An integrated approach to environmental decision-making for offshore oil and gas operations

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ABSTRACT

A brief overview is given of a research program on environmental risks associated with offshore oil and gas industry discharges. The research has two major thrusts: development of environmental risk assessment and risk management methods, and development of underwater vehicle technology for scientific and monitoring missions. This paper focuses on the former. The project is a joint venture between the Ocean Engineering Research Centre at Memorial University of Newfoundland and the Institute for Marine Dynamics of the National Research Council Canada, with the support of several Canadian companies and universities. This paper describes several elements of the project: (a) the development of a risk management methodology for drilling waste discharges in the marine environment, (b) development of a probabilistic hydrodynamic model and risk-based design procedure for produced water discharges, (c) performance characteristics of several candidate sensors for environmental effects monitoring, (d) laboratory investigation of the settling characteristics of drill cuttings, (e) evaluation of various offshore treatment technologies for drilling waste using multi-criteria decision-making, and (f) evaluation of air emissions associated with the offshore petroleum industry and environmental management practice to mitigate the impacts. The ultimate goal of the research is to integrate current and emerging scientific knowledge and technology with the goals of environmental protection and their associated costs in a holistic framework to guide decision-making under uncertainty.

Keywords: Drilling waste, produced water, autonomous underwater vehicle (AUV), chemical sensors, ecological risk assessment, environmental effects monitoring, multi-criteria decision-making, and treatment technologies.

ENVIRONMENTAL RISK, REGULATION, AND POLICY

Offshore oil and gas operations worldwide are facing significant changes in environmental protection regulations, which reflect the evolving values placed on the environment by society and the subsequent adoption of these values in governmental and industrial policies. Different jurisdictions are implementing changes at different paces, but the general direction is the same: more attention is being focussed on environmental risk and more effort is being directed toward mitigating it. There is no shortage of opinion on the questions that arise in this context, such as what should be protected, and at what cost, what is an acceptable level of risk, and how does perception match with reality. These are issues that should be debated by stakeholders in each jurisdiction and the outcomes are not likely to be the same, nor should they be expected to be the same.

Scope

The focus of the work presented here is significantly narrower in scope. It concentrates on the scientific and technical aspects of environmental risks related to the major marine discharges associated with the offshore petroleum industry. The goal of the research is to integrate current and emerging scientific knowledge and technology with the goals and costs of environmental protection in a holistic framework to guide decision-making under uncertainty.

This work is being pursued by a partnership consisting of the Ocean Engineering Research Centre at Memorial University of Newfoundland and the Institute for Marine Dynamics of the National Research Council Canada, with the support of several Canadian companies (Petro-Canada, International Submarine Engineering, Applied Microsystems) and universities (University of Victoria).

Most of this work is being carried out under a major project entitled *Offshore Environmental Risk Engineering Using Autonomous Underwater Vehicles*, which has two major thrusts: development of environmental risk assessment and risk management methods, and development of underwater vehicle technology for scientific and monitoring missions. This paper concentrates more on the former and describes several elements of the project: (a) the development of a risk management methodology for drilling waste discharges in the marine environment, (b) development of a probabilistic hydrodynamic model and risk based design procedure for produced water discharges, (c) performance characteristics of several candidate sensors for environmental effects monitoring, (d) laboratory investigation of the settling characteristics of drill cuttings, (e) evaluation of various offshore treatment technologies for drilling waste using multi-criteria decision-making, and (f) evaluation of air emissions associated with the offshore petroleum industry and environmental management practice to mitigate the impacts.

While much of this work is relevant in an international sense, the project is particularly concerned with the developments off the East Coast of Canada. Of the various discharges to the environment, produced water and drill cuttings are the main focus of this work.

Produced water is a combination of formation and injection water and can be a complex mixture of inorganic and organic compounds, which has the potential to be toxic to the ocean environment. Constituents of concern include metals, petroleum hydrocarbons, nutrients, radionuclides and treatment chemicals. Typical discharge rates for produced water can be high. Over the life of the producing field, the quantity of discharge can be typically 10 times as high as the volume of hydrocarbons produced. Models of the produced water discharge tend to predict that produced water will be rapidly diluted and dispersed when discharged into the ocean, however, real data with which to corroborate these assertions are scant (Mukhtasor 2001).

Produced water is treated continuously and then discharged. Discharge limits of oil in water in the US Gulf of Mexico and the OSPAR (Oslo and Paris) convention countries are 29 mg/l and 40 mg/l, respectively, for a 30 day average. OSPAR plans to move to a 30 mg/l limit within 4 years. New draft regulations for the East Coast of Canada have followed the OSPAR limit of 40 mg/l, but have put operators on notice that this might be reduced to 30 mg/l at the next regulatory review (CNOPB 2002).

Drill cuttings are a product of exploration and production drilling operations and are typically discharged and settle on the seabed. For the most part, cuttings are small rock particles, but some amount of the drilling mud adheres to the rock particles. The drilling fluid (mud) is a mixture of water, base fluids, special clays, minerals, and chemicals that is pumped downhole through the drill string and is ejected through nozzles in the drill bit at high pressure. The jet of fluid lifts the cuttings off the bottom of the hole and away from the bit. The drilling fluid is circulated to the surface through the annulus between the drill string and casing. At the surface, the drill cuttings, silt, and sand are removed from the drilling fluid before it is returned downhole through the drill string.

