MODELING SPILLED OIL PARTITIONING IN NEARSHORE AND SURF ZONE AREAS

Erich R. Gundlach and Timothy W. Kana
Research Planning Institute
Coastal Science and Engineering
925 Gervais Street
Columbia, South Carolina 29201

Paul D. Boehm
Battelle New England Marine Research Laboratory
397 Washington Street
Duxbury, Massachusetts 02332

ABSTRACT: *The shoreline of a potential spill impact area can be divided into units, each with a specific geomorphology. As oil enters each unit, it will (to varying extents) evaporate, dissolve, interact with suspended particles and sink, biodegrade, photo-oxidize, be transported to the next unit, or strand on the shoreline. In the last case, oil will reenter the aquatic system after a given time and again be exposed to these same processes.*

For modeling purposes, the world's shorelines can be divided into sedimentary beaches and tectonic rocky coasts, varying in wave energy and tidal range. The size of beach sediments can range from very coarse grained (gravels) to very fine grained (silts and clays). Coarse-grained shorelines have higher incoming wave energy than fine-grained areas. Along all coasts, several partitioning components remain relatively constant for medium to light crude oils, e.g., evaporation (30 to 50 percent) and biodegradation/photo-oxidation (0 to 5 percent). Others may vary substantially. For instance, sedimentation may reach 10 to 20 percent in fine-grained estuaries, but only 0 to 2 percent along high energy coasts having very coarse-grained bottom sediments. Similarly, along sandy beaches the stranding of oil along the shoreline may reach 25 to 35 percent, as compared to only 1 to 2 percent along steep, rocky coasts. Dissolution, in general, does not vary so radically, being approximately 10 to 15 percent along high-energy rocky coasts, as compared to 5 to 10 percent in sheltered estuaries that do not have the mixing energy to drive additional oil into the water column.

Knowledge of the breakdown or partitioning of oil in nearshore and surf zone areas is the key to understanding the short- and long-term distribution of spilled oil in these areas. Partitioning encompasses such processes as dissolution, evaporation, biodegradation, and sedimentation. The discussion here focuses on the physical dynamics and shoreline interactions that influence oil partitioning. Other factors that, to varying degrees, influence the extent of oil partitioning into individual components are wave action, tides, suspended sediment concentrations, amount of sunlight, and biological factors (including nutrient levels and temperature). For the most part, this discussion is oriented toward light to medium crude oils.

The impetus behind this paper is the development of a coastline SMEAR model for Minerals Management Service of Anchorage, Alaska. The SMEAR model is to continue the transport and weathering of spilled oil from offshore areas directly into the surf zone, where it will further weather or partition into various chemical fractions and interact with the beach and coastal processes. The offshore trajectory model has been previously developed by the Rand Corporation, although it is currently being coupled to a weathering model being developed by Science Applications International Corporation. The SMEAR model, being developed by RPI/Coastal Science and Engineering, Battelle New England Marine Research Laboratory, and Applied Science Associates, will link up with the offshore model to carry the oil onshore. Since this modeling effort has only recently begun (October 1, 1984), the physical and chemical components of the model illustrated in this paper will become better defined, and spilled-oil weathering characteristics will be incorporated.

To categorize these partitioning processes, one must define the physical environment into which the oil is spilled. To avoid discussion of the classification of the world's coastlines, we have taken three coastal systems that have wide applicability. These are rocky shores and beaches, with beaches subdivided as coarse-grained (sands and gravels) and fine-grained (mud-dominated).

The discussion also assumes that the oil is spilled (fresh) in the nearshore zone. In many cases, however, oil may be spilled offshore and weather as it travels toward the surf zone and the shoreline. Thus, much of the original oil may have already lost its lighter components through evaporation. Therefore, other components, particularly sedimentation, would become more important than described in the following models.

Oil along moderate- to high-energy rocky shores

General description. The environments encompassed in this category include rocky headlands, steep, rock-dominated shores, and wave-cut rock platforms. As wave energy is decreased, oil coating of the rocky shore increases.

