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Marine growth in cooling
plant at drilling installation,
Nigeria

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Abstract

The study considers the probability and nature of marine growth (biofouling) in a cooling water plant to be installed at the Nnwa field offshore Nigeria. The cooling water will be taken from approximately 1000 m depth. Literature data and reports from existing installations using deep-water in tropical areas suggest that the main problem will be growth of micro-organisms (microfouling) on the lining of tubes and tunnels. The most relevant data have been reported from an OTEC test facility in Hawaii. Water samples taken *in situ* had a high content of nutrients and organic matter, suggesting that the living material mainly consists of bacteria. Presumably not more than infrequent measures to counteract growth will be needed, e.g by intermittent application of chlorine. The growth may depend on the materials selected for the lining of the tubes. References are given to literature and to R&D institutions working with biofouling from which further information may be sought.

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2. Kjølevannssystem	2. Cooling water system
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**Marine growth in cooling plant at drilling
installation, Nigeria**

Preface

Statoil ASA has contracted Norwegian Institute for Water Research (NIVA) to carry out a project considering the probability of marine growth in a cooling water plant to be installed at the Nnwa Field offshore Nigeria. The contract was finally agreed 15 July 2002, contract no 4500462422. Contact persons in Statoil have been Einar Nygaard, Kenneth Johannessen Eik and Kjerstin Ellingsen.

The cooling water, 30 000 m³/h, will be taken from approximately 1000 m depth. After use in the plant the water will be released to the surface. The project comprises two sub-projects: 1) water samples and analysis from the drilling site (Ref. Enquiry no. 2002/00195); and 2) a literature study of the probability and nature of marine growth (biofouling) in tunnels and pipes of the cooling water plant (Ref. Enquiry no. 2002/00197). The present report summarises the results of the literature study and water samples of nutrients taken *in situ* in order to assess the potential for marine growth. The collection of water samples and results for physical-/chemical water characteristics have been reported in a short note (in Norwegian), which is appended in the present report.

Water sampling was carried out by Tom C. Mortensen, NIVA. Literature search was carried out through the scientific library at NIVA with help from Berit Kramer. The report has been prepared by Eivind Oug and August Tobiesen, the latter has also been responsible for the assessment of the water samples.

Oslo, 19 February 2003

Tom Christian. Mortensen

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Summary

The present study considers the probability and nature of marine growth (biofouling) in a cooling water plant to be installed at the Nnwa field offshore Nigeria. The cooling water, 30 000 m³/h, will be taken from approximately 1000 m depth. The project comprises a literature study of biofouling in tunnels and pipes of existing installations with deep-water intake. In addition, water samples have been taken *in situ* and analysed for hydrophysical and chemical parameters. The aims of the study are to synthesise relevant experience, identify problems, and indicate available knowledge on dealing with the problems.

In tropical areas, deep water may be used for several purposes, including industrial cooling and air conditioning systems, electric power generation, and aquaculture. The information is limited, however, as there are not many installations presently in operation. The most relevant data have been reported from an Ocean Thermal Energy Conversion (OTEC) pilot facility for power production that has been in operation in Hawaii (Natural Energy Laboratory of Hawaii NELHA) for more than 20 years. Other facilities using deep water are in operation in Japan, and recently also in India.

The main fouling problem in deep-water intake systems appears to be the formation of a film of organic material and micro-organisms (microfouling) on the lining of tunnels and tubes. Growth of larger organisms (macrofouling) is very restricted compared to the situation in shallow waters. The studies in Hawaii demonstrated that very little fouling occurred in deep water intake systems compared with simultaneously operated shallow-water systems.

A variety of techniques for controlling biofouling exists. Generally, the techniques can be divided into chemical, usually toxic agents, and non-chemical techniques. The most frequently used chemical agent is chlorine. Most techniques are developed for control of fouling in shallow-water systems.

The studies in Hawaii indicated that the fouling largely could be controlled by the selection of materials for the lining of the tubes. Some intermittent use of chemical agents, e.g. chlorine, to counteract growth might seem necessary, however. Mechanical techniques, such as use of sponge rubber balls for cleaning, did not function adequately. Use of ultra-violet light and ultra-sound were shown to have control potential, but were less efficient considering high energy requirements.

The deep-water samples taken *in situ* had physical-/chemical characteristics within known ranges for deep water. The water had a high content of nutrients and organic matter. The ratios between nutrient elements (C:N:P) and the carbon content suggested that the abundance of living material is low and mainly consists of bacteria. Presumably, some larger organisms such as heterotrophic flagellates and ciliates are also found.

The water samples suggest that the fouling in a cooling plant at the Nnwa field will be at a very low level. The growth will require not more than very infrequent counter measures, probably less than once per year. The most appropriate measure would seem to be the application of chlorine in some form. In addition the choice of materials in the cooling system should be given adequate attention. In all parts of the system light should be avoided.

There are numerous R&D institutions around the world working with biofouling from which further information may be sought. Some examples of academic institutions and commercial companies are given. In addition a list of relevant books and articles is given.

1. Introduction

1.1 Background for the study

In connection with operation of a LNG-plant at the Nnwa field offshore Nigeria, cooling water will be taken from approximately 1000 m depth. The use of cooling water is estimated to be about 30 000 m³/h. The present study considers the probability and nature of marine growth (biofouling) in tunnels and pipes of the cooling water plant.

