Sea Mammals and Oil
Confronting the Risks

Edited by

Joseph R. Geraci
David J. St. Aubin

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Physiologic and Toxic Effects on Cetaceans

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Historical Notes

January 28, 1969, marked the first incident calling attention to the possibility that oil pollution might harm a cetacean. Union Oil's undersea well off Santa Barbara, California, sprung a leak. A flurry of activity followed, with estimates and counterestimates of the size and duration of the spill and of the types and numbers of animals being affected. Union Oil calculated that about 250,000 gal of oil had leaked into the channel by February 8 when the well was sealed with cement (Santa Barbara *News-Press,* March 15, 1969). Oil continued to seep through new leaks and by April 1969, as much as 3 million gal may have been released (Santa Barbara *News-Press,* April 26, 1969; Straughan, 1972).

What happens to whales and dolphins when 800 square miles (Santa Barbara *News-Press,* February 6, 1969) of travel routes and feeding grounds are contaminated with oil? The picture is not clear. At the time of the spill, gray whales were just beginning their annual migration northward through or to the west of the fouled area (Brownell, 1971). One airplane pilot saw a group of whales moving northward through the slick, blowing as they went (Easton, 1972).

The Santa Barbara *News-Press* of March 13, 1969, reported that by the sixth week of the spill three dead gray whales had come ashore in northern California. The mouth and baleen plates of one were coated with

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a light film of oil, later interpreted as an unremarkable finding in a carcass that had floated at sea for some time (Brownell, 1971). Another whale covered with oil was seen "floating listlessly" in the Santa Barbara Channel. By March 15 the number of dead whales was placed at six (Santa Barbara *News-Press,* March 15, 1969), only two of which were fresh enough for necropsy examination. Oil was not found in either, and the whales were thought to have died from natural causes (Santa Barbara *News-Press,* May 15, 1969). One, in fact, may have been harpooned (Brownell, 1971).

During the Union Oil spill, gray whales were the focus of attention for their obvious size, and possibly because they were protected after a long history of exploitation (Rice and Wolman, 1971). But they were not the only cetacean to arouse concern. An unidentified porpoise "coated with old oil" stranded on a sandbar. Two other stranded porpoises examined by representatives of the California State Department of Fish and Game showed no evidence that oil was related to their deaths (Battelle Memorial Institute, 1969). Eyewitnesses, referring to one of the porpoises, a common dolphin (Brownell, 1971), said that its "breathing hole was clogged with oil and its lungs were ruptured" (Easton, 1972). *Time* magazine (February 21, 1969) published a similar account. Yet Brownell (1971) and his colleagues examined five of six dolphins stranded from February through May 1969 and found no evidence of oil contamination.

The final tally? Carcasses recovered from January 28 through March 31, 1969, included six gray whales, one sperm whale, one pilot whale, five common dolphins, one Pacific white-sided dolphin, and two unidentified dolphins. Brownell (1971), acknowledging that these totaled more than the usual number of gray whales and dolphins stranding annually on California shores, concluded that increased survey effort in 1969 had led to higher counts. The Smithsonian Institution Center for Short-lived Phenomena (Anonymous, 1970) summarized the event: "a few sea mammals were found dead; however, for the most part, they seemed to avoid direct contact with the oil." An independent report went a step further in concluding that "the whales were either able to avoid the oil, or were unaffected when in contact with it" (Battelle Memorial Institute, 1969).

Not surprisingly, the Santa Barbara spill set the stage for public reaction toward the threat of oil to whales and dolphins. The oil flowed for a period of months in full view of a newly aroused public. Until that time little thought had been given as to why an occasional whale or dolphin might come ashore. Now, the need for such answers had become crucial, and with neither answers nor an established protocol to determine how a pollutant might fit into the picture, the stage was set for futile speculation.

Vying in magnitude with the Santa Barbara incident was the grounding of the *Exxon Valdez* in Prince William Sound, Alaska, in March, 1989. Eleven million gallons of Prudhoe Bay crude oil were released, causing a flurry of activity. There was concern that, of the 15 or 20 species of cetaceans that occupy the area periodically, some might become victims of the spill. By October, 1989, biologists had documented the carcasses of 25 gray, 2 minke, 1 fin, and 3 unidentified whales, and 6 harbor porpoises. At the time of this writing, the investigation into the cause of their deaths is underway. The tally of dead gray whales was higher than previously recorded, yet may not be extraordinary considering virtually the entire population of 21,000 gray whales had migrated through the area. They would normally leave in their wake a number of carcasses, which in most years would go unobserved along remote stretches of beach. It remains to be seen how many of the animals were actual victims of the spill.

Most of the other incidents have been minor by comparison (Table 6–1). Following a spill of light diesel fuel along the Alaskan shore, two killer whales, one sick and one dead, were reported. There was no additional detail (Anonymous, 1971). A ruptured storage tank released more than 11 million gal of hot Bunker C oil into Japan's Inland Sea. A press report revealed that one porpoise had died (Nicol, 1976). After the *Amoco Cadiz* ran aground spilling 60 million gal of light crude oil along the coast of the Brittany region of France, six badly decomposed cetacean carcasses were examined for evidence of oil. Prieur and Hussenot (1978) noted that one may have shown signs of oil contamination, while the remainder were species which commonly strand. The observers concluded that any relationship between the oil spill and the death of the animals would have been difficult to establish. The *Hellenic Carrier* collided with a ship on the outer banks off Nags Head, North Carolina, and sank, spilling 3000 gal of oil. A report (Anonymous, 1981) told of a porpoise that was killed.

On March 21, 1982, the decomposed carcass of a male pilot whale was found stranded in Rodanthe, North Carolina. On its skin was a 10 × 20–cm patch of dry tar (Anonymous, 1982). No detail was provided. During a survey of cetaceans in the western North Atlantic, a dead *Grampus* was spotted a few kilometers away from an extensive oil sheen (Sorensen *et al.*, 1984).

What conclusions can be drawn from these observations? It seems that unlike sea otters, polar bears, and some seals, there is no gripping evidence that oil contamination has been responsible for the death of a cetacean.

Reactions of Cetaceans to Oil

The Battelle Memorial Institute's (1969) summary of the Santa Barbara spill concluded that whales may have been able to avoid the oil. That casual

Table 6–1
Reports of Cetaceans Associated with Oil

Date	Location and source	Oil type and quantity	Species	Impact	Reference
Feb. 1969	Santa Barbara, Calif.; Union Oil well	Crude oil, $>30 \times 10^6$ gal	Gray, pilot, and sperm whales; common and white-sided dolphins	16 stranded whales and dolphins recovered. No causal relationship	Brownell (1971)
Apr. 1970	Alaska Peninsula	Diesel fuel, quantity ?	Killer whale	1 sick and 1 dead animal observed. No examination.	Anonymous (1970)
1974	Japan	Bunker C, 11.3×10^6 gal	Porpoise	1 dead porpoise found.	Nicol (1976)
Oct. 1976	Aransas Pass, Texas; pipeline leak	Crude oil, 15,500 gal	Bottlenose dolphin	Dolphins swam through oil without apparent effect.	Shane and Schmidly (1978)
Dec. 1976	Nantucket Shoals; *Argo Merchant*	Bunker C, 7.9×10^6 gal	Fin whale, pilot whale, others	43 sightings of animals in and around patches of oil. No obvious reaction.	Grose and Mattson (1977)
Mar. 1978	France; *Amoco Cadiz*	Crude oil, 60×10^6 gal	White-sided and common dolphins; pilot whale	6 stranded animals with no firm evidence of oil.	Prieur and Hussenot (1978)
Sept. 1978	Matagorda Bay, Texas; boat grounding	Fuel oil, 3000 gal	Bottlenose dolphin	20 dolphins swimming through oil without effect.	Gruber (1981)

