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Formate fluids in the marine environment: Risk assessment

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Content

1 Introduction

Drilling fluids based on potassium and cesium formate brines are naturally dense and do not require formulation with solid weighting agents such as barite. This makes them entirely different from traditional drilling fluids which can contain very high concentrations of solid weighting agents. The formate brines get their high density from their high content of solutes, viz. potassium formate and cesium formate. As a consequence their solute content can easily be an order of magnitude higher than some other drilling fluids. As water-based fluids the formate brines are fully soluble in, and miscible with, other aqueous media such as seawater.

Because they have very high value the formate brines are carefully conserved during use in drilling operations and then recovered at the end of each job for recycling and re-use. All discharges or leaks of formate fluids to the environment are minimized and the user is effectively penalized (by charging) for any fluid losses. The main source of losses of formate brines to the environment is the drilled cuttings which are separated from the drilling fluid for disposal. These cuttings are separated as a slurry containing the same volume, or more, of formate fluid. Apart from losses with cuttings the formate fluids should never find their way into the environment unless there is an accidental discharge. This sets the formate fluids apart from conventional drilling fluids that are not subject to the same degree of conservation and discharge control. It also means that regulatory regimes built around the assumption that drilling fluids are indiscriminately lost or discharged to the environment in large volumes may not be appropriate for determining the risk posed by formate brines.

As the reserves of oil and gas are diminishing, it becomes imperative to ensure efficient, timely and safe recovery of those remaining reserves. Many years of field use has confirmed that formate brines help operators to safely achieve their hydrocarbon production targets at lowest cost. For the sake of the future energy security of the USA it would be prudent to ensure that the discharge control guidelines set by the EPA for conventional drilling fluids do not inadvertently present an obstacle to the deployment of formate brines in well construction operations.

Such obstacles could be removed if discharge control guidelines were strengthened by expanding the scope of the drilling fluid risk assessment to include a more comprehensive and multi-dimensional analysis of the impact of the fluids on the environment. To illustrate the merits of this approach we present the following assessment of risk related to the use of formate fluids in the offshore environment and would recommend the EPA to take the key principles of PEC: PNEC risk assessment into consideration in relation to the 2011 Annual Reviews:

- The assessment of risk in relation to PEC:PNEC follows good scientific principles and this should be utilized where available in preference to a one-dimensional single-point hazard assessment bound to an arbitrarily defined value

- The assessment of risk based on PEC:PNEC gives a holistic overview of the total effects in the marine environment as it is based on a food chain approach. Taking this into account will allow a much better prediction of the overall effects. Complementing this with the NOEC values for certain species and measurements of actual concentrations of chemicals in discharges provides additional reassurance that discharges do not pose a risk to the environment.

- Long term effects of introducing potential toxins or heavy metals into the marine environment should be included in the assessment so that overall holistic conclusions can be drawn.

In this document, we include the results from several types of risk assessments utilizing the PEC: PNEC principle. The overall environmental risk assessment for formate brines is also complemented with a brief assessment of safety, as it could be argued that the full effects of drilling fluids on well construction operations should be taken into account when considering use permits.

2 EHS risks related to well drilling and completion fluids

2.1 Risk created by drilling and completion fluids

Drilling and completing an oil or gas well is a complex and risky undertaking. The success of the operation depends on many factors, including the type and design of the drilling and completion fluids used in the construction of the well. Any flaw in the chosen fluid will expose the operator to technical, financial and EHS (Environmental, Health and Safety) risks. These risks are often interconnected, with a technical flaw creating financial losses and potential EHS risks to personnel or the wider community.

In this assessment of EHS risk, the financial risks (and consequences) associated with drilling and completion fluids are not estimated, but reference is made to separate studies on how to use a holistic approach to reviewing overall risk. Equally, technical risks are not assessed in detail, although attention is drawn to the fact that the use of heavy solids-free brines as drilling fluids provides an effective remedy to the various well control problems created by the use of traditional solids-weighted drilling muds. The deployment of heavy brines as drilling fluids significantly decreases the risk of a catastrophic well control incident and its associated toll on the environment and human lives.

If a lifecycle approach to the risk assessment is taken, the drilling fluid progresses from production through logistics and use to end of life disposal, as shown in Figure 1:

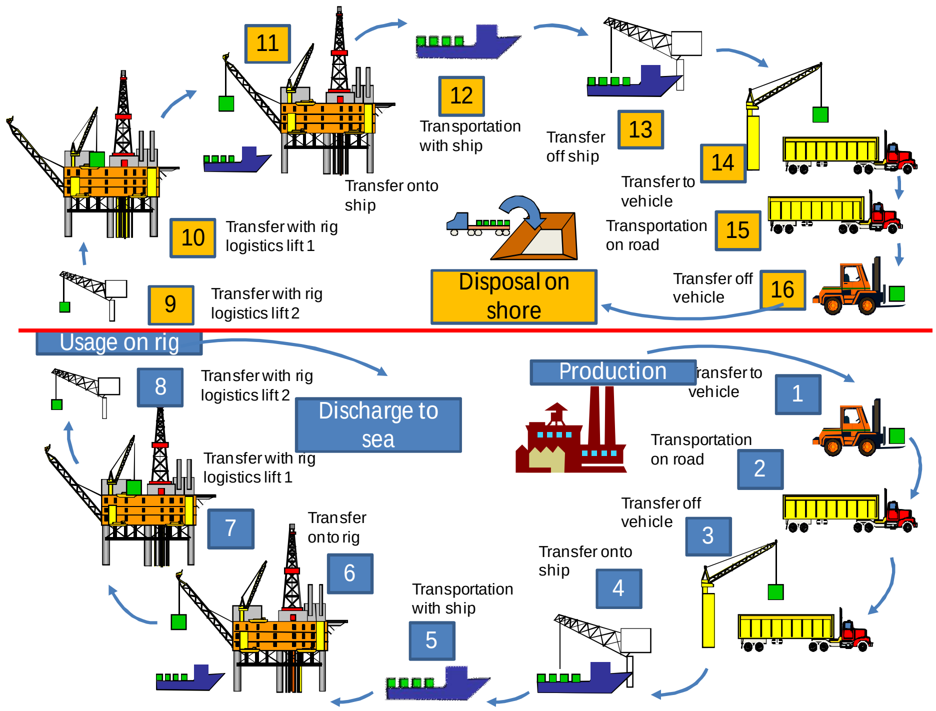

Figure 1. *The fluid lifecycle and process stages when used offshore with two end of life options, discharge to sea (blue) or disposal onshore shown above the red line (additional process steps 9-16 shown in orange)*