The cuttings, sand, and silt are separated from the drilling fluid by a solid separation process. Some of the drilling fluid remains attached to the cuttings after treatment. After solid separation, the cuttings are disposed of in a manner that depends on the type of drilling fluid used, the oil content of the cuttings, and the regulatory regime. The disposal methods include transport to shore for land-based disposal, ocean discharge, and re-injection. The early focus of efforts to reduce the environmental impacts of cuttings discharges was centered on reducing the volumes of drilling fluids discharged with the cuttings, as well as the generic toxicity of the base oil itself. By 1985 it became clear that regardless of the inherent levels of toxicity of the base oils, the cuttings piles persisted and continued to pollute for many years due to leaching of chemicals into the ambient environment (Hall 2000).

The U.S. EPA (1999b) suggested product substitution, e.g., synthetic based fluids (SBFs) instead of oil based fluids (OBFs), as the best way of reducing environmental impacts. The oil industry has developed many base materials, such as vegetable esters, to increase the efficiency of drilling operations. With these improved characteristics, the U.S. EPA (1999a) is still proposing controlled discharge of the cuttings associated with SBFs. SBFs are less dispersible in nature and sink to the seafloor, and may be a potential environmental concern to the benthic community. It is believed that environmental impacts include smothering by the drill cuttings, changes in grain size and composition, and anoxia caused by the decomposition of organic matter (U.S. EPA 1999a). The environmental impacts associated with the zero discharge of OBFs can be more harmful than the discharge of SBFs due to non-water quality environmental impacts, like air pollution and ground water pollution in the case of incineration and land based disposal, respectively (U.S. EPA 1999a).

In addition to the marine discharges, air emissions are coming under increasing scrutiny. Emissions of gases associated with the production of oil and with refining operations are a cause of concern at the local and at the global level. Flaring or venting of associated natural gas, including methane and other light hydrocarbons, is a major contributor to the build up of green house gases directly linked with global warming problems. The adverse impacts of global warming are expected to have a particularly marked effect on the environment.

RESEARCH PROJECT

The major elements of the research project *Offshore Environmental Risk Engineering Using Autonomous Underwater Vehicles* are outlined in Figure 1. This research has two major parts: methodology development for environmental modeling and risk assessment, and development of techniques for environmental effects monitoring (EEM). Environmental modeling research is subdivided into water quality and non-water quality (waste emissions from stacks and flares). Water quality modeling is again subdivided with respect to type of waste discharged. Drilling waste and produced waters are the two major groups. Both waste discharges require fate and transport modeling and ecological risk assessment steps. The development of an autonomous underwater vehicle (AUV) is focused on environmental monitoring and scientific sampling missions.

