



VIEWPOINT

Fate and Effects of Polydimethylsiloxane (PDMS) in Marine Environments

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Polydimethylsiloxanes (PDMS) defoamers are used to improve process efficiency under extreme conditions during gas–oil separation, when other chemicals fail to perform. They are also used to reduce the oil content of process waters discharged to the marine environment, thereby serving an important function in reducing oil pollution. As a consequence of these applications small quantities of PDMS may also be released into the environment. This paper reviews the fate of PDMS in the marine environment and the extensive effect studies that have been conducted. These demonstrate the absence of adverse effects on a wide range of marine species. © 2001 Elsevier Science Ltd. All rights reserved.

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Introduction

Organosiloxane materials (also known as ‘silicones’) are diverse polymeric compounds that contain a backbone of alternating atoms of silicon and oxygen. Organic substituents attached to the silicon atom modify the properties of the polymer (Hamelink, 1992; Allen *et al.*, 1997). The simplest and most widely used organosiloxane materials are polymers of dimethylsiloxane (i.e., polydimethylsiloxane or PDMS) where all the organic substituents are methyl groups. PDMS fluids are an important component in a wide variety of consumer products and applications (Allen *et al.*, 1997; Fendinger *et al.*, 1997a), such as coatings, polishes, detergents,

personal care products, foods and medicines. They are also found in many industrial products, including release agents, dielectric fluids, antifoams and heat transfer fluids and are used extensively as industrial process aids. The same basic PDMS molecule is used for these diverse applications. However, chain-length of the dimethylsiloxane backbone varies such that viscosity of the PDMS fluids ranges from around 10 to >100 000 centistoke (cSt, the standard unit for viscosity of organosiloxane fluids). A 10 cSt fluid has a dimethylsiloxane chain-length of about 15 units and a molecular weight of about 1300. Higher viscosity PDMS fluids have longer dimethylsiloxane chains and greater molecular weights. PDMS fluids that have 10 or more dimethylsiloxane units are essentially non-volatile at environmental temperatures and are virtually insoluble in water.

PDMS fluids are manufactured polymers and are not found in nature. The greatest potential source of PDMS fluids to marine environments is from consumer products and process aids discarded to wastewater (Allen *et al.*, 1997; Powell *et al.*, 1999), rather than from manufacture (Hamelink, 1992). In terms of environmental fate, PDMS fluids have exceedingly low water solubility, with concentrations typically measured in the parts-per-trillion range (Varaprath *et al.*, 1996), and very high adsorption coefficient (K_d 25000) for organic matter (Fendinger *et al.*, 1997a). As such, they are unlikely to be found in the aqueous phase. PDMS fluids disposed to wastewater will be removed from the aqueous phase by adsorption onto sludge during sewage treatment, as demonstrated in laboratory (Watts *et al.*, 1995) and field studies (Fendinger *et al.*, 1997b), or will be adsorbed to suspended solids in the effluent or receiving waters. Therefore, sediments represent the ultimate sink for PDMS fluids in marine environments.

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This conclusion is supported by field studies (Powell *et al.*, 1999, 2000), that demonstrate that concentrations of PDMS in surface sediments are related to the mass of solids discharged with treated wastewater and the basin geomorphometry of the receiving waters.

In this paper, we discuss the sources of PDMS fluids to marine environments and review the studies that demonstrate the absence of adverse effects on a wide range of marine species. While key references to the effect of PDMS on free-swimming species are included, the main focus of this paper is on the fate and effects in sediments. In addition, we will discuss the results of a hazard assessment based upon the Chemical Hazard Assessment and Risk Management (CHARM) model, which predicts that PDMS fluids will not adversely affect marine ecosystems.