As indicated in Figure 1, the logistic stages are multiple. For each logistics stage, there are risks. From a workplace safety point of view, the lifts and transfers are the perhaps most dangerous ones. Each logistic stage is also associated with a risk of incidents such as dropping the load or road accidents. Each step of the normal operations is associated with certain impacts, e.g. through emissions to air, water and soil, waste as well as through energy use, handling strains etc.

But the life cycle of a drilling fluid also involves reconditioning on the rig during use, and sometimes a recycling step after use, as depicted in Figure 2. These additional operations create solid wastes that are contaminated with the drilling fluid

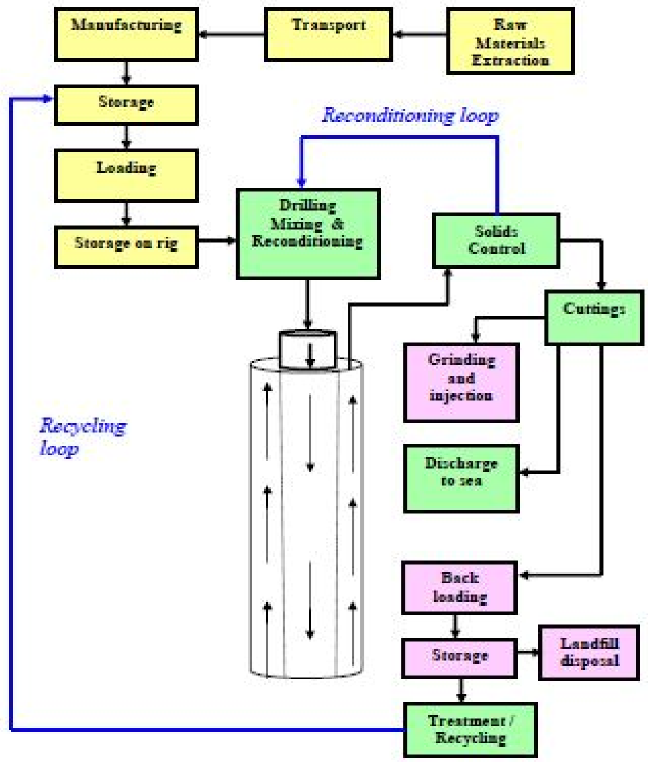

Figure 2: *The life-cycle stages of a well drilling fluid, including reconditioning and an optional recycling loop*

When high value products like formate fluids are used as drilling fluids, the majority (80-90%) of the fluid sent to the rig is recovered at the end of the job and enters the recycling loop. The remaining 10-20% of the fluid is lost downhole (and is later produced with the hydrocarbons) or is lost with the solid drill cuttings separated from the drilling fluid on the rig. Lately the manufacturers of cesium formate brine have been looking into the feasibility of recovering the cesium brine from the drilled cuttings, treating this stream as another kind of mineral (ore) feedstock in its cesium extraction plant. With potassium formate brine, this kind of metal recovery from drilled cuttings may not be economically viable. Nevertheless, the potassium formate still has value and it is in both the supplier's and users' best interests to ensure that as little of the brine is lost as possible. Therefore special care is taken to minimize brine losses with solid waste – whether it is discharged to sea or to taken to a landfill for disposal onshore.

2.2 Environmental risks from drilling fluids

This objective of this report is to provide an assessment of the potential risks to the environment associated with the discharge of formate fluids to the sea. To estimate the exposure of environmental receptors to a chemical, a distinction must be made between substances that are emitted from a point source (to which specific locations can be assigned) and substances that enter the environment through diffuse releases.

The use and discharge of drilling fluids such as formate brines always occurs at specific locations. The local risks relate to the potential impacts in the immediate environment of the drilling rig and are created by intentional discharges with cuttings or unintentional discharges (accidents). The risk a substance poses is related to discharges of specific amounts into a specific location at a specific time. In an offshore environment the waste released undergoes dilution and dispersal in the water column. Cuttings, and any drilling fluid components adhering to the cuttings, can accumulate on the seafloor near a drilling site, with the distribution pattern dependant on the local currents and weather conditions. The majority of the cuttings discharged will probably settle within a short distance from the discharge point, forming a small mound –cuttings pile – beneath the discharge point. The risks associated with the disposal of drilling fluids are dependent on the type of fluid used, its hazardous properties, the local receiving environment and the amount of fluids discharged with cuttings.

2.3 Environmental hazards of the formate brines

The Environmental, Health and Safety hazards posed by formate brines are discussed in a separate report "Formate Fluids hazard assessment" from Gaia Consulting.

2.4 Risk related to disposal of drilling fluids and cuttings to sea

Operators drilling in an offshore environment have the choice of disposing their drilling wastes into the sea, if so allowed by local pollution control regulations, or sending the waste to shore for landfill disposal. The disposal of drilling wastes (i.e. cuttings and associated drilling fluids) into the sea will impact on both the water column and the seafloor environment. The waste released undergoes dilution and dispersal in the water column. Cuttings, and associated fluids adhering to the cuttings, can accumulate on the seafloor near a drilling site, with the distribution pattern dependant on the local currents and weather conditions. The majority of the cuttings discharged will probably settle within a short distance from the discharge point, forming a small mound –cuttings pile – beneath the discharge point. The degree of environmental risk created by the disposal of drilling waste into the sea is dependent on:

- the type of drilling fluid system used;
- the local environment; and
- the amount of cuttings discharged.

