth of penetration for seawater [m]
g_{12} – "geometric mean distance between the conductors" [m]
s - length [km]
I_s - current in seawater (difference between system and riser current) [A]

The calculated induced voltage by **Equation 1** for the Duplex riser as a function of the distance from the heated riser is shown in **Figure 7.1.** The frequency is 400 Hz, the voltage is referred to 300 A system current and a length of 100 m. Alternatively calculations can be derived by finite element method, which also calculates the stationary current distribution.

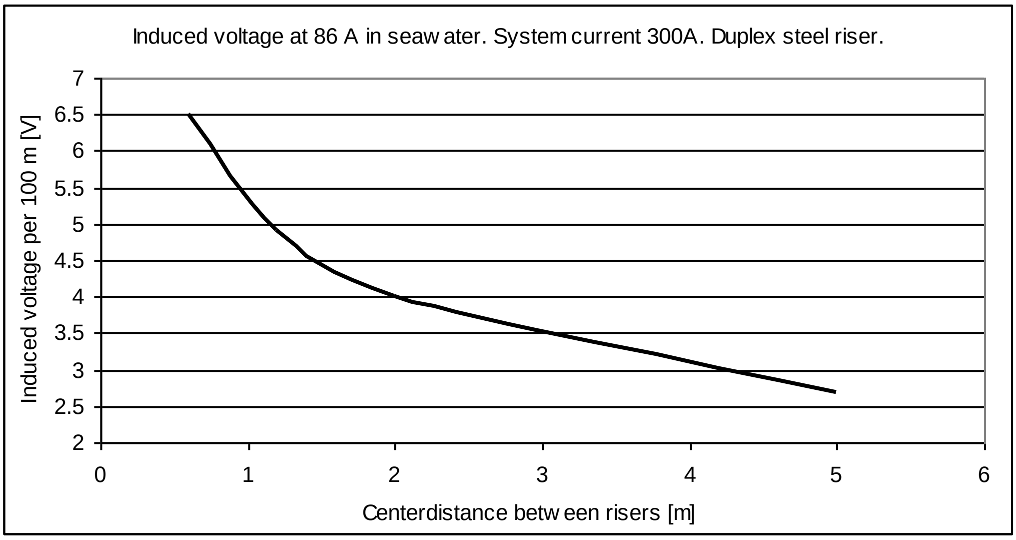


Figure 7.1: Calculated induced voltage for a length 100 m by finite element calculations, [12], for the parallel Duplex test risers at a system current of 300 A as a function of the distance from the heated riser.

The results in **Table 7.1** show good accordance with measurements. The deviation may be explained by:

- It was not possible to keep the risers at constant distance for the entire test length.
- End effect, which is not possible to include in the calculation.

The voltage in **Table 7.1** was measured on the piggyback cable for the parallel riser, which was isolated from ground (seawater) at the hang-off structure and grounded at the subsea end. For the cases of insulated riser the induced voltage in the riser was equal to the induced voltage in the piggyback cable. Grounding of this Duplex riser at the hang-off reduced the voltage considerably. The reason for this reduction is that the circulated current in the parallel riser counter-act the magnetic field from the heated riser. This is the same effect as in a signal cable with a shield grounded at both ends.

For parallel risers the induced voltage will be proportional with the length and the system current. Due to the induced voltage that can occur in an insulated neighboring conductor (cables and insulated risers with single point grounding), it will be necessary with terminations that must be qualified for this voltage.

8 REDUCTION OF CURRENTS BY PIPE-IN-PIPE CURRENT CHOKE AND MAGNETIC CURRENT CHOKES

8.1 Pipe-in-pipe current choke

The pipe-in-pipe current choke has been tested on single Duplex steel riser. **Figure 8.1** shows the 10 m long pipe-in-pipe section mounted on the electrically insulated riser. The outer pipe without electrical insulation was of Carbon steel with OD = 219 mm and WT = 6,35 mm. At the top end the outer pipe was solidly connected to the inner pipe by a ring shaped plate of Carbon steel. At the far end the outer pipe was exposed to seawater. The riser was connected to the simulated hang-off structure topside (grounded to seawater). Theoretically the magnetic coupling will force the return current in the outer pipe to be equal to the centre pipe current (riser current). Furthermore the current will be concentrated on the outer surface of the inner pipe and on the inner surface of the outer pipe. Because the penetration depth at 400 Hz is less than 2,3 mm (and about 6,5 mm for 50 Hz) the current on the outer surface of the outer pipe and on the inner surface of the inner pipe is negligible and no current should be transferred to seawater.