Potential Sources and Fate of PDMS Fluids

Sewage sludge disposal

PDMS fluids (also known as dimethicone) are used in a broad range of industrial, medical, and consumer applications that are eventually discarded 'down-the-drain' to wastewater – for example shampoos, hair conditioners, antifoams, antiflatulants, lubricants, detergents, textile coatings, etc. (Allen *et al.*, 1997; Fendinger *et al.*, 1997a). As such, trace amounts of PDMS are observed in untreated wastewater, with measured concentrations in non-filtered samples ranging from about 0.09 to 0.37 mg l⁻¹ (Fendinger *et al.*, 1997b). The very low water solubility of PDMS (Varaprath *et al.*, 1996), coupled with the very high adsorption coefficient for organic matter (Fendinger *et al.*, 1997a), suggests the material will be removed from the aqueous phase during sewage treatment by adsorption to particulate matter, as demonstrated in laboratory (Watts *et al.*, 1995) and field studies (Fendinger *et al.*, 1997b). Concentrations of PDMS in treated wastewater effluents are typically less than analytical detection limits (<0.005 µg l⁻¹) and do not appear to exceed 0.013 mg l⁻¹ (AATS, 1985; Fendinger *et al.*, 1997b; Pellenbarg, 1979b; Watanabe *et al.*, 1984). In contrast, dry weight concentrations of PDMS in sewage sludge range from 20 to 5100 mg kg⁻¹ (AATS, 1985; Batley and Hayes, 1991; Fendinger *et al.*, 1997b; Pellenbarg, 1979b; Siebert, 1988; Watanabe *et al.*, 1984).

Until 1998, offshore disposal of sewage sludge was common practice in Europe, particularly in the UK and Ireland, where 30% and 35% (respectively) of sludge were discarded via this route (Hall and Dalimier, 1994). In the UK alone, this represented 334 000 t of dry solids per year. As a result, offshore disposal of sewage sludge has represented a primary source of PDMS to marine environments.

Environmental monitoring studies have typically targeted sludge disposal areas as locations where the highest (i.e., worst-case) concentrations of PDMS in marine sediments were likely to occur. For example, the Silicone Industry Association of Europe (Centre Européen des Silicones, CES), in conjunction with The Center for Environment Fisheries and Aquaculture Science (CEFAS) in the UK, analysed sediment samples from sludge disposal areas in Liverpool Bay and Plymouth Sound (CEFAS, 1997). Sediments were also collected from the Minches, off the west coast of Scotland, an area which receives very little wastewater and where sludge had not previously been disposed. Measured dry weight concentrations of PDMS in the sediments ranged from below detection (0.03 mg kg⁻¹) to 2.3 mg kg⁻¹ (Table 1). As was expected, concentrations were below detection in sediment samples from the Minches. Low-level concentrations of PDMS were measured in Plymouth Sound, where only sludge from municipal sources had been dumped. The greatest concentrations of PDMS were found in sediments from Liverpool Bay, where sludge from both industrial and municipal sources had been disposed. In addition, the river Mersey, which receives large volumes of industrial wastewaters, presumably represented a significant source of PDMS to Liverpool Bay.

Other monitoring studies (Table 1) measured 'worst-case' concentrations of PDMS in sediments from former sludge disposal areas in the US. The greatest concentrations were observed in New York Bight, where approximately 17 × 10⁶ t of sewage sludge were dumped in 1975 (Pellenbarg, 1997a). Dry weight concentrations of PDMS in sediments from New York Bight ranged from <1.05 to 126 mg kg⁻¹ (mean <20.5 mg kg⁻¹) and decreased with distance from the primary disposal site (Pellenbarg, 1997a). Similar results were obtained for Boston Harbor (Powell *et al.*, 1999) where dry weight

TABLE 1
Concentration of PDMS in marine surface sediments from areas used for disposal of sewage sludge.

Sample location	N ^a	Concentration (mg kg ⁻¹ dry wt)		References
		Mean	Max.	
Minches ^b	5	<0.03	0.04	CEFAS (1997)
Plymouth Sound	20	0.06	0.41	CEFAS (1997)
Liverpool Bay	20	0.33	2.3	CEFAS (1997)
Boston, Harbor, USA	12	16.6	34.2	Powell <i>et al.</i> (1999)
New York Bight, USA	24	20.5	126	Pellenbarg (1979a)

^a N is the number of sediment samples analysed.