General oil reaction. Depending on wave energy, oil will be held approximately 10–30 m off these coastal types by wave reflection, and therefore be influenced primarily by longshore transport and chemical processes. Under very low wave conditions, a small amount may adhere temporarily to the vertical slope. The relative amount of oil adherence depends on slope, biological encrustations, and tidal range or area of exposure. Deposited oil will adhere or reside on this shoreline type for a short time (less than months and more likely days, depending on wave energies), whereupon it will again enter the marine environment and be subjected to chemical and mechanical processes. Evaporation, in all these cases, is a major loss factor. Gundlach and colleagues used a 30 percent loss calculation for the *Amoco Cadiz* oil spill.[5] Laboratory studies indicate this factor can be up to 50 percent.[9] A model generated by Mackay and colleagues also indicates a 50 percent evaporative loss.[10]

Observation sites.

- *Urquiola* oil spill (Spain)[8]
- *Amoco Cadiz* oil spill (France)[4]

Diagrammatic model. A diagrammatic model of a bedrock-dominated, high-energy coastline is depicted in Figure 1. Oil is shown as coming onto shore (probably wind-driven) and then entering an active surf-zone with noticeable longshore drift. Oil would be held away from the coast by waves reflecting off the steep rocky coast, but because of the intense dispersive action, dissolution and evaporation would be key partitioning components. Emulsification in the surf zone would increase the general mass of oiled material. The maximum extent of shoreline stranding (under calm conditions) would be the rocky intertidal zone. Since only low concentrations of suspended particles are present along these coasts, oil agglomeration and sinking are very minor. Bottom sediments are commonly well-washed boulders or bedrock not appropriate for oil incorporation.

For fresh oil, the relative values of partitioning components in this environment are as follows:

- Evaporation (30 to 50 percent)
- Dissolution (10 to 15 percent)
- Sedimentation (0 to 2 percent)
- Shoreline stranding (0 to 1 percent)
- Biodegradation and photo-oxidation (0 to 5 percent)
- Particle formation and transport (remaining percentage)

Coarse-grained beaches

General description. These environments include fine- to coarse-grained beaches, sand and gravel beaches, and gravel beaches. The silt and clay fraction is usually less than 5 percent. Wave energies vary from low to high.

General oil reaction. On an incoming tide, oil will be deposited along the upper portions of the beach. If tidal levels are high, oil can reach the back-berm and backshore areas. The lower beach face will remain free of oil. On an outgoing tide, oil may temporarily coat the beach face if oil quantities are great. This oil will lift off and be transported toward the backshore or alongshore by currents on the next incoming tide. Oil will reside along the backshore until sufficient wave activity reaches these areas to erode the oiled sediment or mechanically disperse the oil through abrasion of oiled sediment (by grains rubbing against each other). At the BIOS site in northern Canada, however, the oil on each grain was asphaltized, and together, oil and sediment were transported offshore. Once in the active surf zone again, mechanical dispersion and chemical dissolution continue, although longshore or wind-generated currents may transport the remaining oil to another shoreline type.

A major factor influencing the time scale and effectiveness of the above processes is grain size (particle size distribution) of the beach. Although sediment porosity and permeability are major factors influencing oil deposition, we have found that median grain size is a simpler parameter to measure (especially during a rapid aerial or ground survey), yet provides very reasonable accuracy in terms of oil spill interactions. On various beaches, oil can penetrate into the beach and be buried (as oiled sediment layers). Clearly, as illustrated during numerous spills, the depth of oil penetration and burial increases as grain size increases. For example, a moderately to heavily oiled, fine-grained sand beach will show 2–5 cm of oil penetration and up to 15 cm buried within one month, and will have about two months of oil persistence because of little variation in the sweep of topographic profiles. On mixed sand or gravel beaches, oil penetration and burial can exceed 65 cm and residence time can approach a decade (as at the *Metula* site) if oil is deposited above major wave activity and allowed to become asphaltized.

Knowing the probable extent of oil incorporation into beach sediments, and the probably amount of oil per unit sediment volume (an average of 6 to 10 percent), will yield the quantity of oil capable of being "stored" along a given stretch of beach and then released back after the appropriate time interval (depending on storm frequency, tidal range, sediment type, and other factors). In all of this, incorporation of oil into offshore bottom sediments plays a minor role, depending on the types of offshore sediments (most commonly sand-sized or coarser).

Observation sites.