June 1979	Gulf of Mexico; Ixtoc-I	Crude oil, 70 × 10^6 gal	Bottlenose and spotted dolphins	Animals sighted in areas with oil-coated debris. Apparently unaffected.	Bergey (1979)
June 1979	Cape Cod, Mass.; *Regal Sword*	Bunker C, 80,000 gal Fuel oil, 6300 gal	Humpback, fin, minke, right whales; white-sided dolphins	Animals feeding, surfacing and swimming through heavy concentrations of oil.	Goodale *et al.* (1981)
May 1981	Outer Banks, N. Car.; *Hellenic Carrier*	Type ?, 3000 gal	Porpoise	Unconfirmed report of dead porpoise.	Anonymous (1981)
Mar. 1982	Rodanthe, N. Car.; Source ?	Tar	Pilot whale	Stranded whale with small patch of dry tar on skin.	Anonymous (1982)
July 1984	Gulf of Mexico; *Alvenas*	Crude oil, >1 × 10^6 gal	Bottlenose dolphin	1 dolphin swimming in the midst of oil patches. Others at the edge of the slick.	Owen (1984)
Mar. 1989	Prince William Sound, Alaska; *Exxon Valdez*	Crude oil, 11 × 10^6 gal	25 gray, 1 fin, 2 minke, and 3 unidentified whales; 7 harbor porpoises	Stranded carcasses. Possible unrelated natural mortality.	H.W. Braham (personal communication)

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[a] All volumes converted to U.S. gallons, and rounded. 1 barrel = 159 L = 42 gal. 1 ton = 278 gal of bunker oil, 300 gal of crude oil, or 332 gal of diesel fuel.

observation, it now appears, may have some empirical footing. Fragmentary data from subsequent spills support the notion that whereas some cetaceans may avoid oil, others, willing or not, enter it without obvious peril. Shane and Schmidly (1978) studied a group of *Tursiops* in Aransas Pass, a few kilometers north of Corpus Christi, Texas (Fig. 6–1). On October 14, 1976, 15,500 gal of crude oil leaked from pipelines along Aransas Channel and into Morris and Cummings Cut. "The dolphins swam regularly through the oil slick, although they were not observed surfacing in the heaviest concentrations of oil. [They] began feeding and mating once they reached cleaner water. The oil had no obvious effect upon them" (Shane and Schmidly, 1978). That incident was soon paralleled by an event which took place in Matagorda Bay, 100 km north of Aransas Pass (Fig. 6–1). A tugboat ran aground spilling some 3000 gallons of fuel oil into Pass Cavallo where Gruber (1981) was studying the behavior

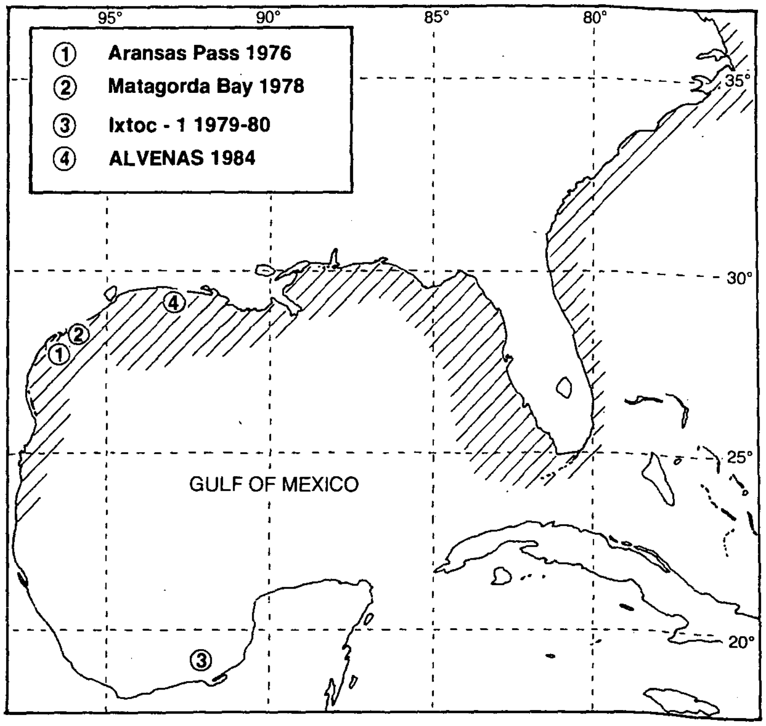


Figure 6-1
Cetaceans have been observed in the vicinity of at least four oil spills in the Gulf of Mexico.

of *Tursiops*. She noted that 20 dolphins, including one calf, would swim back and forth through "large globules" of oil in an extremely polluted section of the intracoastal waterway. The animals repeatedly surfaced in the midst of the thickest concentrations, while playing and tossing fish to one another. Most of the dolphins were precisely in the areas where the slicks were abundant.

Farther north, events were unfolding on a larger scale. On December 15, 1976, the *Argo Merchant* ran aground off Nantucket Island in Massachusetts, spilling nearly 8 million gal of No. 6 fuel oil. Between December 28, 1976, and January 13, 1977, aerial observers recorded 43 separate sightings of cetaceans, including 21 fin, 2 other unidentified rorquals, 7 unidentified dolphins, and 13 to 15 pilot whales. On one occasion, two finback whales were in a heavily oiled area, showing no apparent reaction to it. Limited data showed that there was no bias in the animals' distribution in relation to oil. No marine mammal was seen in obvious distress or in direct physical contact with oil pancakes or sheen (Grose and Mattson, 1977).

A University of Rhode Island research group, whose project was known by the acronym CETAP (Cetacean and Turtle Assessment Program), conducted a 3-year systematic survey of a 210,000 km^2 area of the western North Atlantic. They spotted oil 94 times, and cetaceans were twice seen within oil. Both sightings were of pods of common dolphins. They noted no behavior other than swimming (Sorensen *et al.*, 1984). On June 18, 1979, the CETAP team was on scene to investigate the aftermath of a collision between two tankers southeast of Cape Cod, Massachusetts. One, the *Regal Sword*, sank, liberating 86,300 gal of Bunker C and No. 2 fuel oil. Over the next week, at least three and possibly four species of cetaceans were seen within the slicks. Humpback and fin whales were observed feeding at the surface, some in the middle of a heavy slick. One whale, tentatively identified as a right whale, repeatedly surfaced in oil. Whales and a large number of white-sided dolphins swam, played, and fed in and near the slick. Dolphins were seen in oil slicks and sheens during 8 of the 10 flight passes made over the most heavily polluted areas. The investigators reported that there was no difference in behavior between cetaceans within the slick and those beyond it (Goodale *et al.*, 1981).

The tanker *Alvenas* ran aground and ruptured off the coast of Louisiana (see Fig. 6–1), spilling more than a million gallons of crude oil (Owen, 1984). Aerial observers found heavy slicks extending 2 miles offshore. One *Tursiops* was sighted amid patches of oil inshore; several others were offshore at the outer edge of the slick. There were no dolphins in the immediate vicinity of the vessel.

It is ironic that the search for marine mammals surrounding the largest recorded oil spill was, by any standard, modest. Between June 3, 1979, and March 23, 1980, the Ixtoc-I oil well in the Bay of Campeche in the Gulf of Mexico (see Fig. 6–1) had a blowout which leaked a million gallons of oil daily. Spinner dolphins, bottlenose dolphins, and unidentified porpoises were observed in areas containing oil-coated debris; all appeared healthy and free of oil. Porpoises that were bow-riding veered to avoid tar balls, their only obvious reaction to oil (Bergey, 1979).

