Use of the ALARP Principle for Evaluating Environmental Risks and Impacts of Produced-Water Discharged to Sea

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Summary

When produced water from offshore production is discharged to sea, it contains some oil (aliphatic and aromatic components), production chemicals, and naturally occurring radioactive materials (NORM). These groups of materials are traditionally treated in different ways in the regulations and standards.

Regulations of oil in produced water are mainly related to maximum concentrations and the total discharge of the aliphatic (dispersed) fraction. Regulation of chemicals is based on the environmental risk profile of each production chemical, although efforts are made toward regulations based on risk assessment of the discharge of the mixture of substances. For discharge of NORM dissolved in the produced water, no limit values are imposed. For NORM solids (scale, sludge, sand) from process equipment, discharge to sea is in general not allowed—it is reinjected or taken to a deposit onshore.

Management of safety risks takes place on the basis of the principle that risks shall be reduced to a level as low as reasonably practicable (ALARP). The concept of environmental risk is not as unambiguously defined as safety risks. With respect to accidental environmental impacts, the parallel is relatively straightforward, but with respect to planned environmental impacts (e.g., emissions/discharges during operation), the parallel to the safety ALARP level is not so clear; the consequence (the environmental impact) is not linked to a certain frequency (i.e., we cannot talk about risk as likelihood times consequence).

Costs are normally defined as money, effort, and time. But what if the cost of a reduced health, safety, and environmental (HSE) risk or impact is an increase in another HSE risk or impact? Produced-water reinjection might cause increased carbon dioxide (CO_2) emissions. Handling solid NORM during shipping to shore causes health risks to the people handling the NORM. Can that risk be justified on the basis of the possible reduction in environmental impact by not discharging the solid NORM to sea instead?

This paper highlights the aforementioned issues and proposes a method called "integrated HSE ALARP assessment" for supporting such analysis. The environmental risks and impacts of discharge of oil, chemicals, and NORM, respectively, with produced water to sea are used to illustrate these principles.

Introduction

The development of the concept of risk has previously taken place with respect to safety risk. An important principle developed is the obligation to reduce risk to a level ALARP. The concepts of health risk and environmental risk are also widely used now—and as a parallel to the ALARP principle, the principles of best available techniques/best environmental practice (BAT/BEP) have been developed with respect to environmental impacts. These principles are to a wide extent analogous to the ALARP principle used in health and safety.

In this paper, an overall common definition of HSE risk is sought. This makes weighting of different HSE risks against each other more transparent and objective. The ALARP principle traditionally weights safety risk reduction against the increased cost/effort required for achieving the risk reduction. In this paper, a concept for weighting safety risk against environmental and health risk and impact is presented, using produced water as an example. Also, a situation in which increased environmental impact was weighted against reduced safety risk is presented.

Environmental Risk and Impact

To use the ALARP principle on environmental risk reduction, it is necessary to establish a common understanding of the concept of risk. In connection with environmental management, the following definitions are usually used (ISO 14001: 2004):

- Environmental aspect: Element of an organization's activities or products or services that can interact with the environment.
- Environmental impact: Any change to the environment, whether adverse or beneficial, wholly or partially resulting from an organization's environmental aspects.

Environmental risk is a less well-defined concept, often used inconsistently with respect to planned and/or accidental environmental impacts.

Safety was the first HSE discipline to use risk analysis to determine the hazards associated with oil and gas development. Since the 1970s, the concept of risk and risk assessment has spread into the realm of health and environmental risk assessment as well (Jones and Israni 2012).

The process used for the evaluation and risk management of activities was developed originally to provide a structured approach to the analysis of safety hazards. The approach has been extended to include environmental risk management by assessing both the impacts of planned activities (i.e., emissions and discharges on a daily/regular basis) and the risks associated with unplanned events (e.g., oil spills, gas releases) (Walls et al. 1997).

An implication when considering environmental risk is that objective measures of environmental risk levels are not readily available. For safety risk assessment, parameters such as fatal-accident rate and individual risk are defined clearly. Quantification of environmental impact is more subjective because the impacts usually concern a large number of different parameters, the importances of which are difficult to weight against each other.

The issue of environmental risk assessment is further complicated by the fact that some environmental impacts are local (e.g., an oil spill), some are regional (e.g., emission of acidifying gases), and some are global (e.g., emission of greenhouse gases) (Valeur et al. 2002). For local environmental impacts, the vulnerability of the local

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environment is critical, whereas the local environment has no significance when assessing impacts with a global effect.

In Walls et al. (1997), the concept of an environmental case is introduced as a parallel to the well-established concept of a safety case. The environmental case is a document that describes the environment in which the planned activity will take place, the activity itself, and the management of that activity, demonstrating that its risks on the environment are minimized (Walls et al. 1997).

Risk is defined as a combination of the likelihood and consequence(s) of a specified hazardous event occurring (OHSAS 18001 2007). This definition is well suited for dealing with safety risks, where the hazardous event is always linked to the likelihood for its occurrence. Safety risk definition (OGP 1994): Risk = Probability of Occurrence × Severity of Consequences.

According to OGP (1994), the concept of health risk is not related to likelihood, but instead to the exposure for a certain harmful agent (hazard) combined with the harmfulness of the agent toward the receptor, the person exposed. Health risk definition (OGP 1994): Risk = Severity of Consequences = Exposure × Degree of Harmfulness (e.g., toxicity).

Environmental risks associated with planned activity (e.g., discharge to sea) are treated in OGP (1994) the same way as health risks; here, the receptors are exposed flora and fauna instead of humans. Environmental risk definition, planned impacts (OGP 1994): Risk = Severity of Consequences = Exposure × Degree of Harmfulness (e.g., toxicity, disturbance to habitat).

Environmental risks associated with accidental events (e.g., an oil spill or a gas leak) can be treated the same way as safety risks; hazards and likelihood are linked. Accidental environmental-risk definition: Risk = Probability of Occurrence × Severity of Consequences.

A concept frequently used in environmental risk assessment is that of the source-pathway-receptor. In this model, the pathway between a hazard source (for example, a source of contamination) and a receptor (for example, a particular ecosystem) is investigated. Reducing the environmental risk, therefore, concerns reducing the source and intercepting the pathway, and, in that way, reducing the exposure. For accidental impacts, the likelihood of the event to occur is also part of the equation.