^b Minches represents an uncontaminated area.

concentrations of PDMS ranged from 1.10 to 34.2 mg kg⁻¹ (mean 16.6 mg kg⁻¹). Dry weight concentrations of PDMS were strongly correlated with organic carbon content of the sediments at both study areas, suggesting that PDMS concentration was related to the amount of sludge deposited in the sediments. This conclusion is supported by studies (Powell *et al.*, 1999, 2000) demonstrating that retention of solids during wastewater treatment is a principal component controlling the level of PDMS discharged and deposited to sediments in areas heavily impacted from municipal and industrial wastewater.

Dredging activities

No analysis of PDMS in dredged sediments (i.e., dredge spoil) has been conducted in dredging disposal areas. However, most dredgings dumped at sea are derived from harbours or estuaries. Consequently, PDMS concentrations in dredgings should be similar to those measured in estuarine sediments from depositional areas. Typically, concentrations of PDMS are less than 11 mg kg⁻¹ dry weight and are often below the limits of analytical detection (see Table 2).

Offshore oil and gas production

PDMS fluids have been used for the past two decades as specialty chemicals in various applications by the offshore oil and gas industry. They are primarily used to improve process efficiency under extreme conditions where bulk chemicals fail to perform. PDMS fluids are typically used as defoamers during gas-oil separations and to reduce the oil content of process waters discharged to the environment. In addition, PDMS-based materials are also used in drilling mud formulations, cementing, de-emulsification during oil-water separations, and gas scrubbing. Because they are considerably more effective as processing aids, PDMS-based materials and fluids are used at much lower concentrations (< 20 mg l⁻¹) than other chemicals. Only a minor fraction (< 1%) of the total chemical usage in offshore oil

and gas applications can be attributed to PDMS-based materials and fluids (Stevens *et al.*, 1999). Typically, PDMS-based materials and fluids required for offshore applications have viscosity ranging from 1000 to 60 000 cSt (molecular weight > 15 000).

Approximately 300–400 t of PDMS are annually consumed by oil and gas applications in the North Sea (Stevens *et al.*, 1999), of which unknown amounts are released to the environment as a component in drilling muds or process waters (e.g., from oil-in-water separations and de-emulsification applications). By comparison, 13 600 t of PDMS is annually disposed to wastewater in the US (Allen *et al.*, 1997). Generally, PDMS-based materials and fluids used for offshore oil and gas operations will become part of the solid matrix (e.g., when used for cementing) or will partition with the crude oil and be transported onshore. Only the use of PDMS in production additives and drilling chemicals results in discharges to the marine environment.

Concentrations of PDMS in sediments near offshore oil operations are not known. However, considering that PDMS-based materials and fluids are used at low concentrations in specialized applications, concentrations should be considerably less than those in sediments impacted from municipal wastewater effluents. The conclusion that sediments in the vicinity of offshore oil operations contain low concentrations of PDMS is supported by predicted concentrations obtained using the CHARM model. The CHARM model was developed to identify potential environmental risks associated with production chemicals used for offshore oil and gas exploration and production (Thatcher *et al.*, 1999). Results from the CHARM model indicate that concentrations of PDMS will be greatest in sediments in the vicinity of oil platform operations (Karman and Smit, 1999). Nonetheless, when the simulations are conducted using worst-case scenarios, predicted concentrations of PDMS in the sediments are < 0.2 mg kg⁻¹ dry weight.

TABLE 2

Concentration of PDMS in marine and estuarine surface sediments from areas where disposal of sewage sludge has not occurred (listed in order of increasing mean concentration).

