doi: 10.1255/tosf.6

The Biota Guard marine oil leak monitoring system—novel sampling application of bivalve PAT biosensors

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The Norwegian high-tech company Biota Guard has developed a unique marine oil detection and monitoring system based on biosensors. The system uses marine *in situ* biosystems as novel sampling sensors in a Process Analytical Technology context which are documented to have a detection sensitivity vastly outperforming traditional physico-chemical sensors. The sampling element in the Biota Guard system receives special attention here.

Background

Environmental impact statements often contain elements related to water quality and water availability. These are issues which represent an increasing obligation for many industry players, governmental bodies and the public in general. Today environmental management is a part of the framework conditions for many industries, and often an important strategic factor. For oil and gas and mining companies, compliance with water quality regulations is instrumental for their “license to operate”. In the offshore oil and gas sector, real-time marine environmental monitoring poses particular complications as there is a wealth of operational information (the “cause”) but significantly less data related to the well-being of the recipient biota in open water masses (the “effect”). Throwing traditional Process Analytical Technology sensors at the problem has not been sufficiently successful.

The Biota Guard marine monitoring system (BGMMS) is developed to address these and other challenges, based on a novel sampling sensor system. This combined oil leak detection and environmental effect monitoring system is capable of detecting environmental stress at very low levels in sea water. The winner in this game is the system that can detect ambient condition deviations at the absolutely earliest occasion, with fully documented reliable efficiency.

The Biota Guard marine monitoring system has been in development since 2006, and has received a resounding interest in the offshore oil and gas industry. The company has received numerous awards and prices for its novel technological business concept, e.g. ONS innovation award for SMEs 2012, and has completed three successful joint industry projects backed by six oil operator companies. The first