Traditionally, the standards ISO 14001:2004 and OHSAS 18001 have separated between environmental aspects causing impacts and health and safety hazards causing risks, respectively. Traditional risk-assessment matrices include likelihood and consequence (i.e., from ISO 17776:2000). But for planned environmental impacts, the likelihood is unity; only the consequence is varying, depending on the exposure and the environment in question. Therefore, such matrices are not well suited for evaluating planned environmental impacts.

As obvious from the preceding, the terms environmental risk and environmental impacts are used in a not very consistent way. Therefore, the following definitions are proposed to be applicable:

- Environmental risk is used for accidental events only.
- Environmental impact is used for planned activity. If an accidental risk is realized, it also causes an environmental impact.

Actually, it is believed to be correct to introduce the same kind of distinction between risk and impact when discussing health risk.

The ALARP Principle

Traditional Safety ALARP. The ALARP concept has been developed as an occupational safety risk-reduction philosophy, originally based in British Common Law practice, with the verdict of Edwards vs. National Coal Board (1949 1 All ER 743) as a cornerstone, which "established that a computation must be made in which the quantum of risk is placed on one scale and the sacrifice, whether in money, time or trouble, involved in the measures necessary to avert the risk is placed in the other; and that, if it be shown that there is a gross disproportion between them, the risk being significant in relation to the sacrifice, the person upon whom the duty (of care) is laid discharges the burden by proving that compliance was not reasonably practicable."

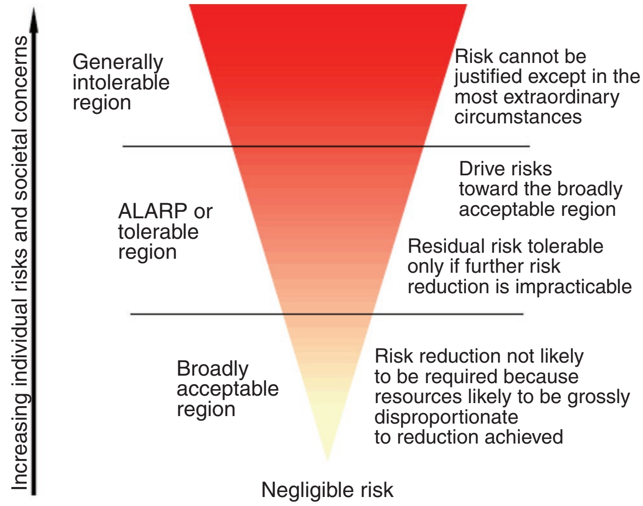

Fig. 1—The ALARP triangle. The upper region is the intolerable region, in which the risk is not acceptable when compared with risk-acceptance criteria and authority requirements.

The ALARP principle assumes that there is a level of risk that is tolerable and requires that the risk be at least below that level. The qualifying term "reasonably practicable" determines how low risks should be pushed toward the region of negligible risks. An infinite amount of effort could reduce the risk to an infinitely low level, but an infinite amount of effort will be infinitely expensive to implement. So, the ALARP principle assumes that there is a risk level that is so low that "it is not worth the cost" to reduce it further. In essence, this means that risk-reduction measures should be implemented until no further risk reduction is possible without very significant capital investment or other resources expenditure that would be grossly disproportionate to the amount of risk reduction achieved (Yasseri and Mahani 2009).

The ALARP principle is illustrated in the ALARP triangle (**Fig. 1**). Risks in the upper, generally intolerable region cannot be justified on any grounds. Risk-reducing measures shall be implemented to bring the risk down below the intolerable risk-level boundary (Wiig et al. 1996). The middle region is also called the ALARP region. This is the region in which effort should take place to reduce the risk and in which it shall be justified that possible risk-reducing measures are grossly disproportional to the achieved reduction in risk. In the lower region, the risk is negligible, so further reducing measures are, in general, not required. However, any risk-reducing measures should be considered in a long-term perspective (Wiig et al. 1996). It should be noted that there is a tendency to remove the lower "broadly acceptable region" (i.e., even when the risk is assessed to be in the lower region, the preceding options for reducing the risk further shall be evaluated).

Making sure a risk has been reduced ALARP is about weighting the risk against the sacrifice needed to further reduce the risk. The decision is weighting in favor of positive action because the presumption is that the company should implement a risk-reduction measure. To avoid having to make this sacrifice, the company must be able to show that it would be grossly disproportional to the benefits of the risk reduction that would be achieved (Dennis and Shobirin 2009).

A suitable and sufficient assessment of cost and risk can often be performed without the explicit valuation of the benefits on the basis of common-sense judgments, while in other situations, the benefits of reducing risk will need to be valued explicitly. The latter is far from easy because the health and safety of people and their societal concerns are not things that are bought and sold, and yet a monetary value has to be attributed to matters such as the prevention of death, personal injury, pain, grief, and suffering (Health & Safety Executive 2001a).

The general hierarchy of risk-reducing measures includes the following (ISO 17776:2000):

1. Prevention (elimination of the hazard)
2. Detection
3. Control (reduce probability, reduce exposure)
4. Mitigation of the consequences
5. Emergency response (curative measures)

Particular attention should always first be given to risk-reducing measures that have the effect of eliminating or reducing the probability of a hazardous event occurring (ISO 17776:2000).

Environmental ALARP. The concept of environmental ALARP is not as well established as health and safety risk reduction to a level ALARP. It is, however, included in the NORSOK Z-013 (2001) standard, in which the risk of damage to the environment caused by accidental events is treated in parallel to the risk of damage to people.

In most situations, deciding whether the risks are ALARP involves a comparison between the control measures in place or proposed and the measures that we would normally expect to see in such circumstances [i.e., relevant good practice (Dennis and Shobirin 2009)]. This is the same principle as for safety risk ALARP, as outlined in the preceding subsection.