Table 8.1 shows the current from the riser end towards simulated hang off structure with and without the pipe-in-pipe current choke at 400 Hz. 6 - 8 m of the pipe-in-pipe section was submerged. Contrary to what was expected the 10 m choke had negligible effect on current towards the hang off structure. The reason is that the pipe-in-pipe current loop had small effect on the impedance and consequently it was not effective to reduce the current through the structure.

Table 8.1: Current towards hang-off structure with and without pipe-in-pipe current choke at 400 Hz.

Configuration	Length of current choke. [m]	System supply current [A]	Current to ground (through riser to platform structure) [A]	Current to ground (through riser to platform structure) referred to system current. [%]
Riser without current choke	-	263	63	24
Current choke above seawater level.	3,5	260	65	25
Current choke partly submerged.	3,5	236	56	24
Current choke partly submerged.	10	273	48	24

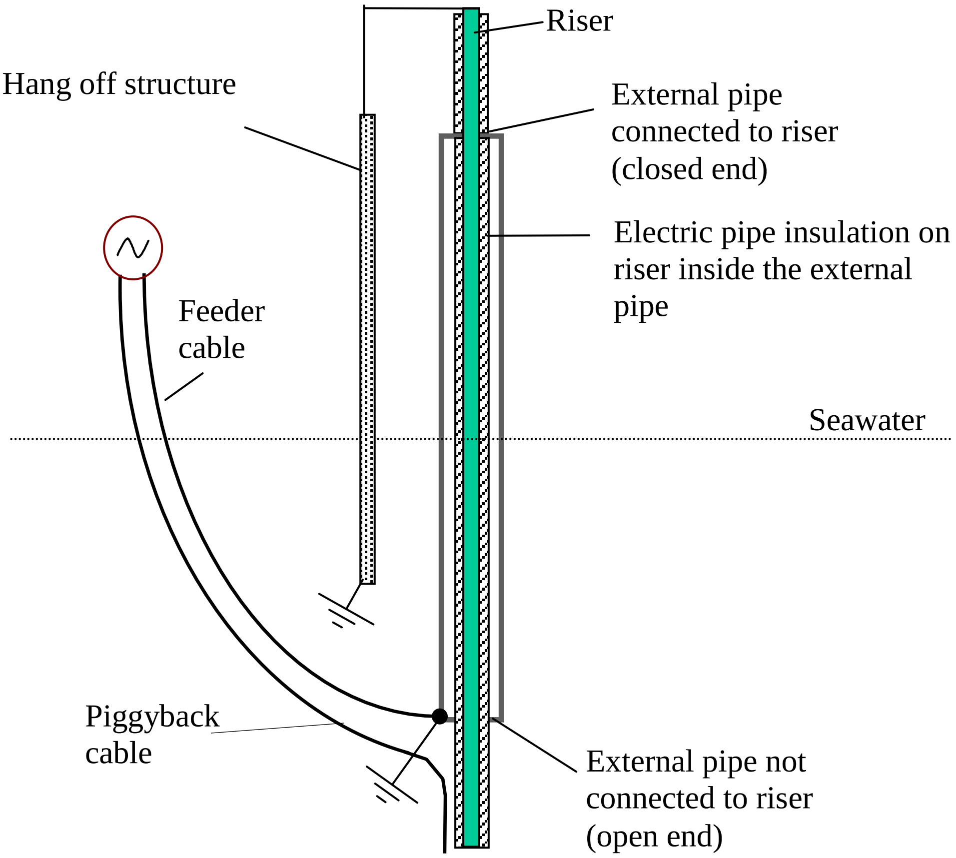


Figure 8.1: Pipe-in-pipe current choke mounted on Duplex steel riser. At the top the riser and outer pipe is solidly connected together. At the far end the outer pipe is connected to the feeder cable. The riser is electrically insulated. The outer pipe has no electrical insulation and the lower part was submerged.