Evans (1982) from Hubbs-Seaworld Research Institute led a team of investigators to study the reaction of migrating gray whales to natural oil seeps emanating from the sea floor. Thus, our story begins and ends with the gray whale. The team established four observatories on land and one on an offshore drilling rig, along a 50-km stretch of the California coast from Point Conception to Coal Oil Point. Within the study area, there were at least four seeps within a 5-km radius of each observation site. The most active seep, near Coal Oil Point, releases a minimum of 30 barrels of oil daily.

From the observatories and from aircraft, the investigators documented swimming speeds, surface behavior, dive times, and respiratory rates of small groups of whales, and found that when entering oiled waters, the animals would modify their swimming speeds and occasionally their direction with no consistent pattern.

In oiled waters they seemed to spend less time at the surface, blowing less frequently but faster. If this reaction is interpreted as an avoidance response, it suggests that gray whales can detect oil. Those showing no response either could not detect the amount or type of oil present or were indifferent to it. The investigators were careful to point out that comparisons were tenuous, as it was not possible to follow specific whales into and out of oiled areas. That should be the subject of future experiments and could well be incorporated into ongoing studies on the behavior of radio-tagged gray whales during their annual migration.

These observations summarize the attempts to determine what cetaceans do when they confront spilled oil. None provides a complete picture, as one might expect from empirical studies. But each account gives a clue to behaviors, some more consistent than others, on which hypotheses can be constructed and tested in subsequent oil spill accidents. The denouement of certain mortality no longer seems reasonable. Instead, we find whales and dolphins in the vicinity, and some in the midst of a spill, behaving quite normally. The questions now are: Were the animals able to detect oil; given the choice, would they have avoided it; might they have been drawn unwittingly to the heart of a spill, perhaps in search of prey organisms attracted by the oil's protective shadow; how might such excursions through oil affect the health of a whale or dolphin? These questions have been addressed through an assortment of speculative writings (Sergeant, 1970; Butler *et al.,* 1974; Fraker *et al.,* 1978; Calkins, 1979; Geraci and St. Aubin, 1980; Cowles *et al.,* 1981) and, more recently, by a series of experiments conducted by the author's research team.

Detection and Avoidance

From 1980 through 1983, we carried out three successive studies to determine how bottlenose dolphins react to oil films in their environment (Geraci *et al.,* 1983; Smith *et al.,* 1983; St. Aubin *et al.,* 1985). The first of these tested the hypothesis that surface oil presents a visual target to an animal. Most crude oils are dark, and as they weather, become thicker and darker still. We intended to learn whether a bottlenose dolphin would be able to detect oils of this kind and dilute preparations with less apparent visual properties. In all, two dolphins were presented with 12 different oils and 22 mixtures.

The studies were carried out in the relatively natural setting of an enclosed lagoon in the Gulf of Mexico in the Florida Keys. Early into the training, each dolphin learned to position itself on a fixed underwater station at a depth of 1 m, and look upward to view a short open-ended cylinder confining various materials and objects at the surface (Fig.6–2).

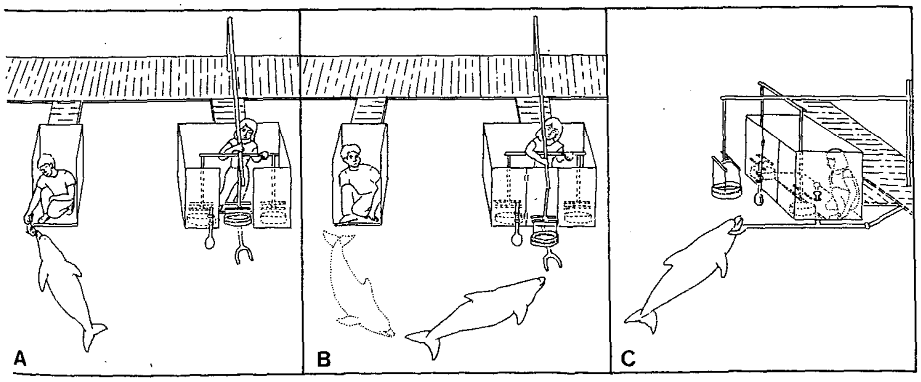


Figure 6-2
Testing procedure to determine whether bottlenose dolphins can detect oil. (A) The trainer calls the animal to the resting dock while an examiner prepares up to three test cylinders in a canal concealed within the trial dock. (B) On command, the dolphin swims to the trial dock, stations on a stirrup, and (C) examines the contents of the cylinder. It leaves the station to press the paddle only when it detects there is something (oil) in the cylinder besides water. The study demonstrated that dolphins quite easily discriminate between oil and the uncontaminated surface of the water (Geraci *et al.,* 1983).

The animal would leave the station to press a paddle only when it detected something in the cylinder besides water. If the dolphin correctly detected nothing, it would remain stationary until called to be rewarded. The behavior was shaped using solid objects made of wood and plastic, and an assortment of buoyant fruits, selected according to the palate of each trainer. After the animal mastered the technique, the objects were gradually replaced with oil, until the cylinder contained only oil. Once trained to detect solid objects, it took only three days for the dolphins to respond to the presence of oil alone.

Through a long series of randomized presentations of different objects and types and thicknesses of oil, the experiment demonstrated that the dolphins quite easily discriminated between oil and the uncontaminated surface of the water. The darker the substance, the easier it was to detect, down to an optical density that corresponded to 1-mm thick films of the three types of crude oils tested. We interpreted these findings as evidence that the dolphins can see the thicker formations of oil that typically occur at the source of a spill, and also weathered fractions which form "pancakes" of much thicker viscous oils. In fact, while blindfolded, one of the dolphins was able to detect presumably by echolocating, 12-mm-thick patches of heavy oil churned so as to entrain air bubbles. Lighter fractions, which spread into thin sheens and typically comprise most of a spill area, would not be detected easily, if at all, nor could lightly colored refined products such as gasoline, diesel fuel, and solvents which disperse very rapidly into surface films. Patterns of weathering and spread of oil are covered in detail by Neff (this volume, Chapter 1).

The study answered a fundamental question and, quite naturally, raised several others. If dolphins can see oil, why do they enter the region of a spill? Might they have a compelling reason to be there? Perhaps they do reject the silhouettes of thicker oil and penetrate only the less visible sheens. This, of course, could bring them into contact with volatile, more acutely harmful substances. These concerns were incorporated into the design of the next experiment.