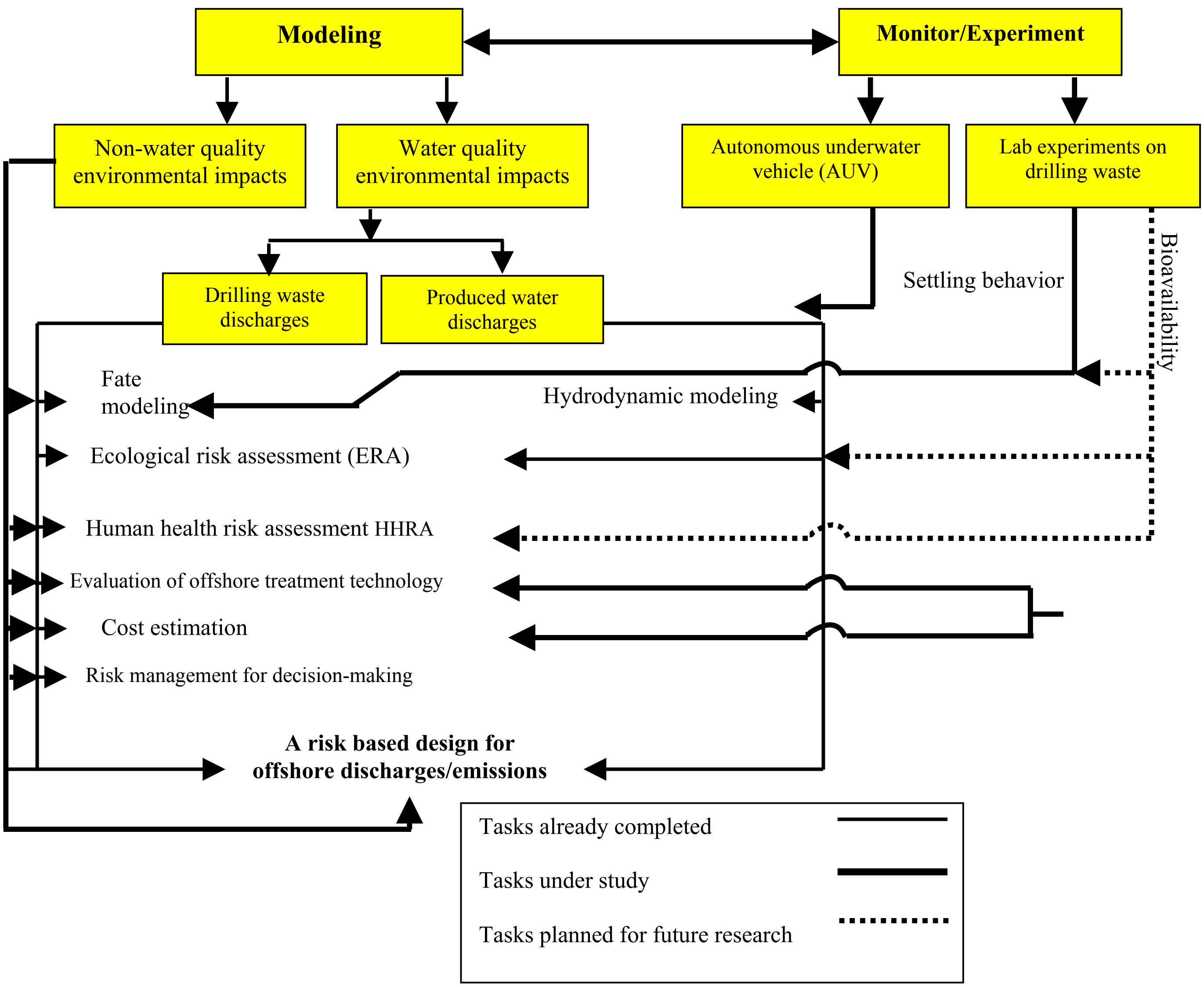

Figure 1. An integrated approach for risk based design for offshore oil operations.

Drilling waste discharges in the marine environment – A risk based decision methodology

The main aim of this work is to develop a risk management framework for determining the best drilling waste discharge scenario for disposal in the marine environment (see Figure 2). The specific objectives are:

(a) development of probabilistic contaminant fate modeling methodology using fugacity and aquivalence based approaches;
(b) development of an ecological risk assessment methodology using probabilistic concepts;
(c) development of human health cancer and non-cancer risk assessment methodologies using probabilistic concepts;
(d) development of a fuzzy composite programming framework for risk management by integrating environmental risk, cost estimates, and technical feasibility for various treatment options; and
(e) an application of the developed risk management framework to a hypothetical case study.

Fate modeling is performed using fugacity and aquivalence based concepts. A chemical specific approach is employed for contaminant fate modeling. A steady state non-equilibrium water and sediment interaction model with probabilistic inputs is used to determine the contaminant concentrations in the water column and pore water. The uncertainty and variability in the model inputs are expressed by statistical distributions. The concentrations in the water column and pore water are estimated using Latin Hypercube sampling (LHS) based Monte Carlo (MC) simulations. The concentrations in the water column and pore water follow lognormal distributions. Estimated parameters of lognormal distribution for known discharge conditions are used for performing multiple regression analyses. The highest 95th percentile is used as the predicted environmental concentration (*PEC*). The uncertainties in the *PEC* are expressed by the coefficients of regression models.

The *PEC* values are converted into exposure concentrations (*EC*) by adjusting for bioavailability and probability of exposure. The whole ecological community is defined as assessment endpoints. The toxicity assessment analyses are based on the lognormally distributed predicted no effect concentrations (*PNEC*). The lowest 10th percentile on *PNEC* distributions is used as a safety level, or *PNEC* criteria value. Bootstrapping is performed on original *PNEC* data to determine the uncertainty in the *PNEC* criteria values. The hazard or risk quotients (*HQ*/*RQ*) are calculated by dividing *EC* with *PNEC* criteria values. The CHARM model's approach is used to convert *HQ*/*RQ* into risk estimates for each contaminant. The composite ecological risk for drilling waste is determined by integrating the individual risk estimates assuming statistically independent events.

The human health risk methodology is based on the consumption of contaminated seafood. A probabilistic framework for human health risk assessment is used for cancer and non-cancer risk estimates. The chronic daily intake rate (*CDI*) is established based on fish ingestion rates, lipid content, bioconcentration factors, exposure duration, and exposure frequency. The LHS based MC simulations are performed to estimate the *CDI*. Arsenic is the only proven human carcinogen in the drilling waste stream. The composite hazard index for non-cancer risks is calculated by simple addition for a given exposure scenario.

A risk management methodology using fuzzy composite programming (FCP) is used. The costs of treatment, drilling fluid loss due to discharge, and ecological and human health damages are estimated. The technical feasibility of various solid control devices is also included from a performance viewpoint. The environmental risk reductions, cost saving and technical feasibility indices are grouped using FCP methodology. A double weighting scheme is employed in FCP. The final utility and centroidal values of the system improvement indices are calculated through fuzzy ranking methods to determine the best management alternative.