8.2 Magnetic current chokes

Magnetic current chokes are made of laminated iron cores formed as closed loops around the current carrying conductor. The cores will cause a significant increase in impedance and hence reduce the current through the core (leakage current). Both splitable (C-shaped) and non splitable (round wounded) cores may be used. In general non splitable cores are most effective.

Tests have been performed with non splitable and splitable cores. The number of chokes is varied and following chokes were used:

- Round wounded choke: OD = 220 mm, ID = 120 mm, Length = 100 mm.
- C-core chokes forming a rectangular core: Outer dimension = 76x130 mm, inner dimension = 36x90 mm (“window “), length = 50 mm.

The test set-up is shown in **Figure 8.2** with the riser connected to the hang off structure by copper cables. At the near end the feeder cable was connected to the riser 11,5 m from the riser end. At this connection point the riser was grounded to seawater by an aluminium electrode of 1x 2 m and thickness 3 mm.

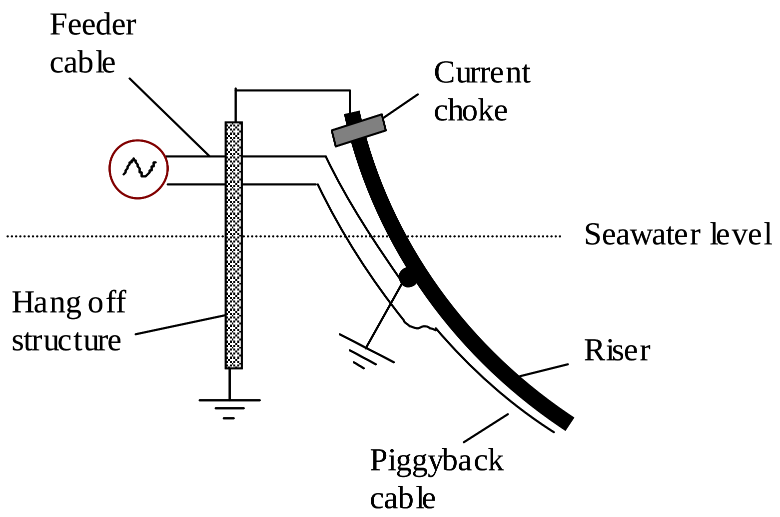


Figure 8.2: Test set up to study current reduction towards hang off by laminated iron cores. At the near end the feeder cable was connected to the riser 11,5 m from the riser end. At this connection point the riser was grounded to seawater.

The results from the tests are shown in **Table 8.2**. As seen from these results non splitable cores are most effective. Two of these cores reduced the leakage current to less than 1 A. Further increase of the number of cores had negligible effect on the leakage current. It is not possible to reduce the leakage to zero because the choke must be magnetized to be effective. For splitable cores it was not possible to reduce the current below 5 A.

Table 8.2: Results from measurements of the leakage current towards hang off (grounded to seawater) from riser end with splitable and non splitable laminated iron cores to reduce the current.

No. of chokes	Choke type	Supply current [A]	Current towards hang off structure from riser end [A]
0	No cores	263	63
3	Round wounded cores (non splitable)	267	1,5
7	Round wounded cores (non splitable)	268	1,0
2	C - core (splitable)	272	20
5	C - core (splitable)	272	10

Tests were also performed on pipe end connections to the hang off with two parallel cables. The most effective way for reduction of leakage current in this case is to use separate cores on each cable in addition to the cores on the riser on each conductor. Separate cores on each cable will limit a possible circulation (loop) current.