The objective was to determine if bottlenose dolphins would avoid a detectable slick. To begin with, three dolphins that, as far as we knew, had not been exposed to oil were allowed to roam freely in an oceanic pen, with the surface divided into three equal areas by oil-containment booms (Fig. 6–3). Observations were made while the animals were in the pens, either alone or as a group. We thereby established their individual swimming and surfacing behaviors and their "desire," if any, to occupy one of the three subdivisions. Following the observation period, the dolphins were removed while an oil slick 1 cm thick was added to one of the subdivisions, then reintroduced individually or as a group. To avoid harm-

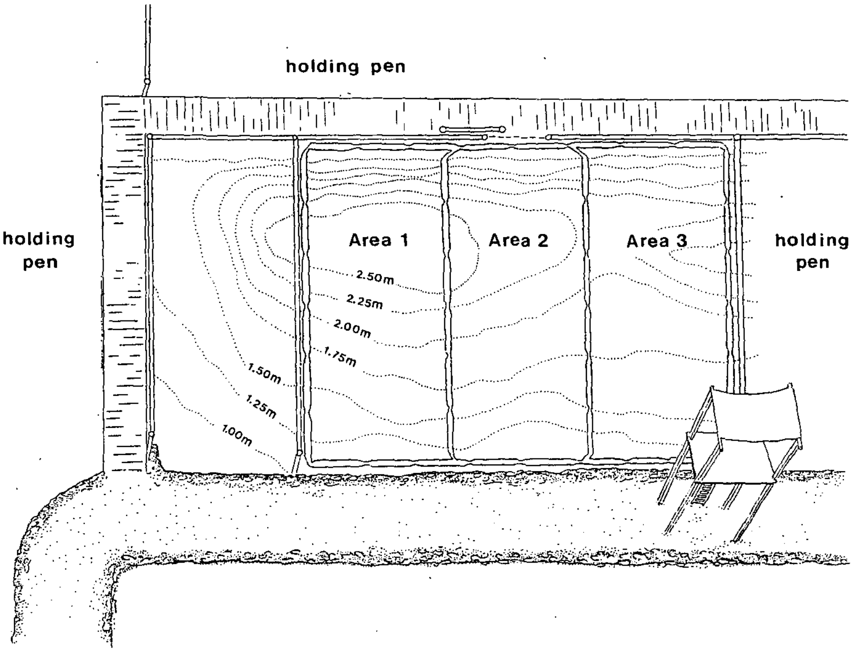


Figure 6-3
Test setting to determine a dolphin's reaction to an oil-covered sector (1, 2, or 3). Each of three dolphins, introduced into the setting, avoided the oiled subdivision for up to 52 minutes. Then each emerged in the oil once on the first day, and never again for the duration of the study (Smith *et al.*, 1983).

ing the dolphins or complicating the experiment, only odorless, tasteless, nontoxic, highly refined mineral oil was used. It was mixed with a black colorant to match the optical density of crude oils that dolphins had been able to detect in the previous study.

After re-entering the pen individually, all three dolphins avoided the oiled subdivision for at least 5 minutes, and one for up to 52 minutes. This initial reluctance was regarded as a probable response to any new stimulus, and not to oil *per se*. Within an hour, however, each dolphin emerged in the oil either accidentally, or as part of an investigative process. Each reacted immediately and overtly with a "startle" response and behavior normally associated with stress or annoyance. Yet the oil was innocuous, indicating that another physical property of the oil, viscosity perhaps, had been enough to disturb them. The behavior suggested that tactile sense may have played a role in the dolphins' reaction to oil.

After the initial contact, the dolphins never again emerged in oil, even when reintroduced four days later to the experimental setting. In fact, their aversion to it prevented them from swimming beneath the oil to adjacent uncontaminated pens. The dolphins had developed an aversion to oil, not unexpected perhaps of a creature genetically driven to regard the water's surface as a secure portal to clean air. But what surprised us was the apparent ability of the animals to "feel the oil."

We undertook a third study, designed to show how sensitive was the tactile response, and how thin or clear an oil slick would have to be for a dolphin to disregard it. We used the same experimental setting, but this time tested the dolphins' response to oils we thought would be less obvious. We kept testing their reaction to the dark-colored mineral oil, more or less as a control, to see whether they might eventually become accustomed to it. They apparently did not because they consistently avoided it. We also presented two of the dolphins with the same mineral oil without the colorant. Both contacted it a total of four times within 15 minutes of exposure, each time showing a marked startle response. They never again touched the clear oil on that or the two subsequent trial days. We established a sheen of 0.1-mm nominal thickness, using automotive motor oil. In that setting, their behavior was erratic. A dolphin would surface there 100 times in a 1-hour session, and not at all in another, perhaps due to the inevitable discontinuities of such a thin sheen, or to reduced cutaneous stimulus presented by the film.

We repeated the study under vastly subdued light to reduce some of the visual properties of the oiled surface. This was done by covering the study pools with a large tent made of polypropylene shade fabric designed to screen out 92% of incoming light (Fig. 6–4). At night there was now insufficient light to activate a conventional light meter. In the pitch-black setting, while observers were stumbling about, dolphins were nimbly avoiding both the colored and clear mineral oil preparations. It appeared that the colorant had been incidental to the studies; the principal cue was cutaneous detection of oil. Their reaction to oil sheens under these conditions was the same as in daylight. One dolphin avoided the area containing the sheen; the other two swam into it, but less frequently.

It has become clear, through these studies, that bottlenose dolphins are able to detect and avoid a variety of oils both during the day and at night. To accomplish this, they rely predominantly on vision, and to some extent echolocation, when facing thick transparent slicks. Once a dolphin surfaces in oil, irrespective of light conditions, its response thereafter is to avoid it. That behavior, it seems, is triggered or reinforced by the sensation that oil creates on the animal's skin.

It is not certain how broadly the findings from the bottlenose

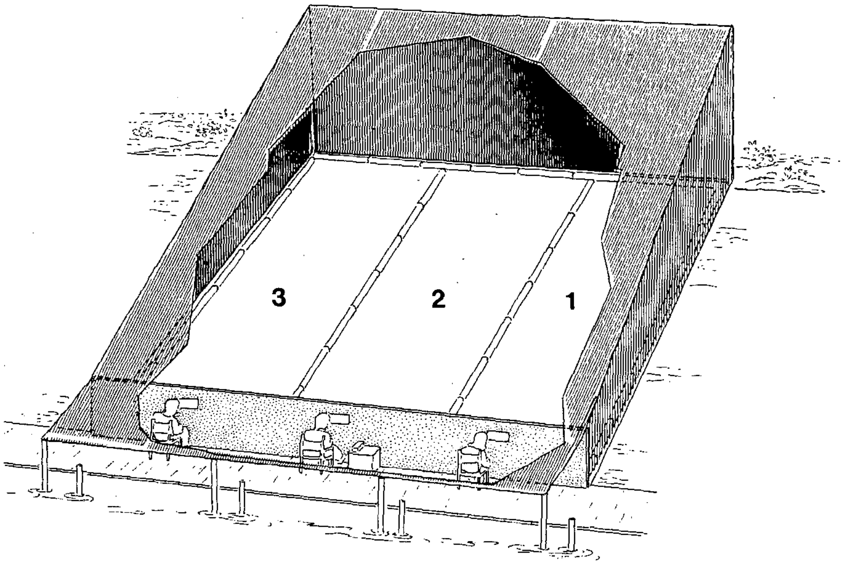
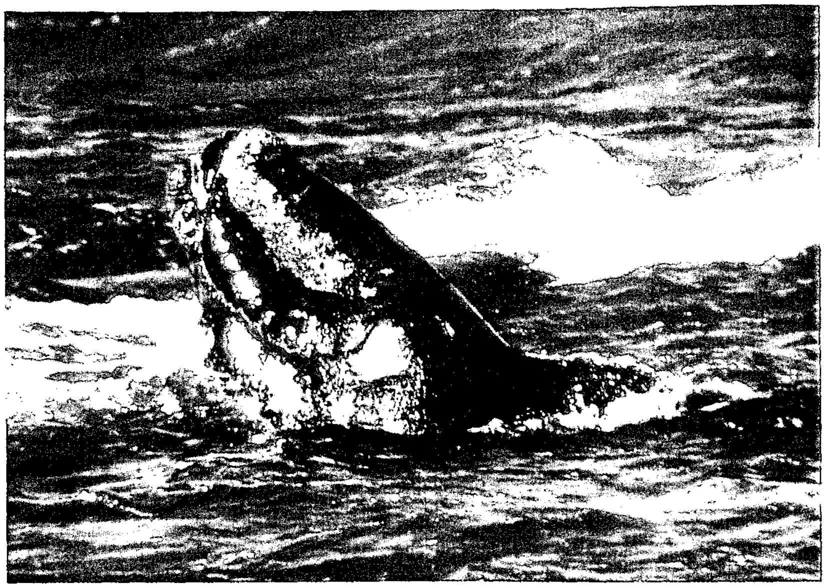


Figure 6-4
Test pool to determine, under subdued light, a dolphin's reaction to an oil-covered sector (1, 2, or 3). The shade canopy screened out 92% of moon- and starlight. While observers were stumbling about, dolphins nimbly avoided both colored and clear mineral oil preparations (St. Aubin *et al.*, 1985).

dolphins relate to other species of cetaceans. A case can be made for other dolphins and toothed whales with comparable sensory capabilities. Using analogies cautiously, certain of these data may be applied to mysticete whales as well. The key element is whether an animal has the sensory capacity to detect oil as the dolphins did, using vision and touch. Studies show that odontocetes have effective underwater vision, and aerial vision comparable to that of many terrestrial carnivores (Spong and White, 1971; Pepper and Simmons, 1973; Dawson, 1980; Madsen and Herman, 1980).