Growth of organisms on surfaces, collectively called *biofouling*, constitutes a major problem for constructions and installations in all marine waters. The problems are of particular concern to shipping, harbour installations, offshore platforms, power plants and a number of coastal based industries. The consequences of biofouling in pipes are increased frictional flow resistance in flow systems, reduced diameter, impairment of heat transfer efficiency in thermal exchange systems and enhanced corrosion of metals and alloys. Larger organisms such as sponges, barnacles, shells, and sea-weeds are the most obvious fouling organisms, which by their presence may reduce water flow and interfere with the operation of the structures. The establishment of larger organisms is dependent, however, on the initial formation of a thin organic layer on the surface produced by bacteria.

1.2 The processes and stages of biofouling

Biofouling may be considered to proceed in stages (Davis & Williamson 2002). A schematic presentation of the stages is given in Fig. 1. A new clean surface which is immersed in surface seawater will rapidly accumulate dissolved organic matter and molecules such as polysaccharids and proteins. This is a spontaneous process, which is driven by physical and chemical forces and leads to the development of a thin organic film covering the surface. In a couple of hours the film will be colonised by bacteria and single-celled algae. In this stage the film thickens into a microbial biofilm. The micro-organisms may produce various sticky substances and chemicals which may have effects on the original surface, for instance by causing corrosion. The development of a bacterial film is generally known as *microfouling*.

The presence of adhesive exudates and the roughness of irregular microbial colonies help to trap more particles and organisms. These are likely to include algal spores, marine fungi and protozoa, some of which may be attracted by sensory stimuli. Gradually the microbial biofilm is transformed into a more complex community that typically includes multicellular primary producers, grazers and decomposers. In the final stage, settlement and growth of larger marine invertebrates such as barnacles, limpets, bivalves, sea squirts and seaweeds takes place. Many of these organisms respond to and develop efficient and highly specific settlement cues. The development of a fouling community of larger organisms is generally known as *macrofouling*.

1.3 Biofouling in seawater intake systems

Organisms that would be anticipated to cause problems in tubes and pipelines include micro-organisms and sessile fauna (e.g. sponges, shells, calcareous tube worms, barnacles). The type of growth will depend on the content of nutrients and the presence of spores and larval stages in the intake water. Microalgae and seaweeds may grow where light is accessible, but will not be found in closed systems which are completely protected against light.

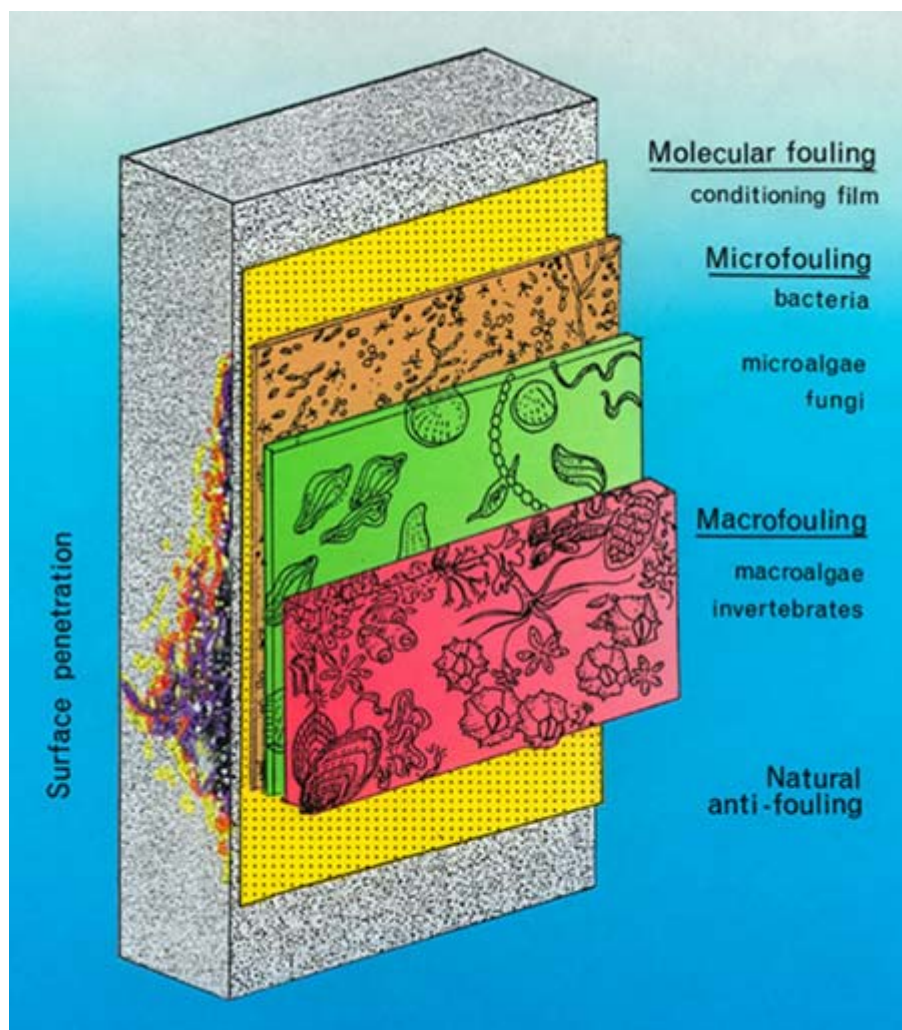


Fig. 1. Schematic presentation of the main stages of marine biofouling (from Davis & Williamson 2002)

Generally the fouling problem is most severe in shallow water intake systems. This is because there are high densities of organisms in shallow waters and a profuse food supply for attached organisms. Organisms which are naturally adapted to current-swept environments, take advantage of the water flow inside pipelines and tubes. Typical problems in shallow pipelines are related to growth of barnacles and shells which more or less reduces the water flow, and eventually, if not removed, occlude the water systems. There are numerous plants and installations taking seawater from shallow and moderate depths. An overwhelmingly large amount of the information on biofouling pertains to macrofouling in shallow-water systems operating in inshore and shelf areas.