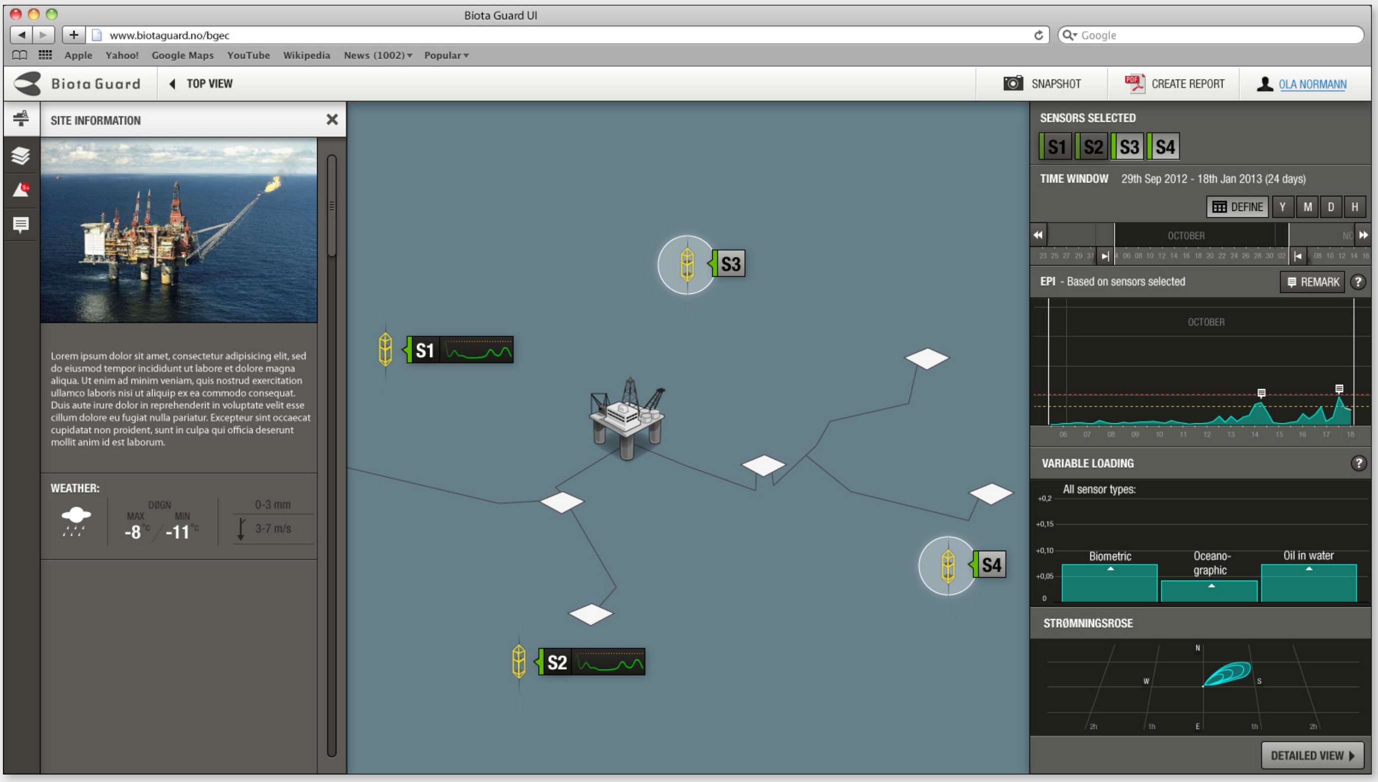

Figure 1. Overview of Biota Guard Marine Monitoring System (BGMMS) user interface. Subsea stations (S1–S4) are here deployed at strategic locations in the vicinity of a North Sea oil producing platform.

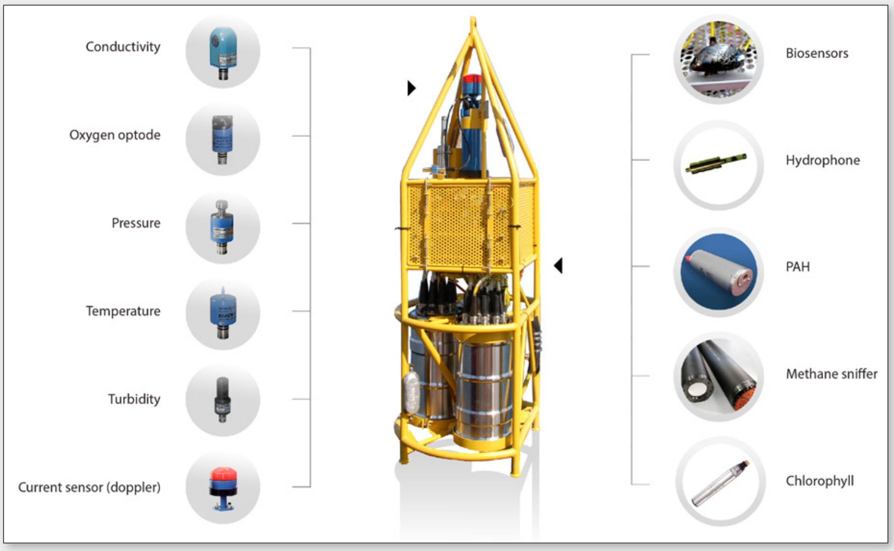

Figure 2. Biota Guard Marine Monitoring System station. The full complement of conventional oceanographic, PAT and the novel biosensors are shown in the side panels. All sensors are integrated in the subsea station (centre). The biosensors are located in the yellow cage (see further in Figure 3).

commercial contracts for to tailor environmental campaigns to assets specifics have been signed.

The general setting of a specific deployment of BGMMS stations is illustrated in Figure 1.

The BGMMS operates as a Process Analytical Technology (PAT) system, e.g. Bakeev (2010), but with a critical new sensor concept added. The system provides an Environmental Performance Index (EPI) by deploying *instrumented live organisms* in addition to conventional oceanographic PAT sensors. The EPI records the effects from chemical changes in the water based on specific biosensor responses. Specifically, ecologically representative bivalves, which typically live in the open water masses of the monitoring object, will show changes in their heart rate activity and other behavioural patterns (e.g. valve opening cyclicity) as a function of both acute and chronic exposure to unique and/or mixed contaminants. The resulting sensor spectra are consequently a reflection of the *total* water quality stressor situation and can be reported in real time. The resulting multi-sensor signals are clearly complex in nature, and critically dependent on the ability to decompose the sum-spectra reliably with respect to the full set of parameters calibrated. There is a huge amount of sensor, and process, technology involved at the front end of the BGMMS as well as chemometric data modelling (multivariate calibration) at the centralised monitoring software systems, before the operator displays emerge, Figure 1. A key issue is that the biosensors act as *sampling sensors*, in the form of "inverted" in-line sensor systems, inverted because the process system is led to the sensor, instead of the sensor being inserted in the process conduit. After this novel twist, however, conventional PAT principles will cover the needs of the full system.