The risk management framework was applied to a hypothetical case study on the East Coast of Canada. Five discharge scenarios, or management alternatives were selected for the analysis: 10.0%, 8.5%, 7.0%, 5.5% and 4.0% attached base fluids to wet cuttings. Sensitivity analysis was performed using four different weighting schemes to account for human subjectivity.

This study has introduced a new concept of integrating probabilistic fate modeling with ecological and human health risk assessment methodologies within a risk management framework to determine the best management alternative under conflicting objectives. It has provided a framework for a decision support system for the selection of the best drilling waste marine discharge option under any known regulatory and technical constraints. The results of this research can be seen in Sadiq (2000, 2001) and Sadiq *et al*. (2000, 2001a-b, 2002a-d).

Hydrodynamic modeling and ecological risk based design of produced water discharge

In the context of produced water discharges, environmental risk assessment (ERA) has usually been directed at monitoring. Mukhtasor (2001) considered the engineering design of a discharge outfall for produced water from an offshore platform using hydrodynamic modelling and considerations of ecological risk assessment. The specific objectives of this research were:

1. Develop an initial dilution model;
2. Integrate the developed initial dilution model with a far field model;
3. Develop a methodology for probabilistic hydrodynamic modeling;
4. Identify methodologies for ERA of produced water;
5. Develop a framework for risk-based design; and
6. Apply the framework to a case study.

Conceptual and numerical problems associated with presently available initial dilution models were identified and a new approach to initial dilution modeling was proposed based on the hypothesis of additive shear and forced entrainment combined with nonlinear regression. The proposed approach is systematic and provides an objective means of evaluating the initial dilution model. The new model is more robust than previous models and is conceptually and numerically more defensible. It gives a unique, continuous solution of centreline dilution. Further, it does not assume that the current has no effect in the buoyancy dominated near field (BDNF), which other models do; in the buoyancy dominated far field (BDFF) region the model has one parameter fewer that an existing model, but is no less accurate; in the transition region it gives a unique solution, which asymptotic models do not; it has approximately the same precision for all regions (BDNF, BDFF, transition); and it can also be presented in a probabilistic form that permits calculation of failure probability for specified model inputs and a threshold dilution.