Once good practice has been determined, much of the discussion about whether a risk is or will be ALARP is likely to be concerned with the relevance of the good practice, and how appropriately it has been (or will be) implemented. ALARP could be demonstrated by deciding good practice, and verification that the management efforts are effective (e.g., a leak-detection and repair program and emissions monitoring) and periodic review of techniques (e.g., viability of a flare recovery system, advances in low-leak fixtures) (Dennis and Shobirin 2009).

Integrated HSE ALARP. How should decisions be made in case there are conflicts between the results of health and safety ALARP and environmental ALARP analysis? As a general principle applied, safety has, in general, highest priority, as it considers protection of human lives. Dennis and Shobirin (2009) touch on the fact that risk and sacrifice are not usually measured in the same units. The authors propose to carry out a formal cost/benefit analysis in such instances. Costs are normally defined as money, effort, and time. But what if the cost of a reduced HSE risk or impact is an increase in another HSE risk or impact?

When performing produced-water reinjection, reduced discharges of produced water might result in increased emissions of CO_2 to the atmosphere because of the power consumption of the process. In case the reinjection takes place for enhanced oil recovery, the increased CO_2 emissions cannot be said to be caused by only the environmental improvement in the discharge-to-sea aspect. But if the produced-water reinjection is carried out solely as an environmental-improvement activity, the tradeoff in increased emissions to atmosphere needs to be analyzed. And how are two so different types of environmental impacts weighted against each other?

No objective tool for such comparison exists. In the following, such comparison of different HSE risks and impacts will be called an integrated HSE risk-reduction ALARP assessment (in short, integrated HSE ALARP).

The BAT/BEP Principle

BAT and BEP. The Oslo-Paris (OSPAR) Convention (1992) requires contracting parties to apply BAT and BEP, including clean technology where appropriate, in their efforts to prevent and eliminate marine pollution. OSPAR has pioneered this concept internationally and adopted a large number of recommendations and decisions on BAT and BEP for various industrial technologies and sources of land-based pollution.

As defined in Appendix 1 of the OSPAR Convention, BAT "means the latest stage of development (state of the art) of processes, of facilities or of methods of operation which indicate the practical suitability of a particular measure for limiting discharges, emissions and waste." BEP is defined as "the application of the most appropriate combination of environmental control measures and strategies." It follows that BAT and BEP for a particular source will change with time in the light of technological advances and economic and social factors, as well as changes in scientific knowledge and understanding.

The BAT concept has been used in the EU Directive 96/61/EC (European Commission 1996) as a principle for setting emission limit values on the basis of BAT (Item 17): "Whereas emission limit values, parameters or equivalent technical measures should be based on the best available techniques, without prescribing the use of one specific technique or technology and taking into consideration the technical characteristics of the installation concerned, its geographical location and local environmental conditions; whereas in all cases the authorization conditions will lay down provisions on minimizing long-distance or trans-frontier pollution and ensure a high level of protection for the environment as a whole."

The principles of BAT and BEP are implemented also in environmental regulation in other regions (e.g., the US Clean Air Act and Clean Water Act).

Environmental ALARP and BAT/BEP. In Dennis and Shobirin (2009), the concept of environmental ALARP has been reviewed. The paper argues for using the concept of BAT as an equivalent and established concept to ALARP in the environment. BAT do not only cover the technology used, but also the way in which operations take place, to ensure a high level of environmental protection as a whole. The concept of BAT takes into account the balance between the costs and environmental benefits (Dennis and Shobirin 2009).

It should be noted that the use of environmental ALARP in the *NORSOK Z-013* standard is related to accidental events only. In contrast, the use of the concepts of BAT and BEP is related usually to planned activities and environmental impacts. This links up to the concepts of environmental risk and environmental impact, as discussed previously.

When using the terms environmental ALARP and BAT/BEP, it should be clear what each concept covers. The following understanding is suggested:

- The ALARP principle is used both for accidental events, during which both the likelihood and the consequences (=impacts) should be minimized, and for planned activity, during which the consequences (=impacts) should be minimized.
- For planned activity, the ALARP principle resembles the BAT/BEP principle.

The preceding means that the ALARP concept is used both in connection with reducing risks to a level ALARP and in reducing impacts to a level ALARP.

Produced-Water Discharge to Sea

Aqueous Discharge From Offshore Oil and Gas Production. Produced water is the most significant water discharge associated with exploration and production (E&P) operations. For every tonne of hydrocarbon produced in 2011 (including oil, condensates, and gas), 0.5 t of produced water was discharged and 1.0 t of produced water was reinjected. In 2011, the average concentration of oil in produced water was 12.2 mg/L for offshore discharges. When expressed in terms of oil production, these discharges are equivalent to 8.8 t of oil for every million t of hydrocarbon produced offshore. For comparison, the amount of oil spilled to sea (spills larger than 1 bbl) were in 2011 on average 5.2 tonnes for every million tonnes of hydrocarbon produced offshore (OGP 2012). It should be stressed that these sta-