In deep-water intake systems, microfouling appears to be the main problem (see e.g. Craig et al. 1977). Deep ocean water generally has a high content of dissolved inorganic nutrients, whereas the amount of organic material and density of organisms is low, so that potential food for larger organisms is low. Hence, growth of larger organisms (macrofouling) is restricted compared to the situation in shallow waters. In addition, the low temperatures of the water also reduces growth rates of organisms.

1.4 Project aims

The study will focus on synthesising experience on cooling systems with deep water intakes in tropical areas, identify typical problems, and indicate available knowledge on dealing with the problems.

Specifically, the study shall:

- indicate the probability of marine growth in the cooling water plant
- describe possible efforts to counteract marine growth
- give proposal to further work

The issues of concern are: i) the formation of biofilm and growth of micro-organisms (microfouling), ii) the settlement and growth of larger organisms (macrofouling), and iii) the problems with corrosion.

1.5 Project design

The present project comprises a literature study regarding probability and nature of marine growth in tunnels and pipes in deep-water intake systems. In addition, water samples have been taken *in situ* at the Nnwa Field and analysed for relevant parameters. In the literature study, information from development projects and existing installations have been assembled. In tropical areas, deep water may be used for several purposes, including industrial cooling and air conditioning systems, electric power generation, and aquaculture. The information is limited, however, as there are not many installations presently in operation.

The water samples have been collected at the water intake depth (1000 m) at the Nnwa Field. The samples have been analysed for nutrients and organic matter which are essential for the initial formation of a biofilm and growth of micro-organisms. The sampling was coordinated with the parallel project 'Water samples and analyses from drill installation offshore Nigeria'. Together, the data for nutrients and physical/-chemical parameters obtained from the latter project (salinity, pH, oxygen) give information on the quality and characteristics of the water. The description of the water characteristics is important for the comparison with biofouling in cooling water systems in other tropical waters.

2. Methods

2.1 Literature study

Relevant literature and background information has been searched using the literature bases ISI Science Citation Index, Aquatic Sciences and Fisheries Abstracts (ASFA) and Cambridge Scientific Abstracts (CSA). Several scientific articles have been published in connection with scientific meetings and conferences, i.e. from the Caribbean, Mexico, Hawaii and India.

More general background information about relevant activities and operation of deep-water pipelines has been searched for at the Internet (world-wide web).

In addition, a brief contact has been made to the OTEC installation in Hawaii, for comments on their experience on water intake at great depths.

2.2 Water samples

2.2.1 Collecting

Water samples for analysis of chemical parameters, nutrients and organic content were collected 13 August 2002 (see field report in Appendix 7.2). Samples were taken at 0, 100, 400, 700 and 1000 m depth using Niskin water samplers. Samples were then prepared for transport according to NIVA's standing operation procedures. The samples were registered at NIVA laboratory in Oslo 15 August 2002.

Due to an incidental accident, the samples for nutrients and organic matter got lost during transport from Nigeria. After agreement with Statoil, new samples were taken in October 2002. These were taken at 800 and 1000 m depth and were transported to NIVA in Oslo in 5 l plastic canisters without any prior treatment.

2.2.2 Analyses

The samples for chemical parameters (collected in August) were analysed with respect to pH, conductivity, alkalinity, salinity, oxygen, total phosphorus silicate, and a selection of 13 metals. The samples for nutrients and organic carbon (collected in October) were analysed for particulate nitrogen (PON), particulate phosphorus (POP), particulate carbon (POC) and dissolved organic carbon (DOC).

In this report, data for nutrients and dissolved organic carbon are presented and evaluated with respect to the potential for biofouling. The complete data for chemical parameters are given together with the field report in Appendix 7.2.

2.2.3 Analytical methods

All samples were analysed at the chemical laboratory at NIVA accredited according to the NS-EN ISO/IEC 17025 standard.

Particulate carbon (POC) and particulate nitrogen (PON) were analysed according to NIVA method G6: "Bestemmelse av karbon og nitrogen i fast stoff med Carlo Erba elementanalysator." The detection level is 1.0 µg/g with respect to both carbon and nitrogen.

Particulate phosphorus (POP) was analysed according to NIVA method D2-1: "Bestemmelse av totalfosfor i ferskvann og sjøvann med Skalar Autoanalysator etter oppslutning med peroksidisulfat, Norsk Standard, NS 4725. Bestemmelse av totalfosfor – Oppslutning med peroksidisulfat. 3. Utg. 1984". The detection level is 1.0 µg/g.

Dissolved organic carbon (DOC) was analysed according to NIVA method G4-2: "Bestemmelse av totalt organisk karbon med peroksidisulfat / UV metoden" or "Wet Chemical Oxidation IR-detection (EPA approved method. 415.1 - STANDARD)". The detection level is 0.1 mg/l C.