9 CONCLUSIONS

Calculations based on two-dimensional modelling and measurements of electrical parameters and current distribution at 400 Hz show good accordance for all configurations of the rigid Duplex steel risers with OD = 99,8 mm and WT = 5,3 mm. For single point and two points grounded systems the deviation between measurements and calculations of supply voltage and generated heat is less than 11%. The system impedance and thermal rating depends on the riser configuration, grounding alternatives, application of intermediate anodes and if the heating is supplied on one or simultaneously on neighbouring risers. The thermal rating of the heating system is determined by the minimum riser current and a piggyback cable is required for each riser to be heated. The neighbouring effect is not sufficient for heating, but must be considered when rating the system.

- For single point grounding the neighbouring effect to the other risers can be neglected. The riser current is equal to the piggyback current.
- For two points grounding without intermediate anodes the current can be calculated by two dimensional configuration using an equivalent spacing.
- When only one of the risers is heated for system with two point grounding and intermediate anodes the minimum current appears at min. spacing (topside). It is calculated for parallel risers at this spacing.
- For two points grounding with intermediate anodes the minimum current appears at max spacing (subsea) between risers for simultaneous heating. It is calculated for parallel risers at this spacing.

For two point grounding without intermediate anodes the effect of varying distances between neighbouring risers is different for simultaneous heating and the case for only one heated riser:

- When heating one riser the current in the riser increases with increasing spacing between risers.
- When heating two risers simultaneously, the current in the risers decreases with increasing spacing between risers.
- The riser current is 81% of the piggyback current compared to 72% if only one of the risers is heated for a spacing topside of 0,6 m and 5 m subsea.
- When heating two of three risers or three risers simultaneously, the spacing between risers has small effect on the riser current (less than 5%).
- The riser current is 88% of the piggyback current for parallel risers of spacing 0,6m and 85% for a spacing topside of 0,6 m and 5 m subsea.

The spacing subsea for two neighbouring risers has only a small effect on the system impedance:

- For heating one of two risers the increase in the impedance is less than 2 % and approx. 9% in the resistance at a spacing of 0,6 m topside and 5 m subsea, compared to parallel risers with a spacing of 0,6 m.
- For heating one of three risers the increase in the impedance is less than 4 % and 12 % in the resistance at a spacing of 0,6 m topside and 5 m subsea, compared to parallel risers with a spacing of 0,6 m.
- For simultaneous heating of two or three risers the impedance decreases less than 2 % and the resistance decreases by 4% for the same configurations.

Measurements indicate that a surface area of 0,3 m^2 for the intermediate anodes is sufficient at both 50 and 400 Hz.

The 400 Hz measurements show that it is possible to reduce stray currents between risers and structure by laminated iron cores:

- Non splitable cores are most effective. Two of these cores reduced the leakage current to less than 1 A. Further increase of the number of cores had negligible effect on the leakage current.
- For splitable cores it was not possible to reduce the current below 5 A.

Measurements show that a 10 m long pipe-in-pipe current choke has negligible effect on current towards the hang off structure.

Induced voltage can be determined by two-dimensional numerical electromagnetic calculations. Due to the induced voltage that can occur in an insulated neighbouring conductor (cables and insulated risers with single point grounding), it is necessary with terminations that are qualified for this voltage.

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[10] J. K. Lervik, H. Kulbotten, D. E. Nordgård, G. Klevjer, A. Lenes. Concept Verification of Direct Heating of Oil & Gas Pipelines, Phase III. Results from Measurements on Cr13 Steel Pipes, By-pass of Template, Parallel Pipes and Induced Voltage in Cables. TR F5006, ISBN 82-594-1601-8, 1999-11-04.

[11] Halvorsen, H; Lervik, J K; Klevjer, G: Hydrate and wax prevention of risers by electrical heating. ISOPE Seattle USA 2000; No 2000-HEK-02.

[12] Flux2d, version 7.5, Cedrat, France – Two dimensional computer program for two-dimensional electromagnetic problems based on the finite element method.