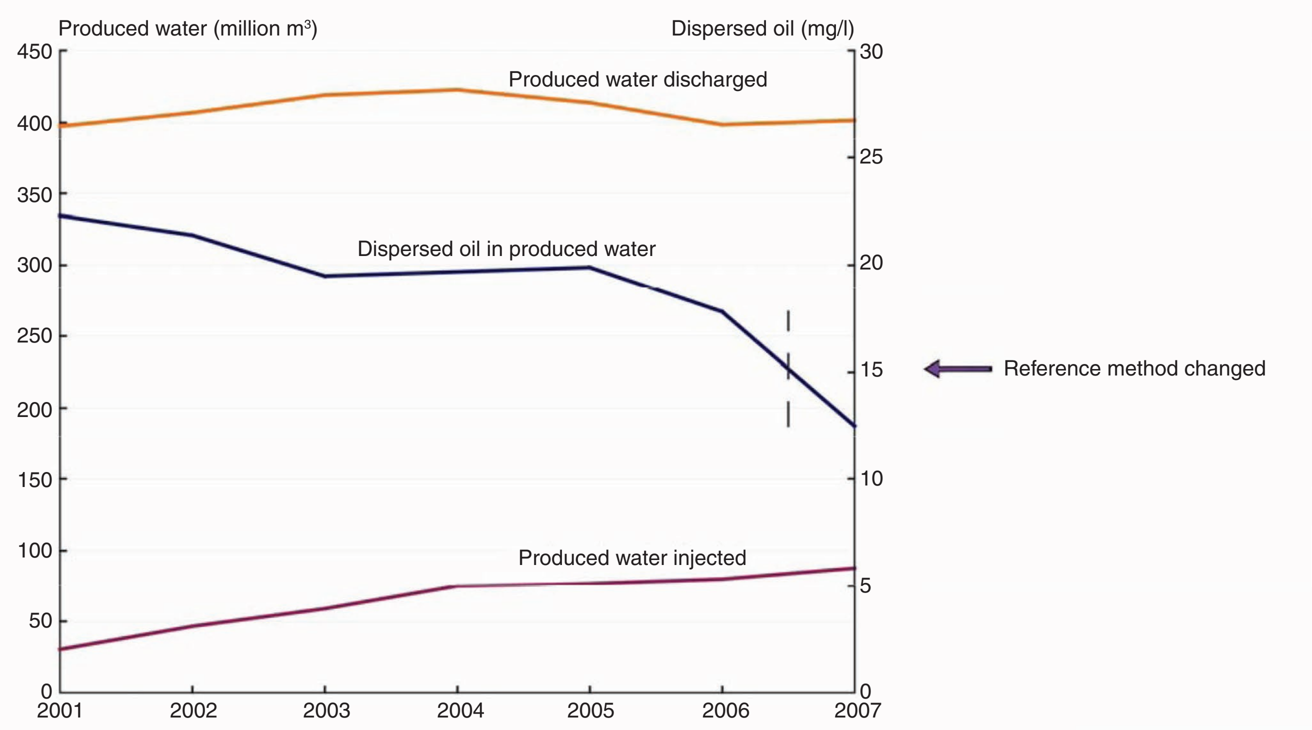

Fig. 2—Produced water discharged, produced water reinjected, and concentration of dispersed oil in produced water in the OSPAR countries from 2001 to 2007 (Iversen et al. 2009).

tistics are based on reporting from OGP member companies only, which account for 32% of the total wellhead production in 2011.

In **Fig. 2,** the development in produced water discharged, produced water reinjected, and concentration of dispersed oil in produced water in the OSPAR countries (producing in the North Atlantic) is shown for the period 2001–2007. The figure shows that in this area, the amount of produced water has been relatively constant; an increased reinjection of produced water has mitigated the effect of increased production of water during the period. A clear trend for the period is the large decrease in the concentration of dispersed oil in the produced water. The environmental impacts related to discharge of produced water to sea are summarized in Appendix A.

Environmental Regulations, Oil, Chemicals, and NORM in Produced Water. In Europe, OSPAR is the regulatory body for the prevention of pollution of the Northeast Atlantic (which includes the producing areas of the North Sea and the North Atlantic). OSPAR has decided to move form a prescriptive approach on the quantity and concentration of oil discharged to sea with the produced water to a risk-based approach (Garland 2011). The first measure was taken in 1978 by the Paris Commission (which since has been expanded to the OSPAR Commission), which set a provisional target for concentration of dispersed oil of 40 mg/L for discharges from existing platforms. This was valid until the OSPAR Recommendation 2001/1 for the Management of Produced Water from Offshore Installations entered into force in June 2001. In 2000, OSPAR made a significant step toward control of offshore chemicals, introducing a system for assessing and classifying chemicals according to their hazard to the marine environment (*OSPAR Decision 2000/2*).

In 2010, the OSPAR Commission adapted a new strategy for the years 2010–2020, aiming at developing and implementing a harmonized method for the assessment of environmental risk (risk-based approach) relating to the management of produced water discharged from offshore installations (Garland 2011). This has led to the *OSPAR Recommendation 2012/5—Risk-Based Approach to the Management of Produced Water Discharges from Offshore Installations (2012a) and OSPAR Guidelines in Support of Recommendation 2012/5 for a Risk-based Approach to the Management of Produced Water Discharges from Offshore Installations (2012b).*

Risk is defined by OSPAR (2012a) as the likelihood that adverse effects may occur, expressed as the predicted environmental concentration to the predicted no-effect concentration (PEC:PNEC) ratio or the fraction of species potentially affected.

OSPAR (2012a) defines a risk-based approach as an approach to produced-water discharges based on a characterization of the risk to the environment of a produced-water discharge by examining both the exposure resulting from discharge of the produced-water e fluent and the sensitivity of the receiving environment to this exposure and by taking appropriate measures to avoid or minimize exposure levels above the PNEC.

The purpose of OSPAR (2012a) is to

- Guide contracting parties (i.e., the OSPAR member states) in the application of a risk-based approach to assess the environmental risk posed by produced-water discharges, including naturally occurring substances
- Describe methods to characterize the risks
- Guide contracting parties in the application of BAT and BEP to reduce those risks that are not controlled adequately.

It should be noted that the preceding list is in addition to the existing, more-prescriptive OSPAR recommendations and decisions [i.e., it introduces the ALARP principle (the BAT/BEP principle) to drive the environmental risk further down than according to the prescribed limit values]. The contracting parties may elect to use a so-called substance-based approach or a whole-effluent approach, or a combination of these approaches, in the risk-reduction measures (OSPAR 2012a).

The whole-effluent-toxicity (WET) approach assessed the combined toxicity from all substances in the produced water, including unknown substances. Water samples for bioassays and for chemical analysis should be collected in parallel for this assessment. WET also determines the possible residual toxicity of substances already addressed by the BAT/BEP OSPAR measures, such as dispersed oil and offshore chemicals. A whole effluent assessment (WEA) consists of a combination of tests for determining the potential for bioaccumulation, persistence, and toxicity (OSPAR 2012b).