3. Literature study

3.1 Installations with intake of deep water in tropical areas

3.1.1 Ocean thermal energy conversion (OTEC)

Ocean Thermal Energy Conversion (OTEC) is a facility for power production that uses the temperature difference between surface and deep water to drive an open- or closed-cycle thermodynamic generator. No large operational plants have yet been built, but a 50 kW pilot facility has been tested for decades at Keyhole Point in Hawaii (NELHA), and the Japanese have operated a 100 kW plant at Nauru. The technique ideally needs a temperature difference of 20° C over a depth of 700 to 1000 metres, thus favouring tropical locations (McEwan 1996). A proposed side-benefit is that the raised deep water, being rich in nutrients, might sustain an associated mariculture installation

At the OTEC facility in Hawaii (Natural Energy Laboratory of Hawaii NELHA) several deep water pipelines have been installed. The pipelines range in diameter from 300 millimeters to one meter and have intake depths ranging from 650 to 700 meters. The pipelines have been developed and tested for several purposes in addition to OTEC such as air conditioning (refrigeration) and aquaculture. The 1-meter-diameter pipeline, if used exclusively for air conditioning purposes, could supply almost 5,000 tons of air conditioning and replace more than 4 megawatts of normally generated electrical power. This pipeline has been in continuous operation for nearly five years. A smaller, 300-millimeter pipeline of the same design has been servicing Keahole for more than 20 years (Ryzin & Leraand 1992, Makai Ocean Engineering 2002, NELHA 2002).

Recently, a large pipeline has been installed in India for the National Institute of Ocean Technology in Madras (NIOT). The pipeline will supply 1.4 m³/s water from 1000 m depth (Makai Ocean Engineering 2002). There has been a brief report on deposit problems in the pipeline from the use of NaOCl (sodium hypochlorite) for biofouling prevention (OTECnews 2002).

3.2 Biofouling and nature of marine growth in pipes and tubes

The most relevant studies appear to have been conducted at the OTEC experimental installation in Hawaii. Initial research began in 1976 using a buoy deployed offshore for biofouling studies of candidate elements for heat exchanger systems (Daniel 1999). From 1982 through 1987, a long term test project of biofouling and corrosion of candidate OTEC heat exchanger materials was conducted (The Argonne Test Project ATP). Deep and surface seawater were pumped continuously, under varying flow conditions, through a series of test loops containing sample coupons and heat transfer monitors installed in tubes of various materials. The deep seawater was taken from 580 m depth.

The ATP tests generally demonstrated that: 1) significant micro-biofouling developed quickly in the tubes carrying warm surface seawater, but this could be easily controlled with intermittent application of low concentrations of electrolytically generated chlorine; 2) no significant fouling occurred in tubes carrying cold deep seawater; and 3) inexpensive aluminum alloys worked well in the flowing seawater environment, especially in the warm surface water where pitting corrosion rates indicated the feasibility of 40 year lifetimes. Slightly more rapid corrosion in the deep cold water could be reduced by inexpensive "claddings" of nearly pure aluminum (Pancal et al. 1990).

Details of the experiments were reported by Berger & Berger (1986). While 9 different set ups were tested with respect to surface water only 3 were tested with deep water. The materials selected for deep water tubes were stainless steel, aluminium claddings and aluminium, for further information with respect to the specific

quality of materials one should refer to Berger & Berger (1986). Tubes with aluminium cladding had corroded completely within one year. Aluminium had a significant growth, mostly bacterial biomass, which increasing linearly during the 2 year period. However the fouling level (thickness of biomass film) was within 50 % of tolerable level. With stainless steel no significant biofouling was recorded during the 1 year period tested. No countermeasures were tested with respect to surfaces exposed to deep water, however in their discussion of results they envision that some sort of fouling countermeasures would be needed, but at infrequent intervals.

The ATP tests (Berger & Berger 1986) also demonstrated that sponge rubber balls used for mechanical heat exchanger cleaning in other applications did not adequately remove the microfouling and also unacceptably accelerated the corrosion of aluminium test elements. This may be caused by friction of sponges uncovering non oxidised aluminium for oxidation or corrosion. In an additional series of tests the efficacy of other non-chemical biofouling control measures for OTEC systems was investigated. Both ultra-violet light and ultra-sound were shown to have biofouling control potential, but the energy requirements for both were significantly higher than for chlorine generation (Takahashi 1986).

Later studies at the test facility have generally corroborated the early findings. Some of the major research supported by the existing cold water pipelines at Keahole, Hawaii, over the last decade has been directed at biofouling and corrosion-testing of heat exchangers. Furthermore, innovative and low cost aluminum heat exchangers that are corrosion-free have been developed and successfully tested by Alcan Aluminum at this facility. Corrosion-free titanium heat exchangers have also been shown to be ideal for this application (Ryzin & Leraand 1992).

3.3 Methods to counteract marine growth

A variety of biofouling control techniques exists (Jenner 1980, Brankevich et al. 1990, Cloete et al. 1998). Generally, the techniques can be divided into two groups, chemical and non-chemical. Chemical techniques include the discharge of oxidising and non-oxidising biocide agents into the intake water, the use of toxic materials in the construction elements, and the application of antifouling paints to exposed surfaces. Non-chemical techniques involve mechanical, osmotic, anoxic, and thermal energy controls.

In the following, techniques are described with no preference for shallow or deep water intake. It may be assumed that only some of the methods will be appropriate for deep water intake systems.

3.3.1 Chemical techniques

Oxidising agents

Chlorine is the most frequently used industrial water system biocide. It is used extensively in power plant cooling systems both in temperate and tropical environments (Berger & Berger 1986, Sasikumar & Nair 1994, Venugopalan et al. 1997). Chlorine may be applied continuously at low levels, discontinuously in periods alternating with periods without dosage, or intermittently in short periods when high dosages are injected in the water system. Chlorine is relatively low in cost but is highly toxic (Jenner 1980, Brankevich et al. 1990).

It has been demonstrated that the use of chlorine in cooling water of power stations leads to the formation of toxic halogenated by-products which may have environmental effects when discharged in the effluent water (Jenner et al. 1998, Allonier et al. 1999).