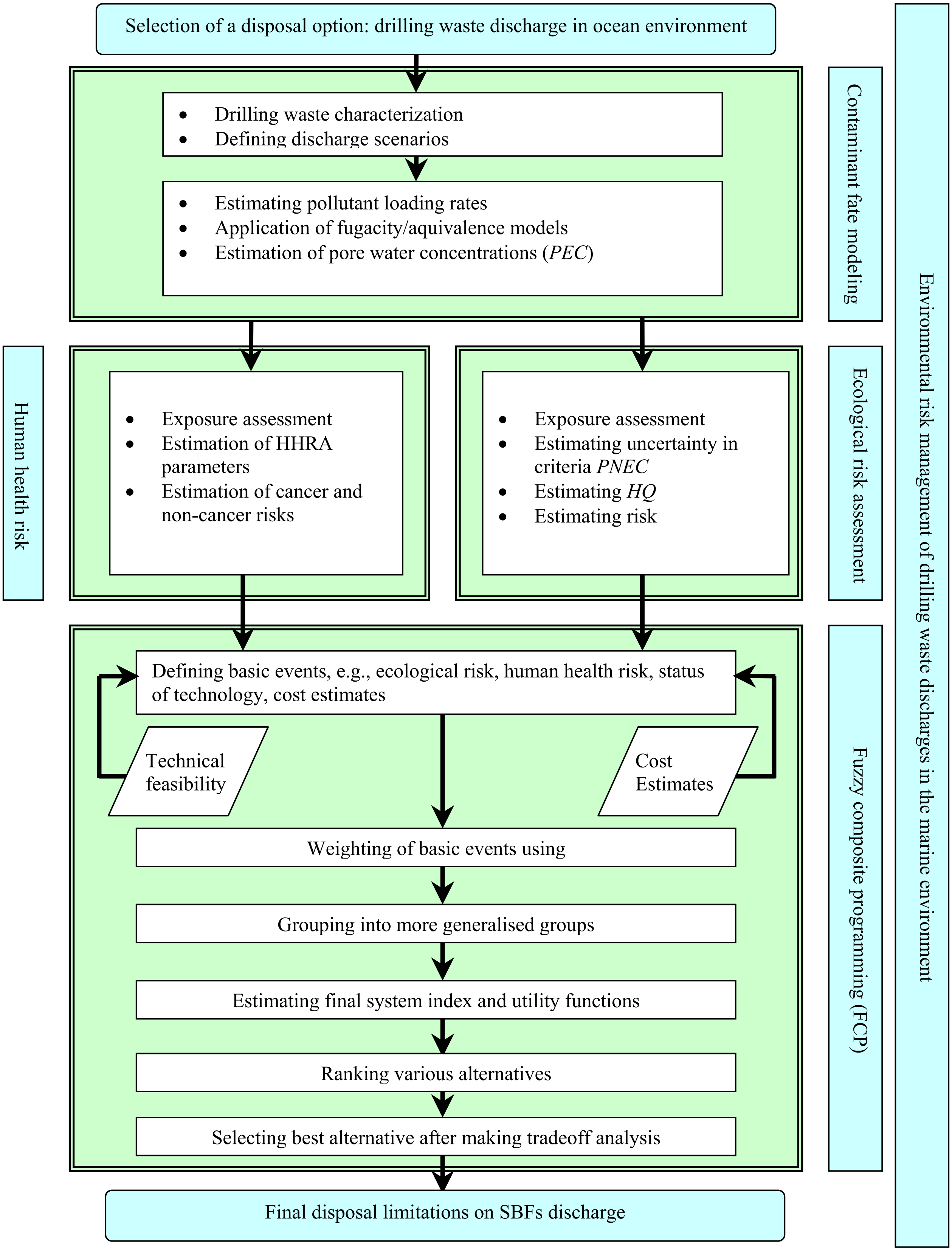

Figure 2. An integrated approach for risk management of drilling waste discharges.

Hydrodynamic modeling was carried out by integrating the near and far field models. The initial dilution model was used as the near field model. The far field model and control volume approach for connecting near and far field models were adapted from published methods. A comparison using a case study showed that the proposed hydrodynamic model and the CORMIX model are generally in good agreement, particularly in estimating average effluent concentrations. The new model also provides the concentration field in the *x-y* directions so that it may also be applicable for analysis of mixing zones, which in some cases is defined in terms of the horizontal area around the discharge location. The new model can also be used in a probabilistic analysis to take into account the uncertainty associated with the model inputs, coefficients, and error term. The probabilistic analysis was done using Latin Hypercube Sampling (LHS) based Monte Carlo (MC) simulations.

Performance characteristics of candidate sensors for environmental effects monitoring

Several candidate autonomous underwater vehicle missions have been proposed. At this early stage, these missions serve as both trials of the AUV technology, and an opportunity to gather information to validate predictive models, such as the produced water fate models described above. Conventional strategies for ocean sampling involve the collection of samples of water and biological specimens using equipment that is usually deployed over the side of a ship, and the return of these samples to land laboratories for analysis. Such methods are tedious and sometimes inaccurate, as volatile chemicals will disappear quickly. Thus in-situ chemical analysis of samples is desirable in order to keep the quality of the samples high. This could be achieved by equipping an AUV with suitable sampling and chemical analysis equipment.

An AUV is a self-propelled submersible robot capable of carrying out pre-programmed tasks without human intervention. AUVs are particularly suited for applications in hazardous environments because they do not require a human support team nearby or a tether to the surface. These vehicles provide a platform for a wide variety of offshore tasks, including oceanographic sampling and research, environmental monitoring, under-ice mapping, pipeline inspections and surveys, and offshore oil and gas systems maintenance and support. In the present context, an AUV might provide a suitable platform for sensors to detect the presence of chemicals in drilling wastes and produced waters, and for validation of numerical models that predict the consequences of these discharges.

In a recent trial, a mass spectrometer was used for identifying the chemical constitution of a substance by means of the separation of compounds according to their differing mass and charge. The Applied Microsystems Limited (AML) mass spectrometer is an innovative underwater mass spectrometer first developed at the Center for Ocean Technology at the University of South Florida. The subsequent development of the mass spectrometer at AML is an on-going process that continually changes to suit the needs of the mission.

The underwater mass spectrometry system is housed in three separate pressure vessels that are connected in series for deployment. The front vessel serves as the sample collection system and contains a pump and a flow injection system. Sample water is continuously pumped into a 1-ml sample loop, the contents of which are periodically swept into the membrane introduction mass spectrometer (MIMS) system in the central vessel by switching the flow injection valve. Pumping deionized water from a reservoir bag into the MIMS interface probe displaces samples. In this manner changes in ion intensities for selected masses can be continually compared to background levels in the mass spectrometer. It is possible to use a carbon filter rather than deionized water that will reduce the complications associated with the reservoir bag and related plumbing. In addition, a continuous mode of sampling can be used. This type of sampling will eliminate the need to switch the flow injection valve, which will reduce sample time.

A continuous mode of sampling was chosen for the trials. The continuous sample mode does not compare samples against a background level to give discrete values. Instead, it compares changes in concentration as the mass spectrometer is moved through the water stream. The central pressure vessel contains the main components of the mass spectrometer. These components include the vacuum chamber and mass analyzer with membrane introduction probe, associated electronics, turbo molecular vacuum pump and controller, CardPC™ motherboard with 72MB DiskOnChip memory, and a power distribution board which can be interfaced with an external computer that activates the various components in sequence. The third vessel contains two dry diaphragm pumps in series that serve as backing pumps for the turbo pump. The practical depth of deployment for this system is presently limited to 30 m.

The trials were conducted over a three day period from February 4 through February 6, 2002 in Burrard Inlet, near Vancouver, BC. The AUV used for the trials was the ARCS vehicle supplied by International Submarine Engineering in Port Coquitlam, BC. The first step was to install the mass spectrometer on the AUV. There were no complications in adding the equipment to the payload bay of the AUV. The mass spectrometer was also user-friendly. The software included with the instrument is Windows based and allows for easy control of the mass spectrometer. A picture showing the mass spectrometer installed on the AUV is presented in Figure 3.

