# FINAL PUBLISHABLE REPORT

**CONTRACT N° :** ENK6-2000-00074

**PROJECT N° :** NNE5-1999-20097

**ACRONYM :** PDT-COIL

**TITLE** : Research and Development of an Intelligent Power and Data Transmitting Composite Coiled Tubing for the Exploration of Hydrocarbons

**PROJECT CO-ORDINATOR :** SHELL International Exploration and Production B.V.,

**PARTNERS :** BJ Services Company Ltd.
BJ Services International B.V.
AIRBORNE Development B.V.
CORROCEAN AS
SMARTEC SA
Swiss Federal Institute of Technology ZÜRICH
Katholieke Universiteit Leuven, Research & Development

**REPORTING PERIOD: FROM** October 1st, 2000 **TO** February 28th, 2003

**PROJECT START DATE:** October 1st, 2000

**DURATION :** 22 months

**Date of issue of this report:** April 28th, 2003

**Project funded by the European Community under the Programme Energy, Environment and Sustainable Development (1998-2002)**

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# 2 Executive publishable summary

***Objectives and strategic aspects***

The subject of the PDT-COIL project is the development of a power and data transferring composite coiled tubing for the exploration and production of hydrocarbons with integrated fibre optic based systems for semi-continuous monitoring of both drilling process and structural integrity. The project was originally proposed as a four year R&D project, including a demonstration of the developed product. On advise of the EC the project was split up in two separate phases (a research phase and a demonstration phase) due to a foreseen high risk of the R&D on the PDT-COIL.

In the first phase research will be conducted on all components of the Intelligent PDT Coil. The objective of the research phase is proving the principle of the PDT-Coil and the determination of the product design. The product consists of the coil and the connectors.

***PDT-COIL management report***

The PDT-COIL project has known several changes in the composition of the consortium. Most of them were the result of inter company reorganisations. Only one of them was due to the results of the R&D work.

All partners started off with great enthusiasm, even before the kick-off meeting was held. A few partners had problems with the start-up of the actual project. New employees were required to execute the planned work. The KU-Leuven had some difficulties in finding qualified personnel for the research work envisaged, but after three months these problems were solved.

A few months after the project-start it became obvious that Deutag would possibly be sold to another company. Therefore their commitment could not be guaranteed, especially since one of the main possible buyers was not a European company. Around the mid-term of the project the sale of the company to the UK Company KCA was confirmed. Even though this company was European, Deutag still requested to be released from its project obligations since the new owner would not support it.

At the first half-year meeting in Lugano it was decided that the project management would try to find a new partner to replace Deutag. The consortium found a new partner in BJ Services Company in Aberdeen, which is very experienced in coiled tubing operations using steel CT technology. With full cooperation from Deutag, BJ stepped in and took over all obligations.

Coiled tubing is core business for BJ and the company has performed a lot of research in this field. The company is convinced that composite coiled tubing is definitely "the way to go". The entry of BJ meant access to great experience in the CT field for the consortium.

The first year meeting was held at the KU in Leuven, and was equally well organised. Although on very short notice, BJ managed to send two experienced representatives. Their inputs proved to be very valuable already and the project team was very happy to welcome this new committed partner.

Apart from the official consortium meetings a number of technical meetings were held and documented between technicians of the different partners. These meetings were necessary because many design topics required solutions that influenced the design envelopes of most other partners. These meetings have proved to be very effective.

CorrOcean was involved in the project to perform chemical ageing tests and to develop a chemical resistance sensor, which would be built in the thickness of the PDT-Coil. The company had great interest in the project because it was to be the future supplier of these sensors for the manufacturer of the PDT-Coil. However the results of the research showed that the chemical ageing could also be monitored with fiber optics and this option was preferred because of its versatility. It would lead to a more efficient and cost efficient solution.

With this the main commercial objective for CorrOceans involvement in the project had ceased to exist. With full consent of the consortium CorrOcean decided to step out of the project.

Another company of the BJ organisation, BJ Services International BV, which is sited in Emmen, agreed to take over the chemical ageing tests of CorrOcean. The company was added to the consortium as well.

Leaving out the chemical sensor lead to modifications in the work packages of several partners. Smartec, Airborne and KU Leuven researched alternative solutions and more samples had to be manufactured for testing.