The issue of hydrocarbon contamination of the cuttings by drilling fluids is not relevant where the drilling is undertaken with the water based formate brines. However, discharges of cuttings from drilling operations using formate brines may:

- cause short-term increase in the turbidity of the water column;
- cause short-term increases in the ionic content and pH of the water column
- physically smother the seabed and benthos with a layer of formate-contaminated waste minerals excavated from the wellbore (sand, clay, limestone, coal, etc)
- alter sediment structure; and/or

- provide a nutrient source - e.g. for bacterial activity with potentially beneficial (organic enrichment) or adverse effects (oxygen depletion).

Of these, the temporary ionic imbalance caused in the water column is the most relevant one associated with the use of highly water-soluble and rapidly biodegradable formate fluids. The risk assessment in the next section focuses on this particular environmental risk.

3 Risk assessment results

The objective of an environmental risk assessment is to assess whether the used chemical represents a risk to the natural ecosystem. A chemical or formulation (e.g. drilling fluid) is judged to not cause a risk to the environment if the Predicted No Effect Concentration (PNEC)—e.g. the concentration that causes no adverse effect to the environment--is higher than the Predicted Environmental Concentration (PEC) from an intentional or unintentional release. The PEC/PNEC ratio is used as an indicator of risk and is called the Risk Quotient (RQ). When the RQ is above 1, there is a potential risk to the environment.

3.1 Predicted No Effect Concentrations (PNEC)

In this report, the calculation of the predicted no effect concentration has been based on OECD guidelines. The tests taken into account in the calculation are given in Table 1.

Table 1: Test results used in PNEC calculations for potassium formate

Organism	Taxonomic group	Test	Endpoint	Potassium formate	
Mysidopsis bahia	Arthropod, Crustacean	7 d chronic, definitive	Survival NOEC	720	ppm
Mysidopsis bahia	Arthropod, Crustacean	7 d chronic, definitive	Survival LOEC	1200	ppm
Mysidopsis bahia	Arthropod, Crustacean	7 d chronic, definitive	Growth NOEC	**432**	ppm
Mysidopsis bahia	Arthropod, Crustacean	7 d chronic, definitive	Growth LOEC	720	ppm
Mysidopsis bahia	Arthropod, Crustacean	7 d chronic, definitive	Survival IC25	760	ppm
Mysidopsis bahia	Arthropod, Crustacean	7 d chronic, definitive	Growth IC25	551	ppm
Mysidopsis bahia	Arthropod, Crustacean	7 d chronic, definitive	Survival IC50	908	ppm
Mysidopsis bahia	Arthropod, Crustacean	7 d chronic, definitive	Growth IC50	796	ppm
Mysidopsis bahia (Drilling fluid)	Arthropod, Crustacean	96 h, definitive, SPP	LC50	6900	mg/l
Menidia beryllina	Fish	7 d chronic, definitive	Survival NOEC	1200	ppm
Menidia beryllina	Fish	7 d chronic, definitive	Survival LOEC	2000	ppm
Menidia beryllina	Fish	7 d chronic, definitive	Growth NOEC	**432**	ppm
Menidia beryllina	Fish	7 d chronic, definitive	Growth LOEC	720	ppm
Menidia beryllina	Fish	7 d chronic, definitive	Survival IC25	1430	ppm
Menidia beryllina	Fish	7 d chronic, definitive	Growth IC25	1270	ppm
Menidia beryllina	Fish	7 d chronic, definitive	Survival IC50	1670	ppm
Menidia beryllina	Fish	7 d chronic, definitive	Growth IC50	1540	ppm
Skeletonema costatum	Algae	72 h, acute	EC50	3400	mg/l
Scopthalmus maximus	Juvenile Fish	96 h, acute	LC50	1700	mg/l
Crangon crangon	Shrimp	96 h, acute	LC50	1300	mg/l
Oncorhynchus mykiss	Fish	96 h, semistatic	LC50	3500	mg/l
Daphnia magna	Crustacean	48 h, static	LC50	540	mg/l
Desmodesmus subspicatus	Algae	72 h, static	LC50	>1000	mg/l

According to the OECD guidelines, if chronic NOEC data are available from three species representing three different trophic levels- i.e. fish, algae, and crustacean - an assessment factor of 10 may be applied to the lowest NOEC. However, potassium formate has not been extensively tested as it has been classified by PARCOM as a PLONOR (Poses Little or No Risk to the Environment) chemical. Therefore there are only two NOEC values available from manufacturer-owned data sources. For this reason a higher assessment factor of 50 has been applied to the lower of these two, i.e. the figure of 432 mg/l for fish. Therefore the calculated PNEC value is 8.64mg/l.

The tests done on cesium formate have been more extensive (see Table 2). As more than three species have been tested with cesium formate, a factor of 10 is applied to the lowest NOEC value. The calculated PNEC for cesium formate is 5.6 mg/l.