APPENDIX
Drawings and Pictures

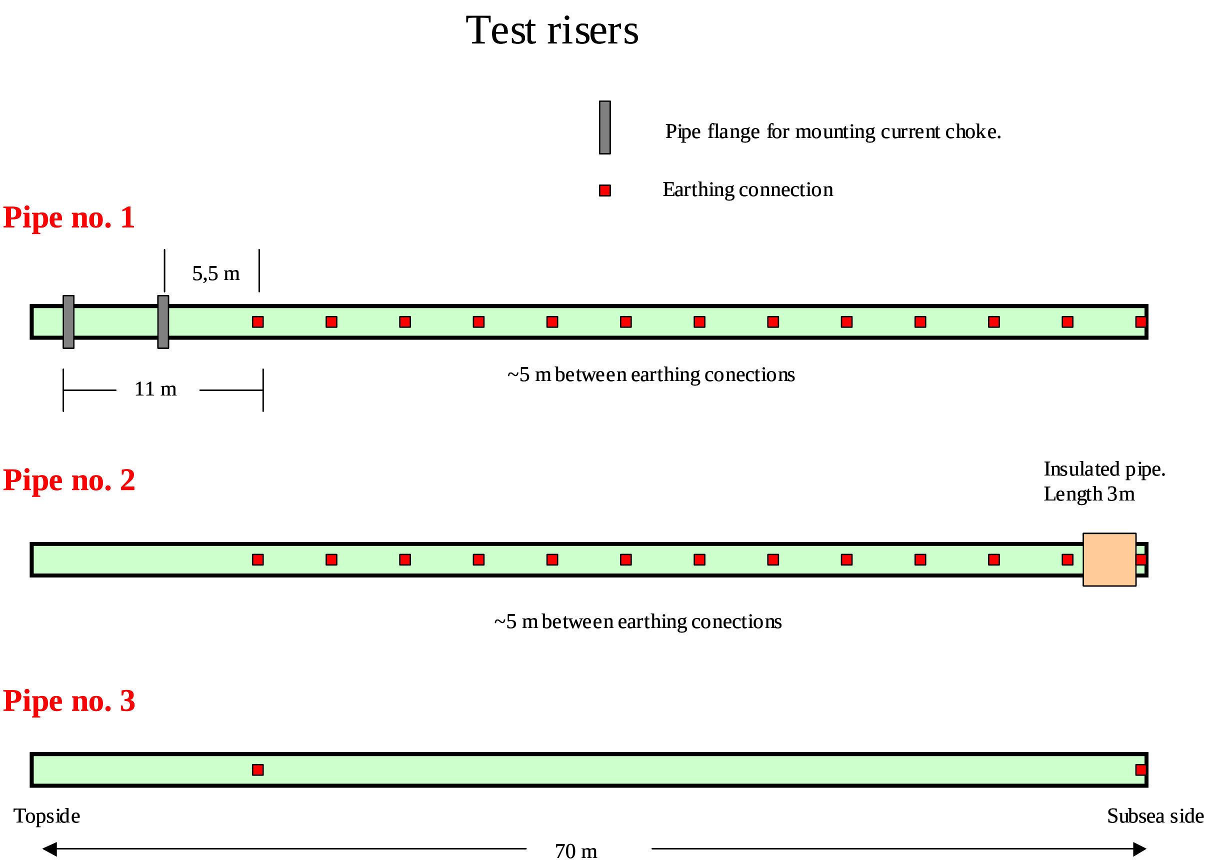

Figure A1: Sketch of test risers.

Flat bar steel at riser ends.