The consortium also decided to put more effort in the R&D of a fast connector concept for the PDT-Coil. Connectors are indispensable for successful application of CCT technology since lengths of no more than 500 – 800 meters would be road transportable in most densely populated areas around the world.

Due to the delayed start of some of the partners and the mentioned changes within the composition of consortium a project extension of three month was requested and granted by the European Commission.

Unfortunately this was not the end of all the changes in the PDT-COIL consortium. For cost efficient arguments the Shell higher management had decided to focus their total R&D efforts on only a few promising technology developments. In the second year of the R&D phase of the project SIEP gave Nolan Norton, the business consultancy office of KPMG, the assignment to draw up a business case on the PDT-COIL technology. Amongst others all project partners were consulted. The result showed the technology to be extremely profitable for some applications, but the return on investment period was estimated at 8 to 10 years.

SIEP decided to remain supportive to the project, but to withdraw from the succeeding demonstration phase, for which a project proposal had already been submitted. Many of the management and network administration tasks were transferred to Airborne.

Mainly because the chemical ageing tests had not been finished by the end of the project, a second request for a project extension was submitted. Also the CorrOcean withdrawal and the entry of BJ Services International entry had to be formalised. In the subsequent project amendment No 2 all partner changes were settled, the description of work was modified according to the outcome of the research work and a second extension of three month was confirmed.

***Scientific and technical performance***

The design of the PDT-Coil is established through research, design proposals, calculations and tests performed by the consortium members. The work was performed under intricately interconnected work packages.

**WP1: Mechanical performance (Airborne)**

In this work package, the design, manufacture and test of the PDT-Coil were executed. The design of the PDT-COIL structure has been conducted and evaluated using analytical and FEM modelling tools. Several short specimens of the PDT-COIL were manufactured and tested at room temperature, as well as at elevated temperature. Different types of connectors have furthermore been designed and tested. The results of the first tension tests were very positive. The connection at the end fitting proved to be stronger than the coil itself. The tensile strength of the coil was always found to be higher than the design operation load, even thought a drop in tensile strength of about 15% was observed in the elevated temperature tests. The failure load values came within 10% of the predicted analytical and

FEM values. Bending, compression and internal pressure tests were also performed. The results from these tests also showed a good correlation with the predicted results, although it was found that the manufacturing quality had a large influence on the achievable strength of the specimens. Further work addresses this issue. Together with ETH Zurich, Smartec, KU Leuven and Airborne, the research and test results of the structural, electrical and optical design of the PDT-COIL was evaluated. With the aim of improving the structural and electrical performance, as well as integrating the optical sensing system, a new lay-up of the PDT-Coil assembly has been proposed and implemented. The updated lay-up was based on a newly developed analytical model. Furthermore, in the new design the optical and electrical connections are now integrated into the PDT-Coil core. The connectors have been modified accordingly.

**WP 2: Electrical performance (ETH Zurich)**

In this work package, the assessment of the electrical performance of the PDT-Coil was conducted. The feasibility of the electrical part of the PDT-COIL was evaluated in three areas:

1. Determination of electric stresses
2. Development of electric insulation system
3. Data transmission and measurement of electric system integrity

Firstly, computer modelling of the entire electrical system was performed in order to determine the electric stresses applied on the electric insulation system of the PDT-COIL in service. The calculations gave good indications for the electric stresses, yet it was recognised that a supplier providing a specific drilling motor and frequency-converter has to be found in order to derive specific input parameters for the simulation. This part of the work is showing good progress. Secondly, the numerical simulations were supplemented by experimental tests such as: partial discharge tests, breakdown tests and water penetration tests, performed on short test samples. Tests and simulations show that the material is dielectrically stressed to its limits. It is essential that any penetration of liquids be prevented. A completely electrically and chemically shielded insulation system for integration into a tube wall was designed and produced. The electrical part of the PDT-COIL connector was also designed and tested. To test the insulation system under down-hole conditions an autoclave (1000 bar at 200°C) was built. The results showed a good liquid sealing performance. To qualify the different insulation materials and chemical protection layers, a set of electrical, mechanical and chemical tests (single or combined) have also been carried out. Mica insulation shows good electrical performance. Finally, signal transmission characteristics on samples of the actual electrical system were measured within 10 kHz to 10 MHz. It was shown that the signal transmission capacity is very low, due to high damping. However, as alternative possibilities of signal transmission via optical fibres exist. For condition monitoring, alternative possibilities like offline diagnosis with polarisation – depolarisation measurements or oscillating-wave-tests are under further investigation.