Roex et al. (2012) compared the WEA (bioassays) and the substance-based approach (PNEC) on the basis of analysis of samples of

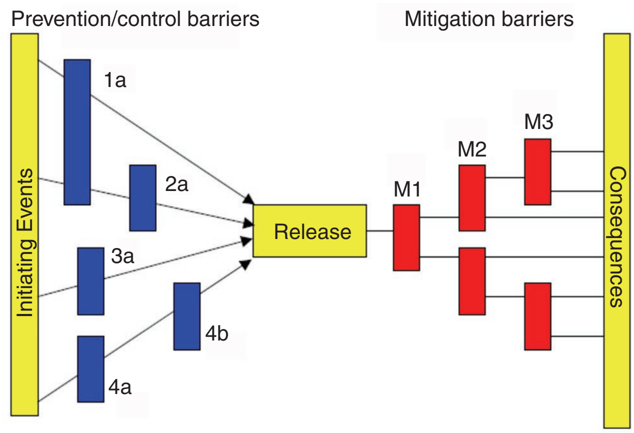

Fig. 3—Example of a bow-tie diagram (Salmon 2006).

produced water from 30 samples in the OSPAR region. They found that the WEA is practicable and sensitive enough for estimating the potential risk of produced-water discharges from offshore platforms. Poor correlation was found between the results of two methods, and, in general, the effect-based approach displayed a higher risk than the substance-based approach. They suggest a tiered approach, with WEA as a first step, for identifying the discharges with the greatest potential risk to the receiving environment. In the next step, a more-detailed substance-based risk assessment could be performed, indicating which substances cause the risk in the concerned discharges. With the tiered approach, a more cost-effective way of monitoring is developed, focusing merely on the discharges with the highest risk.

In the exposure assessment, the predicted fate of the produced water is determined. For the purpose of modeling the dilution/dispersion in the receiving environment, information about the environmental parameters at the location/area is useful (OSPAR 2012b).

Risk characterization includes the comparison between the predicted environmental concentration of the substance and/or the effluent (PEC) and the hazard (PNEC) at a given distance as a minimum. The PNEC value calculated in the hazard assessment and the PEC value calculated in the exposure assessment are used to determine the PEC:PNEC ratio for the whole effluent (OSPAR 2012b).

The risk characterization can be dominated by uncertainty leading to high assessment factors in the derivation of the PNEC. Therefore, before looking at physical measures, it may be prudent to address uncertainty because reductions here can reduce the resultant PEC:PNEC by factors of 10 to 100 (assessment factors generally drive the risk up as uncertainty increases) (OSPAR 2012b).

Risk-reduction measures may comprise some or all of the following (OSPAR 2012b):

- Technical measures, such as abatement at the source by redesign of the applied processes (water shutoff in the well)
- Substitution of chemicals
- Application of closed systems (e.g., injection of produced water)
- End-of-pipe techniques, such as separation or clarification techniques to treat produced water before discharge
- Organizational measures, such as management systems in place (training, instructions, procedures, and reporting)

This very much resembles the hierarchy of risk-reducing measures listed in a previous section regarding traditional safety ALARP.

Garland (2011) points to the fact that, usually, the starting point of an OSPAR measure is a background document explaining the need for such a measure, and that such a document does not exist (i.e., no scientific study does apparently demonstrate that the current discharges of produced water in the North Sea cause any significant harm to the environment). He also points to the fact that the conservatism used in the PNEC calculation may increase safety factors up to 10,000 times whenever information about toxicity is lacking.

The implementation of the preceding OSPAR measures is not settled yet. Garland (2011) expects that the WEA in most cases will be limited to the WET, forgetting biodegradation and biomagnifying effects, which, in many cases, probably will lead to a more pessimistic assessment. He finds the risk-based approach intellectually interesting, with focus on effects rather than some threshold values, an approach that is used largely in safety studies (the ALARP principle). But key is that documentation of environmental improvements is difficult to establish when documentation of significant environmental impacts caused by the existing discharge of produced water is lacking.

Disposal of radioactive material at sea is regulated by the London Dumping Convention of 1972. With respect to the North Sea/North Atlantic, the discharges of radioactive substances to sea are regulated by the Convention on the Protection of the Marine Environment of the Northeast Atlantic (OSPAR 1992), and specifically by the *PARCOM Recommendation 91/4 on Radioactive Discharges,* the *PARCOM Recommendation 94/8 Concerning Environmental Impact Resulting from Discharges of Radioactive Substances, and the OSPAR Decision 98/2 on Dumping of Radioactive Waste* (OSPAR 1992).

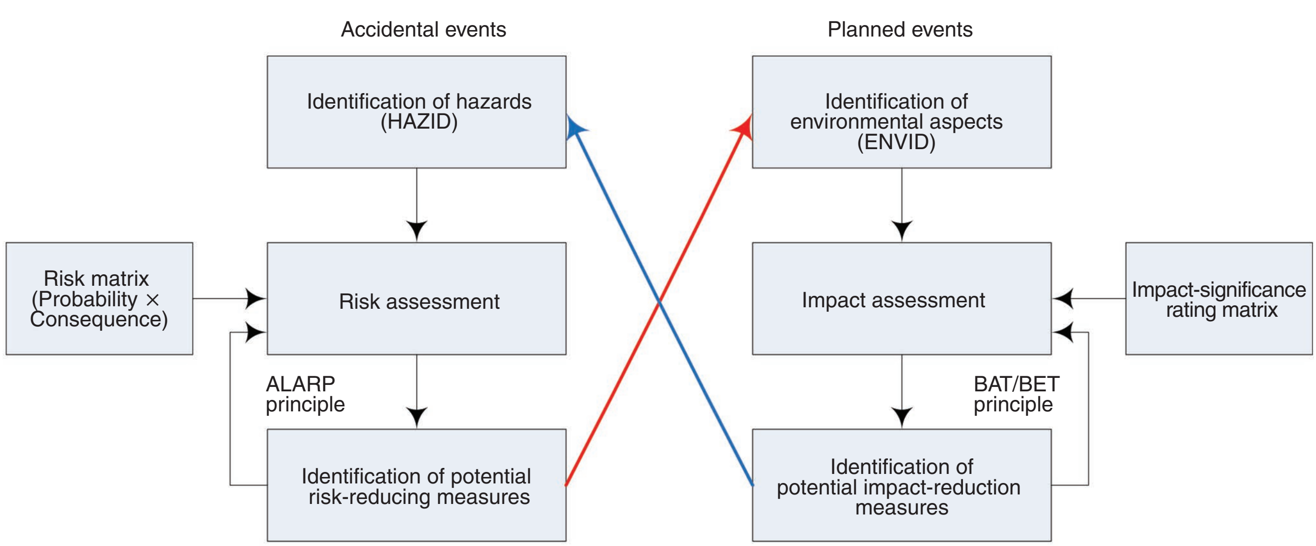

Fig. 4—Integrated HSE ALARP assessment, including traditional ALARP assessment and environmental BAT/BEP assessment.