Sample location	N ^a	Concentration (mg kg ⁻¹ dry wt)		References
		Mean ± SD	Range	
Tokyo Bay, Japan	21	Detected in 17 samples		Watanabe <i>et al.</i> (1984)
Ise Bay, Japan	21	Detected in nine samples		Watanabe <i>et al.</i> (1984)
Osaka Bay, Japan	15	Detected in seven samples		Watanabe <i>et al.</i> (1984)
Various locations, Australia	9	0.3 ± 0.4	0.05–1.4	Batley and Hayes (1991)
Mud Flat, Germany	1	0.6	0.6	Siebert (1988)
Puget Sound, USA	12	0.6 ± 0.1	0.1–3.5	Powell <i>et al.</i> (1999)
Hillborough Bay, USA	12	0.9 ± 0.2	0.2–2.8	Powell <i>et al.</i> (1999)
Curtis Bay	5	1.7 ± 2.8	< 0.3–6.8	AATS (1985)
Delaware Bay, USA	9	1.7 ± 0.9	0.3–3.3	Pellenbarg (1979b)
San Francisco Bay	12	1.8 ± 0.1	0.7–2.6	Powell <i>et al.</i> (1999)
Delaware River, USA	5	5.5 ± 6.7	0.5–14.6	AATS (1985)
Chesapeake Bay, USA	24	11.0 ± 20.6	< 0.5–95.3	Pellenbarg (1982)

Accidental spills

In the event of a spill to surface water, PDMS will spread rapidly on the surface to form a very fine film, as a result of its very low surface tension (~ 20 dynes cm^{-1}) and a density less than water. Depending on the environmental conditions, this film will break up to form tiny droplets which adsorb to suspended particles, eventually settling out of the water column and becoming part of the sediment compartment. Emulsions will behave similarly, as particularly in saltwater, the sudden decrease in surfactant concentration will cause the PDMS to quickly coalesce into droplets, before ultimately sedimenting out.

Environmental Effects of PDMS Fluids

Bioavailability

Bioavailability refers to the ability of a substance to interact with the bio-system of an organism. In terms of the aquatic environment, this means that the substance must be absorbed either from water, foodstuffs or sediment via the gut, via respiratory surfaces such as the gills, or directly from the water via the skin.

PDMS has a number of physico-chemical characteristics that support the view that it is likely to have minimal effects on sediment-dwelling organisms or free-swimming benthic species. The key feature is the high molecular weight of PDMS, which restricts absorption into an organism, as a consequence of the sheer physical size of the PDMS molecule. In fact, PDMS molecules are too large to pass through the bilipid layer of a cell membrane. Opperhuizen *et al.* (1987) clearly demonstrated this by comparing the bioconcentration in guppies that had PDMS mixed with their feed. Anything greater than 10 cSt fluid (molecular weight > 1000) showed no potential for bioaccumulation over a 20-day period. This was also confirmed by Annelin and Frye (1989), who showed that PDMS with a molecular weight of greater than 600 was not absorbed by bullhead catfish (*Ictalurus melas*). With regard to the relationship between molecular weight and bioconcentration, it is worth noting that the bulk of PDMS products sold commercially have a viscosity of greater than 100 cSt (molecular weight ~ 6000), and they are thus not bioavailable.

The other important characteristic is the very high binding affinity of PDMS for sediments. Although the partition coefficient (K_d) has not been determined for marine sediments, Watanabe *et al.* (1985) reported a sediment K_{oc} of 10 000 for a 10 000 cSt PDMS. As a commercially available PDMS fluid containing low molecular weight soluble siloxanols was used for this experiment, this probably represents a significant underestimate of the true partition coefficient. This is supported by the fact that the K_d of ^{14}C -PDMS on sludge was measured as 25 000 (Fendinger *et al.*, 1997a). Substances that are tightly bound to sediment (such as PDMS) will have very low bioavailability for sediment-

dwelling or benthic organisms. The reason for this is twofold. Firstly, the concentration in the pore water is very low, (particularly for PDMS which has a water solubility in the parts per trillion range), and there is therefore very little potential for uptake via respiratory surfaces. Secondly, PDMS will not be readily desorbed during assimilation of ingested particles.