A method for electrocatalytic chlorine production is the "Concentric Tubular Electrode" system which consists of two concentric titanium tubes between which salt water (seawater) flows. By passing electric current through the salt water, the system converts the sodium chloride into sodium hypochlorite, which is

the active ingredient required for anti-fouling. The system can be worked in a continuous or discontinuous mode and requires little maintenance (Electrocatalytic Ltd. 2002).

Ozone may be used as an alternative to chlorination (Viera et al. 1999). However, ozone may also have negative environmental effects if excess ozone is discharged in effluent cooling water. The effects may be prevented by adding organic substances to the effluents before discharge, as free ozone will react immediately with organic matter and disappear (Leynen et al. 1998).

Non-oxidising agents

Non-oxidising agents are generally organic-based chemical biocides such as aldehydes, ammonia and amines, organometals and chlorophenols. Many of the chemicals are extremely toxic to aquatic organisms and some are also highly persistent and can cause chronic toxicity problems long after application is discontinued. For these reasons, high costs, and generally little information about their proper use, these agents are not a good alternative for use in open systems (Brankevich et al. 1990).

Toxic metals

Toxic metals having antifouling properties include lead, copper and copper-nickel alloys. Copper-nickel alloys appear to be most used. When applied in the sea, the alloys form an adherent oxide-corrosion film with copper ions, which inhibit the attachment of fouling organisms to the surface. The alloys will generally not prevent fouling entirely.

Antifouling paints

Antifouling paints are made of various organometallic compounds, copper oxides etc, incorporated into a paint base. They act by slowly releasing the toxic agent into the water that inhibit or kill attaching organisms (Brankevich et al. 1990). Because of the mode of action, their effectiveness decreases with time and regular renewal is necessary. Because of the maintenance demands, they are generally impractical to use in tubes and other little accessible structures.

3.3.2 Non-chemical control techniques

Mechanical cleaning

Mechanical cleaning may be performed by brushes or sponge balls. Sponge balls are used to clean heat exchange tubes. Slightly oversized balls are released into the intake water and remove fouling and corrosion products from the surfaces as they are pressed through the tubes (Berger & Berger 1986).

High velocity flow in pipes

The use of high velocity to prevent the attachment of fouling organisms has been considered for years. Studies have shown that the current velocities needed to prevent settlement of larval fouling organisms lies in the range of 0.6-1.2 m/s on smooth surfaces and 1.2-1.8 m/s on rough surfaces (Mitchell & Benson 1980).

Thermal backwash

Thermal backwash requires that the temperature of the water be raised over the thermal tolerance of the fouling organisms. The effectiveness of the techniques depends on the water temperatures, the duration of exposure, and the frequency of backwash.

Pulsed electric fields

Recently, the use of pulsed electric fields has been proven to be a means of controlling biofouling. By applying short electric pulses, organisms are stunned and prevented from settlement. The electric field generator is installed like a filter in the cooling system (Schoenbach et al. 1997).

Gamma irradiation and UV radiation

These techniques have been proposed, but have not been sufficiently developed for use in large-scale water supply systems.

3.3.3 Environmental concern

The use of chemical agents for counteracting growth represents a potential hazard to marine life when discharged in the effluent water. In the case of using chlorine, the Environmental Protection Agency (EPA) in the USA allows a maximum chlorine (Cl_2) discharge of 0.5 mg l^{-1} and an average of 0.1 mg l^{-1} . In the case of OTEC plants, the need for chlorine is at levels of less than 10 percent of the EPA limits (Vega 2002). In addition, when chlorine is released in seawater, between 0.05 and 0.5 % will get incorporated into toxic halogenated substances (Harboe & Poléo 1997). The most common substances are bromoform and chloroform, but a variety of other mono- or dichlorine organic substances have also been detected. All compounds are biologically biodegradable (although some are fairly slowly degradable) and are less toxic than the effective dosing concentration of chlorine $0.1\text{-}1 \text{ mg/l}$. Many of these compounds are also produced naturally by for instance planktonic algae (Harboe & Poléo 1997).

The potential risks of using chlorine have led to a search of alternatives for biofouling control. However, in many cases the alternative substances, for instance ozone and hydrogen peroxide, have been shown to yield much the same by-products as chlorine. The search for alternatives has therefore largely faded (Jenner et al. 1998).

3.4 General evaluation of methods and needs for use of antifouling agents

In cases of heavy biofouling various methods may be considered for counteracting the growth. However, the selection of methods and the correct application depends heavily on knowledge of the organisms to be eliminated and system hydraulics. Many of the methods fail due to incorrect selection and application in chemical control programmes. A further complicating factor is the build up of bacterial resistance to many of these compounds. One way of limiting resistance is the alternation of oxidising and non-oxidising biocides at the correct minimum inhibitory concentration and using these in combination with surface active compounds to dislodge any biofilm. A variety of surface monitoring techniques are in use in order to monitor the success of biofouling control programmes. Unfortunately none of these techniques are ideal and results have to be considered very carefully (Cloete et al. 1998)

The results from the OTEC experiments show that biofouling essentially only occurs on heat exchangers exposed to surface seawater. Therefore, it is only necessary to protect the closed cycle OTEC evaporators against marine growth. Depending upon the type of evaporator, both chemical and mechanical means could be used, but chlorine (Cl_2) has been proposed along with several mechanical means.