Dimethyl sulphide (DMS) was used as a chemical tracer for this experiment. It was pumped into the inlet at a rate of about 7 l/h. The AUV support staff programmed ARCS to do a mission with the mass spectrometer on board. The captain and crew of the research vessel estimated the current direction, and ARCS was programmed to do a lawnmower pattern back and forth perpendicular to the current direction. The reason for this choice was that the current was the means of transport for the DMS. Initial results indicate that the mass spectrometer detected the DMS during the sea trials. This result shows the potential for the use of such an instrument for environmental monitoring of chemicals in an effluent plume. The picture in Figure 4 shows the ARCS vehicle on its mission.

Figure 3. Mass spectrometer in ARCS vehicle.

Figure 4. The ARCS AUV on trial mission.

Laboratory investigation of the settling characteristics of drill cuttings

The settling behaviour of drilling waste is uncertain and will undergo a number of physical-chemical processes upon discharge. The fate of these discharged drilling wastes (cuttings and fluids) will depend upon the local oceanographic conditions, quantities and conditions of discharge, amount, type and concentration of fluids on cuttings, and fall velocity of cuttings particles. The synthetic base fluids (SBFs) are not water miscible and tend to aggregate and fall rapidly through the water column. To predict the fate of SBF drilling cuttings, it is important to understand how they behave upon discharge. A detailed risk management study for drilling waste has already been conducted (see above) in which some assumptions were made to determine the fate of drilling waste in the marine environment. Additional work is underway in order to improve the knowledge of the physical characteristics of the cuttings waste stream in order to improve fate modeling.

A number of mathematical models have been used to assess drilling discharge during the past three decades. Many of the available models for the various processes were developed based on simple concepts and have had limited testing. Predictions made by different models differ significantly. For example, Huang (1992) conducted laboratory investigations on the transport properties of water based drilling fluids (WBFs), including resuspension, flocculation, and settling speeds.

In the current project, flocculation properties of drilling waste will be examined by using a blade type flocculator, which can generate a wide range of turbulent shear. Typical values of shear rate in the ocean environment are in the range from 0.01 to 10 s^{-1} (David *et al*. 1994). The cohesive fine particles (d<38 μm) will be sieved out from the SBF cuttings slurry and diluted to 5, 10, 25, 50, 100, 200, 500, and 1000 mg/l by mixing with synthetic seawater. The flocculator will be run at a series of constant rotational speeds to generate fluid shear in the samples. At specific time intervals, the flocculator will be stopped and samples put into a 2.5 m high settling column for a particle size analysis and settling speed test. High resolution and high speed digital photographs will be employed to track the falling particles. The recorded images will be used to determine the particle size distribution and settling speed of each particle. Both the non-cohesive and cohesive particles will be tested. Through the analysis of experimental data, the flocculation time, floc size distribution with flocculation conditions, and the settling velocity-size relationship in quiescent water will be obtained.

The setup for the quiescent water settling experiment has been tested using sand particles. The experimental results for terminal velocity are compared with the settling velocities of glass spheres (Gibbs *et al*. 1971) and sand particles (Sleath 1984) in Figure 5. The settling of fine particles was found to reach a constant speed (terminal velocity) in a very short time after discharge. Even very coarse particles were found to approach their terminal velocity within a few seconds. It was also shown that the shape of particles has a strong effect on the terminal settling velocity and this effect is more significant for large particles. The shape of SBF drilling cuttings varies a lot, especially when flocculation occurs.

Turbulence in the water body has a significant effect on the settling of suspended particles. These turbulence effects have been studied by number of investigators, but inconsistencies in results have been reported (Peter 1993). In order to investigate the turbulence effect on settling and the dispersion of drilling particles in dynamic conditions, tests in a wave tank may be done.

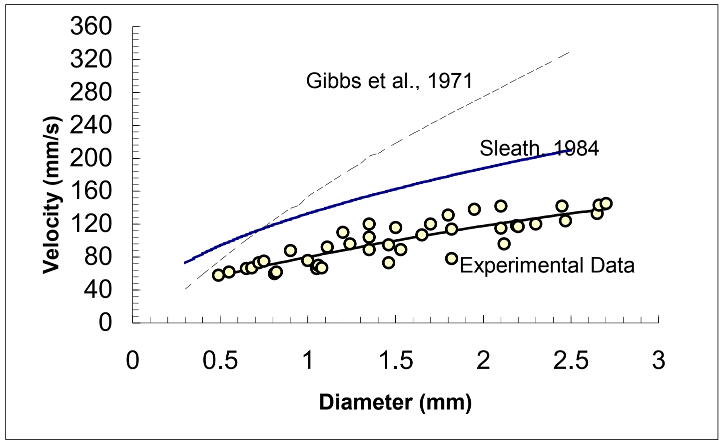

Figure 5. Settling column (left) & results for sand particles.