Potential for bioaccumulation

The very low bioavailability of PDMS and the absence of bioconcentration (Opperhuizen *et al.*, 1987; Annelin and Frye, 1989), clearly demonstrate that the potential for bioaccumulation in the food chain is very low. Biomagnification or food-chain transfer of a PDMS emulsion in the marine environment was studied by Aubert *et al.* (1985) and Guillemaut *et al.* (1987). In a series of studies, organisms in the first level of the food chain were exposed to 70 mg l^{-1} 50 cSt PDMS in the following combinations:

- Phytoplankton (*Tetraselmis* sp) were exposed for 9 days and then fed to mollusks (*Mytilus edulis*) for 12 days;
- Phytoplankton and crustacea (*Artemia salina*) were exposed for 8 days and then fed to fish (*Carassius auratus*) for 15 days;
- Annelids (*Nereis diversicolor*) were exposed for 8 days and then fed to fish (*Scorpaena porcus*) or crabs (*Carcinus maenas*) for 15 days. PDMS was not bioconcentrated in the phytoplankton or zooplankton, and the annelids had a bioconcentration factor (BCF) of less than 1. The bioaccumulation factor between the two trophic levels was low, ranging between 0.05 and 1.4, indicating no biomagnification of PDMS in the aquatic food chain tested.

In summary, while PDMS fluids have a high *n*-octanol/water partition coefficient, suggesting the ability to partition preferentially into cells and organisms, the high molecular weight of PDMS (> 10 cSt viscosity) prevents the fluid from bioaccumulating.

Sediment-dwelling (benthic) organisms

A variety of organisms may be exposed to contaminants in sediments, either directly or indirectly. Animals that ingest sediments or particulate detritus are exposed directly. Others may live in the sediment and be exposed to contaminants via the pore water. Both may in turn form part of the food chain for higher trophic level organisms, such as fish, marine mammals or sea birds.

For toxicity tests using marine sediments, SETAC (1993) recommends that amphipods should be used as the standard test organisms, preferably *Corophium volutator*, which is now part of the regimen required by PARCOM for the testing of chemicals used in offshore oil and gas exploration/production (PARCOM, 1995). Another infaunal amphipod that is preferred for testing in the US is *Ampelisca abdita*. PDMS has been tested with both species (see Table 3). Except in the *Corophium* test, where there were some signs of narcosis at the very

TABLE 3
Effects of PDMS on infaunal amphipods and copepods.

Species	Test material	Test	References
<i>Acartia tonsa</i>	10 cSt	EC ₅₀ (10d) > 88 900 mg kg ⁻¹	Aunaas (1996b)
<i>Corophium</i> sp	10 cSt	EC ₅₀ (10d) > 30 700 mg l ⁻¹	Aunaas (1996c)
<i>Ampelisca abdita</i>	350 cSt	EC ₅₀ (10d) > 2300 mg l ⁻¹	Putt and Mihaich (1996)

highest test concentration (30.7 g kg⁻¹), no adverse effects were observed. Also included in Table 3 is the result of acute toxicity testing on *Acartia tonsa* (EC₅₀ value = 88.9/kg). This is an estuarine copepod, with a wide geographical distribution. It is also included in the battery of tests required by PARCOM (International Organization for Standardization, 1995), as it is an ecologically important representative of a crustacean living in the water column.

Because of the variety of organisms that may live in or on the sediment and the number of different exposure routes, a battery of tests has been conducted with PDMS in order to reduce uncertainty. These include other infaunal organisms such as polychaete worms, which are not only exposed via the pore water but also via continuous ingestion of large quantities of sediment. Early studies focused on exposing the worms to very high concentrations (up to 10 000 mg l⁻¹) of a silicone emulsion (Aubert *et al.*, 1985). Some evidence of toxicity was observed at the highest dose level, however this was attributed to the surfactant that was present. The no observed effect level (NOEL) was 2000 mg l⁻¹, which is considerably higher than any concentration likely to be found in the environment. More realistic studies with PDMS alone (avoiding any adverse effects due to a surfactant or other component) have been conducted with *N. diversicolor* in sediment amended with 10 000 mg kg⁻¹ and 1000 mg kg⁻¹ PDMS (50 cSt), for 96 h and 28 days, respectively (Craig and Caunter, 1990). There was no evidence of acute toxicity or effect on body weight gain in either test. However these very high concentrations (1000–10 000 fold higher than typical measured concentrations from estuarine areas, (see Table 2) that caused a slight reduction in burrowing activity.

