larger test, about the size of Hanna 4, to get a better idea of the economics of the process.

Those economics may be the critical problem with the Soviet process. The Soviet economy is structured in such a manner that cost effectiveness is not necessarily a consideration in the establishment of projects such as the UCG power plants. Some observers thus speculate that the cost of gas from the Soviet process may be higher than that from the LERC process. Beyond that, the consensus seems to be that the Soviet process is neither better nor worse than the LERC process. Its chief advantage is the years of experience that have been accumulated in its use, experience that may be sufficient to outweigh a slightly greater cost.

There are several potential problems with either the Soviet or the LERC process, but none of them seem too serious. One of them is the potential for subsidence of the overburden as the supporting coal is burned away beneath it. Decora estimates, for example, that burning a 10-meter seam 200 meters underground might produce a subsidence of about 1 meter. This would be a problem not only because of its effect on the landscape, but also because subsidence during gasification could allow gas to leak out of the chamber and disrupt the process. Initially, this problem might be avoided if the sites are chosen so that the overburden is strong enough to support itself. Another approach might be gasification of deep seams at sites where shallow seams have been strip-mined. Any damage from subsidence could thus be repaired when the surface was recontoured from the mining.

Another potential problem is water pollution. There has been concern that by-products of the gasification process, particularly aromatic hydrocarbons and phenols, would contaminate aquifers near the site. According to Stephens, however, this may not be as big a problem as it once appeared. Results from initial tests suggest that unburned coal in the seams adsorb these by-products much like activated charcoal, so that few pollutants escape the site. The Soviets have experienced no water pollution problems, even though they have gasified deposits very close to the municipal water supply of Angren in the Uzbeckistan Republic.

In sum, then, the technology for UCG will apparently be readily available in the very near future, and the sole remaining question will be the economics of the process. These should be relatively good. The capital investment for a UCG project should be sharply lower than that for a surface gasification plant of comparable capacity. UCG would have the additional advantage that gasification can be started as soon as part of the drilling is completed, whereas no gasification can be performed in a surface plant until the entire plant is finished.

Texas Utilities obviously thinks the economics look favorable, as do most of the other investigators. Apparently this view is shared by some of the major energy companies. Few of them are willing to discuss their plans, but at least two companies are thought to be contemplating their own tests of UCG, and they and other companies are believed to be investigating the acquisition of coal resources that would be suitable for UCG. As is the case with oil shale, it is easy to be overoptimistic about the prospects for UCG. Nonetheless, it would appear that at least some of that optimism is justified and that underground coal gasification stands a very good chance of becoming a commercial reality.—THOMAS H. MAUGH II

Oil in the Ocean: Circumstances Control Its Impact

What happens to oil entering the ocean and how it affects marine life are among the most complex problems in environmental research today. New analytical sophistication and the increasing duration of studies on spills have allowed investigators to clarify some long-term, subtle effects of petroleum in a number of situations. A striking finding of this work is that oil from major spills disperses rapidly and has minimal effects in some areas, such as open coastal waters, but may persist and remain toxic for many years in protected coves and marshes. Even in the latter areas, the original biological communities appear to return to normal as the oil is dispersed and degraded, sometimes within 5 to 10 years of the spill. A major type of oil pollution, the chronic discharge of oil into estuaries and coastal zones, is receiving less intensive study.

Although it is generally agreed that tanker accidents are responsible for only a few percent of the oil entering the ocean, large spills from tankers have received much attention from researchers. Among the more thoroughly studied spills are the *Argo Merchant* spill in shoal waters off Nantucket in December 1976, the *Florida* spill near the marshes of West Falmouth, Massachusetts, in 1969, and the *Arrow* spill in Chedabucto Bay, Nova Scotia, in 1970.

Each of these spills involved different refined petroleum products and each encountered a different physical environment. The *Argo Merchant* carried a heavy fuel oil, which was nearly congealed when it was spilled in the open waters of Nantucket Shoals. Prevailing winter winds moved the oil, which had "pancaked" in large lenses on the surface, toward the southeast where it was picked up first by a slowly rotating Gulf Stream ring and then by the Gulf Stream itself. None of the oil ever touched land, and the slick was never sighted again.

The barge *Florida* spilled lighter, more toxic fuel oil, which was driven by winds onto the sandy beaches and into the peaty marshes of Cape Cod. The *Arrow*'s heavy fuel oil was whipped into a frothy water emulsion, dubbed "chocolate mousse," as it was swept onto the rocky, storm-churned shores and quieter lagoons of Chedabucto Bay.