- *Metula* spill (Chile)[2,6]
- *Urquiola* spill (Spain)[6]
- *Amoco Cadiz* spill (France)[1,4,5,11]
- *Ixtoc I* spill (Texas)[7]
- *Burmah Agate* spill (Texas)[13]

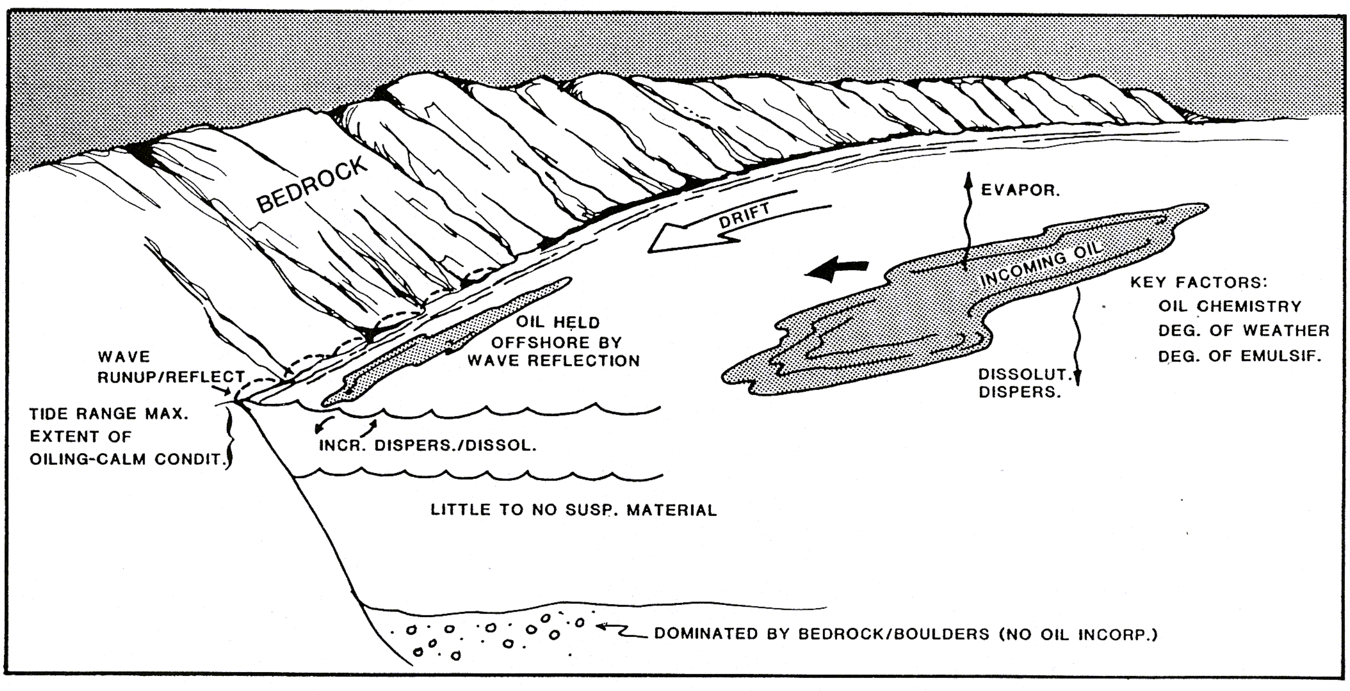

Figure 1. Oil partitioning and interaction along a moderate- to high-energy rocky shoreline