In the benthic ecosystem, mollusks are an important group of suspension feeders, continually filtering particles from the water. Not only are they exposed to large quantities of particulate matter, but they are also an important component of the human food chain. Species such as oysters, winkles and cockles are always found on, or buried in, the sediment (infaunal). Acute studies on all three species show no evidence of mortality when exposed to saturated solutions of PDMS (Maggi and Alzieu, 1977; Hobbs *et al.*, 1975).

In addition to acute studies, more extensive physiological studies have been conducted on the common mussel (*Mytilus edulis*). This species lives attached to rocks, where the constant agitation of the waves causes

the waters to be rich in particulate matter, and it is often used as a 'pollution indicator'. A number of acute studies have been conducted with PDMS fluids and emulsions of varying viscosities, at concentrations considerably in excess of the water solubility (Aubert *et al.*, 1985; Hill *et al.*, 1980). In none of these tests was there any evidence of lethality or acute toxicity.

The effect of PDMS on physiological functions of *Mytilus edulis* has also been studied (Houvenaghel, 1980; ECETOC, 1996). Filtering capacity, an essential requirement for mussel survival, was not influenced over a 2-h period by the presence of a filtrate containing 100 mg l⁻¹ PDMS adsorbed onto 30 µm starch particles; nor was there any effect on osmoregulation. A slight effect on filtration rate was observed with a 100 mg l⁻¹ PDMS emulsion, probably due to the presence of the surfactant.

Other epibenthic organisms that are an important part of the food chain are crabs and shrimp. In acute toxicity tests, no adverse effects were observed on these organisms at concentrations up to 1000 mg l⁻¹ (Hill *et al.*, 1984). While this is very reassuring in demonstrating that PDMS is effectively non-toxic to crustacea, as the concentration is about a million-fold higher than the water solubility of PDMS, its significance for the real environment is minimal.

More relevant is a study by Houvenaghel (1980) on the osmoregulation and respiration of the crab (*C. maenas*). In crustaceans, water circulation over the gills is maintained by appendage movements. Any clogging or coating of the respiratory surface due to foreign particles or insoluble substances such as PDMS, may result in a lower respiration rate and impaired osmoregulation. No impairment of either parameter was observed when crabs were exposed to PDMS emulsions (1-, 10- or 100 mg l⁻¹ PDMS).

Free swimming species

As PDMS preferentially partitions onto the sediment and is present in only trace concentrations in the water, evaluating the effect on free-swimming species is only important to simulate potential effects in the event of a spill. Studies have been conducted on a wide range of marine species (ECETOC, 1996) that show that even at concentrations a million times greater than the water solubility, no acute toxicity was observed. From these studies, it can be concluded that there are no effects of PDMS on mature fish. Even more important are studies on early life stages. In one study, Sheepshead minnow

(*Cyprinodon variegatus*) embryos and larvae were exposed for 33 days to a PDMS emulsion (Hill *et al.*, 1984). As a consequence of the very low water solubility, this emulsion had to be prepared using a surfactant. No definitive results were obtained, because although a statistically significant effect on hatchability was observed at 670 mg l⁻¹, adverse effects such as increased mortality and decreased larval weight/length were also observed in the surfactant control. It is therefore likely that the observed toxicity was due primarily to the surfactant.

Primary producers

Inevitably in any evaluation of a chemical's impact on the marine environment, consideration must be given to the effect on primary producers. These are organisms that usually incorporate light energy into organic molecules by the process of photosynthesis. Thus, they produce food for other organisms and oxygenate the water at the same time.

The species stipulated by PARCOM (International Organization for Standardization, 1995) for evaluating chemicals for offshore applications is *Skeletonema costatum*, as these organisms are found in the open ocean as well as coastal areas. PDMS (10 cSt) was evaluated in an acute test (72 h) at nominal concentrations up to 100 000 mg l⁻¹ and evaluated for growth and biomass. Apart from a slight effect on biomass at 33 900 mg l⁻¹, no adverse effects were observed (Aun-aas, 1996a). The effects of a range of PDMS viscosities have also been tested at saturation concentration on diatoms and flagellates, and no adverse effects on growth were observed over a 9-day period (Maggi and Alzieu, 1977).