Integrated HSE ALARP Methodology

Traditional Safety ALARP Assessment Methodology. Traditional safety ALARP assessment includes the following steps (Salmon 2006):

1. Hazard identification (HAZID).
2. Selection of an appropriate risk matrix.
3. Risk assessment (probability times consequence).
4. Ranking the risks, for systematic consideration.
5. Identification of potential risk-reduction measures.
6. Any risk identified as intolerable must be reduced until tolerable.
7. Reduction of all risks to a level ALARP.

Fig. 3 shows a so-called bow-tie diagram. When assessing options for risk reduction, these can be both measures intending to reduce the likelihood of an accidental event happening (the blue bars to the left) and measures for mitigating the consequences of an accidental event should it happen (the red bars to the right).

Introduction of a health and safety measure to control a hazard may transfer risk to other employees or a member of the public. This is referred to as transfer of risk (Health & Safety Executive 2001b). If the transferred risk arises from the same hazard, then it should be offset against the benefit from the measure under consideration. If the transferred risk arises from a different hazard, it should be treated as a separate matter for which control measures must be introduced to reduce its risk to a level ALARP (Health & Safety Executive 2001b).

When comparing different risks, as is done with respect to the transferred risk, it makes comparison relatively straightforward when the measuring unit (frequency of fatalities) is the same for each risk. And the sacrifice can usually be measured in monetary terms.

Integrated HSE ALARP Assessment Methodology. An integrated HSE ALARP assessment is performed by use of the same methodology as the safety-risk ALARP assessment outlined in the preceding subsection, but including HSE hazards as well as environmental aspects. All significant HSE hazards and environmental aspects are identified, and all HSE risks and environmental impacts are assessed. The process when carrying out an integrated HSE ALARP assessment is outlined in **Fig. 4.**

The steps from the traditional safety ALARP assessment methodology are then modified to the following:

1. HSE hazards identification (HAZID) and environmental-aspects identification (ENVID).
2. Selection of appropriate metrics for risk and impact assessment (HSE risk matrix and impact-significance matrix).
3. Risk assessment and impact assessment [(Severity× Consequence) / (Exposure×Vulnerability)].
4. Ranking both the risks and impacts for systematic consideration.
5. Identification of potential risk- and impact-reduction measures.
6. Any HSE risk and impact identified as intolerable must be reduced until tolerable.
7. All significant risks and impacts are reduced to a level ALARP (≈BAT/BEP for planned environmental events).
8. Assessment of possible increase in environmental impacts caused by HSE risk-reduction measures (the red arrow in Fig. 4).
9. Assessment of possible increase in HSE risks caused by environmental-impact-reduction measures (the blue arrow in Fig. 4).

The preceding process includes both a traditional safety ALARP assessment and a traditional environmental BAT/BEP assessment in the same process. It makes it possible to weight conflicting HSE risks and impacts against each other, and to make well-documented decisions that are useful in subsequent engagement with stakeholders.

The integrated ALARP process described in Fig. 4 cannot be carried out as a fully integrated process. Risk-rating matrices (in, for eample, ISO 17776:2000) often include both HSE monetary and reputational loss, but only as a result of accidental events (i.e., linked to a frequency). Frequency is not a dimension in environmental-significance matrices. This, and the fact that HSE metrics are different, means that the units when expressing the HSE risk level and the environmental-impact-significance level are different. A direct quantitative comparison is therefore not possible.

Ranking different types of HSE risks and environmental impacts against each other is, hence, not an objective or straightforward process. But doing it anyway, with buy-in from the main stakeholders, makes the weighting process transparent, and the arguments for the weighting can be made open and subject for discussions. Once the ranking of the various HSE risks/impacts have been agreed upon, they can be weighted toward each other, and the outcome will be a robust case for the chosen solution.

A main advantage of the integrated HSE ALARP assessment is that possible increases in other HSE risks or environmental impacts caused by risk- or impact-reduction measures are identified and addressed. This is important both for an overall risk- and impact-reduction process, and for justifying decisions that may cause increase in HSE risks or impacts, as a consequence of other HSE risk- or impact-reduction measures. This is valuable in the communication with stakeholders [e.g. with health and safety authorities, with environmental authorities, and with nongovernmental organizations (NGOs)].

Examples of Integrated HSE ALARP Assessment Cases

Conflicting Environmental Impacts. Ekins et al. (2005) reviewed the BAT produced-water-abatement and -management techniques for reduction of discharge of oil with produced water and estimated the cost associated with each kilogram of oil-discharge reduction of the various techniques. They distinguish between physical separation, enhanced separation (in addition to physical separation), alternative (new) technology, and produced-water reinjection (PWRI).

In addition to the cost implications, they also calculated the excess CO_2 emissions caused by each technique. For PWRI, they found that PWRI into an existing predrilled well would lead to an excess CO_2 emission of 810 t for every tonne of oil diverted from the marine environment. If PWRI had taken place anyway for pressure support (with seawater, for example) the excess CO_2 cannot be said to be on the expense of the oil removal exclusively. In that case, the equation is more complicated.

Geijerstam and Nesse (2004) investigated the implications of possible requirements for zero discharge to sea for oil and gas E&P activities in the northern areas of the Norwegian Continental Shelf. Scenarios with zero discharge to sea, high regularity of reinjection of produced water, and reinjection/transportation to land of drill cuttings were analyzed. The analysis showed that large-scale reinjection may increase emissions of CO_2 to air from these operations by up to 15 or 20%.

Reduced Safety Risk on the Expence of Increased Environmental Impact. In the preceding, various environmental impacts are weighted against each other; measures leading to reduced discharges to sea might cause increased emissions to air. But what if a reduced environmental impact leads to increased HSE risk—how are these concerns weighted toward each other?