The mysticete eye is proportionately smaller and may not function as effectively as that of an odontocete at comparable depths (Mann, 1946; Walls, 1963; Waller, 1984). However, at or near the surface, their eyesight seems to be quite good. Indeed, mysticete whales may rely on visual cues for orientation. "Scouting" and "spy-hopping" is a typical behavior in which a whale may rear or bob out of the water, apparently viewing surface features and the shoreline (Cummings and Thompson, 1971; Eberhardt and Evans, 1962; Pike, 1962). Bowhead whales have been



A southern right whale pokes its head above the water, perhaps to obtain visual cues for orientation. Photo by B. Würsig.

seen preoccupied with floating logs and with bright green sheens of fluorescent dye (Würsig *et al.*, 1982). Echelon swimming, in which whales move in unison, appears also to rely on visual signals, as does the ability of humpbacks to pace whale-watching vessels, and of bowheads to punch holes selectively in newly forming ice (Ljungblad *et al.*, 1983). Such evidence indicates that mysticetes have evolved with odontocetes to rely on vision for spatial orientation and navigation to some extent. Should oil be present in a form which sufficiently alters the optical properties of the surface, a variety of cetacean species seems to have the visual capability of detecting it.

There are many lines of evidence to show that cetaceans generally have well-developed cutaneous sensitivity. Odontocete skin has nerve endings which in other mammals function in part as mechano-receptors (Palmer and Weddell, 1964; Schmidt, 1977; Agarkov *et al.*, 1974; Slijper, 1979; Purves and Pilleri, 1983). The structures are found particularly in the head region and in the skin of the lips, rostrum, and melon. It would be useful to know whether these nerve endings are responsible for receiving the cutaneous signals that reinforced the oil-avoidance behavior by the dolphins. If so, it might be possible to predict more accurately the probable response to oil by a particular cetacean with similarly endowed skin (Herman and Tavolga, 1980). Receptor-like structures have also been observed in the integument of mysticetes, including the fin whale (Giacometti, 1967). Virtually the entire surface of the mouth of baleen whales contains modified Golgi-Mazzoni corpuscles considered by Ogawa and Shida (1950) to be highly tactile organs. Vibrissae along the snouts of mysticetes (Yablokov *et al.*, 1974) and non-myelinated nerve fibers within dermal papillae of bowhead whales (Haldiman *et al.*, 1985) are also thought to be related to epidermal sensation.

Hence, it seems that the skin of the great whales is suitably equipped to receive cutaneous signals. It is not surprising in view of their obvious responsiveness to touch. In fact, this sensory mode may underlie basic affiliative and courtship behaviors (Herman and Tavolga, 1980), and for certain species like the bowhead whale, a sensitive tactile response would be a useful aid when navigating through vast fields of ice. Research into the nature and sensitivity of these and other sensory receptors would ignite a new level of thinking while providing fundamental data needed to extrapolate to species which cannot be tested experimentally.

Surface Contact

We assume that large whales and dolphins must be affected by contacting crude oil or a petroleum compound. But how? Because they have no fur, we are not concerned over loss of insulation. Instead we suggested that cetacean skin might, because of its unusual properties, respond to noxious substances in a manner approaching sensitive mucous membranes, with consequent effects on ionic regulation and water balance (Geraci and St. Aubin, 1980). The literature on humans accidentally contacting oil products provides some clues as to how studies on cetaceans might be developed.

Petroleum compounds, especially the short-chain fractions in gasoline, typically irritate skin and mucous membranes (Dutton, 1934; Hansbrough *et al.*, 1985). This irritation is due in part to solubilizing and removing cutaneous lipids (Wolfram *et al.*, 1972; Cornish, 1980), triggering an inflammatory response which first appears as reddening of the skin (Hansbrough *et al.*, 1985). Persistent contact causes necrosis (Walsh *et al.*, 1974) and inflammation—reactions which can be mapped and described quantitatively.

With that background, we designed a number of experiments to test how exposure to petroleum hydrocarbons might damage cetacean skin (Geraci and St. Aubin, 1982, 1985). We took a cautious approach, which began by applying a small sponge soaked in crude oil to discrete areas of skin of four species of odontocetes. Contact for up to 45 minutes was ineffective, in marked contrast to similar tests on human volunteers. We then progressed to longer exposures, up to 75 minutes, with gasoline. At this point it became clear that even unrealistically long contact times could not elicit the kind of severe reaction that typically occurs in other mammals (Hunter, 1968; Hansbrough *et al.,* 1985). Subtle changes that did occur were evident only histologically and, in each case, healed within a week.

The studies pointed to the effectiveness of cetacean epidermis as a barrier to the noxious substances found in petroleum. Whereas these normally damage the skin by permeating intercellular spaces and dissolving protective lipids, their penetration in cetacean skin was impeded by tight intercellular bridges, the vitality of the superficial cells, and the extraordinary thickness of the epidermis. The intercellular and intracellular lipids which are abundant in cetacean epidermal cells, and which we had assumed to be a vulnerable target for petroleum, were unaffected. In fact, they are protected well enough that after exposing skin from a white-sided dolphin to gasoline for 16 hours *in vitro*, we could not detect a change in lipid concentration (Geraci and St. Aubin, 1985).

By then, we had completed a study on repair of superficial wounds in the skin of *Tursiops*. An important finding was that following a cut, newly exposed epidermal cells degenerate to form a zone of dead tissues which shields the underlying cells from seawater during healing. We wanted to determine how oil might affect this process. For 30 minutes we massaged cuts with crude oil or tar. The substances had no effect on healing. Applied in the same manner, leadfree gasoline caused an exaggerated inflammatory response, which by 24 hours subsided and was indistinguishable from control cuts. We concluded that the devitalized shield had protected underlying tissue from gasoline in the same way it repels osmotic attack by seawater.

Biochemical and metabolic probing did reveal subtle reversible changes in cells exposed to petroleum. Each of these effects could have been explored in greater depth, but the exercise would not have provided a clearer understanding of the issue. Already the studies had progressed beyond a probable scenario for oil contact at sea. A script can be created in which a dolphin or whale is trapped in fresh oil rich with volatile short-chain fractions which are toxic when inhaled or ingested. Effects on mucous membranes would be inevitable, but of lesser concern. Spilled crude oil exists in this form only briefly. A cetacean is more likely to contact weathered oil, which is far more persistent but contains little of the more toxic light hydrocarbon fractions. Studies show that, in real life, contact with oil would be less harmful than we and others had proposed (Geraci and St. Aubin, 1980; Albert, 1981).