**WP3: Fibre-optic system (SMARTEC & KUL)**

In a first part of this work package, the integration and sensing capabilities of the optical fibres system was assessed (SMARTEC). The work on the Fibre Optic System (DiTeSt monitoring system) showed good progress and concentrated in three areas:

1. Integration and connection of the sensors
2. Strain and temperature measurement
3. Software design

The research and selection of connectors, as well as their integration, was performed in order to connect the parts of the optical fibres placed in different modules of the tubing. It was shown that specially designed sensor configuration makes possible monitoring of primary parameters such as temperature and strain, but also more complex parameters such as torsion, flexion and extension. The strain and deformation sensors were integrated into a particular carrier called SMARTape. It consists of a thermoplastic composite tape with integrated optical fibre. The SMARTape was tested and results of the tests are encouraging. The temperature sensors are to be installed into the metallic tubes incorporated in liner of the PDT-Coil. Initial tests confirmed a very good performance of the sensor configuration. The fabrication of a 1m long specimen with integrated fibre optic sensors, built in the same manner as the PDT-coil, was shown to be possible, as well as the testing of all the performances. The testing will be performed in demonstration phase of the project. The requirements for the software design were identified, the algorithms and procedures were developed and the software prototype created. It allows management of measurements, data storage and processing, quasi-real-time calculus of the complex parameters, visualisation of results and generation of pre-warnings and warnings.

A second part of this work package dealt with the detection of damage transient via optical fibres (KUL). Good progresses have been shown for the implementation of the optical fibres in the thermoplastic coil for damage monitoring. Data from several series of tensile tests performed on flat C/epoxy specimens have been analysed. Also, the filtering sequence has been improved and optimised. Although it was initially shown that no damage related transient was visible neither in the time-domain signal nor in the frequency domain signal, the propagating high-energy elastic waves may be sensed by the embedded multimode optical fiber. The frequency analysis range has been extended up to 625 kHz.

**WP4 and WP 5: Chemical performance and Operational issues (BJ)**
These work packages focused primarily in In-the-field application and validation. The work concerning in-the-field applicability of the PDT-Coil has concentrated on the following aspects:

1. Overview of the created technology from an industrial and coiled tubing service perspective (technical resource, guidance and advisory function provided by BJ Services)
2. Help define and specify PDT-CCT product design and material performance requirements
3. Define laboratory testing requirements and specify testing parameters for PDT-CCT specimens
4. Perform chemical fluid compatibility and other autoclave corrosion testing
5. Perform theoretical stability and extended reach analyses
6. Perform bend fatigue and corrosion fatigue tests
7. Perform collapse tests
8. Upgrade BJ's proprietary CIRCA software to accommodate PDT-CCT string well bore analyses
9. Perform full scale CCT prototype string field testing using conventional BJ coiled tubing unit (CTU) equipment.

The chemical environment that the PDT-coil will be exposed to has been clearly established. Tasks 1 to 5 inclusive have been completed with additional autoclave testing pending receipt of necessary PDT-CCT specimens. At the special request of Shell Oil, BJ was amiable to modifying CIRCA to handle PDT-CCT strings. However, this request was subsequently withdrawn and no further action is contemplated. Preparations for performing the bend fatigue and collapse testing were completed. Unfortunately, the necessary test specimens and end fittings could not be supplied in time for completion in the initial R&D phase of this project. The European Community has therefore relegated these tasks to Phase II that has received approval for continued funding. *BJ Services intends to honour its commitments to this project and complete the outstanding tasks over the course of Phase II commencing in early 2003. BJ also confirms its interest to conduct the potential field trial operations and demonstration involving a full scale PDT-CCT prototype string at an appropriate test well location.* The abbreviated theoretical analysis of coiled tubing stability has shown that PDT-CCT drill strings behave distinctly different from conventional steel coiled tubing. The extended reach capability of PDT-CCT in horizontal wellbores is substantially *greater* than steel CT at lower values of weight-on-bit (WOB). For example, for a vertical section of 1,880 m and at a WOB of 445 daN, the PDT-CCT can drill a horizontal leg of nearly 10,000 m in length or 5-1/2 times longer than a conventional 60 mm diameter coiled tubing that is a commonly used size for drilling. This assumes a coefficient of friction for the PDT-CCT that is 1/3 that of steel on steel, a value that remains to be confirmed by experiment. However, at higher than 1,250 daN bit force the PDT-CCT cannot penetrate further than a 60 mm steel coiled tubing which in turn can apply a drill force of more than 2,000 daN and still advance the wellbore by several hundred meters. Conversely at zero bit weight, the PDT-CCT can reach 14,500 m compared to only 2,070 m for the 60 mm steel CT in this well. Such a high extended-reach capability would be extremely desirable for a PDT-CCT used as a workover string for which a WOB capability is not essential. The theoretical analyses also showed a strong response of WOB to varying hook load. This greatly improves the control of bit force applied by the PDT-CCT drill strings. Other comparative features are described in the full report. With continued support, a successful outcome to the *technological* objectives can be anticipated.