Table 2: Test results used in PNEC calculations for cesium formate

Organism	Taxonomic group	Test	Endpoint	Cesium formate	
Mysidopsis bahia	Arthropod, Crustacean	7 d chronic, definitive	Survival NOEC	420	mg/l
Mysidopsis bahia	Arthropod, Crustacean	7 d chronic, definitive	Survival LOEC	700	mg/l
Mysidopsis bahia	Arthropod, Crustacean	7 d chronic, definitive	Growth NOEC	**252**	mg/l
Mysidopsis bahia	Arthropod, Crustacean	7 d chronic, definitive	Growth LOEC	420	mg/l
Mysidopsis bahia	Arthropod, Crustacean	7 d chronic, definitive	Survival IC25	369	mg/l
Mysidopsis bahia	Arthropod, Crustacean	7 d chronic, definitive	Growth IC25	260	mg/l
Mysidopsis bahia	Arthropod, Crustacean	7 d chronic, definitive	Survival IC50	481	mg/l
Mysidopsis bahia	Arthropod, Crustacean	7 d chronic, definitive	Growth IC50	392	mg/l
Mysidopsis bahia	Arthropod, Crustacean	48 h	Survival LC50	521	
Mysidopsis bahia (Drilling fluid)	Arthropod, Crustacean	96 h, definitive, SPP	LC50	1700	mg/l
Menidia beryllina	Fish	7 d chronic, definitive	Survival NOEC	420	mg/l
Menidia beryllina	Fish	7 d chronic, definitive	Survival LOEC	700	mg/l
Menidia beryllina	Fish	7 d chronic, definitive	Growth NOEC	**252**	mg/l
Menidia beryllina	Fish	7 d chronic, definitive	Growth LOEC	420	mg/l
Menidia beryllina	Fish	7 d chronic, definitive	Survival IC25	471	mg/l
Menidia beryllina	Fish	7 d chronic, definitive	Growth IC25	440	mg/l
Menidia beryllina	Fish	7 d chronic, definitive	Survival IC50	553	mg/l
Menidia beryllina	Fish	7 d chronic, definitive	Growth IC50	532	mg/l
Menidia beryllina	Fish	96 h	Survival LC50	787	mg/l
Menidia beryllina	Fish	96 h	Survival LC50	787	mg/l
Desmodesmus subspicatus	Algae	72-h	NOEC, growth rate	56	mg/l
Desmodesmus subspicatus	Algae	72-h	LOEC, growth rate	180	mg/l
Desmodesmus subspicatus	Algae	72-h	LC50, yield	67	mg/l
Desmodesmus subspicatus	Algae	72-h	NOEC, yield	56	mg/l
Desmodesmus subspicatus	Algae	72-h	LOEC, yield	180	mg/l
Acartia tonsa	Crustacean, copepod	48 h	EC50	340	mg/l
Skeletonema costatum	Algae	72 h	EC50	710	mg/l
Onchorhynchus mykiss	Fish	96 h	LC50	>1000	mg/l
Scopthalmus maximus	Fish	96 h, Juvenile Turbot	LC50	260	mg/l
Scopthalmus maximus	Fish	96 h, Larval turbot	LC50	1400	mg/l
Corophium volutator	Arthropod, Malacostraca	10 d	LC50	6653	mg/kg
Crangon crangon	Crustacean	96-hour	LC50	875	mg/l
Brachydanio rerio	Zebra fish	96-hour	LC50	>100	mg/l
Daphnia magna	crustacean	24 h	LC50	>100	mg/l
Daphnia magna	crustacean	48 h	LC50	>100	mg/l
Ctenogobius gymnauchen	Fish	96-h, acute	LC50	862	mg/l
Crassostrea gigas	Mollusc	24 h, Pacific oyster embryos	LC50	1100	mg/l

However, it makes little sense that the PNEC value for the presumably less toxic potassium formate brine should be only slightly higher than the much more extensively tested cesium formate. It is therefore suggested that the same assessment factor, e.g. 10, should be applied to both formate products. This would give a PNEC of 43.2 mg/l for potassium formate. This more realistic figure has been used in risk modeling calculations made later in this document.

These PNECs are however for continuous discharges. For intermittent discharges, organisms are exposed to the chemicals for much shorter times and assumedly have higher chance of survival as a result of their limited exposure. To assess the PNEC for intermittent discharges, it is common practice to use the lowest acute (LC_{50}) toxicity values rather than the lowest NOEC value from longerterm chronic toxicity tests. The PNEC for intermittent discharges of potassium formate is calculated from acute toxicity data shown in Table 3 while those of cesium formate are calculated from acute toxicity data shown in Table 4. In both cases an assessment factor of 10 is applied as both products have been tested for acute toxicity against species from three different trophic levels.

The calculated intermittent discharge PNEC value for potassium formate is 54 mg/l and for cesium formate is 52.1 mg/l.

Table 3: Acute toxicity values for potassium formate, where the Mysid data is for the SPP test (e.g. diluted 1:9)

PNEC intermittent	54				
Mysidopsis bahia (Drilling fluid)	Arthropod, Crustacean	96 h, definitive, SPP	LC50	6900	mg/l
Skeletonema costatum	Algae	72 h, acute	EC50	3400	mg/l
Scopthalmus maximus	Juvenile Fish	96 h, acute	LC50	1700	mg/l
Daphnia magna	Crustacean	48 h, static	LC50	540	mg/l

Table 4: Acute toxicity values for cesium formate

Cesium formate intermittent PNEC	52,1				
Mysidopsis bahia	Arthropod, Crustacean	48 h	Survival LC50	521	mg/l
Menidia beryllina	Fish	96 h	Survival LC50	787	mg/l
Menidia beryllina	Fish	96 h	Survival LC50	787	mg/l
Skeletonema costatum	Algae	72 h	EC50	710	mg/l
Scopthalmus maximus	Fish	96 h, Larval turbot	LC50	1400	mg/l
Ctenogobius gymnauchen	Fish	96-h, acute	LC50	862	mg/l
Crassostrea gigas	Mollusc	24 h, Pacific oyster e	LC50	1100	mg/l

3.2 Modeling risk from a major intermittent release

When discharging intermittently to the water column, the PEC:PNEC ratio for intermittent discharges in various volumes of water at a standard depth of 1000 m are given in Figure 3 and at a depth of 100 m in Figure 4. These are based on an unintended release of 250 tonnes of drilling fluid, equivalent to (e.g.) 1,000 bbl of 13.1 ppg potassium formate brine. This is taken to illustrate an absolute worst case incident where, as result of some catastrophic or emergency event, a large fraction of the drilling fluid held on an offshore rig was lost to the sea. This would be a very rare event – in 18 years of offshore use there has never been a recorded discharge of this amount of formate brine into the sea.