Figure 2 illustrates the full array of physico–chemical oceanographic as well as the novel biosensor complement as employed in standard BGMMS stations.

Sampling sensors: bivalves

The Biota Guard sensor array employs a complement of 32 individual biosensors in addition to a wide array of potential chemical and physical sensors, not all of which are necessarily deployed in each specific situation. The combined sensor complement enables the proprietary Biota Guard software monitoring system to extract *latent* information from the specific suite of multiple sensors, resulting in an unprecedented, game-changing sensitivity with respect to oil concentration. Detection sensitivity in laboratory tests (e.g. trials at SINTEF Sealab in February 2013 over a 24-hour period) has been shown to be three orders of magnitude lower than traditional physico-chemical sensors that need to interact with the leaking medium. The sensitivity has also been tested and verified in extensive exposure studies at the International Research Institute of Stavanger – Environment (IRIS) carried out in Joint Industry projects, 2007–2013.

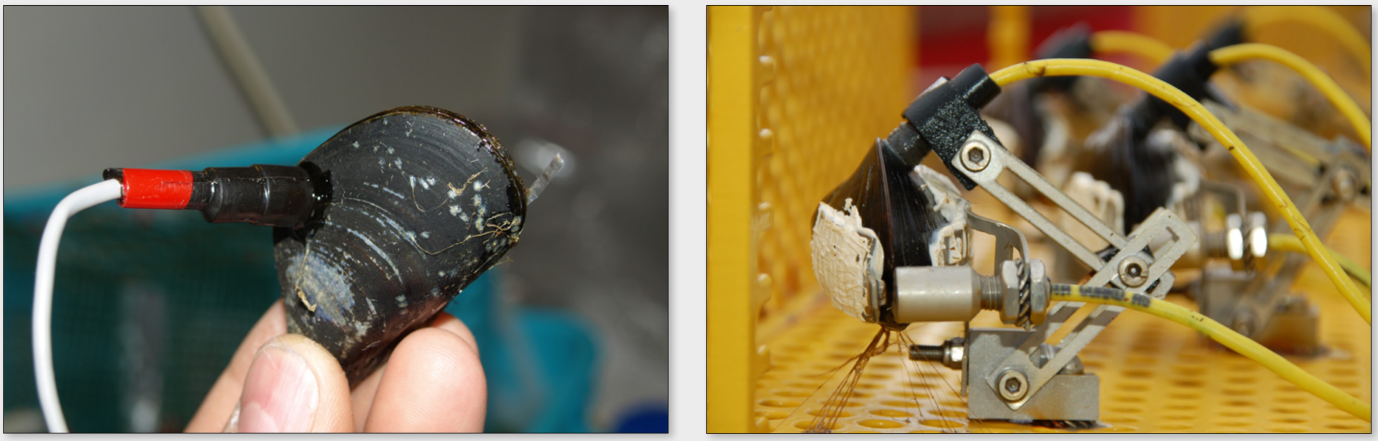

Figure 3. Instrumented bivalves fitted with an infrared sensor for heart rate determination (left), and with added calipers for recording valve gape (opening–closing) characteristics as well (right).

Figure 4. Training a "school" of bivalves in Biota Guard's water exposure tank. Signal acquisition is otherwise reminiscent of PAT and is further processed by chemometric methods. Training can be simple employing only one parameter at a time, or more realistically, targeted on several interacting parameters in order to reach full compliance with the natural open sea characteristics at a target location.

The core of the system is comprised of a general patented bivalve sensor concept, while the specific bivalve species selection is dependent upon the oceanographic conditions at the target location. Details of sensor instrumentation and acquisition system, digital signal transfer, signal processing and conditioning, data analysis and operator presentation principles and methods are only indicated in the selected illustrations. A key insight which can be disclosed, however, is that the information processing system is based on a core of advanced Theory of Sampling (TOS) elements as well as chemometric data modelling features (PLS regression).

The most interesting part of the system for readers of *TOS forum* is no doubt the *sampling biosensors* which are described in more detail below within the proprietary concept context (Figures 3 and 4).

The EPI reflects both acute chemical changes in water over short time spans, as well as accumulated effects over longer durations, all of which are reflected in minute changes in the characteristic biosensor spectral responses. A leak detection event is triggered when the EPI crosses a predefined threshold. The EPI threshold needs to balance sensitivity and specificity, in order to provide a reliable, robust detection with well documented zero false leak detection events. This is where a significant amount of chemometric data pre-treatment and data modelling is involved.