***(Deliverables and) Expected end results***

The expected end result of this project is the "prove of principle" that the technology will function in the targeted applications, and the know-how required to develop the infrastructure necessary to perform a small-scale field trial.

***(Dissemination and) Intentions for use***

The intentions for use of the results of the first phase are to prepare a new project proposal for the demonstration phase and the execution of a field trial on several applications to demonstrate the concept of the PDT-COIL. In the demonstration phase the separate components and contributions will be integrated into a test model. This scale model will be mounted at the end of a steel version of coiled tubing and field-tested. The objectives of this test are to prove the feasibility of electric drilling with a PDT-COIL and the (semi) continuous monitoring of both the drilling process and the structural integrity of a coil.

The consortium has succeeded in this objective, since the demonstration phase was awarded at the end of 2002. The consortium is confident that with the knowledge developed the chances of success of a technology demonstration are high.

***Intellectual Property Right Protection***

A request for patent protection has been submitted by the ETHZ.

| | |
|---|---|
| Submission date: | 19th of April 2002 |
| EU-patent application: | No. 02 008 817.5-2208 |

Patent title:

> ***"A flat, solid, shielded electrical conductor (with chemical protection layer) for integration in a tube wall"***

Inventors:

- Stefan Neuhold
- Roland Hug
- Klaus Fröhlich

# 3 Objectives and strategic aspects

The main objectives of the project as described in the first project proposal are still unchanged.

- To bring down the costs of drilling operations;
- To improve the performance of drilling operations;
- To decrease the impact on the environment of drilling operations.

This project aims to research and develop a high-temperature, corrosion and fatigue resistant thermoplastic Power & Data Transmission Composite Coiled Tubing (PDT-COIL) for electric drilling applications. This PDT-COIL contains embedded electrical power and data conductors and a fibre-optic sensing and monitoring system.

The PDT-COIL will result in 35% overall cost savings on the exploration of hydrocarbons.
Time to first oil will be reduced due to the support of enhanced logging while drilling capabilities.
Compared to conventional rotary drilling, such a PDT-COIL will lead to:

- 45% less required workspace,
- 50% reduction of rig height,
- 60% noise reduction,
- 70% less rock cuttings, and
- 85% reduction of power exhausts generation.

Although it is too soon to determine if all the above objectives can indeed be met, there have been no developments or (lack of) results that necessitate adjustments of these targets.

The main scientific and technical objectives are provided in the current specifications below:

| Property | Units | Operation Load | Design Load | Total Failure Design Load | Comment |
|---|---|---|---|---|---|
| ***Bending radius*** | m. | 2.0 | 2.0 | 1.6 | Road transportable reel $L_{min}$ = 1000 m Design on fatigue!! |
| ***Tensile Load*** | kN | 220 | 275 | 330 | Weight 1 x string length at 4.5 kg/m (5 km string) |
| ***Compress Load*** | kN | 465 | 582 | 698 | 2 x $F_{snub}$ |
| ***Torsion*** | Nm | 1356 | 1695 | 2034 | From ED (1,000lbft) |
| ***Internal pressure*** | bar | 690 | 759 | 863 | Maximum test pressure at R=5m! (10000 psi) |
| ***External pressure*** | bar | 500 | 625 | 750 | Collapse pressure (with ovality of 2%) |
| ***Operating temp*** | ºC | -40 to +150 | | | |
| ***Buckling load*** | kN | 6.7 to 17.8 | | | Depends on WOB!! + stripper friction |
| ***Impact*** | g | | | | - |
| ***$ID_{min}$ $OD_{max}$*** | mm | 45 - | | | Hydraulic perform. |
| ***Weight*** | kg/m | < 4.35 | | | < 50% SCT OD = 2 7/8 " |

