ABSTRACT: Portions of an Arabian Gulf coral reef were exposed to oil/dispersant mixtures, oil alone, and dispersant alone, while others were left untreated as controls. Arabian light crude and Corexit 9527 dispersant were the test toxicants.

Two series of experiments were conducted, one with a 24-hour exposure period and the other with a five-day (120-hour) exposure period. Corals were stained with Alizarin Red S for growth rate studies and were extensively photographed to document observed effects. Corals were examined for biological impacts immediately after the exposures, and then at three-month intervals for one year. Water temperature, salinity, dissolved oxygen, and hydrocarbon concentrations were recorded during the exposure periods.

Coral growth appeared unaffected by exposure to the toxicants under test conditions. Some Acropora species exposed to the dispersed oil for five days exhibited delayed, but minor, effects, which became apparent only during the relatively cold and stressful winter season.

On the other hand, Loya suggested that chronic oil spills might affect the reproductive systems of corals and prevent normal development of coral larvae. During a field study conducted in areas subjected to chronic oil pollution in the Gulf of Eilat, Rinkevich and Loya documented a decrease in the viability of corals, a decrease in the number of gonadal cells, and a decrease in the number of planulae (larvae) produced per coral head. In a subsequent laboratory study, Rinkevich and Loya reported that when corals were subjected to replenished oil for two to six months, a decrease in gonadal content per colony and an increase in colony mortality occurred. After a similar experiment, Cohen, Nissenbaum, and Eislers found that corals exposed to crude oil expelled larvae at an inordinately high rate, which could have detrimental effects on the long-term viability of the system, particularly if, as stated by Rinkevich and Loya, the larvae are shed prematurely. Bak suggests that severe changes in coral reef viability and growth may become apparent primarily in cases of long-term chronic growth; his example was the coral reef system in the area of refinery operations in Aruba. He reported that the spatial structure of the reef has deteriorated, living coral cover is low, and fewer juveniles are present in front of and downcurrent from the refinery. Also, some distributional anomalies were noted concerning some species.

Knap et al. provide several additional pertinent references offering similarly variable conclusions.

Most of these and similar reports consisted of either opportunistic observation on uncontrolled oil spills, or controlled laboratory experiments under artificial conditions. Although these types of investigations provide much useful information, it was believed desirable to supplement them with an experiment conducted under controlled field conditions, in response to a plea by Buikema and Cairns for more realistic toxicity testing and field verification of laboratory test results.

A study was designed to attempt clarification of responses of corals to dispersed oil under typical oil spill conditions in their natural Arabian Gulf environment. Appropriate design required minimal interference on natural phenomena that might influence test results, and an ability to isolate the cause-and-effect relationships under study.

Jurayd Island (latitude 27° 11’ 30” N, longitude 49° 59’ 25” E) was selected as the site of the experiments. Jurayd is one of several Saudi Arabian offshore islands, and is located approximately 51 km northwest of the coastal city of Jubail (Figure 1). This small (about 0.7 x 0.3 km) sand island is surrounded by coral reef; the experimental site was near the reef edge of the leeward (southeast) side of the island. Following the zonation scheme of Basson et al. (1977) for similar Arabian Gulf coral reefs, the experimental site was located in Zone 4, immediately landward of the reef edge.

Water depth over the site varies from one to three m, depending on...
tidal phase. In the study area, this zone is colonized primarily by reef corals and occasionally by the coralline alga *Lithothamnion*. The ramose staghorn corals, *Acropora* spp., account for more than 95 percent of the corals; scattered among the *Acropora* are occasional specimens of *Platygyra* sp. (brain coral), *Goniopora* sp. (daisy coral), and *Porites* sp. All of the corals in this zone are rather small, typically less than 1 m in diameter for ramose *Acropora*, and less than 40 cm in diameter for massive corals. A few meters seaward, in the deeper "buttress" and "table" zones, the same coral species form large colonies along with other coral species not found within the experimental site. For a more detailed description of coral reefs of the western Arabian Gulf, see Basson et al.2

**Materials and methods**

The study design required delineating test plots with enclosed barriers to contain the oil and oil-dispersant mixtures. After a prescribed exposure period, the toxicants were removed, the barriers were dismantled, and the biological effects were monitored quarterly for one year. Water samples were collected before, during, and immediately following the exposure period for chemical analysis.

All test plots were 2 m x 2 m in size, and were at an approximate water depth of 1 m at mean low tide and contained similar coral communities. In addition, they were virtually identical with respect to light intensity, water salinity and temperature, dissolved oxygen levels, suspended particulate load, water currents, and wave action. The perimeter of each test plot was marked by securing a nylon line to the substrate. These lines remained in place throughout the 12-month study; lines loosened by storms or cut by vandals were repaired as needed.

Each study plot was surrounded by an oil containment barrier (OCB) made of Nordan boom with attached nylon-reinforced vinyl skirts extending to the bottom. Although the field experiments were conducted in 1 m depths at mean low tide, the flexible skirts were made 3.5 m wide to allow for tidal fluctuations and wave disturbance. The OCBs were constructed to form rough 7.5 m x 7.5 m squares (Figure 2). Construction details are provided in Figure 3.

Each OCB was held in place by four 400-lb corner anchors made of 3-in plate steel and attached to the boom float with polypropylene line, which passed down the inside of the skirt to aid in shaping the enclosure. Each corner of the OCB float was also held in position by a "shape line" anchored approximately 16 m from the corner with a grappling hook anchor constructed of concrete reinforcing bar. This configuration produced a square enclosure roughly centered around the test plot, depending on tidal phase and current. The large dimensions of the OCB relative to the 2 m x 2 m test plot prevented the vinyl skirts from scraping over or settling on the test plots during low tide.