Environmental modeling

Regulation of the use and discharge of offshore E&P chemicals in the North Sea area is based upon the use of the CHARM-model (Thatcher *et al.*, 1999). The CHARM-model evaluates the intrinsic environmental impact ('hazard') and actual environmental impact ('risk') of the discharge of production and drilling chemicals. In 1999 the use of PDMS as a production, drilling, cementing and utility chemical was evaluated using the CHARM-model (Karman and Smit, 1999). The results are presented in Table 4.

For this evaluation, the default (realistic worst case) values of the CHARM-model were used. The results indicated that it is unlikely that adverse effects on the marine ecosystem will occur due to the use of PDMS. In all usage options evaluated (production, drilling, cementing or utility chemical), and assuming either median or worst case dosage rates, the hazard quotient of PDMS is far below 1 (Thatcher *et al.*, 1999).

Beneficial uses

Rather than having a detrimental effect on the marine environment, there are some circumstances where

TABLE 4

Results of the environmental evaluation of PDMS using the CHARM-model.

Use of PDMS	Maximum HQ ^a in water	Maximum HQ in sediment
Production chemical	0.0002	0.00002
Drilling chemical	0.0000004	0.0005
Cementing chemical	0.00005	— ^b
Utility chemical	0.00002	— ^b

^a Hazard Quotient.

^b Not relevant.

PDMS fluids have been highly beneficial. For example, a silicone product was a vital element in helping to save otters caught in the *Alaskan* oil spill disaster. The crude oil had soaked into their fur, destroying the air layer which helps to keep them warm and placing them in danger of dying from the icy waters. Detergents were found to remove the natural waterproofing oils from the otters' fur, but treating the otters with PDMS fluids (similar to a hair conditioner) gave their fur a temporary waterproof layer that protected them until they recovered their natural hydrophobic layer.

Silicone-based polymers are also being evaluated as oil spill treatment agents, where they have shown promise as gelling agents or solidifiers that facilitate the recovery of spilled oil from the water surface (Pelletier and Siron, 1999). Marine mesocosm experiments that have been conducted to evaluate any potential effects of the silicone-based polymers on bacteria and phytoplankton have shown no adverse effects. Also there was no impairment of the subsequent biodegradation of the oil (Padros *et al.*, 1999).

Conclusions

PDMS fluids are large innocuous macromolecules for which there is no demonstrated environmental concern. The physical and chemical properties of these materials indicate that the principal compartment for PDMS fluids in the environment, are sediments; any PDMS processed through wastewater treatment will be adsorbed to sludge [44,45]. The vapour pressure of PDMS fluids rapidly decreases with increasing molecular weight and viscosity. Hence, PDMS fluids with viscosities greater than 10 cSt are not volatile at environmental temperatures. Similarly, PDMS fluids, including low molecular weight materials, are not soluble in water.

PDMS fluids have high octanol/water partition coefficients ($\log K_{ow} > 4-5$) but do not bioaccumulate because they are insoluble in water and have molecular weights considerably greater than 600. Bioaccumulation of chemicals with water solubility <0.002 mole m³ (equivalent to about 2.6 mg l⁻¹ for a 10 cSt PDMS fluid) or molecular weights greater than 600 do not bioaccumulate because of low concentration and

decreased permeability of biological membranes [46–51].

The information presented here indicates that there is no risk of PDMS to either free swimming or sediment-dwelling organisms in the marine environment. Nor has any risk been found of bioaccumulation into top predators or tainting of seafood. The virtual absence of PDMS in the samples of sediment from uncontaminated areas indicates that its use is not widely contaminating the marine environment. Only where sewage sludge dumping has been practiced in the past, and in locations where river sediments are deposited, is PDMS likely to be found.

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