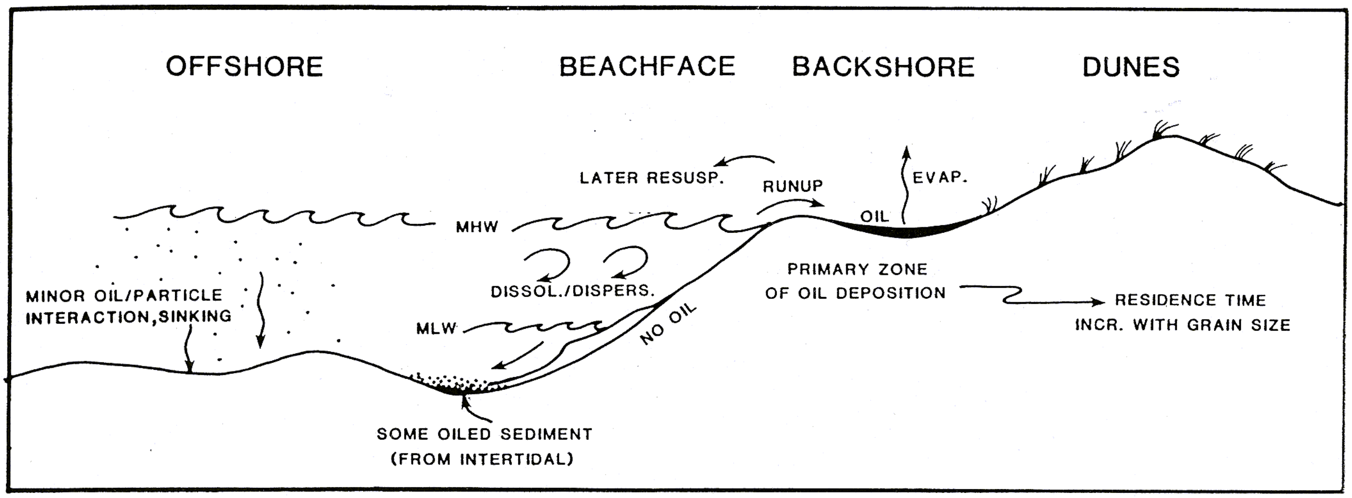

Figure 2. Oil interactions along a coarse-grained beach, in this case coarse-grained sand to mixed sand and gravel in a moderate- t high-wave-energy environment

Diagrammatic model. A depiction of oil spill interactions along this shoreline type is presented in Figure 2. Most of these interactions have been discussed previously. Relative to each other, oil is likely to be partitioned as follows:

- Evaporation (30 to 50 percent)
- Particle formation and transport (20 to 50 percent)
- Sedimentation (2 to 5 percent)
- Biodegradation and photo-oxidation (0 to 5 percent)
- Shoreline stranding (20 to 35 percent; release later)[1]
- Dissolution (10 to 15 percent)

Fine-grained beaches

General description. These areas are primarily mud-dominated tidal flats and marshes, but they also include such areas as the organic-rich, fine-grained shores fronting major depositional deltas. Tidal currents and wave activity are commonly very low, while concentrations of suspended particles are very high. Estuaries are the most typical environment for these areas.

General oil reaction. These areas are particularly important in terms of modeling, since they:

- Act as sinks for oil
- Have high sedimentation rates, which tend to incorporate oil within shoreline deposits
- Are sheltered, thereby inhibiting wave-, current-, and storm-related processes and increasing oil persistence
- Contain high quantities of suspended matter, which increases oil and sediment transport to the bottom
- Commonly contain fine-grained offshore sediments, thereby increasing potential oil incorporation into bottom sediments

Areas dominated by fine-grained sediment are inherently depositional. Incoming spilled oil, in turn, acts as sediment and will be deposited in the same areas as the sediment, on the surface of the marsh or sheltered tidal flat. However, some fresh oil will refloat on the following high tide and may exit during the subsequent ebb tide, so that total oil accumulation in these sites may be 50 to 100 percent of the total incoming oil. Onshore winds, in particular, will tend to increase the final value.

1. The secondary releases of oil from the shore back into the surf zone will again be partitioned, but in a differing relative percentage. Evaporation will be less; sediment may be more; stranding will occur again; and much of the oil will be transported alongshore or offshore.

On the surface of the flat or marsh, oil will be more prone t evaporation and chemical weathering. Mechanical weathering is neg ligible. While in or on the surface of the water column, oil will interac with suspended particles, whereupon it will likely sink to the bottor and be incorporated into the bottom sediments. As indicated in Fig ure 3, oil can be incorporated into bottom sediments directly, throug dissolution as well as dispersion. In these oil/sediment interaction several researchers have indicated, aliphatic components are muc more likely to interact with suspended sediments than are aromat compounds.[3,12] If the area is also dominated by fine-grained bottor sediments, as in the estuaries in France affected by the *Amoco Cadi* substantial amounts of oil can be taken up, and its persistence will b great. After three years, Marchand and colleagues found an appro imate 50 percent reduction in oil content in the estuarine sediment compared to more than 90 percent in offshore sediments.[11]

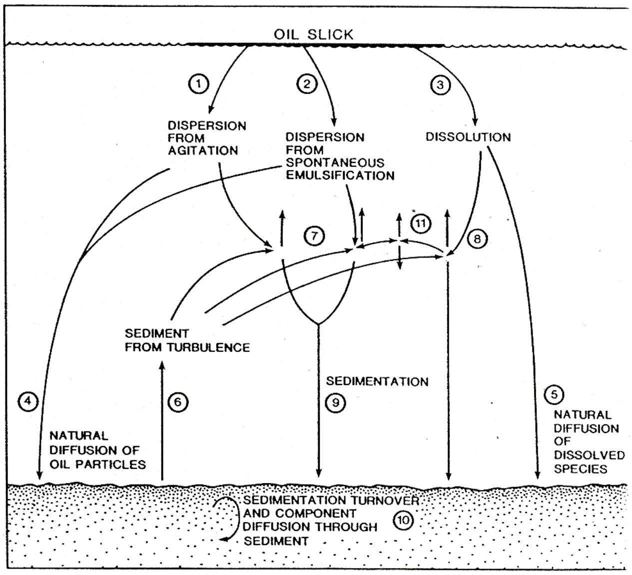

Figure 3. Transport and interaction path diagram for oil and su pended particulate matter[12]