4. Water characteristics at the rig site

4.1 Water analyses

4.1.1 Chemical analyses and water masses

Selected data from the chemical analyses are presented in Table 1. The results illustrate that the water column down to 1000 m represents different water masses. The surface sample shows indication of influence of fresh water, most probably from the river Niger. The low phosphorus and fairly high oxygen levels indicate that nutrients have been depleted by algal growth. The high salinity found at 100 m is due to water which comes from the Mediterranean Sea. This water is characterised by high salinity and is caught in intermediate depths in the Atlantic due to temperature differences. Oxygen reaches a minimum at 400 m, this water comes from the Antarctic and is also low in silicate due to growth of diatoms. Low oxygen is due to previous high biological activity in this water. Water at 700-1000 is old Atlantic water with a temperature around 4-6 °C. The vertical profile is in agreement with the general knowledge of the ocean water masses in tropical and subtropical Atlantic areas (see figure of salinity and temperature distributions in Appendix 7.2).

Because of the high water intake into the cooling plant, an amount of the water brought in will actually be taken from depths ranging both above and below 1000 m. Despite the low stability of the deep water, it is not expected that the depth interval will be more than ± 20 m. Within this range, significant changes of relevant parameters are not expected to occur.

Table 1. Results for samples taken August 2002. Complete results are given in Appendix 7.2.

Depth (m)	pH	Salintiy	Oxygen ml/l	Total P $\mu\text{g/l}$	Si mg/l
0	8.13	33.64	4.56	7	0.005
100	7.85	35.67	2.72	43	0.01
400	7.72	34.82	1.52	74	<0.0011
700	7.77	34.55	2.85	78	<0.0011
1000	7.79	34.64	3.30	74	0.01

4.1.2 Nutrients and organic matter

The measurements for particulate nutrients and organic matter are presented in Table 2. It may seem that the values are within known ranges for deep water. For instance, the DOC at 1000 m was measured to be 0.62 mg C/l. In several studies, Romankevich & Ljutsarev (1990), Bussmann (1999) and Carlson et al. (1999, 2000) have given values in the range of 0.45-0.70 mg C/l for samples taken from >1000 m depth.

Table 2. Results for samples taken October 2002

Depth (m)	Part P $\mu\text{g/l P}$	Part N $\mu\text{g/l N}$	Part C $\mu\text{g/l C}$	DOC mg /l C
850	<1	4.4	26.9	0.79 (mean)
1000	<1	3.9	28.8	0.62 (mean)

4.1.3 Comparison with water from OTEC test site

Table 3 shows a comparison of water characteristics at the Nnwa site with deep water at the OTEC test site in Hawaii. The table shows several similarities. Most relevant with respect to microfouling is the amount of organic carbon and temperature. Organic carbon is somewhat higher at the Nnwa site, but the difference is small. The temperature is lower at the Nnwa site. The differences, however, are mostly small, so that practical experience gathered at the OTEC test site for deep water therefore may be considered to be directly relevant to Nnwa Site.

Table 3 Comparison of deep water characteristics at the Nnwa rig site with deep water at the OTEC test site in Hawaii (NEHLA 2002). Notice that some data has been transformed to other units in order to enable direct comparison.

Parameter	Nnwa	NEHLA
Depth (m)	1000	600
Temperature (°C)	4-6	8.8
Salinity (‰)	34.6	34.3
pH	7.79	7.61
Alkalinity (mmol)	2.27	2.36
NO ₃ (μM)	-	39
PO ₄ (μM)	2.46	2.89
Si (μM)	35	74.6
DON μM	-	41.4
Oxygen mg/l	4.8	1.24
Tot Org. C (mg/l)	0.64	0.50

4.2 The composition of the organic material

The results for nutrients and organic matter are directly relevant to the assessment of potential for biofouling. At 1000 m the ratio between carbon, nitrogen and phosphorus (C:N:P) is 29:3.9:<1, whereas the C:N ratio is 7.4 (Table 2). Living biological organic matter has a C:N:P of 100:14:1 (often called the Redfield ratio) and a C:N of 7.1. In comparison, dead and partly degraded organic matter (detritus) usually have higher C:N and C:P ratios. The data therefore suggest that the particulate matter in the samples consists of living material. Algae are not expected to be present as no sunlight reaches these depths. It may therefore be assumed that bacteria may constitute a large fraction of the living material. This assumption is substantiated by the POC value (28.8 μg/l C), which is generally low. One bacterial cell has a carbon content of about 0.025×10^{-12} g. If all of the organic carbon represented bacterial biomass, the bacterial density would be 1.15×10^9 cells/l, which is a typical figure for surface waters, but a factor of 10 too high with respect to deep water. Presumably therefore, the living material consists of other organisms as well in addition to bacteria, such as heterotrophic flagellates and ciliates.

The source of food for the microcell community is dissolved organic carbon (DOC). This matter is a mixture of humic acids which have low turnover rates and are considered to be very refractory (little degradable). Turnover times of 4000-6000 years have been estimated for the deep sea organic DOC (Druffel et al. 1992, Bauer et al. 1992). Bacterial growth in deep water has been measured by i.e. Bussmann (1999) and found to be about 5 % of that in surface water. His measurements were performed at elevated temperatures compared to actual *in situ* deep water, therefore actual growth is presumably even lower. It may therefore be concluded that bacterial growth is very slow.

5. Conclusions and proposals for further work

5.1 Probability of marine growth in cooling water plant at the Nnwa Field

5.1.1 Expected type of growth

The results for nutrients and organic matter have direct relevance for biofouling, as all biofouling starts with the establishment of a bacterial film. The low bacterial abundance and low source of biodegradable dissolved organic matter in deep water at the rig site suggest that the production of bacteria films will be at a very low level. The growth will require not more than very infrequent counter measures, probably less than once per year or at even longer intervals depending on the type of lining in pipes used. At no time is it expected that the main sea pipe will encounter growth of biofilms necessitating the use of frequent counter measures. However even a thin microfouling layer may reduce the effectiveness of the cooling transmission in the heat exchange pipes where the surface to volume ratio is high.