Evaluation of offshore treatment technologies for drilling waste using MCDM

The main objective of this element of the program is to evaluate available offshore treatment and disposal technologies for drill cuttings in order to recommend the optimum offshore management option for a particular case. The focus of the research is the offshore techniques to treat and dispose of synthetic based drilling fluid-contaminated cuttings.

Due to disadvantages of onshore treatments, such as those requiring transportation of wastes to shore for treatment, only treatment and disposal methods that can be used offshore are evaluated. The treatment methods include both those that are currently used offshore, and those that are used onshore but have potential for offshore application. Disposal by re-injection is also included as one alternative in the evaluation. In the initial stage, the drill cuttings treatment and disposal techniques that are of interest include five major groups: mechanical, thermal, chemical, and biological treatment techniques, and drilling cuttings re-injection.

The mechanical treatments, which include shale shakers and centrifuges, are widely used as solid separation units. These technologies are not able to reduce the amount of drilling fluid on cuttings to a sufficiently low level to comply with discharge restrictions in some jurisdictions. Other kinds of treatment, such as thermal desorption, and other chemical treatments, for example supercritical extraction and micro emulsion, can reduce the adhering drilling fluid to a relatively low level. They are more typically used as onshore treatment systems, but have potential for use on offshore platforms.

In conducting the research, baseline treatment technologies for drill cuttings will first be identified. After that, from the data collected, multi-criteria decision-making method will be used to evaluate the treatment technologies based on various criteria including technical, environmental, and economical issues.

The evaluation method will include criteria that are grouped into four major categories: technical, rig compatibility, environmental, and cost criteria. Under the technical category, reliability and operational ease are two of the issues that will be included. As for rig compatibility, issues such as size and mass will be considered. Reduction of fluids on drilling cuttings, as well as health and safety risks will be considered under the environmental criteria; capital and operational costs will be parts of the cost criteria (see Figure 6).

The criteria will be weighted according to their importance; the total of the weights will sum up to one. Each criterion will be scored using either natural or constructed evaluation measures. The natural evaluation measures are those that can be commonly interpreted by any person, while the constructed evaluation measures are created for a specific or comparative purpose (Parnell *et al*. 1999). Then, each value from the evaluation measures will be converted into a value ranging from zero to ten. The value conversion can be conducted using single dimensional value functions which are assumed to be linear functions. The overall scores can be calculated from the additive function or the sum of the product of the evaluation score and its weight for each criterion.

The overall scores will then be used to compare treatment options. The option with the highest score will be recommended as the optimum cutting management method. The method is now being modified so that it is able to differentiate and determine the best method. Uncertainties might also be included in the evaluation in a later stage.