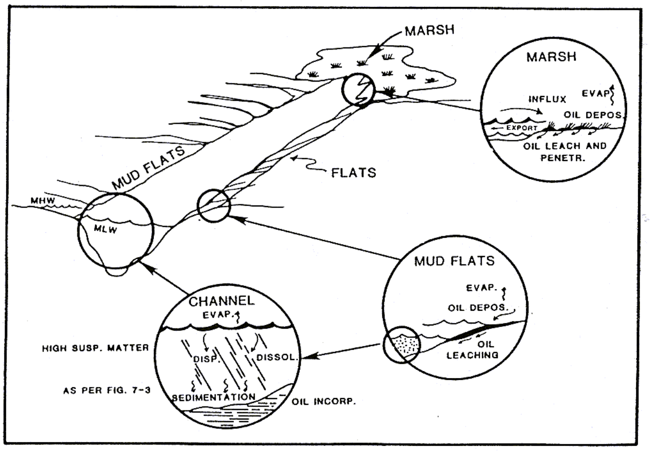

Figure 4. Oil partitioning in a fine-grained estuary composed of a main channel with muddy bottom sediments lined by mixed muddy tidal flats with a marsh at its head

Observation sites.

- *Metula* spill (Chile)[6]
- *Amoco Cadiz* spill (France)[11]
- *Ixtoc I* spill (Mexico)[3]
- Laboratory studies[12]

Diagrammatic model. The estuarine model depicted in Figure 4 includes oil interaction in the channel, adjacent mudflats, and an upper marsh. The channel contains high concentrations of suspended particular matter, which interacts as in Figure 3, causing oil sedimentation and incorporation into fine-grained bottom sediments. The mudflat portion indicates oil stranding along the upper intertidal zone, with leaching or oil penetration into the flat sediments and transport toward the channel through the groundwater. The marsh illustration indicates oil deposition on the marsh surface, with some leaching and penetration into the marsh sediments. Some minor oil export occurs during each successive tidal cycle.

Initial oil impact would be relatively partitioned as follows:

- Evaporation (30 to 50 percent)
- Shoreline stranding (40 to 60 percent; slow release)[2]
- Sedimentation (10 to 20 percent)
- Dissolution (5 to 10 percent)
- Biodegradation and photo-oxidation (1 to 2 percent)
- [Net export (10 to 20 percent, over time)]

Summary

A summary of the three major shoreline types and the relative breakdown of spilled oil components is presented in Table 1. Certain factors such as evaporation and biodegradation and photo-oxidation, remain similar in all three systems. Dissolution is expected also to be similar, although somewhat lower in more quiescent, fine-grained environments. The major components of interest, which vary directly with respect to shoreline characteristics, are sedimentation, shoreline stranding, and particle formation and transport. Sedimentation increases dramatically as the concentration of fine-grained material increases. Similarly, shoreline stranding is minimal on high-energy rocky shores and very high in sheltered, fine-grained estuaries. Coarse-grained beaches differ greatly from estuaries in that oil on coarse-grained beaches is subject to reworking and additional transport, while export of oil through resuspension is relatively low in the depicted estuary. Particle formation and transport is also greatest on coarse-grained beaches, where oil is commonly and rapidly reworked.

The physical descriptions discussed in this paper provide initial guidance for the development of a coastal-interactive oil spill model. Future refinements include a detailed breakdown of the relative quantities of oil incorporated into beach sediments with respect to grain size, the addition of a persistence factor, and the further classification of shoreline types and wave energy. The chemical components will be defined in agreement with those weathering factors being added to the offshore model. Other work being performed to determine spilled oil and suspended sediment interactions will also help further define the model.