Inhalation

To some, oil spills conjure an image of a sea blackened with a thick coagulum which can endanger a whale by clinging to its surface and preventing it from feeding. The scene may reflect our own experience with tar ball-strewn beaches, but a greater threat to whales or dolphins is not the thick murky residue, but the invisible gaseous compounds that escaped from it. Vapors arise from volatile fractions in fresh crude oils and many of the refined products (Neff, this volume, Chapter 1). They irritate and damage soft tissues such as mucous membranes of the eyes (Carpenter *et al.,* 1977) and airways. Depending on the concentration of vapors and duration of exposure, their effects range from mild irritation (Valpey *et al.*, 1978) to sudden death (Wang and Irons, 1961).

On a positive note, vapors dissipate rapidly from the environment. Few investigators have analyzed vapor concentration or characteristics associated with a spill, perhaps because there has been little concern regarding their effect on humans. A cetacean, however, must draw its breath from the narrow blanket of air immediately overlying the surface of oil (or water), thereby intensifying its exposure. What will it inhale? In an early study (Geraci and St. Aubin, 1982), we calculated the concentrations of hydrocarbons associated with a theoretical spill of a typical light crude oil. We made the improbable assumption that all of the volatile substances in a 5-mm slick would evaporate instantaneously and completely into a 1-m layer of static air above the surface, thereby exposing an animal to an artificially maximized concentration of vapors. For each volatile compound, we calculated vapor pressure and concentration, then graphed the findings with those from toxicity studies on experimental animals other than whales.

The results showed that vapor concentrations could reach critical levels for the first few hours after a spill. A whale or dolphin unable to leave the scene during that time would inhale vapors and might be harmed. For a given exposure, the effect would depend on the health of the animal and its immediate response to stress (Thomson and Geraci, 1986). A panicking whale or swiftly moving dolphin would breathe rapidly and probably inhale more vapors. If this behavior were aggravated by excessive release of adrenalin, sudden mortality could result, as has been observed occasionally in humans (Bass, 1986). More likely, the animals would experience some irritation of respiratory membranes and absorb hydrocarbons into the bloodstream, a process which might be facilitated by their habit of submerging with full lungs. Whatever the mechanism, it is clear that for the short time they persist, vapors are one feature of an oil spill that can threaten the health of a cetacean.

Baleen Fouling

A great deal of interest has been expressed in the possibility that residues of oil may adhere to baleen plates so as to block the flow of water and interfere with feeding. The concerns are largely speculative (Fraker *et al.*, 1978; Calkins, 1979; Albert, 1981; Fritts *et al.*, 1983; Hansen, 1985), as there is only one relevant report, that of a gray whale found dead during the Santa Barbara oil spill with a light film of oil and dirt on its baleen plates (Brownell, 1971). Such an effect might be imperceptible, though leading to subtle, long-term consequences to the affected animal. With that in mind, two independent studies have been undertaken on the effects of oil fouling on baleen whales.

The feeding apparatus consists of two rows of fringed horny plates set into the gum tissue of the upper jaw. The plates are formed of hair-like tubules embedded in tough flexible keratin. The tongue of the animal rubs against the inner margin of the plates, abrading them and exposing the hairs which entwine to form a dense sieve. After the animal has taken a mouthful of food, pressure of the tongue against the plates drives water through the sieve, leaving behind the mass of food which the tongue delivers to the esophagus.

Baleen structure varies with the feeding habits of the whale. Right whales typically skim the surface, while rorquals (eg., fin, blue, and humpback whales) gulp their food. Gray whales are unlike other mysticetes in scouring the bottom in search of infaunal benthic species which they gather along with silt, sand, and gravel (Rice and Wolman, 1971). Pivorunas (1976, 1979) has written a detailed account of the relationship between baleen structure and feeding habits, and Würsig (this volume, Chapter 5) has examined the flexibility of feeding strategies within each group.

A safe assumption is that any substance in seawater which alters the characteristics of the plates, the integrity of the hairs, or the porosity of the sieve may jeopardize the nutritional well-being of the animal. A series of studies was conducted to determine whether petroleum compounds were capable of such mischief (Braithwaite, 1981; Geraci and St. Aubin, 1982, 1985; St. Aubin *et al.*, 1984).

Our studies began by evaluating the effects of various petroleum hydrocarbons on isolated baleen plates. Samples from seven species of whales were soaked in gasoline, crude oil, or tar, some for unrealistically long periods of time so as to exaggerate changes which might otherwise have been difficult to detect. For example, plates were exposed to crude oil for 8 hours, gasoline for up to 14 days, and roofing tar (our commercially available equivalent of weathered oil) for 21 days. Subsequently, the plates were tested for their breaking strength by tensiometer, analyzed for keratin integrity by x-ray diffraction, and finally, ground, ashed, and subjected to elemental analysis by atomic absorption spectrophotometry and colorimetry.

Immersion in gasoline for 90 minutes or in crude oil for 8 hours had no effect on protein structure or breaking strength of the plates. After 21 days in tar, x-ray diffraction patterns showed no change related to protein degradation (St. Aubin *et al.,* 1984). Nitrogen concentrations increased in all immersed samples, likely resulting from the loss of lipids which normally comprise up to 10% of the dry weight of baleen. There was also a consistent decrease in concentrations of manganese, copper, boron, and iron in exposed baleen hairs, but not plates, of fin and gray whales. Right whale samples were unaffected. There was no tensiometric evidence of increased plate fragility associated with these changes in elemental composition. We concluded the study at this point and directed our emphasis toward determining the effects of oil on baleen function.

There is very little information on how the baleen apparatus actually operates, which complicates the design of any experiment to determine how oil fouling affects function. The main difficulties in our study were in estimating water flow rates and pressure across the baleen filter, impediments to flow under normal conditions of feeding, and the functional reserve capacity of the system. In other words, at what point does a loss in function constitute a hazard to the animal? Thus, even the most carefully considered approach to the study has shortcomings, and findings are not easily generalized.

In the only study on bowhead whale baleen, Braithwaite (1983) used horizontally mounted plates to filter brine shrimp, *Artemia salina,* from a volume of chilled water discharged onto the upper fringed margins of the plates. Flow rates were established as the maximum volume that could pass through the baleen filter preparation in a 1-minute test. Water pressure was curiously low; the system was gravity-fed by a constant water column of only 7.5 cm over the baleen plates. After control values were established, the baleen hairs were brushed to uniform orientation, then light or medium crudes were brushed on to a nominal thickness of 0.5 to 1 mm, or poured to achieve a 1-cm-thick layer. An experimental run was considered valid only if the thickness of the oil coating remained uniform during the test. That was required for the purpose of analyzing data and was not intended to be a realistic portrayal of a fouling pattern. After the plates were fouled, the volume of water flowing through the preparation was measured and compared with control values. Brine shrimp were then introduced and water flow was measured again.

Details of the experimental protocol are not entirely clear. It appears that most of the 45 or more oil-fouling tests were performed with a single sample of baleen, with no information on whether control values were re-established following each successive fouling test. Results showed a 5 to 10% decrease in filtration rate after the plates had been fouled.