An example is the design work for a gas-receiving terminal surrounded by a protected-bird area. Safety concerns dictate that a thermal oxidizer be moved away from the process area to reduce the risk of igniting a potential gas cloud. This caused the thermal oxidizer to move closer to the bird area, with potential impacts caused by the noise from the thermal oxidizer. In this situation it was obvious that safety had the highest priority. But other similar conflicts between HSE risk/impact reductions might be less obvious.

An example such as the preceding shows the value of integrating the analysis of HSE risks/impacts. Justification toward the environmental authorities and NGOs for the slightly increased noise level in part of the protected bird area was much easier when the gains with respect to plant safety were presented. Nobody will argue against the justification of saving human lives.

Environmental-Impact Reduction on the Expence of Increased Health Risk. Another example of conflicting HSE risks/impacts is handling of solid NORM from offshore installations. Usually, the NORM is reinjected or taken to shore to a long-term storage facility. Handling the NORM during these processes causes a health and safety hazard to the personnel handling the solid NORM. Discharging the NORM to sea would reduce these HSE risks, but may cause an impact to the marine environment, depending on the environment in which the discharge takes place (see Appendix A).

Conclusion

Environmental risk is a concept used in many connections, often defined in different ways. In some connections (accidental events), it is defined parallel to safety risks (i.e., as probability times consequence). In other connections (planned events), it is defined as exposure times degree of harmfulness (or vulnerability) (i.e., similar to what in other connections are called environmental impacts). It is suggested to use environmental risk only for accidental events, both for having an unambiguous definition and for allowing the use of analysis developed for safety risk assessments to also be used for environmental risk assessments.

The ALARP principle is developed and traditionally used within the field of safety. It is shown that the principle can be used for analysis of the risk of accidental environmental events and the environmental impacts of planned activity. In the latter case, the ALARP principle resembles the BAT/BEP principle, which is usually used for such cases. Making such an overarching conceptualization between the HSE concepts makes integrated analysis of HSE risks and impacts possible.

In the OSPAR region, the regulation of produced water discharged to sea has moved from a prescriptive regime to a risk-based (or impacts-based, according to the above definition) regime. This is very much in line with the development of the safety case and ALARP principle within the safety field. Also the hierarchy to be used for risk (impact) reduction specified by OSPAR resembles the traditional risk-reduction hierarchy used when analyzing safety-reduction options.

Aligning the HSE risk/impact concepts enables an integrated analysis of overall HSE risk/impact reduction. Such an approach, called integrated HSE ALARP assessment, is introduced. The assessment ensures buy-in from key stakeholders when weighting conflicting HSE risk/impact reductions against each other. Moreover, it makes the process transparent, and it provides a better overview of the overall HSE risk/impact picture. This makes justification of the chosen solutions toward authorities and other key stakeholders easier.

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Appendix A—Environmental Impacts Related to Discharge of Produced Water to Sea

Ecological Hazards Related to Oil in the Marine Environment. Oil does not affect all components of marine ecosystems equally; some are more vulnerable to physical impacts, others to chemical toxicity, and some are relatively resilient to both. The key effects of oil include the following (Iversen et al. 2009):

- Oil in large quantities may coat the feathers of seabirds and the fur of some marine mammals. This reduces their ability to provide buoyancy and insulation, leading to increased mortality.
- Mammals and turtles may ingest oil with food and thereby be exposed to potential toxic effects. When preening oiled feathers, birds may also ingest oil with attendant toxic effects. There is evidence to suggest that some tissue hydrocarbons may reduce breeding success in birds and mammals.
- Fish eggs and larvae are more susceptible to toxic effects of oil than are adults. Adult fish may accumulate hydrocarbons in their tissues that may affect their health and also taint their flesh. Toxic components in crude oil include polycyclic aromatic hydrocarbons (PAHs), phenols, naphthalene, phenanthrene, and pyrenes. PAHs can also be mutagenic and carcinogenic.
- Invertebrates vary greatly in their sensitivity to oil. Corals are among the most sensitive, whereas some barnacles and limpets may withstand a degree of oiling. As with finfish, shellfish may accumulate oil residues with attendant secondary effects, particularly relating to health.
- Though individual planktonic organisms can experience toxic effects from oil in water, the very high turnover of plankton populations means that the plankton is relatively unaffected by oil.
- Oil does not always stick to seaweeds because of their mucilaginous coating, but cultured algae can become tainted and lose their commercial value. Vascular plants, such as seagrasses, may be affected, and the species balance of communities exposed to oil or oil residues in water may shift from perennial species to more-rapidly-growing annual species.

Ecological Hazards Related to Discharge of Chemicals Offshore. The main discharges of chemicals arise from drilling activities and discharges of chemicals in produced water. The use of chemicals is critical for the production of oil and gas. The main use of chemicals is for drilling and production operations and includes chemicals for rig and turbine washes; pipe dopes used to lubricate drillpipe joints; hydraulic fluids used to control wellheads, blowout preventers, and subsea valves; chemicals used in the actual production and processing of hydrocarbons; water-based and organic phase drilling fluids; cementing chemicals; workover chemicals; stimulation chemicals; completion chemicals; water-injection chemicals; water and gas tracers, chemicals used in “closed systems” in which periodic refill is required; and jacking grease. Chemicals are also used to maintain pipelines and ensure pipeline integrity; these include biocides and oxygen scavengers (Iversen et al. 2009).

Unwanted effects from chemicals discharged into the marine environment can include acute or long-term toxic effect to marine organisms. Among the long-term effects, especially hormone interfering, mutagenic and reprotoxic effects give rise to concern. Persistent and bioaccumulative chemicals can magnify in the food chain and result in high exposure levels for top predators such as seabirds and marine mammals and for human seafood consumers. Low concentrations of some substances are sufficient to interfere with the hormone and immune system and reproduction processes. Biological effects can extend beyond individual marine organisms to a whole population, with adverse consequences for species composition and ecosystem structures (Iversen et al. 2009).