Researchers have found that spilled oil not only mixes with water and sediments but that it also undergoes changes in its chemical composition. Studies of possible biological effects demand that the composition of such altered, or weathered, oil be analyzed in the greatest detail possible. An increasingly important tool in such analyses is the combined use of gas chromatography and mass spectroscopy (GC-MS) in place of simpler methods to identify and measure the components of oil.

Crude oil is a mixture of many tens of thousands of different chemical compounds containing hydrogen and carbon. Some of these compounds may contain oxygen, nitrogen, or sulfur. Their properties vary over a continuous range depending on their molecular structure and size. Products as diverse as gasoline and asphalt result from the distillation of a single crude oil. After making a preliminary extraction of oil from a sample, investigators use gas chromatography to sort out individual compounds and groups of very similar compounds on the basis of these varying properties, specifically volatility and chemical affinity for an adsorbent. Then the sorted components enter a mass spectrometer where their ionized and fragmented molecules are sorted magnetically by weight to allow precise identification.

GC-MS of the marsh areas affected by the *Florida* spill revealed that, while some oil may be protected from weathering, a preferential loss of lighter, lower molecular weight compounds generally occurred. John Teal and his colleagues at Woods Hole Oceanographic Institution found that within the series of two- and three-ring aromatic compounds the lighter ones decreased to undetectable levels over 7 years while the heavier ones decreased less rapidly. They also found oil 20 centimeters below the surface of the marsh, and it had a composition very similar to that of the original oil. The loss of lower molecular weight compounds from oil is favored by their higher volatility, greater susceptibility to microbial degradation, and higher solubility in water. The protection of oil from air and water within the peaty sediment of a marsh would thus favor more complete preservation.

If a spill comes ashore on a more exposed coastline, its chances for dispersal appear to be much increased. The 8.5 million liters of heavy fuel oil spilled in Chedabucto Bay left about 300 kilometers of the bay's shoreline with a coat of thick, sticky oil. Workers then mechanically but incompletely cleaned the intertidal zone (between low and high tide lines). Six years later, researchers from the Bedford Institute of Oceanography found little oil below the intertidal region outside of heavily protected coves. Within the intertidal region, they found only a few isolated areas where stranded oil remained, usually combined with sand to form a physically resistant "pavement" that was sometimes further protected by overlying beach sand.

If dispersal forces are high and opportunities to adsorb to solid surfaces are few, readily detectable amounts of spilled oil do not appear to persist. Soon after the release of the *Argo Merchant*'s 31 million liters of heavy fuel oil onto the waters of Nantucket Shoal, researchers from a number of institutions found oil in the water beneath the slick but only within 3 to 5 kilometers of the hulk in the bottom sediments. Six months later, only one of the sediment samples collected from the same area by Eva Hoffman of the University of Rhode Island contained even a trace of oil. She tentatively concluded that even the bottom sediments had been scoured by tides and storm turbulence and that the oil may be in another location or is too dispersed for further tracing.

Rapid dispersal was also observed by P. R. Mackie and his associates at the Torrey Research Station (Aberdeen, Scotland) after the Ekofisk blowout in the North Sea this year. About half of the crude evaporated before it hit the water. Two months later, Mackie's preliminary studies indicate few signs of oil in the vicinity of the platform. No oil ever reached shore.

While oil from specific spills may be lost from sight in the vastness of the sea, it still contributes to the background of petroleum products observable in the ocean. James Butler of Harvard, Byron Morris (now in Anchorage at the Alaska Outer Continental Shelf Office), and others find that a large part of the oil in the open ocean floats at or near the surface as highly weathered tar balls, ranging in size from that of a football to a mere speck. As the exterior of these tar balls weathers further, smaller flakes are formed. These particles are small enough so that they may be weighted down by debris or incorporated into zooplankton fecal pellets. The sinking of these particles to the bottom in this manner is not yet confirmed by observation, Butler points out, but can be hypothesized by analogy with known processes.

Such complex and variable weathering of oil has presented considerable problems for biologists looking for long-term effects on biological communities. The type and degree of weathering is crucial to biologists because the components of oil not only respond differently to weathering agents but they also have differing toxicities. For example, it is well known that the series of straight-chain alkanes shows decreasing toxicity with increasing size, a general trend in petroleum constituents. Alkanes containing 8 to 10 carbon atoms, as in gasoline, are very toxic while those with more than 12 are almost nontoxic.