The importance of the material in the pipe linings for growth was demonstrated in the OTEC experiments, e.g. by Berger & Berger (1986). They found that stainless steel exposed for 1 year to running cold deep seawater did not accumulate significant biofouling, whereas aluminium grew a biofilm consisting mostly of bacteria imbedded in a porous hydrated aluminiumoxide matrix. The choice of materials in the cooling system should therefore be given adequate attention

5.1.2 Measures to counteract growth

As long as the requirements to counteract growth may seem to be low, an appropriate measure would be the application of chlorine in some form (see Belluati et al 2001, Nihous 2002). Chlorine (ClO_2) may be directly produced electrocatalytically from sea water or may be added to the sea water in the form of sodium hypochlorite (HClO) or chlorine gas. It is evident from literature that this is the most efficient way to handle microfouling problems. In the present case, where the application of the agent would be very infrequent, presumably in the range of once per year or less, the electrocatalytical method might however be an "overkill".

There are however some environmental concern related to the use of chlorine because of the formation of halogenated organic compounds. Such concerns are clearly most relevant with the continual use of chlorine often demanded in surface water cooling systems. Use of chlorine at the frequency anticipated for the present deep water cooling system do not constitute any environmental risk.

A very important point is to avoid light. All materials in tubes and lining should therefore be non-transparent. Any exposure to light will create a swift biological reaction because of the high concentration of nutrients in the water (Nihous, 2002). Some autotrophic organisms (e.g. microalgae) which need light for growth will always be present in the system

5.2 Proposals for further work

5.2.1 Contact with experienced milieu

Experience with deep water cooling systems is limited. Much of the practical use for such systems seem to have been concentrated at Hawaii at the OTEC experimental facility at NELHA. Two contractors have been identified who has been working with deep waters pipes: Healey Tibbits Builders Inc. and Makai Ocean Engineering Inc. At present, Makai is involved in a OTEC feasibility study in India for a floating OTEC

plant (Makai Ocean Engineering 2002). Further information on the systems and pipeline technology may be obtained by direct contact to NELHA and the technical operators.

5.2.2 Avoidance of intake of larger objects in the cooling water

The risk of having larger floating objects being sucked into the system in the intake water may already have been considered. Such objects could be various large planktonic animals. Most probably the risk is low at 1000 m depth. Nevertheless, some type of net or filter system should be mounted in the intake pipe to avoid the entrance of larger objects that may clog the small dimension pipes in the cooling units.

5.3 Further search of information

There are numerous research groups at R&D institutions around the world working with biofouling. Most of the groups appear to specialise on biofilms, i.e. the initial stages of biofouling and microbiofouling. All aspects are covered, from the formation of biofilms, the types of organisms growing in the films, corrosion processes, and interactions between materials and biofilms. Some of the groups offer teaching and specialised courses. Some examples of institutions are :

Academic institutions:

Faculty of Mathematics and Natural Sciences at Göthenburg University

(<http://www.bbl.gu.se/BBL/BBL.welcome>)

Centre for Marine Biofouling and Bio-Innovation, Univ. of Australia.

(<http://www.unsw.edu.au/clients/bioscience/centre.htm#cmbb>)

MASTEC Multidisciplinary research program focusing on marine biofouling.

(<http://www.gmf.gu.se/Mastec/index.htm> and <http://eee.eng.gla.ac.uk/marine/brossumm.htm>)

In addition, there are a number of commercial and consultancy companies that offer services with regard to biofouling. Many of these develop or operate monitoring systems and perform cleaning services. The commercial companies may generally be traced on the internet. Some examples are (no preferences implied):

Commercial Services:

Fawley Biofouling Services

(<http://biofouling.co.uk/foulingintro.html>)

Biosurface technology Corp.

(<http://www.imt.net/mit~mitbst/9201s.htm>)

InterCorr International, Inc.

(<http://www.clihouston.com/mms.htm>)

Tenera Energy

(<http://www.teneraenergy.com/envir/biofoul.htm>)

More information may be found on:

(http://www.biology.bham.ac.uk/external/BioFoulnet/Related%20sites/rel_sites.htm)

Research groups and further information may be traced by internet searches using appropriate keywords, for instance 'biofouling, microbiofouling, biofilms, cooling water, industrial systems, corrosion', etc.

Scientific studies are presented in ordinary scientific journals, at symposia and workshops, and in reports. Particularly relevant are scientific journals devoted to biofouling such as 'Biofouling' and 'The journal of bioadhesion and biofilm research'. Much information is also contained in symposium and workshop reports. The availability of these varies, some of these are published as books or special issues of scientific journals,

whereas some appear as rather informal reports with a limited distribution. A list of various reported studies are given in Appendix 7.1.

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7. Appendix

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7.2 Field report and analysis of water samples

NOTAT

12. november 2002

Til: STATOIL ASA v/Kenneth Johannessen Eik

Fra: Tom Chr. Mortensen, NIVA-Oslo

Bakgrunn

NIVA ble kontaktet av Statoil våren 2002 (Enquiry no. 2002/00195) og bedt om å gi tilbud på gjennomføring av vannprøvetaking og analyse av utvalgte fysiske og kjemiske parametre fra ulike havdyp ved en boreinstallasjon på Nnwa-feltet utenfor Nigeria. Arbeidet er gjennomført i henhold til kontrakt (ref.nr. 4500462422) og som beskrevet i NIVAs prosjektilbud av 02.04.02. NIVAs prosjekt nr. 21349.