Figure 3: PEC:PNEC ratios in water depth 1 km

Name of the chemical	Potassium Formate			
Depth	1000	m		PNEC
PNEC	54	mg/l	For continuous source	43,2
Amount of instant release	250 000	kg	For batch source	54

Radius (m)	V (m^3)	PEC (mg/l)	PEC/PNEC
5,65	100287	2492,833	46,164
17,84	999861	250,035	4,630
56,42	10000369	24,999	0,463
178,41	99997297	2,500	0,046
564,19	1000001476	0,250	0,005
1784,12	9999953858	0,025	0,000

Name of the chemical	Cesium Formate			
Depth	1000	m		PNEC
PNEC	52,1	mg/l	For continuous source	5,6
Amount of instant release	250 000	kg	For batch source	52,1

Radius (m)	V (m^3)	PEC (mg/l)	PEC/PNEC
5,65	100287	2492,8333	47,847
17,84	999861	250,0348	4,799
56,42	10000369	24,9991	0,480
178,41	99997297	2,5001	0,048
564,19	1000001476	0,2500	0,005
1784,12	9999953858	0,0250	0,000

As can be seen, the PEC:PNEC ratio is above 1 for both potassium formate and cesium formate in a water column with a radius of less than 57 m and depth of 1000m, e.g. moderately deep water environment.

Figure 4: PEC:PNEC ratios in water depth 100 m.

Name of the chemical	Potassium Formate			
Depth	100	m		PNEC
PNEC	54	mg/l	For continuous source	43,2
Amount of instant release	250 000	kg	For batch source	54

Radius (m)	V (m^3)	PEC (mg/l)	PEC/PNEC
5,65	10029	24928,333	461,636
17,84	99986	2500,348	46,303
56,42	1000037	249,991	4,629
178,41	9999730	25,001	0,463
564,19	100000148	2,500	0,046
1784,12	999995386	0,250	0,005

Name of the chemical	Cesium Formate			
Depth	100	m		PNEC
PNEC	52,1	mg/l	For continuous source	5,6
Amount of instant release	250 000	kg	For batch source	52,1

Radius (m)	V (m^3)	PEC (mg/l)	PEC/PNEC
5,65	10029	24928,3332	478,471
17,84	99986	2500,3479	47,991
56,42	1000037	249,9908	4,798
178,41	9999730	25,0007	0,480
564,19	100000148	2,5000	0,048
1784,12	999995386	0,2500	0,005

The calculations show that the PEC:PNEC ratio is above 1 for both potassium formate and cesium formate in a water column with a radius of less than 178 m and depth of 100m, e.g. relatively shallow environment.

The calculations above have assumed that the release of the formate brine was made into an entirely still and static water column. However, in real life there is always continuous mixing in the marine environment — driven by currents, wind and tides — which leads to the refreshment of the water column. An example of a refreshment rate calculation is included below.

A body of water of 1 km^3 at an average water depth of 100 m represents a surface area of some 10 km^2, or a cylinder with the radius (r) 1,784 m. This is also the distance used for CHARM dilution factors in the Bos model (Thatcher *et al*, 2001). As can be seen, the catastrophic loss of some 250 tonnes of potassium formate would lead to an overall 0.25 mgl^{-1} increase in the potassium concentration in the corresponding water column.

The average time (T2 in hours) it will take the water column to be completely refreshed – assuming the only mechanism aiding the lateral movement of water out of a predefined cylinder with the radius r (m) is the average residual current (U_a, in ms^{-1}) – is calculated using Equation E.1:

$$T2 = (2 * r) / (U_a * 3600) \quad \text{(E.1)}$$

In the high energy environment of oceans, it is more than likely that tidal mixing and wind-driven surface turbulence will add considerably to the refreshment rate. Therefore, it can be considered that this approach ensures the precautionary principle is applied and the worst case scenario depicted.

In addition, each part of the water column will continuously undergo refreshment, and it is considered unlikely that actual concentrations would increase to detectable levels apart from in the very immediate vicinity of the discharge outlet. A tabulation of the likely water column refreshment times for 3 different residual current speeds is contained in Table 5.

Table 5: Refreshment rate variable values

1780 m radius, variable current speed	**Value**		
U_a (residual current) /ms^{-1}	0.1	0.05	0.01
R (refreshment rate)	0.101124	0.0505	0.01
T2 (refreshment time) /hours	9.9	19.77	98.9
0.05 current speed, variable radius	**Value**		
r (radius) /m	5.64	17.84	56.42
R (refreshment rate)	15.97	5.05	1.59
T2 (refreshment time) /hours	0.06	0.20	0.63
T2 (refreshment time) /minutes	**3.8**	**11.9**	**37.6**

The above calculations assume a worst case accidental or emergency-driven release of some 250 tonnes of drilling fluid. To get a more realistic reflection of the actual discharges during drilling, it is better to apply a dynamic model that takes into account both the chronic toxicity based PNEC and the change of water volumes. The results are shown in Figure 5.

These examples all relate to major accidental or emergency-driven releases. It is highly unlikely that releases of such dimensions would ever occur during drilling or completion operations with formate brines. The high value of formate brines ensure that they are never deliberately discharged to the sea in any volume, and at the end of the drilling/completion operations they are shipped ashore for clean-up, recovery and reuse. If drilled cuttings are being discharged to the sea there will some low level continuous releases of formate brine that is adhering to the cuttings. The rate of release is determined by the amount of cuttings being discharged, which in turn is related to the hole size and drilling rate of penetration (speed). Average drilling speeds can typically range between 5 and 20 m/hour in wells where formate brines are deployed. Losses from wells being drilled with formate brines at these speeds are in the range 40-150 liters per meter drilled, with a median of somewhere near 95 liters per meter drilled.