Life cycles

| | | | |
|---|---|---|---|
| ***Fatigue cycles (r = 2.0 m.)*** | Number of cycles | 1,000 | |
| ***Fatigue cycles (r = 5.0 m.)*** | Number of cycles | 10,000 | |
| ***Operational service life*** | Number of wells | 500 | |
| ***Total service life*** | Years | | At .. wells per year |

Operational Specifications

| Operation | Operation Load |
|---|---|
| ***Transport on reel*** | |
| ***Temperature*** | between -40 and +60 ºC |
| ***Minimum bending radius*** | 2.0 m |
| ***Endurance*** | 1000 cycles |
| | |
| ***Big loop spooling*** | |
| ***Temperature*** | between -40 and +60 ºC |
| ***Minimum bending radius*** | 5 m. |
| ***Axial load*** | 8.9 kN (2000 lbs) |
| ***Pressure difference*** | 690 bar (burst) |
| ***Endurance*** | 10.000 cycles |
| | |
| ***Snubbing**** | |
| ***Temperature*** | between -40 and +60 ºC |
| ***Axial load (buckling)*** | between –465 and +440 kN |
| ***Torsion load*** | +/- 1356 Nm |
| ***Pressure difference*** | 690 bar (burst) |
| ***Endurance*** | 10.000 cycles |
| | |
| ***Down-hole running in*** | |
| ***Temperature*** | between -40 and 150 ºC |
| ***Axial load*** | –465 kN |
| ***Buckling load (WOB)*** | 17.8 kN |
| ***Torsion load*** | +/- 1356 Nm |
| ***Pressure difference*** | 500 bar (collapse) |
| ***Endurance*** | 10.000 cycles |
| | |
| ***Down-hole pulling out*** | |
| ***Temperature*** | between -40 and 150 ºC |
| ***Axial load*** | 440 kN |
| ***Pressure difference*** | 500 bar (collapse) |
| ***Endurance*** | 10.000 cycles |

* Assumed tubing guide arch radius > big loop radius

# 4 Scientific and Technical assessment

## 4.1 Critical overview of the technical state of the project

***Scientific and technical performance***

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### 4.2 Comparison of achieved objectives and stated objectives

The stated objectives are regarding the full project, which not only comprises the R&D phase, but also the demo phase. However in he following we will make an effort to relate the achievements of the project in the R&D phase to the objectives of the total project.

Strength and stiffness tests were positive, and showed an acceptable correlation with the models that were developed. All load cases can be met at this moment already, except for the spooling on a small transport reel. However, the results of the tests in combination with the recommendations are indicating that improvements in allowable strain are still feasible. Airborne is still working on this issue by changing the applied grate of PPS and improving the production process.

The production process has been dramatically improved. It became possible throughout the project to build samples of a substantially better quality than at the start. The bwork done on this topic also gave us the direction in which to go to further inprove the technology in order to get it ready for continuous production in the demo phase.

The tests that have been carried out to prove that both optical fibers and conductors can be embedded were positive. The quality improvements that are required to meet the objectives of continuous production for the demo phase are considered well within reach.

The chemical stability and behaviour of the choosen polymers looks very positive, both in the theory as in the first tests that were performed. Therefore the consortium is confident that the objective of a stable composite structure in the demanding downhole environment is feasible.

The DiTeSt® fibre optic system was selected for structural monitoring of the PDT-COIL and laboratory tested. The main parameters to be monitored were identified and the sensor layout, number and positions were defined. Algorithms describing the relation between the monitored parameters and structural performance of the PDT-COIL were developed. Integration techniques were developed for both fibre optic sensors and optical connectors. The achieved objectives correspond to the stated ones.

Advanced signal processing tools (time-frequency analysis, noise filtering using generalized spectral subtraction and the signal value decomposition, exponential data modelling for extraction of features that are able to interpret damage status and localisation) have been
investigated and implemented in Matlab. their success under several strain conditions (tensile tests) has been validated on flat C/epoxy specimens with embedded optical fibres used as intensity-modulated sensors (microbending concept), as well as on PDT coil tube prototypes. The results were promising with regards to the potential in the demo-phase.