A critical success factor is proper *calibration* of the sensor system(s), i.e. multivariate calibration in the chemometric parlance. Figure 4 shows bivalve sensors in a pre-deployment holding tank in Biota Guard's laboratories, where training and calibration first takes place. Note that extensive sensor redundancy is needed to counteract the inherent biological variability between individual sensor elements. There is a certain analogy with electro-chemical "Electronic Tongue" arrays,[2–4] where the individual sensor dose-response differences are admittedly much larger, but also here only brought under full control by multivariate calibration and judicious validation.[5] In the somewhat simpler bivalve-stressor context, the experience is for excellent averaging results over 32 bivalves.

Calibration of the system follows experimental design principles, but not necessarily standard DOE layouts. From the number of stressor parameters involved in natural systems and the number of concentration levels needed, the potential total number of experimental runs will very easily reach impossible levels—one of the still proprietary elements in the BGMMS development plans is directly aimed at the means needed to circumvent this formidable obstacle.

Figure 4 shows a "class" of bivalves in the exposure tank about to graduate from such full and comprehensive schooling at the training academy to be installed in an active subsea station. It is not all finally deployed bivalves that need to be trained prior to live operation, however. Laboratory work gathers important input–output data during exposure study that increases our understanding and improves real-time models for ocean deployment.

Test campaigns

Two specific oil leak feasibility detection tests have been devised (in collaboration with SINTEF, Trondheim) in order to demonstrate the system's sensitivity to oil stress. Two leak scenarios were defined with specific oil exposure profiles. The objective was to determine the effective detection limit of the subsea sensor array under fully realistic deployment conditions. Table 1 gives an overview of the most important test parameters and their performance.

The BGMMS detected both types of leakage in these scenarios. The oil concentration at the point of detection was 1.2 mg L^{-1} and 0.5 mg L^{-1}, respectively. A key system sensitivity feature in comparison to other types of sensors concerns transition from ideal lab tests and calibration to operations in oceanic open water masses. BGMMS is more tolerant of varying oceanographic conditions, such as turbidity, luminous sources etc. To date this is a substantial challenge for other leak detection sensors based on optical principles.

SINTEF also performed a 3-D spatial simulation based on a given leak scenario with a leak rate of 1 m³ per day. This simulation provided Biota Guard with concentration fields in the water column at various distances from the leak. Table 2 gives an overview of the distance from leaks required in order to *trigger* a leak detection event.

Test results from the full OSCAR simulation experiment, Table 2, allowed determination of an operative EPI threshold, which was set to ±3 std, which is the level used in the system illustrated in Figure 1.

Discussion

Continued monitoring of the marine environment and especially early warning oil leak detection is a challenging and complex endeavour. A range of different technologies are currently in use, based either on

Table 1. Leak detection results (SINTEF).

Scenario	Oil type	Exposure range	Leak duration	Leak detected	Concentration at point of detection	EPI threshold	Modelling mode
Minor leak	Statfjord	0–3 mg L^{-1}	10 days	Yes	1.2 mg L^{-1}	3 std	Batch
Acute spill	Statfjord	0–5 mg L^{-1}	1 day	Yes	0.5 mg L^{-1}	3 std	Batch

Table 2. Overview of leak detection ranges of the BGMMS, based on concentration fields generated by SINTEF's OSCAR (Oil Spill Contingency and Response) simulation.

Oil leak rate	Subsea sensor array distance from leak	Gradient concentrations	EPI threshold	In detection range
1 m^3 per day	100 m	2.75 $mg\,L^{-1}$	3 std	Yes
1 m^3 per day	200 m	2.5 $mg\,L^{-1}$	3 std	Yes
1 m^3 per day	500 m	0.180 $mg\,L^{-1}$	3 std	Yes
1 m^3 per day	1000 m	0.07 $mg\,L^{-1}$	3 std	No
1 m^3 per day	2000 m	0.045 $mg\,L^{-1}$	3 std	No

physico–chemical interaction with the leaking medium, on active or passive acoustics or on optical spectral detector principles (NIR in particular) or "fly-by" inspection enabled by ROVs. The comprehensive BGMMS sensor array represents a group of leak detector systems that is based on direct interaction with the leaking medium utilising several advantages. Because of the very low concentrations needed to be quantified, the sensitivities of traditional sensors has to date called for some sort of physical collection, *physical sampling*, in order to accumulate and amplify the oil concentration to detectable levels, requiring various analytical system additions and complexities.