Tables 6-12 shows the potential losses per hour of formate brine to the environment with drilled cuttings, assuming different drilling speeds and different amounts of formates lost with cuttings.

The formate brine density used has been varied between 1.5 (potassium only) to 2.0 (mainly cesium). In order to reflect worst cases, the loss of fluids to cuttings has been increased with increasing density of fluid. The lowest value used here is 1.5 tonnes per hour and the highest value is of 180 tonnes per hour. Note that the measured rates from field data indicate formate fluid losses of typically less than 100 liters per meter drilled and the values used here were chosen to find how much the overall potential increases of PEC would need to be in order to bring the PEC:PNEC ratio above 1.

Table 6: Loss per hour to the environment with different drilling rates of 0.2 m^3 fluid lost with cuttings per meter drilled

s.g of fluid	**1,5**	kg/l	
Fluids	**0,2**	m3	
Drilling speed m/h	**Fluids m3 lost with cuttings per m drilled**	**s.g of fluid**	**Tonnes of fluid lost with cuttings per hour**
5	**0,2**	**1,5**	**1,50**
10	**0,2**	**1,5**	**3,00**
15	**0,2**	**1,5**	**4,50**
20	**0,2**	**1,5**	**6,00**
30	**0,2**	**1,5**	**9,00**

Table 7: Loss per hour to the environment with different drilling rates of 0.5 m^3 lost with cuttings per meter drilled

s.g of fluid	**1,5**	kg/l	
Fluids	**0,5**	m3	
Drilling speed m/h	**Fluids m3 lost with cuttings per m drilled**	**s.g of fluid**	**Tonnes of fluid lost with cuttings per hour**
5	**0,5**	**1,5**	**4**
10	**0,5**	**1,5**	**8**
15	**0,5**	**1,5**	**11**
20	**0,5**	**1,5**	**15**
30	**0,5**	**1,5**	**23**

Table 8: Loss per hour to the environment with different drilling rates and 0.8 m^3 fluid lost with cuttings per meter drilled

s.g of fluid	1,75	kg/l	
Fluids	0,8	m3	
Drilling speed m/h	**Fluids m3 lost with cuttings per m drilled**	**s.g of fluid**	**Tonnes of fluid lost with cuttings per hour**
5	0,8	1,8	7
10	0,8	1,8	14
15	0,8	1,8	21
20	0,8	1,8	28
30	0,8	1,8	42

Table 9: Loss per hour to the environment with different drilling rates and 1 m^3 fluid lost with cuttings per meter drilled

s.g of fluid	1,75	kg/l	
Fluids	1	m3	
Drilling speed m/h	**Fluids m3 lost with cuttings per m drilled**	**s.g of fluid**	**Tonnes of fluid lost with cuttings per hour**
5	1,0	1,8	9
10	1,0	1,8	18
15	1,0	1,8	26
20	1,0	1,8	35
30	1,0	1,8	53

Table 10: Loss per hour to the environment with different drilling rates and 2m^3 fluid lost with cuttings per meter drilled

s.g of fluid	2	kg/l	
Fluids	2	m3	
Drilling speed m/h	**Fluids m3 lost with cuttings per m drilled**	**s.g of fluid**	**Tonnes of fluid lost with cuttings per hour**
5	2,0	2,0	20
10	2,0	2,0	40
15	2,0	2,0	60
20	2,0	2,0	80
30	2,0	2,0	120

Table 11: Loss per hour to the environment with different drilling rates and 3 m^3 fluid lost with cuttings per meter drilled

s.g of fluid	2	kg/l	
Fluids	3	m3	
Drilling speed m/h	**Fluids m3 lost with cuttings per m drilled**	**s.g of fluid**	**Tonnes of fluid lost with cuttings per hour**
5	3,0	2,0	30
10	3,0	2,0	60
15	3,0	2,0	90
20	3,0	2,0	120
30	3,0	2,0	180

These data were used to calculate the increased concentration of potassium formate and cesium formate in the water column surrounding the drilling rig during 24 hours of drilling and one hour of drilling for different refreshment rates for and the subsequent changes in PEC:PNEC ratios. The values used were 1.5 tonnes, 23 tonnes and 53 tonnes of fluid. The data from the field indicate that these values are much too high, e.g. from the six Huldra wells drilled with cesium formate brine in the North Sea the fluid losses were monitored and related to meters drilled. The results showed that the formate fluid lost per meter of 8.5 inch wellbore drilled ranged between 21.7 liters and 168.9 liters. The average was 95.1 liters of fluid lost per metre of wellbore drilled, lower than the lowest figure of 200 liters per drilled meter of rock used in Table 6. However, including such unrealistically high rates of fluid losses allows a very conservative approach to the risk assessment to be taken. Note that the higher values of continuous release would already indicate catastrophic losses due to accidents. This was already modeled in the 250 tonne release.