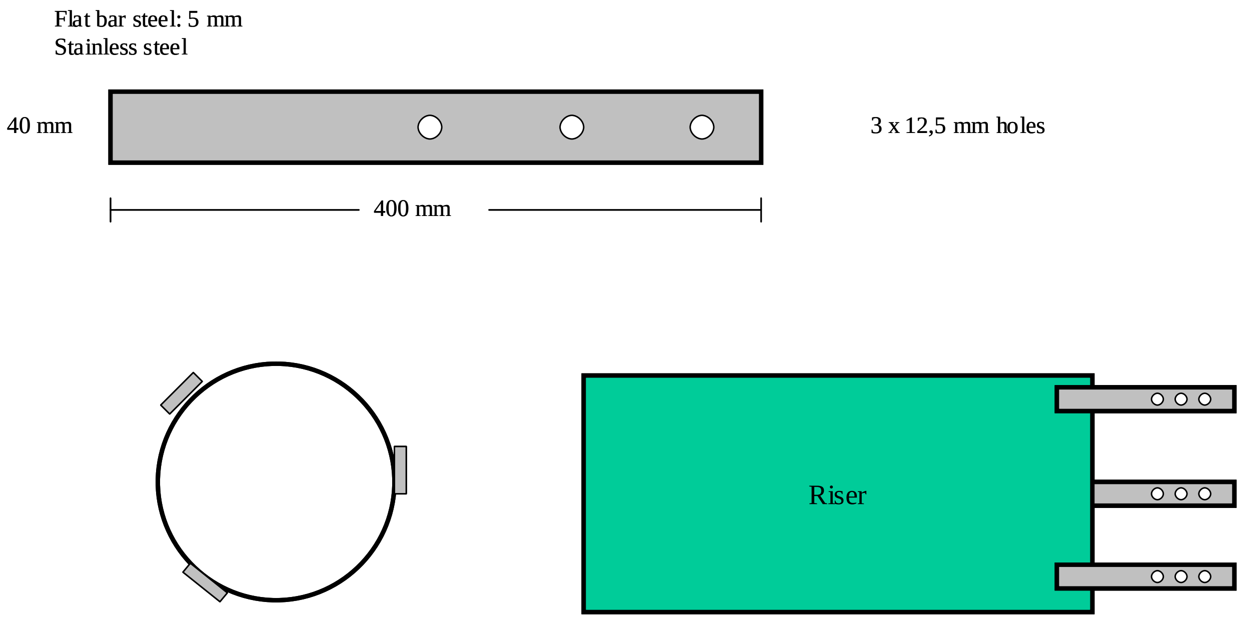

Figure A2: Sketch of flat bar steel at riser ends.

Grounding anode

Material: Aluminium
Thickness: 5mm
Length: 60 cm
Width: 25 cm

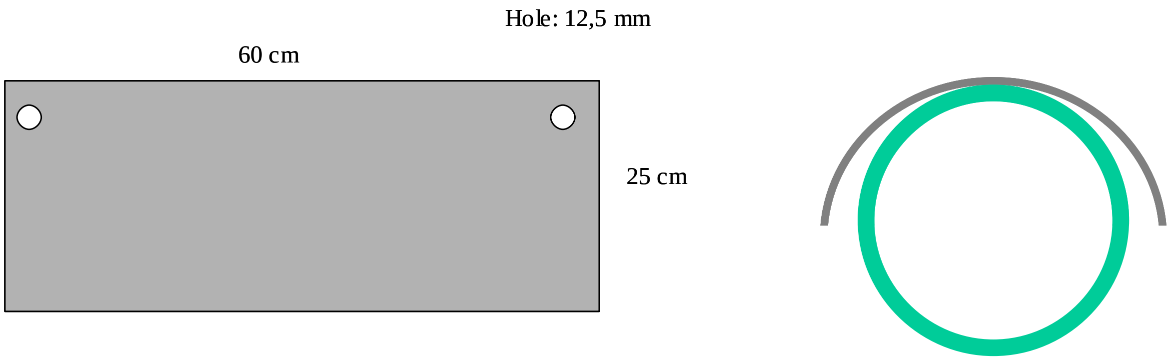

Figure A3: Sketch of grounding anode.

Figure A4: Riser connection at structure.

Figure A5: Structure and risers at the quay.