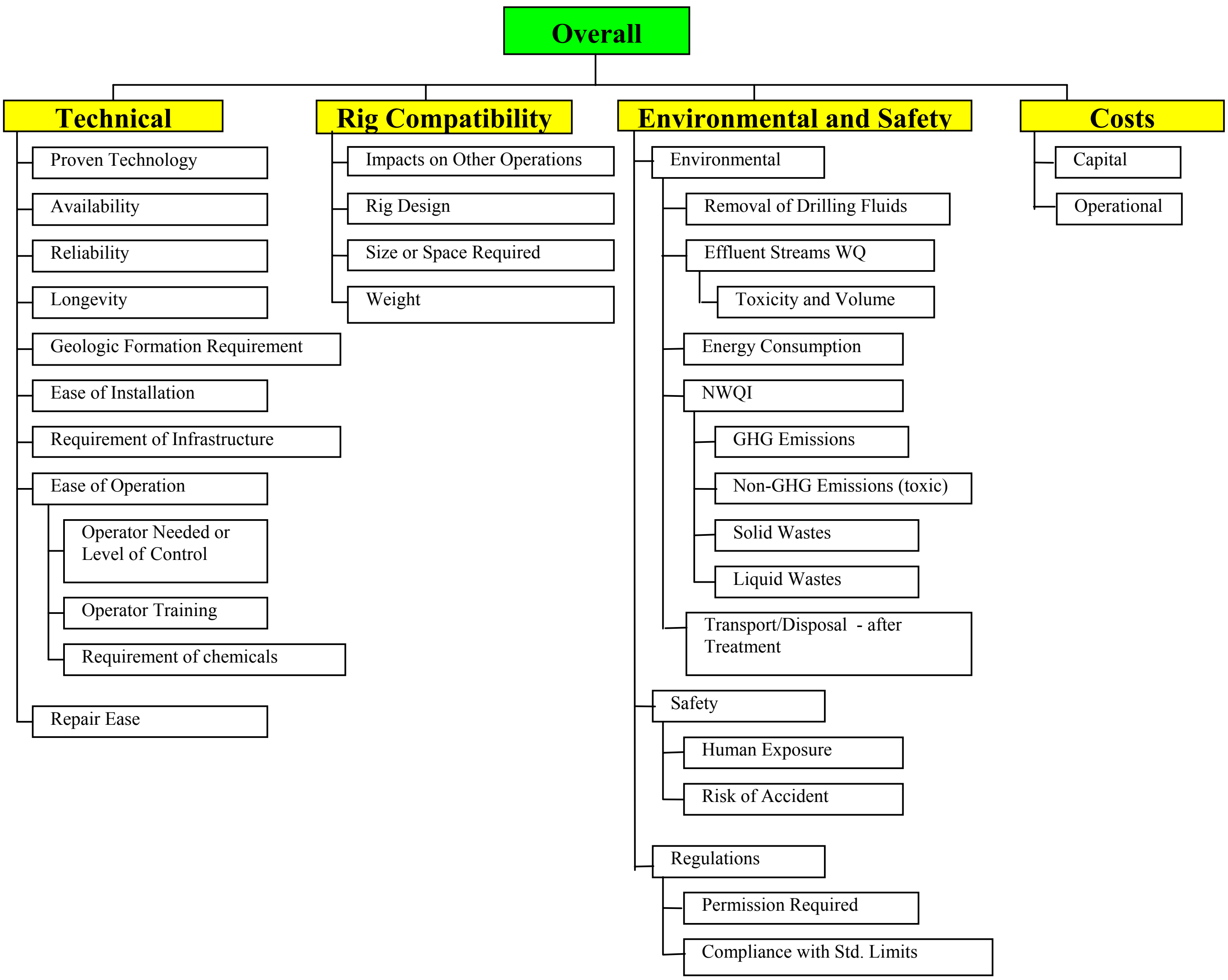

Figure 6. Development of criteria for the selection of treatment technology for drilling waste discharges.

Evaluation of air emissions and environmental management practice

The main objective of this element of the research program is to evaluate air emissions associated with offshore operations (source and composition), determine the significance of the emission (from a toxicity and regulatory perspective), and determine methods of mitigating the effect of the air emissions (e.g. through gas recovery and other methods).

Air emissions associated with oil and gas operations are often not considered as significant as liquid or solid waste. However, international agreements, such as the Kyoto Protocol, highlight the necessity to mitigate air emissions. Often, minimizing air emissions, particularly from offshore facilities, is thought to be a process where the economic losses far outweigh the environmental gains. However, new technologies, gas management practices, and disposal techniques can benefit the facility both environmentally and economically. In order to accomplish air emission mitigation in a sustainable development way, it is important to first quantify the emissions associated with the facility from a compositional and volume perspective.

For instance, an ongoing project is concerned with determining the composition of emissions from waste gas flares and comparing these emissions with other waste gas destruction technologies to compare the toxicity and greenhouse gas emissions. With this information, decisions on the type of waste gas destruction technology can be assessed properly. This project will be further extended to gas management and gas recovery on platforms. Due to limited space and stability on offshore platforms, gas management and recovery is not as straightforward as at onshore facilities. Therefore the analysis of emission on a platform has to be undertaken differently. One such project addressing this issue is the recovery of ethane from the produced gas generated on Newfoundland's offshore platforms. Due to the remoteness of the platforms and lack of proven gas reserves, neither a pipeline to transport produced gas onshore, nor recovery of the gas on the platform is currently viable. In our research, we are looking at the possibility of recovering the ethane plus part of the produced gas stream (which amounts to 10-20% of the total gas stream) through small-scale LNG plants, which would be modified for ethane plus recovery. The smaller volume of gas would require smaller storage areas or transport ships and the higher value ethane could be used to supply the petrochemical market on the East Coast and Europe.

The focus of this research is to mitigate gaseous emissions in ways that benefit both the environment and economics. This can only be done by first determining what these waste gas streams are composed of and then using this information to establish the best waste management strategies.

Development of an AUV for EEM

There are many potential applications of AUVs in the context of environmental issues relevant to the offshore petroleum industry. Ultimately, the aim is to carry out cost effective monitoring in deep water fields. The monitoring might be related to drill cutting discharges and produced water issues, as described above, or it may be for inspecting subsea pipelines or other infrastructure. In the near term, the missions will likely focus on scientific objectives and be limited to relatively shallow water. A vehicle has been designed and built to act as a platform for sensors and equipment to carry out such monitoring and research missions. Initial trials have been done in a large tank.

The vehicle, called C-SCOUT (see Figure 7), is torpedo-shaped and designed to have a high degree of manoeuvrability and operational versatility. It was designed with high functionality and low cost as primary drivers. C-SCOUT is constructed of modular sections and outfitted with off-the-shelf components. The AUV is also designed for ease of operation, and is sized to be launched from a small boat. The batteries can be replaced while the vehicle is floating on the surface, with no special tools or equipment. Open water trials of C-SCOUT are planned for later this year.

Figure 7. C-SCOUT AUV.

SUMMARY

Work on environmental risk assessment and management issues relevant to the offshore petroleum industry is being done under a research program called *Offshore Environmental Risk Engineering Using Autonomous Underwater Vehicles*. The main focus to date has been on produced water and drill cuttings discharges. In parallel, an autonomous underwater vehicle is being developed that will eventually be used to carry out scientific and monitoring missions. The project brings together several industry and academic organizations and a diverse group of researchers, technicians, and students. The ultimate goal of the research is to integrate current and emerging scientific knowledge and technology with the goals of environmental protection in a holistic framework to guide decision-making.

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