Table 12: Release of 1.5 t of potassium formate 1 h and 24 h – PEC:PNEC calculation for water volumes

Potassium Formate, Time of drilling (h): 1, Amount of instant release (kg): 1500						
		Residual current speed				
	Radius (m)	0,05	0,1	1	3	5
PEC / PNEC	5,65	0,017	0,009	0,001	0,000	0,000
	17,84	0,006	0,003	0,000	0,000	0,000
	56,42	0,002	0,001	0,000	0,000	0,000
	178,41	0,001	0,000	0,000	0,000	0,000
	564,19	0,000	0,000	0,000	0,000	0,000
	1784,12	0,000	0,000	0,000	0,000	0,000

Potassium Formate, Time of drilling (h): 24, Amount of instant release (kg): 36000						
		Residual current speed				
	Radius (m)	0,05	0,1	1	3	5
PEC / PNEC	5,65	0,022	0,011	0,001	0,000	0,000
	17,84	0,007	0,003	0,000	0,000	0,000
	56,42	0,002	0,001	0,000	0,000	0,000
	178,41	0,001	0,000	0,000	0,000	0,000
	564,19	0,000	0,000	0,000	0,000	0,000
	1784,12	0,000	0,000	0,000	0,000	0,000

Table 13: Release of 23 t/h of potassium formate 1 h and 24 h – – PEC:PNEC calculation for water volumes

Potassium Formate, Time of drilling (h): 1, Amount of instant release (kg): 23000						
		Residual current speed				
Radius (m)		0,05	0,1	1	3	5
PEC / PNEC	5,65	0,267	0,133	0,013	0,004	0,003
	17,84	0,084	0,042	0,004	0,001	0,001
	56,42	0,027	0,013	0,001	0,000	0,000
	178,41	0,008	0,004	0,000	0,000	0,000
	564,19	0,003	0,001	0,000	0,000	0,000
	1784,12	0,001	0,000	0,000	0,000	0,000

Potassium Formate, Time of drilling (h): 24, Amount of instant release (kg): 552000						
		Residual current speed				
Radius (m)		0,05	0,1	1	3	5
PEC / PNEC	5,65	0,333	0,167	0,017	0,006	0,003
	17,84	0,106	0,053	0,005	0,002	0,001
	56,42	0,033	0,017	0,002	0,001	0,000
	178,41	0,011	0,005	0,001	0,000	0,000
	564,19	0,003	0,002	0,000	0,000	0,000
	1784,12	0,001	0,001	0,000	0,000	0,000

Table 14: Release of 53 t of cesium formate 1 h and 24 h – PEC:PNEC calculation for water volumes

Cesium Formate, Time of drilling (h): 1, Amount of instant release (kg): 53000						
		Residual current speed				
Radius (m)		0,05	0,1	1	3	5
PEC / PNEC	5,65	0,637	0,318	0,032	0,011	0,006
	17,84	0,202	0,101	0,010	0,003	0,002
	56,42	0,064	0,032	0,003	0,001	0,001
	178,41	0,020	0,010	0,001	0,000	0,000
	564,19	0,006	0,003	0,000	0,000	0,000
	1784,12	0,002	0,001	0,000	0,000	0,000

Cesium Formate, Time of drilling (h): 24, Amount of instant release (kg): 1272000						
		Residual current speed				
Radius (m)		0,05	0,1	1	3	5
PEC / PNEC	5,65	5,924	2,962	0,296	0,099	0,059
	17,84	1,876	0,938	0,094	0,031	0,019
	56,42	0,593	0,297	0,030	0,010	0,006
	178,41	0,188	0,094	0,009	0,003	0,002
	564,19	0,059	0,030	0,003	0,001	0,001
	1784,12	0,019	0,009	0,001	0,000	0,000

As can be seen, the PEC:PNEC ratio would only be exceed the critical value of 1 in the case of drilling for 24 hours with an hourly release of 53 tonnes. Note that this is entirely hypothetical, as the total release of over a 1200 tonnes of cesium formate to the sea with cuttings is close to the maximum quantity of brine that would ever be stored on an offshore rig.

3.3 Evidence from marine surveys after use of formates

In a paper presented to the Society of Petroleum Engineers, the oil company ENI presented results from a high resolution environmental survey on the physical, chemical and biological conditions of the benthic sediments, in the vicinity of a well drilled using formates where the cuttings and fluids from the well were released to the environment. The aim of the study was to verify findings in a life cycle assessment (LCA) that had been conducted for formate brine, which concluded that: "The findings of the study indicate that the discharge of moderate amounts of Formate Brines is not likely to lead to potentially significant negative impacts on the marine environment."

Samples were collected from 22 stations and analyzed physically/chemically while samples from 19 stations were analyzed biologically, in addition to the reference station. As the stations were very close to each other, a high level of sampling accuracy was of crucial importance. The findings from these analyses and study are in line with the conclusion in the LCA, i.e. only minor environmental impact in the vicinity of the drilling location was detected. The full SPE paper is attached.

3.4 Long term effects

Formate brines, and their content of low levels of organic polymer additives, can give rise to organic enrichment of the seabed. The formate molecules and the additives (long-chain polymers of sugar molecules) are readily biodegraded aerobically by bacteria. This can potentially give rise to localized reduction in oxygen levels. The chronic toxicity of the formate brines is not considered to be significant. Long-duration lethal or adverse sub-lethal effects in local organisms are not expected. Some temporary avoidance behavior may be experienced, such as migration of zooplankton. The hazard this represents to organisms is, therefore, likely to be short-term, and mainly related to sessile benthic organisms. Mobile organisms are likely to exhibit avoidance behavior and recolonization is expected to occur rapidly.