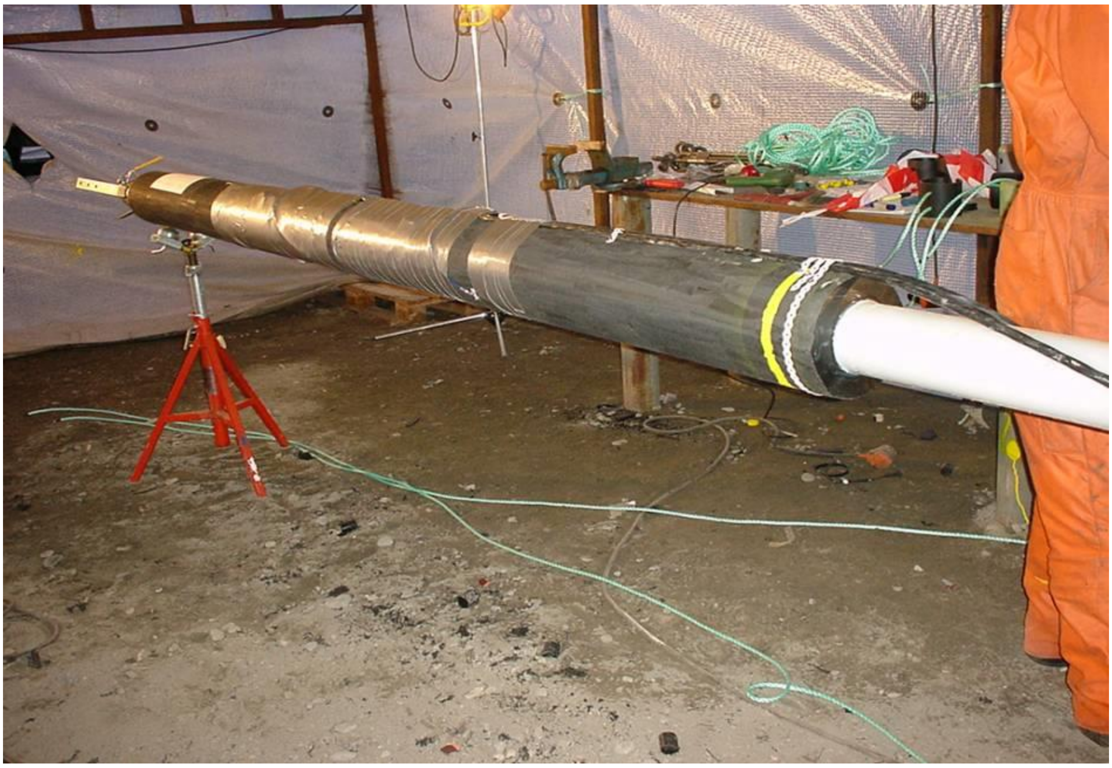

Figure A6: Thermal insulated riser.