Gjennomføring

NIVAs-medarbeider Tom Chr. Mortensen sto for gjennomføringen av feltnålingene og prøveinnsamlingen. Han ankom Lagos, Nigeria 12.08.02 og dro videre via Port Harcourt til Statoils boreplattform 13.08.02. Prøvetakingsarbeidet ble så satt i gang i samarbeid med mannskap fra Oceaneering (ROV-operatører).

Fire Niskin vannhentere ble montert på Oceaneering sin ROV. Det ble hentet fem liter sjøvann på hvert av følgende dyp: 1000, 700, 400 og 100 m. Fem liter i overflaten ble tatt med håndholdt prøvetaker. Vannprøvene fra de forskjellige dyp ble fordelt på tre en-liters plastflasker for analyse av ulike parametre på NIVAs laboratorium i Oslo og to 200 ml glassflasker for analyse av oksygeninnhold. I henhold til kontrakt, skulle oksygenprøvene analyseres på riggen. Dette lot seg ikke gjøre da Air France ikke fikk med seg Mortensens analyseutstyr fra Oslo til Nigeria. Oksygenprøvene ble derfor konservert i henhold til prosedyre for Winkler-Titrering (NIVA-metode nr. F1-2), og sendt sammen med de øvrige vannprøvene for analyse på NIVAs laboratorium i Oslo.

Det ble også montert en SD-204 CTD på ROVen for måling av en standard CTD-profil. SD-204 måler sjøvannets konduktivitet, temperatur og trykk og ut fra dette beregnes i tillegg salinitet og lydshastighet. Dataene lagres i internt minne og lastes ned til pc etter retur til overflaten. For mer informasjon om instrumentet, se www.saivas.no. Målingene fra SD-204 (profil fra overflate til 1000 m) er vist i en figur bakerst i notatet. Om ønskelig kan datamaterialet leveres på tallformat i en Microsoft Excel-fil.

Mortensen returnerte fra boreplattformen 14.08.02 og ankom Oslo 15.08.02 etter transitt i Port Harcourt og Lagos.

Analyseresultater

Resultatene av analysene er gitt i tabeller under. Følgende parameterkoder er brukt i tabellene:

pH = pH

KOND = Conductivity

ALK = Alkalinity

SAL = Salinity

O2-Sj = Oxygen

Tot-P/L-Sj = Total Phosphorus/ low method sea water

Al/ICP = Aluminium

Ba/ICP = Barium

Ca/ICP = Calcium

Cu/ICP = Copper

K/ICP = Kalium

Mg/ICP = Magnesium

Na/ICP = Natrium

P/ICP = Phosphorus

Pb/ICP = Lead

S/ICP = Sulphur

Si/ICP = Silisium

Sr/ICP = Strontium

Zn/ICP = Zinc

Prøvenr		Merket	pH	KOND	ALK	SAL	O2-Sj	OPP-SA	Tot-P/L-Sj	Al/ICP	Ba/ICP	Ca/ICP
				mS/m	mmol/l		ml/l		µg/l P	mg/l	mg/l	mg/l
			A 1	A 2	C 1	A 3	F 1-2	E 10-1	D 2-1	E 9	E 9	E 9
2002-01831	1	100 m	7.85	5170	2.307	35.673	2.72		43		0.0047	428
2002-01831	2	400 m	7.72	5060	2.276	34.819	1.52		74		0.006	412
2002-01831	3	700 m	7.77	5010	2.258	34.545	2.85		78		0.007	408
2002-01831	4	1000 m	7.79	5030	2.273	34.629	3.3		74		0.007	409
2002-01831	5	0 m	8.13	4910	2.181	33.64	4.56		7		0.0052	413
2002-01831	6	100 m filter						x		0.008	0.004	0.01
2002-01831	7	400 m filter						x		0.002	0.001	0.001
2002-01831	8	700 m filter						x		0.001	0.001	0.002
2002-01831	9	1000 m filter						x		0.006	0.003	0.002
2002-01831	10	0 m filter						x		0.003	0.002	0.005

Prøvenr		Merket	Cu/ICP	K/ICP	Mg/ICP	Na/ICP	P/ICP	Pb/ICP	S/ICP	Si/ICP	Sr/ICP	Zn/ICP
			mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
			E 9	E 9	E 9	E 9	E 9-5	E 9	E 9	E 9	E 9	E 9
2002-01831	1	100 m		370	1350	11200		<0,02	950		7.77	
2002-01831	2	400 m		370	1300	10700		<0,02	950		7.79	
2002-01831	3	700 m		380	1270	10700		<0,02	940		7.64	
2002-01831	4	1000 m		340	1300	10600		<0,02	940		7.8	
2002-01831	5	0 m		380	1290	9780		<0,02	980		7.27	
2002-01831	6	100 m filter	<0,0001	<0,01	0.003	0.04	<0,003	<0,0005	0.005	0.01		0.0001
2002-01831	7	400 m filter	<0,0001	<0,011	<0,0005	<0,005	<0,003	<0,0006	<0,003	<0,0011		0.0002
2002-01831	8	700 m filter	<0,0001	<0,011	0.002	0.03	<0,003	<0,0006	<0,003	<0,0011		0.0001
2002-01831	9	1000 m filter	<0,0001	<0,011	0.001	<0,005	<0,003	<0,0006	<0,003	0.01		<0,0001
2002-01831	10	0 m filter	0.0002	<0,008	0.003	0.04	0.003	<0,0004	0.004	0.005		0.0007

Salinitet og temperatur fra SD-204 monteret på ROV