4 Health and safety aspects

4.1 Safety

The use of potassium and cesium formates as the sole weighting agents in reservoir drill-in fluids has enabled operators to enjoy the full economic and safety benefits of creating low-skin open-hole completions in deep high-angle HPHT gas wells. Field evidence reviewed in paper SPE 145562 shows that the use of heavy formate brines as reservoir drill-in fluids over the past 10 years has facilitated the safe and efficient development of deep HPHT gas reserves by:

- Virtually eliminating well control and stuck pipe incidents
- Enabling the drilling, in overbalance or in MPD mode, of long high-angle wells with narrow drilling windows

- Typically reducing offshore HPHT well completion times by 30 days or more
- Improving the definition and visualization of the gas reservoirs
- Eliminating the need for clean-ups, stimulation treatments or any other form of intervention to remove formation damage caused by the drilling fluid

4.2 Well control

There have been no well control incidents of any kind in the 29 HPHT wells drilled and completed with cesium formate brine over the past 10 years. For the 14 wells drilled/completed in overbalance in the Huldra and Kvitebjørn fields this means a total of 432 days in HPHT open hole without an incident. This remarkable "zero incidents" record set in a hostile environment is a tribute to both the professionalism/skills of the drilling crews and the improved HPHT well control environment provided by cesium formate drill-in and completion fluids. The specific attributes of cesium formate brines that increase the security of well control in deep HPHT gas wells:

- Elimination of barite and its sagging problems
- Virtual elimination of gas diffusion into high-angle wells
- Lower ECD and swab/surge pressures
- Inhibition of hydrate formation
- Rapid surface detection of any gas influx resulting from a kick or well swab

The fluid gains during well flow-checks have been small and of short duration. The wells typically flow around 70-140 litres of drilling fluid in the first 15-30 minutes and then become static.

4.3 Well ECD management

In at least three of the offshore HPHT fields drilled with cesium formate the drilling window between pore pressure and formation fracture pressure in the reservoir sections has been very narrow. In Kristin the riser margin of SG 0.09 reduced the already narrow drilling window to only SG 0.09 (i.e. SG 2.05 to SG 2.14 – see Figure 3). The high ECD of an oil-based mud in this environment would have been, in the words of operator, "close to impossible to live with" while maintaining a riser margin (Gjønnes and Myhre, 2005). The actual ECD measured with PWD while drilling the Kristin wells with cesium formate brine was SG 0.05-0.06.

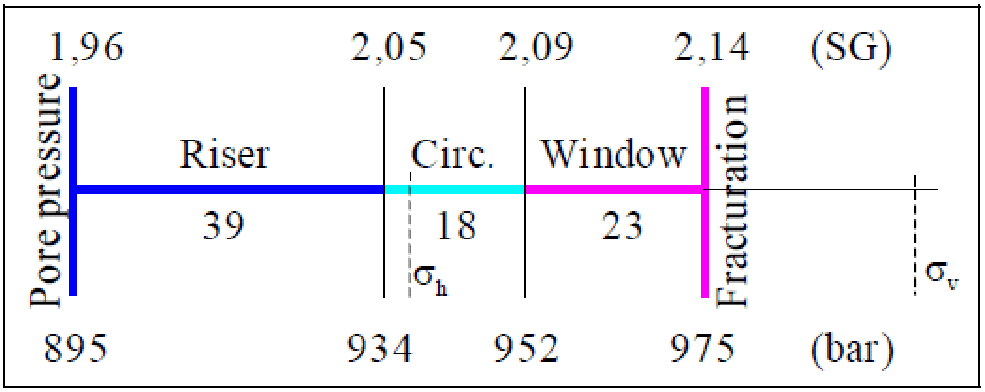

Figure 3: *Kristin drilling window (from Gjønnes and Myhre, 2005)*

In the Huldra and Kvitebjørn wells the use of cesium formate drill-in fluid combined with reduced pumping rates and capped ROP kept the ECD within the range SG 0.04-0.06, although excursions up to SG 0.09 could happen when drilling shale. When production on Kvitebjørn eventually made the window too narrow for conventional drilling the operator was able to continue with the field development by using cesium formate brine in MPD operations.

4.4 Occupational health

The occupational health hazards associated with the formate fluids are low. A more detailed evaluation of the hazards is contained in the Formate Fluids Hazard Assessment report from Gaia Consulting. The occupational health risks associated with handling, use and storage of drilling and completion fluids are:

- Acute dermal risk due to splashes or spills
- Acute inhalation risk due to fumes or dust
- Acute health risks due to ingestion
- Chronic health risks due to long term exposure.

The acute dermal risks posed by splashes or spills to the personnel handling the fluids are low. None of the formate fluids are corrosive, and cesium formate is considered an irritant whereas potassium formate is considered a possible irritant (e.g. not enough evidence of this exists). The risks of serious damage to eyes always exists when handling chemicals, but as neither of the fluids are corrosive nor classed as dangerous to eyes, the risk is considered to be limited.

There are neither fumes nor dust associated with the handling or use of the fluids.

It is considered that there is little risk of accidental ingestion of large and repeated amounts of either fluid. As indicated in the hazard report, accidental ingestion of small amounts would not cause undue risk.

There is no evidence of long term health risks due to long term exposure and chronic health risk is therefore not seen as a significant risk.

5 Conclusions

Formate brines have a relatively low toxicity, the metal cation components are naturally abundant in the sea and the formate anion is readily biodegradable. It is considered that even a catastrophic release of some 250 tonnes of formate brine would be rapidly dispersed in the water column, and would be unlikely to exceed PNEC concentrations for any length of time. It might be concluded that the hazards associated with discharges of cuttings contaminated with formate brines are in main associated with the short-term physical effects of smothering and increased turbidity.

The risk assessments conducted here in this report indicate that the risk associated with the formate fluids to the marine environment is low or very low. This conclusion would not be supported by the results of the single mysid shrimp SPP test used for regulating drilling fluid discharges from offshore rigs in USA. High-density potassium and cesium formate brines give LC_{50} values that are below the acceptable threshold value of 30,000 ppm in this SPP test, meaning that discharge of the cuttings would be prohibited from wells drilled with these fluids.

Formate brines are high value fluids that are not discharged at the end of a well. The fluids are recycled and reconditioned as far as possible. Specific fluid loss minimization plans are put together for each job. However, the containment requirement for the cuttings based on a single hazard test places the innovative and green formates in a different competitive position from synthetic based fluids.

It is therefore argued that the formate fluids should be assessed on a risk assessment approach rather than using a single hazard test. As the risk assessment indicates, there is really little or no significant risk to the marine environment from the release of formate fluids on cuttings.