In the case of the *Argo Merchant* spill, the free-floating plankton seem to have been affected by fresh oil dissolved and emulsified in the water. Visible contamination of fish eggs and zooplankton was observed. This contamination was probably responsible for the observed high mortalities among fish eggs in the area of the spill, according to Kenneth Sherman (National Marine Fisheries Service, Narragansett, R.I.), who is editor of a preliminary report on the spill. The oil may also have triggered a decrease in phytoplankton abundance and species diversity and an accompanying local bloom of a toxic blue-green alga, although these are very tentative conclusions, Sherman points out. The impact of such transitory effects on the area's fisheries is not yet known.

The greater accessibility and physical stability of the intertidal zone have allowed biologists to study the same biological communities for long periods after the oil spill. The investigators have found that recovery closely follows dispersal and weathering of the oil. For example, the *Florida* spill provided a convenient gradient of contamination in the bottom sediments of Wild Harbor from a heavily oiled area to an essentially clean area. The initial effect at the most heavily oiled stations, according to Howard Sanders of Woods Hole, was "almost complete annihilation of the bottom-living animals," but the sediment remained nearly lifeless only a short time. Within 2 to 3 months a single species of oil-tolerant worm was thriving in the contaminated mud. In some areas, the worms reached a density of more than 200,000 individuals per square meter. A few months later, the number of worms dropped abruptly as the gradual weathering of the oil apparently permitted the intrusion of other opportunistic species. The heavily oiled stations continued to follow this erratic pattern during the 4½ years that they were studied.

Areas receiving intermediate amounts of oil responded in a similar, but less extreme, fashion and showed some signs of recovery within a few years, Sanders believes. Such fluctuations were also observed by A. J. and Eve C. Southward of the Marine Biological Laboratory, Plymouth, England, in the rocky intertidal zone of Cornwall after the *Torrey Canyon* spill. The net effect of the spilled crude oil and the toxic solvent used to disperse the oil was similar to that of removing all plants and animals from an area of rocky shore, the Southwards point out. An unstable community initially developed, dominated by a single species of alga; subsequently there was a return of grazing animals that led to progressively more complex and stable systems. Essentially complete recovery of the *Torrey Canyon* spill area required 5 to 10 years. At Wild Harbor, some parts of the bottom are still contaminated, but other areas have recovered to the point that natural variability is tending to mask oil-related effects, according to A. D. Michael of the University of Massachusetts.

In the marsh affected by the *Florida* spill, it appears that the greater the extent of weathering, the faster indigenous animals can recover. Charles Krebs of St. Mary's College, St. Mary's City, Maryland, and Kathryn Burns, now at the Marine Chemistry Unit, Melbourne, Australia, found that fiddler crab population densities were at first inversely correlated with the log of the total concentration of oil, but later, densities in one area of the marsh increased out of proportion to the total oil remaining. Krebs believes that a decrease of the lighter, more toxic aromatics relative to the other components of the oil has allowed a more rapid resurgence of the crabs. Complete recovery may still require several more years, Krebs predicts.

A major problem encountered in spill studies has been the difficulty of locating appropriate control areas for comparison with contaminated areas. An ambitious approach to solving this and other inherent problems in studying spills is the use of controlled ecosystem enclosures. These are structures containing a relatively large volume of water to which controlled amounts of pollutants can be added so that their effects can be observed over a period of weeks or months. Experiments with these systems show that even small amounts of oil, typical of the water beneath a spill, severely disrupt the biological equilibrium of natural systems, but weathering processes act strongly to reduce oil's effects.

The first such work was the Controlled Ecosystem Pollution Experiment (CEPEX) at Saanich Inlet, Vancouver Island, British Columbia. The CEPEX structures are cylindrical plastic bags (10 by 30 meters) suspended from the water's surface. They allow neither exchange of water with the exterior nor contact of the water column with bottom sediments. Experimenters have made single additions of a variety of oils at concentrations of 15 to 150 parts per billion. Observation of the tanks continued for up to 1 month.

A striking observation was the rapid loss of oil from the enclosures. As much as half of the oil disappeared from the water column within 3 days. Most of this loss has been attributed by CEPEX researchers to microbial degradation and adsorption to falling particles. In spite of these losses, changes in the plankton population of oiled enclosures, as compared to those of unoiled controls, were usually apparent. For example, in one experiment, a decrease in the abundance of the dominant phytoplankton was immediately followed by a surge in the population of a previously minor species. A shift in zooplankton species distribution also occurred, apparently in response to the shift to a smaller phytoplankton species. On the basis of this kind of experiment, Richard Lee, a CEPEX experimenter from Skidaway Institute of Oceanography, Savannah, Georgia, concludes that "the long-term effects of oil will likely be found in the sediments, not in the water column."