We used another approach to evaluate the fouling effects of oil (Geraci and St. Aubin, 1982, 1985). In a preliminary study, specimens from fin and gray whales were mounted in their natural hanging, or inverted position, in a continuous-flow water flume (Geraci and St. Aubin, 1982). Each preparation was oriented so that water flowed from the medial (lingual) to lateral (labial) surface, simulating the water expulsion–food retention phase of feeding. The flume contained freshwater at 15–20°C, and provided uniform flow with a velocity of 5–15 cm/second. Water movement was measured simultaneously along the incurrent and excurrent surfaces of the preparation and between the plates, using thermistor flowmeters. Once the flow pattern through a preparation was determined, the system was fouled either with a light or medium crude oil, or Bunker C. These were added to the water, and thus they struck the baleen preparation as a churned mixture, possibly in natural fashion. For some tests, roofing tar was applied directly to the fringed surface of the plates. Flow rates were again measured. Light to medium oils caused transient changes in water flow, which returned to normal within 40 seconds. Repeated oiling of the same preparation did not produce an additive effect. Bunker C had a more pronounced impact, restricting water flow for up to 15 minutes. Thereafter, though the plates were still noticeably fouled, normal flow patterns were recovered.

The study set the stage for a more detailed evaluation, using a system which allowed for testing in saltwater over temperatures ranging from 0 to 20°C and velocities up to 350 cm/second (Fig. 6–5). Samples from humpback and sei whales were tested along with new specimens from fin and gray whales. Pressure transducers were used to monitor water velocity at various points within the elliptical flume; resistance to flow could thus be calculated and used as the index of functional change. As expected from the pilot study, Bunker C had the greatest impact on water flow through baleen, particularly at temperatures of 0–5°C. Resistance to flow increased more than 100% in some humpback samples, and less than 75% in fin and sei whale preparations. Gray whale samples were relatively unaffected. Medium weight oil had little effect at any temperature.

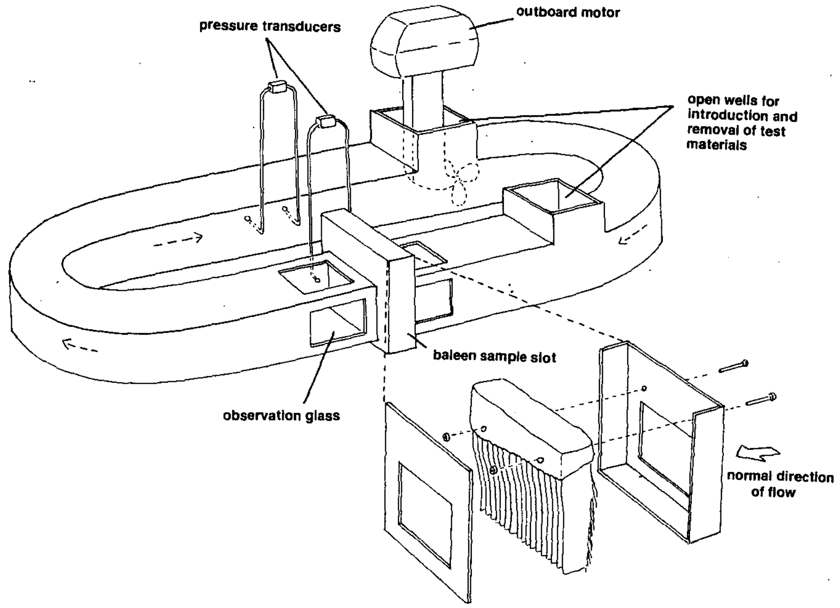


Figure 6-5
Tests were conducted in an elliptical tunnel with an outboard motor to circulate the water. Pressure transducers were positioned upstream and downstream from the baleen sample. Baleen specimens were mounted in a wooden frame for testing.

Selected samples were rinsed in continuously flowing saltwater for 32 hours; samples of baleen fibers were removed periodically and analyzed for residual oil (Fig. 6–6). Over 70% of the oil was lost within 30 minutes. In 8 of 11 trials, over 95% of the oil was cleared after 24 hours. We could not detect any change in resistance to flow in baleen after that time.

Combined evidence from the studies suggests that a spill of heavy oil, or residual patches of weathered oil, could interfere with the feeding efficiency of the fouled plates for several days at least. Effects would likely be cumulative in an animal feeding in a region so blanketed by weathered oil that the rate of cleansing is outpaced by fouling. That condition could describe the heart of a spill, or a contaminated bay or lead.

One can only speculate on consequences for a whale that occasionally eats a tar ball or engulfs a mouthful of weathered oil. The degree of fouling or damage required to impair feeding cannot be calculated with any precision, but in general, organs have some functional reserve. It seems that baleen does also; robust whales have been observed with damaged (Pivorunas, 1976) or rudimentary (Rice, 1961) plates. Judging from the low

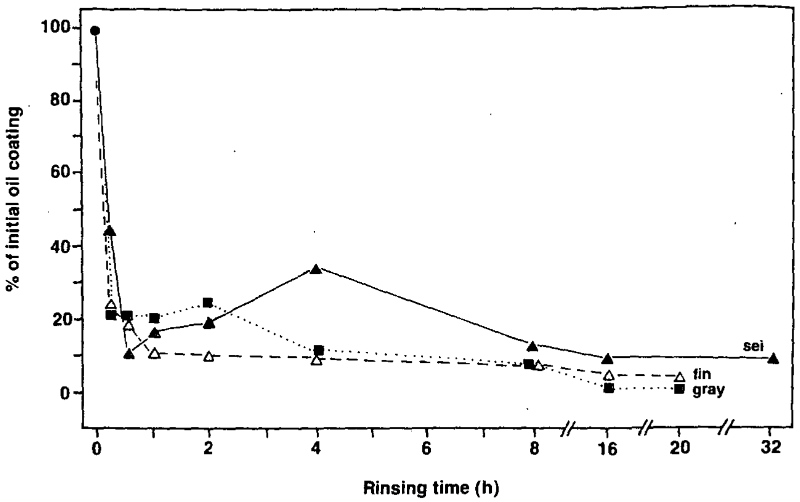


Figure 6-6

Amount of oil, as a percentage of initial coating, on fouled baleen preparations rinsed for up to 32 hours. Data are shown for one sample each from fin (△), sei (▲) and gray (■) whales. Over 70% of the oil was lost within 30 minutes. In 8 of 11 trials, over 95% was cleared after 24 hours.

level immediate impact in Braithwaite's (1981) study and the rate of clearance of oil in ours (Geraci and St. Aubin, 1985), it would appear that the concern for oiled whales is becoming less defensible. The cost and technology required to continue laboratory studies on fouling may not be worth the price.

Ingestion and Accumulation

Ingested petroleum hydrocarbons are toxic to many mammals. The subject evokes considerable interest because of the prevalence of, and devastating effects of, accidental hydrocarbon ingestion by young children (U.S. Department of Health and Welfare, 1978a,b). Oil compounds are systemically harmful, the degree depending on their chemical composition. Those with low viscosity and surface tension irritate the gastrointestinal tract and induce vomiting which leads to aspiration of the material into the lungs, causing pneumonia and death (Zieserl, 1979). Larger quantities, as much as 140 times the aspirated dose (Gerarde, 1964), can be tolerated if the substance remains in the gastrointestinal tract, but that is harmful as well.

Hydrocarbons can be directly toxic to the mucosal epithelium (Rowe *et al.*, 1973) and, when absorbed, travel throughout the body and produce their greatest effects on the central nervous system.

There has been some speculation that cetaceans could consume oil while feeding. Fraker *et al.* (1978) suggested that bowheads, because of their feeding behavior, could ingest damaging quantities of oil. Hansen (1985) affirmed that baleen whales that skim the surface and water column are more likely to ingest oil than gulp-feeders or toothed whales. Gray whales, because of their versatile feeding habits, could conceivably consume floating tar balls (Calkins, 1979) or contaminated bottom sediments (Hansen, 1985). Virtually any species might ingest oil by feeding on contaminated prey. The assumptions are logical, and one could fairly believe that of the vast quantities of oil discharged at sea (Neff, this volume, Chapter 1), at least a gulp or two must find its way into the gullet of a hungry whale. Yet these animals bear no evidence obvious enough to have drawn attention. As far as we know, the literature consists of only a threadbare notation that "hydrocarbons" were found in the intestines of two bottlenose dolphins along the coast of France (Duguy and Toussaint, 1977).