Simulations done by BJ show good operational predictions. The results indicate positive effects of the enhanced operational envelope on drilling efficiency (costs, impact on the environment etcetera). However these elements need to be explored and planned in more detail in the demonstration phase.

### 4.3 State of the art review

The only known system at this moment PDT-COIL is competing with is a thermoset tube system with a very limited power capability and a limited load envelope. The PDT-CCT has a much better mechanical performance combined with a high power capability and on top of that optical data transmission. This combination is the result of the thermoplastic design as opposed to the competitor's thermoset design, and the state of the art electrical and optical solutions provided by the partners.

# 5 Deliverables

## 5.1 List of deliverables

The original deliverables of the PDT-CCT project are shown in table 1. The following code has been used:

| | |
|---|---|
| (green) | Deliverable realised |
| (orange) | Deliverable not realised |

| List of deliverables | | | |
|---|---|---|---|
| **Deliverable No** | **Deliverable title** | **Delivery date planned** | **Delivery date realised** |
| D1 | Report: Design and FEM modelling of PDT-COIL<br>AD07.247R001 Design and analysis of PDT-COIL<br>AD07.247R002 Design and analysis of PDT-COIL connector<br>AD07.247R003 FEM analysis bare PDT-COIL<br>AD07.247R004 FEM analysis PDT-COIL connector | 3 | <br>6<br>9<br>9<br>12 |
| D2 | Report: Mechanical test results PDT-COIL<br>AD07.247R005 Mechanical testing of PDT COIL | 14 | <br>15 |
| D3 | Report: GRP insulation material<br>Mid term report ETH | 12 | <br>12 |
| D4 | Report: Design study on optic fibre sensing system<br>Mid term report Smartec | 9 | <br>12 |
| D5 | Report: Optical fibres in thermoplastic composite materials<br>Full partner report Smartec | 12 | <br>22 |
| D6 | Report: Chemical behaviour of thermoplastic composites<br>Literature study on chemicall ageing of thermoplastic composites | 11 | <br>12 |
| D7 | Software: Composite CT software | 12 | |
| D8 | Report: Conceptual design of surface equipment<br>PDT CCT interim report Phase 1 “R&D” | 12 | <br>22 |
| D9 | Report: Optimised design and updated FEM model of PDT-COIL<br>AD07.247R006 Design optimisation and updated model of PDT-COIL<br>AD07.247R007 PDT COIL Connector redesign<br>AD07.247R008 PDT COIL redesign FEA | 22 | <br>22<br>22<br>22 |
| D10 | Report: Insulation material test results<br>Scientific and Technical assessment ETH | 22 | <br>22 |
| D11 | Software: Optical sensor system software<br>Full partner report Smartec | 17 | <br>22 |
| D12 | Report: Thermoplastic composite – sensor interface<br>Full partner report Smartec | 17 | <br>22 |

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| D13 | Report: Sensor system test results<br>Full partner report Smartec | 22 | <br>22 |
| D14 | Report: Chemical ageing test results<br>PDT CCT interim report Phase 1 "R&D" | 19 | <br>22 |
| D15 | Report: Chemical ageing monitoring system design | 22 | |
| D16 | Progress report compilation every 6 months | 6, 12, 18, 24 | |
| D17 | Report: Exploitation plans, dissemination of RTD results, IPR distribution, Description of state-of-the-art, Identified RTD needs, Network Strategy<br>Evaluation of PDT-CCT technology; business case for an emerging technology | 10, 24 | <br><br><br>22 |

Table 1 List of deliverables

Some of the deliverables which are realised are in a few occasions combined in one report, while in other cases more reports make up one deliverable. On the CD "deliverables of the PDT-COIL project" the reports making up these deliverables are brought together. This CD is highly confidential and for internal use within the EC only.

### 5.2 Comparison of planned activities versus accomplished work

Two deliverables are not realised: D7 and D15. In the contract amendment Corrocean left the consortium. CorrOcean was involved in the project to perform chemical ageing tests and to develop a chemical resistance sensor, which would be built in the thickness of the PDT-Coil. (mainly deliverable 15). The results of the research showed however that the chemical ageing could also be monitored with fiber optics and this option was preferred because of its versatility. It would lead to a more efficient and cost efficient solution.

With this the main commercial objective for CorrOceans involvement in the project had ceased to exist. With full consent of the consortium CorrOcean decided to step out of the project. As a result of this deliverable 15 was cancelled.