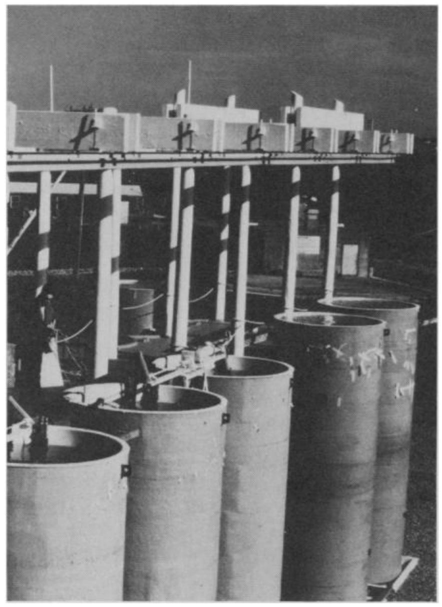

Fig. 1. Controlled ecosystem enclosures at the Marine Ecosystem Research Laboratory (MERL), Narragansett, R.I. Motor and shaft above tank tops operate stirrer within the water column to simulate the natural mixing of an estuary.

A system of enclosures at the University of Rhode Island, which was designed for the study of such sediment-water interactions, is demonstrating that the outcome of any single experiment may be dependent on the particular oil chosen and its mode of entry into the system. This system, the centerpiece of the Marine Ecosystem Research Laboratory (MERL), is operated by a consortium of investigators from a number of institutions. It includes 12 fiberglass tanks, 5.5 meters high and 1.8 meters in diameter, set up outdoors on the shore of Narragansett Bay (Fig. 1). A layer of natural sediment from a site in the bay is placed in the bottom of each tank; the tanks are then filled with 13 tons of bay water by means of a flow-through system. The tanks are operated to duplicate as closely as possible the temperature, turbulent mixing, water exchange, and species composition of the bay itself.

A preliminary 1-month and a major 6-month experiment have been conducted so far, with the "water accommodated" fraction of light fuel oil, which contains the fractions of oil most likely to enter the water column from a surface slick. As in the CEPEX experiments, half of the added oil disappeared within a few days, but in this case MERL researchers attribute most of it to evaporation that was apparently aided by the slow rising of tiny oil droplets to the surface. Contrary to the expectations of many researchers, only a few percent of the oil ended up in the sediment.

According to Candace Oviatt, MERL project manager, concentrations of oil ranging around 150 parts per billion, maintained by twice-weekly additions, were sufficient to sharply reduce the spring increase in zooplankton observed in control tanks and in the bay. As in the CEPEX experiments, distributions of phytoplankton were altered, but the abundance of phytoplankton actually increased in oiled tanks. In addition, the oil prevented the growth of fouling organisms that tended to grow on the walls of control tanks. Bottom-dwelling animals in oiled tanks showed a steady decrease in numbers and some changes in species distribution so that after 5 months very few organisms were left. These effects were brought about by the addition of about 250 grams of oil to the 70 tons of water that flowed through each tank over the 6-month period.

Little is known about the fate or effect of repeated or continual oil inputs to the ocean from routine tanker operations, municipal sewage, highway runoff, and fossil fuel burning, although they are all generally regarded to be larger sources than tanker accident releases. Studies of oil pollution in the Providence River and Narragansett Bay by James Quinn and his colleagues at the University of Rhode Island point up the possible significance of such chronic inputs. They found that 40 to 50 percent of the oil entering the bay comes from municipal sewage outfalls. The ultimate sources probably include used crankcase oil disposal and industrial discharges. Unlike the oil in the MERL tanks, much of this oil enters the sediment. When native shellfish were transferred from the polluted Providence River to clean water, they were very slow to flush the oil from their tissues, in contrast to the results from short-term exposures in the laboratory. Large-scale systems designed to purge polluted shellfish for commercial use operate under the assumption that shellfish cleanse themselves sufficiently within a certain period of time, although safe levels of oil for human consumption have not been determined, Quinn notes.

Spill studies have provided a starting point for unraveling the complex path of oil through the marine environment, but more controlled approaches will have to be pursued. It is apparent that weathering processes can be reasonably efficient in decreasing the toxicity of a single oil spill and physically dispersing it, allowing the recovery of the original biological systems. But in the cases of less favorable spill conditions and continual inputs, recovery is less certain.

—Richard A. Kerr