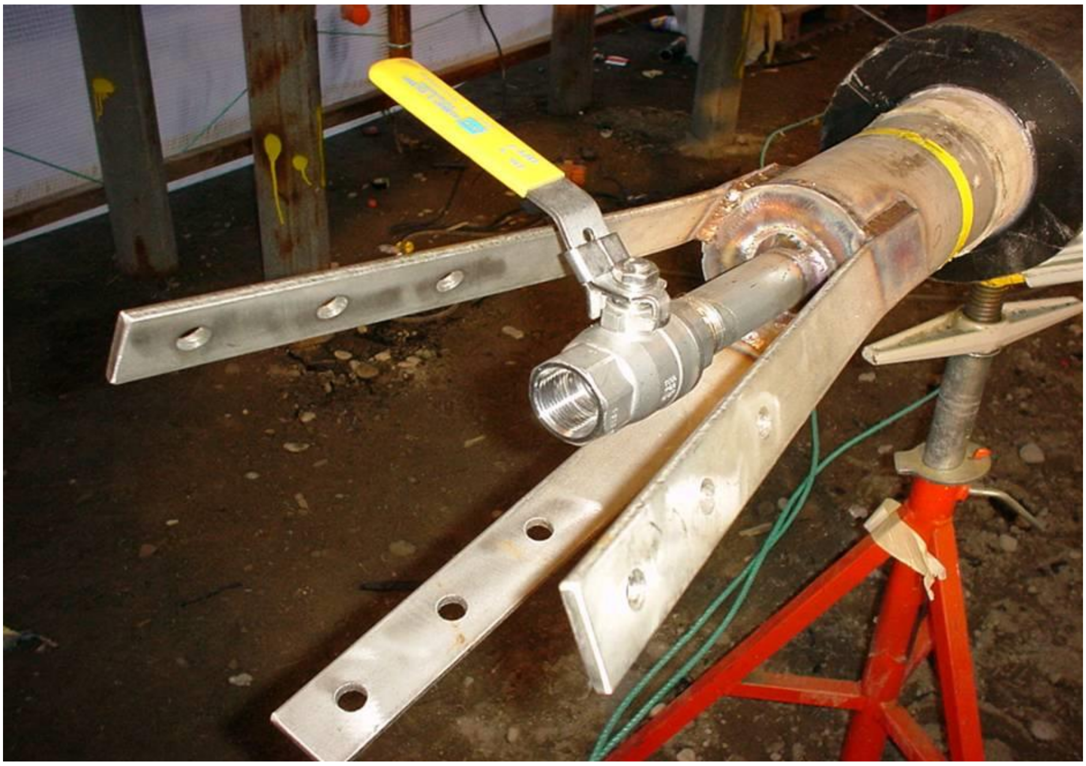

Figure A7: Riser end.

Figure A8: Electrically insulated pipe joint.

Figure A9: Risers at Vigor.

Figure A10: Raising the riser into seawater.

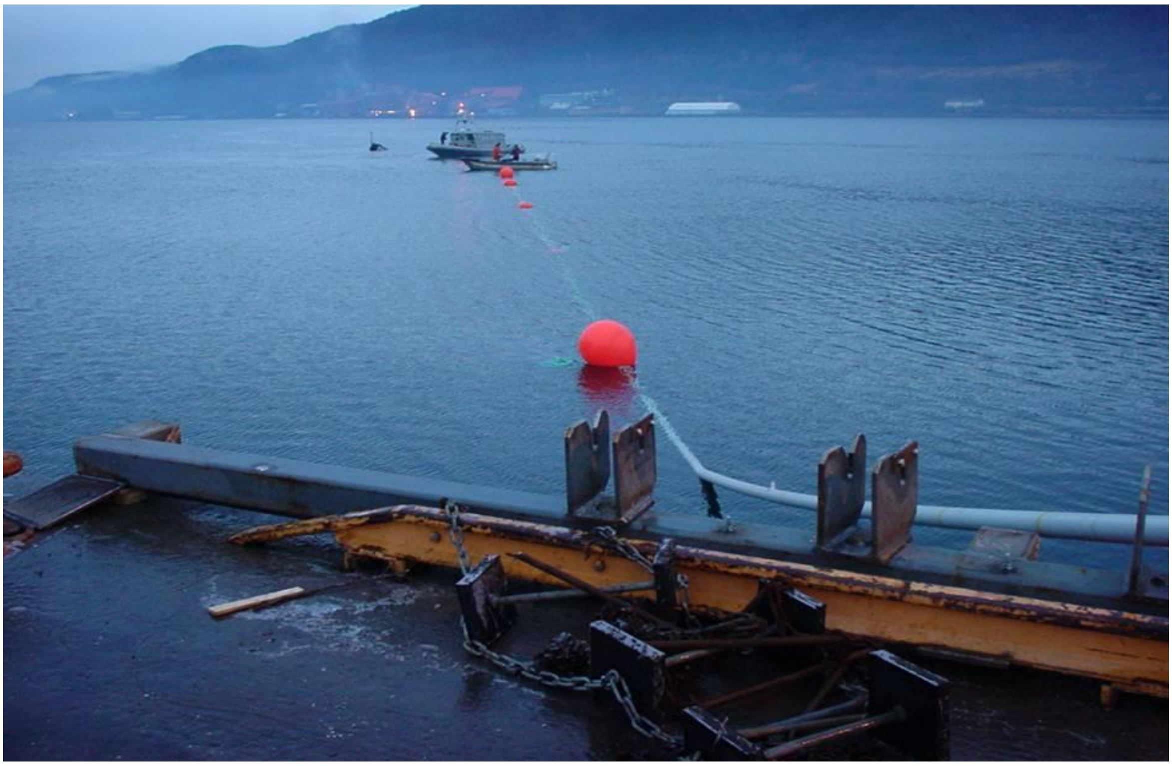

Figure A11: Floating the riser to position at the quay.

Figure A12: Pipe in pipe section mounted on the riser.

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