Another company of the BJ organisation, BJ Services International BV, which is sited in Emmen, agreed to take over the chemical ageing tests of CorrOcean. The company was added to the consortium as well.

Soon it became clear that BJ owns a CCT software code which can be used to to perform some primary simulations on the behaviour of PDT COIL. In the course of the project BJ conducted experiments with their software to see whether it could simulate composite coils. The conclusion was drawn that it would be much more cost and time effective to start using the existing software for the demo-trials, and use the experience to define the required improvements.

Leaving out the chemical sensor lead to modifications in the work packages of several partners. Smartec, Airborne and KU Leuven researched alternative solutions and more samples had to be manufactured for testing.

Deliverable 9 has become much more extensive that originally planned. This is the result of the fact that the design of the connector was much more difficult than anticipated. In the course of the project the solutions for the electrical conductors and the fibre optics evaluated such, that they required more and more space. At a certain moment in the project the strength and stiffness requirements could not be met anymore in combination with the electric and optical equipment and (very important) the assembly procedures. Therefore in close consultation with the partners it was decided to radically change the basic design of both the coil structure as the connectors. As a result of this new extensive design cycles were required for both the coil as the connectors, which were not originally budgeted.

# 6 Management and co-ordination aspects

***PDT-COIL management report***

The PDT-COIL project has known several changes in the composition of the consortium. Most of them were the resultof inter company reorganisations. Only one of them was due to the results of the R&D work.

All partners started off with great enthusiasm, even before the kick-off meeting was held. A few partners had problems with the start-up of the actual project. New employees were required to execute the planned work. The KU-Leuven had some difficulties in finding qualified personnel for the research work envisaged, but after three months these problems were solved.

A few months after the project-start it became obvious that Deutag would possibly be sold to another company. Therefore their commitment could not be guaranteed, especially since one of the main possible buyers was not a European company. Around the mid-term of the project the sale of the company to the UK Company KCA was confirmed. Even though this company was European, Deutag still requested to be released from its project obligations since the new owner would not support it.

At the first half-year meeting in Lugano it was decided that the project management would try to find a new partner to replace Deutag. The consortium found a new partner in BJ Services Company in Aberdeen, which is very experienced in coiled tubing operations using steel CT technology. With full cooperation from Deutag, BJ stepped in and took over all obligations.

Coiled tubing is core business for BJ and the company has performed a lot of research in this field. The company is convinced that composite coiled tubing is definitely “the way to go”. The entry of BJ meant access to great experience in the CT field for the consortium.

The first year meeting was held at the KU in Leuven, and was equally well organised. Although on very short notice, BJ managed to send two experienced representatives. Their inputs proved to be very valuable already and the project team was very happy to welcome this new committed partner.

Apart from the official consortium meetings a number of technical meetings were held and documented between technicians of the different partners. These meetings were necessary because many design topics required solutions that influenced the design envelopes of most other partners. These meetings have proved to be very effective.

CorrOcean was involved in the project to perform chemical ageing tests and to develop a chemical resistance sensor, which would be built in the thickness of the PDT-Coil. The company had great interest in the project because it was to be the future supplier of these sensors for the manufacturer of the PDT-Coil. However the results of the research showed that the chemical ageing could also be monitored with fiber optics and this option was preferred because of its versatility. It would lead to a more efficient and cost efficient solution.

With this the main commercial objective for CorrOceans involvement in the project had ceased to exist. With full consent of the consortium CorrOcean decided to step out of the project.

Another company of the BJ organisation, BJ Services International BV, which is sited in Emmen, agreed to take over the chemical ageing tests of CorrOcean. The company was added to the consortium as well.

Leaving out the chemical sensor lead to modifications in the work packages of several partners. Smartec, Airborne and KU Leuven researched alternative solutions and more samples had to be manufactured for testing.

The consortium also decided to put more effort in the R&D of a fast connector concept for the PDT-Coil. Connectors are indispensable for successful application of CCT technology since lengths of no more than 500 – 800 meters would be road transportable in most densely populated areas around the world.

Due to the delayed start of some of the partners and the mentioned changes within the composition of consortium a project extension of three month was requested and granted by the European Commission.