Judicious use of novel instrumented biosensor systems, acting as direct integrating sampling agents and delivering direct digital multi-spectral signals, has allowed Biota Guard to develop a unique monitoring and detecting system with a very promising application potential in the oil and gas offshore industry, but also beyond (environmental and mine waste water monitoring in rivers and lakes etc.). The results listed in Table 1 testify to a very high sensitivity compared to other competing leak detectors that also interact directly with the leaking medium. As per the test results reflected above, this advantage is estimated to be up to ~1400 times more sensitive in these realistic scenarios.

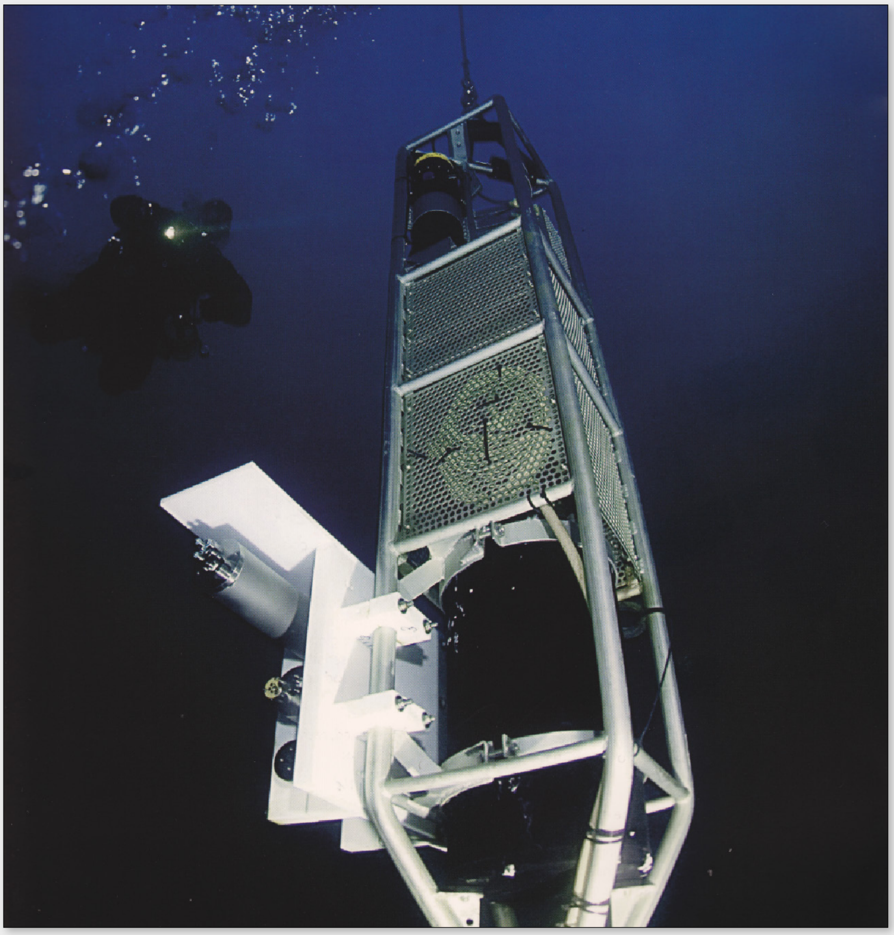

Figure 5. Fully calibrated bivalves are located in Biota Guard's subsea station (upper cage). The station shown here was deployed in a fjord in the Norwegian North Sea during one of Biota Guards full-scale testing campaigns. Credit: Vidar Skålevik.

Conclusions

The Biota Guard Marine Monitoring System (BGMMS) employs novel *sampling biosensors* which are representative of the deployment target site. The critical success factor of this system is intimately bound up with the use of novel instrumented biosensor systems, acting as passive, integrating sampling agents, delivering digital multi-spectral signals. Through chemometric data analysis principles (PAT) and dedicated design of experiment training, these signals are decomposable allowing a highly relevant Environmental Performance Index, EPI, to be developed and displayed on operator displays, increasing the reliability of decision-making.

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