Table 1. Summary of spilled oil mass balances for different shoreline type components (in percentage of total spilled)

	Moderate-to high-energy rocky shores	Coarse-grained beaches	Fine-grained beaches
Evaporation	30–50	30–50	30–50
Dissolution	10–15	10–15	5–10
Sedimentation	0–2	2–5	10–20
Shoreline stranding	0–1	20–35[1]	40–60
Biodegradation and photo-oxidation	0–5	0–5	1–2
Particle formation and transport	Remainder	20–50	Remainder

1. Subject to refloating, additional transport, and weathering

2. Much of the stranded oil from a large spill will remain for years, and probably decades, in sheltered tidal flats and marsh environments unless mechanically cleaned. Principal degradation processes are biochemical. Some secondary release, however, will occur as tidal influence continues. Of this oil released, partitioning components may be approximately sedimentation (30 percent), evaporation (10 percent), particle formation and export (30 percent), and additional stranding (30 percent).

References

1. Beslier, A., 1981. Les hydrocarbures de l'*Amoco Cadiz* dans les sediments subtidaux au nord de la Bretagne, distribution et evolution: Thesis, Universite de Caen, U.E.R. des Sciences de la Terre et de l'Amenagement Regional. 204pp
2. Blount, A. E., 1978. Two years after the *Metula* oil spill, Strait of Magellan, Chile: oil interaction with coastal environments. Technical Report No. 16-CRD, Coastal Research Division, Department Geology, University of South Carolina, Columbia, S.C. 214pp
3. Boehm, P. D. and D. L. Fiest, 1980. Surface water column transport and weathering of petroleum hydrocarbons during the *Ixtoc I* blowout in the Bay of Campeche and their relation to surface oil and microlayer compositions. *Proceedings of a Symposium on Preliminary Results from the September 1979* Researcher/Pierce Ixtoc-I *Cruise, Key Biscayne, Florida, June 9–10, 1980.* NOAA/OMPA, Rockville, Md. pp267–338
4. Gundlach, E. R. and M. O. Hayes, 1978. Investigation of beach processes. *in* The *Amoco Cadiz* Oil Spill, A Preliminary Scientific Report, W. N. Hess, ed., NOAA/ERL, Boulder, Colo. pp85–196
5. Gundlach, E. R., P. D. Boehm, M. Marchand, R. M. Atlas, D. M. Ward, and D. A. Wolfe, 1983. The fate of *Amoco Cadiz* oil. *Science,* v221, pp122–129
6. Gundlach, E. R., D. D. Domeracki, and L. C. Thebeau, 1982. Persistence of *Metula* oil in the Strait of Magellan six and one-half years after the incident. Oil and Petrochemical Pollution. Graham & Trotman, Ltd., London, pp37–48
7. Gundlach, E. R.. K. J. Finkelstein, and J. L. Sadd, 1981. Impact and persistence of *Ixtac I* oil on the south Texas coast. *Proceedings of the 1981 Oil Spill Conference,* API Publication No. 4334, American Petroleum Institute, Washington, D.C., pp477–488
8. Gundach, E. R., C. H. Ruby, M. O. Hayes, and A. E. Blount, 1978. The *Urquiola* oil spill, impact and reaction on beaches and rocky coasts. *Environmental Geology,* v2, n3, pp131–143

9. Mackay, D. and S. Paterson, 1980. The physical properties of fresh and weathered crude oils. Environmental Protection Service, Ottawa
10. Mackay, D., S. Paterson, and K. Trudel, 1980. A mathematical model of oil spill behavior. Environment Canada, Ottawa. 50pp
11. Marchand, M., G. Bodennec, J.-C. Caprais, and P. Pignet, 1982. The *Amoco Cadiz* oil spill, distribution and evolution of oil pollution in marine sediments. *in* Ecological Study of the *Amoco Cadiz* Oil Spill, E. R. Gundlach, ed. NOAA-CNEXO Joint Scientific Commission, Rockville, Md., pp143–158
12. Payne, J. R., et al., 1984. Final report, multivariate analysis of petroleum weathering in the marine environment—subarctic; Volume 1—Technical results. Environmental Assessment of the Alaskan Continental Shelf, Final Report of the Principal Investigators, 21, NOAA/MMS
13. Thebeau, L. C. and T. W. Kana, 1981. Onshore impacts and cleanup during the *Burmah Agate* oil spill—November 1979. *Proceedings of the 1981 Oil Spill Conference,* API Publication No. 4334, American Petroleum Institute, Washington, D.C., pp139–148