There has also been a study to determine how small quantities of refined petroleum oil consumed over a fairly long period of time would affect the health of *Tursiops* (Caldwell and Caldwell, 1982). It was an attempt to establish whether machine oil accidentally seeping into an aquarium pool might have been responsible for an unprecedented increase in mortality of captive dolphins. The only notable clinical finding had been elevated circulating levels of the enzyme glutamic pyruvic transaminase, suggesting that the liver might have been injured.

In the experiment, one dolphin was given the same machine oil in capsule form, at a rate of 5 mL/day, 5 days/week, for a total of 335 mL in 14 weeks. Another dolphin, used as a control, was given mineral oil under the same conditions, for a total of 225 mL in 10 weeks. The animals were examined for clinical, hematologic, and blood chemical changes during the study. None was found, nor was there any found during necropsy examination of the test dolphin when it was euthanized one month later for reasons unrelated to the study.

The results are not surprising. The quantity of machine oil consumed by the dolphin was substantially lower than the toxic dose for other mammals. Seals had also shown no effect after ingesting similar quantities (Geraci and Smith, 1976). In fact, the amount of substance considered to be critical is higher than one would reasonably wish to administer to a cetacean. In mice, it is in the order of 5 to 25 mL/kg for heavy fuel oils, and 14 to 20 mL/kg for lighter fuel oils (Elars Bioresearch Laboratories, Inc., 1979a,b, 1980a–d). Let us assume that a cetacean would be at risk after taking a quantity of fuel oil at a midrange concentration of 15 mL/kg. To achieve that, an adult harbor porpoise would have to consume 1 L, a bottlenose dolphin 3–4 L, and a pilot whale 30 L. A forty-ton whale would require an estimated 600 L, or roughly 150 U.S. gal.

Could a cetacean in the wild ingest such quantities of oil? It is not feasible to predict the behavior of an excited animal unavoidably confronting a spill. It may swallow oil accidentally or, as we observe in terminally stressed odontocetes, drink seawater liberally, and with that, consume oil. Otherwise, it would seem unlikely, in the normal course of events, that a whale or dolphin would ingest much floating oil. A dolphin may drink 500 to 1500 mL of seawater daily (Ridgway, 1972). If contaminated, only a small portion of that would be oil. Odontocetes are predators that normally would not scavenge oil-killed fish, except perhaps for some bottlenose dolphins that have learned to forage behind fishing boats for a net-spilled meal. Lessons from captivity suggest that they would probably disregard tainted fish. Mysticetes in the area of a spill are more likely to ingest oil-contaminated food, particularly zooplankters which actively consume oil particles. Assuming toxic oils comprise 10% of the estimated 1600 kg of food consumed in a day by a 40-ton fin whale, the total quantity of ingested oil would be 160 kg. This approaches the critical dose calculated for highly toxic fuel oils. The question is, would fin whales feed around a spill of fresh volatile oil long enough to accumulate such quantities? There is no evidence from observational studies or stranding records to suggest that they do.

Petroleum hydrocarbons persist in the food chain, particularly in species that have a low capacity to detoxify them. Molluscs and other benthic invertebrates can accumulate residues from bottom sediments and remain contaminated for many years (Gilfillan and Vandermeulen, 1978). Gray whales and other bottom-feeding cetaceans might therefore ingest petroleum long after a spill has dissipated.

To predict the consequences of chronic ingestion of sub-lethal quantities of oil, we should know whether a cetacean can detoxify petroleum compounds or petroleum metabolites that persist in tissues of fish and other prey (McCain *et al.,* 1978). Cytochrome P-450, an iron-containing protein in liver cells, is part of a dynamic enzyme system involved in that metabolic process. It has been identified in liver from the bottlenose dolphin, white-sided dolphin, harbor porpoise, and minke whale (Geraci and St. Aubin, 1982; Goksoyr *et al.,* 1986), and is probably common to cetaceans generally. A pilot study on rats has shown that oil is a potent inducer of cytochrome P-450 (Geraci and St. Aubin, 1982), and we would expect it to have a comparable effect in a cetacean. These findings call for expanded studies on detoxifying systems in cetaceans. Animals suspected of having been exposed to oil should be analyzed for cytochrome P-450.

It is also possible to examine tissues for metabolites of petroleum hydrocarbons. We undertook a search for naphthalene in samples of liver and blubber from 15 species of whales which either had stranded, been taken in a fishery, or died in captivity. The analytical procedure was not particularly sensitive owing to limitations on methods for extracting naphthalene from tissue homogenates. Nevertheless, certain trends were evident. Highest levels were found in the blubber of small odontocetes; values in mysticetes were considerably lower. The pattern of accumulation seems to be consistent with the habitat of the animals. Beluga whales and narwhals, which had the highest concentrations in that study, live in a cold environment which retards hydrocarbon metabolism in fish (Collier *et al.*, 1978), potentially leaving more available to be consumed. Mysticetes generally feed on organisms that accumulate and eliminate hydrocarbons relatively rapidly (Neff *et al.*, 1976). Alternatively, the difference in the levels of naphthalene residues in odontocetes and mysticetes could reflect specific hydrocarbon detoxification capabilities in the two groups. These possibilities should be tested, and to do so, it will be necessary (1) to develop a sensitive method for analyzing naphthalene and its metabolites in marine mammal tissues; (2) to correlate levels with controlled ingestion of petroleum compounds; and (3) to analyze tissues from animals available through strandings or other opportunities. Data from these studies will provide the means to test the hypothesis that a cetacean may be harmed by ingested oil.

Summary

An oil spill at sea adds an element of risk to the environment of a whale or dolphin. Fresh crude oil or volatile distillates release toxic vapors that can damage sensitive tissues; harmful fractions may be swallowed or consumed through contaminated prey; and thicker tarry substances with entrapped debris may linger at the surface, plugging the vital baleen and digestive apparatus of whales that engulf them.

In spite of numerous observations of cetaceans in spills, none of these effects has been detected, or at least recorded with any certainty. Experimental evidence shows that dolphins can see oil at the surface and that they prefer to avoid it. Other cetaceans seem to be comparably equipped to detect oil. Yet in the wild, whales and dolphins have been

observed swimming and feeding in its presence without apparent ill effect. Perhaps, in these instances, the stimulus was not noxious enough, or perhaps cetaceans disregard oil when they are engaged in more engrossing or important activities. Unlike furbearers, cetaceans do not lose heat through fouling of the skin. Furthermore, cetacean epidermis is nearly impenetrable, even to the highly volatile compounds in oil, and when skin is breached, exposure to these fractions does not impede the progress of healing. There is no evidence that oil or tar balls significantly foul the feeding apparatus of baleen whales; laboratory studies suggest that such fouling has only transient effects.

Current technology provides the means to probe deeper—to the molecular level, if necessary—for damage by oil to cetaceans. Probing may satisfy our scientific curiosity, but would not bring us closer to an understanding of the central question. On the whole, it is quite improbable that a species or population of cetaceans will be disabled by a spill at sea, whatever the likelihood that one or a few animals might be affected or even killed. Yet some habitats, and therefore their residents, are more vulnerable than others. The ice-edge, refuge for bowheads, narwhals, and beluga whales, is a riskier trap for them than pelagic waters. And in coastal areas with bustling oil production activity, dolphins might be the unwitting sentinels of a deteriorating environment. The stage is now set for decisions to identify, wisely utilize, and monitor such habitats.

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