Unfortunately this was not the end of all the changes in the PDT-COIL consortium. For cost efficient arguments the Shell higher management had decided to focus their total R&D efforts on only a few promising technology developments. In the second year of the R&D phase of the project SIEP gave Nolan Norton, the business consultancy office of KPMG, the assignment to draw up a business case on the PDT-COIL technology. Amongst others all project partners were consulted. The result showed the technology to be extremely profitable for some applications, but the return on investment period was estimated at 8 to 10 years.

SIEP decided to remain supportive to the project, but to withdraw from the succeeding demonstration phase, for which a project proposal had already been submitted. Many of the management and network administration tasks were transferred to Airborne.

Mainly because the chemical ageing tests had not been finished by the end of the project, a second request for a project extension was submitted. Also the CorrOcean withdrawal and the entry of BJ Services International entry had to be formalised. In the subsequent project amendment No 2 all partner changes were settled, the description of work was modified according to the outcome of the research work and a second extension of three month was confirmed.

# 7 Conclusions

In general it can be concluded that the project is performing very well. It is only halfway now, but the confidence in the outcome is growing. Based on the results of this R&D phase the consortium is moving very positively into the demonstration phase.

The mechanical performance of the design of both the coil and the connector proved to be very good for all load cases, except for the spooling on a small transport reel. However, the results of the tests in combination with the recommendations are indicating that improvements in allowable strain are still feasible.

Recommendation: improve the allowable strain of the laminate by:

- applying a more ductile grate of PPS and
- improving the control of the production process (i.e. the time-temp curve)

The production process was dramatically improved. It became possible throughout the project to build samples of a substantially better quality than at the start. The work done on this topic also gave us the direction to further improve the technology in order to get it ready for continuous production in the demo phase.

Recommendation: improve process control by:

- optimising the temperature – time profile
- investigating other heat sources

The integration tests that have been carried out to prove that both optical fibers and conductors can be embedded were positive. The quality improvements that are required to meet the objectives of continuous production for the demo phase are considered well within reach.

Recommendations: perform more tests in a semi continuous fashion. Especially the integrity of the optical and electronic components will have to be improved, by optimising the embedding technique.

The chemical stability and behaviour of the choosen polymers looks very positive, both in the theory as in the first tests that were performed. Therefore the consortium is confident that the objective of a stable composite structure in the demanding downhole environment is feasible.

Recommendations: Once the application to be demonstrated has been decided upon the final design will be made. This design will have to undergo extensive long term testing. These tests are well described and prepared by BJ.

Computer modelling of the entire electrical system was performed in order to determine the electric stresses applied on the electric insulation system of the PDT-COIL in service. The calculations gave good indications for the electric stresses, yet it was recognised that a supplier providing a specific drilling motor and frequency-converter has to be found in order to derive specific input parameters for the simulation. Secondly, the numerical simulations were supplemented by experimental tests on short test samples. Tests and simulations show that the material is dielectrically stressed to its limits. It is essential that any penetration of liquids be prevented. Tests on the insulation system under down-hole conditions showed a good liquid sealing performance.

Recommendations: the work of the PHD students is only half way. It will have to be continued and finalised through the demo phase.

The DiTeSt® fibre optic system was selected for structural monitoring of the PDT-COIL and laboratory tested. The main parameters to be monitored were identified and the sensor layout, number and positions were defined. Algorithms describing the relation between the monitored parameters and structural performance of the PDT-COIL were developed. Integration techniques were developed for both fibre optic sensors and optical connectors. The achieved objectives correspond to the stated ones.

> Recommendations: For this workpackage it is soley recommended to move ahead into the demonstration phase as planned.

Advanced signal processing tools (time-frequency analysis, noise filtering using generalized spectral subtraction and the signal value decomposition, exponential data modelling for extraction of features that are able to interpret damage status and localisation) have been
investigated and implemented in Matlab. Their success under several strain conditions (tensile tests) has been validated on flat C/epoxy specimens with embedded optical fibres used as intensity-modulated sensors (microbending concept), as well as on PDT coil tube prototypes. The results were promising with regards to the potential in the demo-phase.

> Recommendations: the work of the PHD students is only half way. It will have to be continued and finalised through the demo phase.

Simulations done by BJ show good operational predictions. The results indicate positive effects of the enhanced operational envelope on drilling efficiency (costs, impact on the environment etcetera).

> Recommendations: operational results will have to be compared with the simulations. Based on this information the strategy for upgrading the software will be established in the demo phase.