Ecological Hazards Related to the Discharge of NORM Offshore. The majority of NORM from offshore oil and gas production is from produced water, which, to a large extent, is discharged to sea. Likewise, in some areas, solid NORM is ground and discharged to sea from offshore installations, or from processing areas onshore from which it is discharged to sea through a pipeline.

The radio-nuclides in the water have a strong affinity for particulate matter. Therefore, the majority of the discharged NORM will be adsorbed onto fine-grained sediments and particulate matter relatively soon after introduction to the marine environment. They will then follow the natural-transport pathways for fine-grained sediments in the sea.

The radio-nuclides adsorbed to fine-grained sediments and organic particles will settle to the seabed. In high-energy environments,

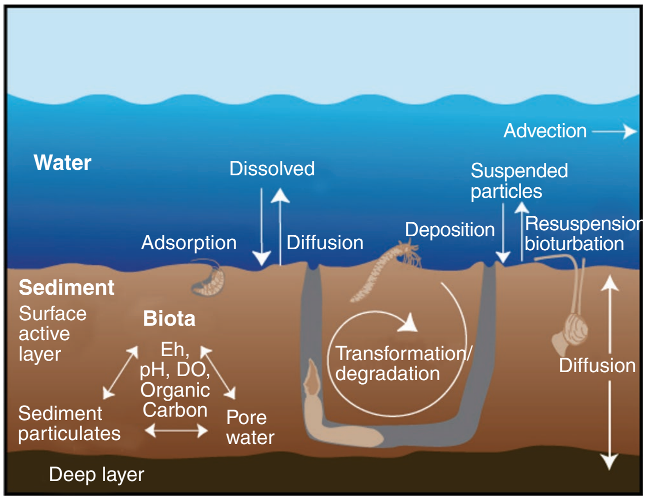

Fig. A-1—Sediment processes taking place in the benthic mixing layer of the seabed, in which sediment resuspension and bioturbation take place (illustration courtesy of Southern California Coastal Water Research Project; DO=Dissolved Oxygen).

the particles will be resuspended after initial settlement because of the action of waves (depending on the water depth) and currents in the area (Valeur 1994). After a series of settlements and resuspensions, the particles will end up in low-energy environments that serve as accumulation areas for fine-grained sediments. This is typical for deep parts of the sea, in a direction from the discharge point toward the direction of the sea currents. In these waters, the fine-grained sediments and organic particles, with the associated radio-nuclides, will be buried gradually beneath sediments as the sedimentation process continues (see **Fig. A-1**).

In an analysis of the fate and effects of NORM discharged to sea in the North Sea from offshore installations, it is shown that the majority of discharged NORM will end up associated to solid particles in accumulation areas for fine-grained sediments, where it will be buried eventually beneath the benthic mixing layer of the seabed and in that way be isolated from the biosphere (Valeur 2011).

Environmental Impacts of Produced Water Discharged to Sea. In Ekins et al. 2005, a literature review of the impacts of produced water discharged to sea is reported. The paper highlights that the possible harm caused by produced water discharged to sea depends on the bioavailability (the capability of a component of produced water to be taken up by living organisms) and on the toxicity (the capacity of a component of produced water to cause harm once taken up by a living organism).

OSPAR introduced in 2000 (*OSPAR Decision 2000/2*) a system for ranking offshore chemicals according to a defined hazard quotient (HQ). The HQ is defined as the PEC divided by the PNEC (i.e., the HQ decreases with distance from the discharge point as a result of dilution of the produced water).

The PNEC is a theoretically determined value representing the highest concentration level that is assumed to have no chronic effect on reference species. Deriving the PNEC usually involves adjusting the lowest known toxic-effect level by an "assessment factor" (typically, some power or multiple of 10) to take account of uncertainties in the measurement of toxicity and in species vulnerability, and of differences between acute and chronic exposure, and between humans and other species. When the PEC÷PNEC=1, the theoretical risk of an effect is defined as 5%. This means that at this concentration level of a certain chemical, 5% of the species in the influence area would theoretically be affected in a significant way (Ekins et al. 2005).

The preceding risk definition differs from risk of an incident happening. Here, risk is defined as the proportion of species that is impacted—not as the likelihood that species will be impacted.

Another concept used in relation to produced-water discharge is the environmental impact factor (EIF), developed by the Norwegian Oil Industry Association. The EIF is based on a combined environmental-risk and -hazard assessment of the produced-water discharges, accounting for both composition and amount of discharge. The EIF is presented as an absolute figure for a single platform or discharge point, for a production field including several platforms, or for all producing platforms in an entire region. Determination of the EIF for a single platform allows the operator to rank the available technologies for produced-water-discharge reduction on a cost/benefit basis (Johnsen et al. 2000).

In Durell et al. (2004), the theoretically derived environmental risks are compared with the impacts quantified by water-column surveys. The conservatism inherent in the HQ was obvious, as the measured impacts in general were significantly lower than the theoretical risk calculated by use of the HQ approach.

The components of produced water that cause the largest concern with respect to environmental impacts are PAHs and alkylated phenols. With respect to aromatic components (including PAHs) discharged, no toxic effects from produced water have yet been observed in the field. Theoretical work has suggested that produced water has a relatively low capacity to have effect on marine organisms after short exposure (Ekins et al. 2005).

The scientific literature does not demonstrate that any harm is being caused by discharges of produced water in the North Sea. Furthermore, the best available assessments of risk are able to exclude significant risks of reproductive effects at the population level with the exception of fish in the close vicinity of the discharges. This suggests that the risk of harm from the level of alkylphenols in produced water is also low. However, there is general scientific uncertainty associated with the risks from alkylphenols, and their consequences are potentially serious enough to seem to warrant further precautionary investigation (Ekins et al. 2005).

An issue of outstanding concern associated with both aromatic and phenols in produced water is the interaction between the biological reef effect around jackets and produced-water discharge plumes, potentially leading to higher toxic bioaccumulation in fish. This has not yet been investigated adequately, suggesting that further work needs to be undertaken in this area (Ekins et al. 2005).

Review of the scientific literature on produced water has failed to identify NORM as an area of concern with respect to environmental risk (Ekins et al. 2005).

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