This boom configuration allowed sufficient water interchange between the enclosed space and water from the outside to maintain acceptable conditions for coral maintenance. Some minor water exchange occurred between the skirt and the irregular bottom. Major exchange occurred during the tidal cycle as the water volume within the enclosure varied with the tidal phase.

Two field experiments were conducted, the first with a 24-hr (one-day) toxicant exposure period, and the second with a 120-hr (5-day) exposure period. Toxicants used were Arabian light crude oil and Corexit 9527 dispersant. Each experiment included eight study plots, with two each of the following:

- Controls, using no toxicant
- Exposure to crude oil only
- Exposure to dispersant only
- Exposure to premixed oil plus dispersant

Because the intent of these experiments was to stimulate conditions of a typical Arabian Gulf oil spill, rather than to overwhelm the corals with extraordinary and catastrophic stresses, the toxicant doses administered to the OCB systems corresponded to a representative oil slick thickness. A typical spill produces a drifting slick 0.10 mm thick.

The amount of oil applied in the 24-hr experiment corresponded to a slick thickness of 0.25 mm, requiring a total of 14 liters of oil to be
applied to each oil-only enclosure. A 20:1 mixture of oil: dispersant was previously determined to provide complete emulsification, so 14 liters of crude oil were premixed with 0.7 liter of dispersant for application to each oil-plus-dispersant enclosure, and 0.7 liter of dispersant was applied to each dispersant-only enclosure.

The amount of oil initially applied in the five-day experiment corresponded to a slick thickness of 0.10 mm, or a total of 5.63 liters. For the oil-plus-dispersant enclosures, 0.28 liter of dispersant was pre-mixed with 5.63 liters of oil, and 0.28 liter of dispersant was applied to each dispersant-only enclosure. Because of tidal flushing, redosing of the five-day enclosures was accomplished on a daily basis (except for day 3, when the supply of crude was interrupted), as near to static low tide conditions as possible. The amount of toxicant used to redose the enclosures was equal to the original dose in each case.

Toxicants were administered at 2 to 4 liters/min at a depth of 1 m from glass containers through Teflon tubing propelled by a hand-operated air pressure pump. The terminal end of the tubing was fitted with a diffuser, which produced a mean "dispersed" oil particle of 6.4 microns diameter (5.9 to 6.8) in prettrial tests.

During the experimental exposure periods, water samples were collected from approximately 15 cm above the test plot corals for hydrocarbon analysis. This was accomplished by attaching the terminal end of Teflon tubing in place with a plastic ratchet strap prior to the beginning of the experiment. The other end of the tube was fastened to a corner post of the OCB. For sampling, this tube was attached to a vacuum bottle in a small boat, and the sample was pulled in using a hand vacuum pump. Bottles were rinsed twice with collected water before retaining a sample.

Water samples were extracted and analyzed using infrared protocols of Brown et al. The samples were extracted immediately with carbon tetrachloride aboard the on-site base ship, and the extracts were air-shipped to the United States in volatile organic sampling bottles (VOA) with Teflon-lined septum caps.

During the 24-hr experiment, water samples were collected prior to dispersing the toxicants, and at 3, 6, 9, 18, 21, and 24 hours into the experiments from each plot. During the 120-hr (five-day) experiment, hydrocarbon samples were collected from each plot prior to dispersing the toxicants, at two to three hours after the initial dose application, and two to three hours before and after each daily reapplication of additional toxicant.

All plots were also monitored for water salinity, water temperature, and dissolved oxygen following the same schedule as for hydrocarbon sampling.

Corals within the study plots were monitored by direct visual inspection immediately before and after the exposure experiments, and then at three-month intervals for a period of one year. Each plot was inspected for signs of coral mortality or stress (such as abnormal polyp retraction or extension, bleaching due to loss of zooxanthellae, copious amounts of mucus secretion, and infestation by pathogens or "black line" disease). Observations were recorded on underwater writing pads.

Underwater color photography was used extensively to recognize and document any changes that may have occurred in the plots. A complete set of photographs was made of each square meter in each plot before the exposure experiments, within a few hours after the experiments, and at three-month intervals for one year. Selected individual corals were also extensively photographed. When possible, underwater photographs were taken from the same aspect and direction throughout the study. Photographs were then compared with sets from earlier monitoring periods, and changes were noted and recorded.

For growth rate studies, specimens of Acropora were stained with Alizarin Red S; Alizarin stains the porous aragonitic coral skeleton red, and subsequent skeletal growth after staining is white in color, allowing measurement of new growth (Figure 4). Clear polyethylene bags were placed over the corals and tied to the base of the coral colony. Stain was then injected into the bag to yield a stain concentration of approximately 20 mg/liter. The concentration was maintained by the periodic addition of Alizarin solution; the concentration was judged by the color of the seawater within the bag. The bags were removed after 18 to 24 hours, and each stained coral was tagged with a plastic strap to facilitate relocation. New straps were added after six or nine months, as most corals had overgrown the original straps. After one year, the stained corals were collected and transported to the laboratory for growth rate determination. Corals were washed to remove adhering tissue, and the skeletons were sectioned using a rock saw. Each Acropora branch was cut along the axis of growth to expose the internal stained skeleton and adjacent unstained skeleton. Maximum skeletal extension for each branch was measured and recorded.

For scanning electron microscopy, the stained/unstained interface of representative coral skeletons was exposed by being sectioned, polished, cleaned in an ultrasonic bath, etched for 10 seconds in hydrochloric acid, coated with gold/palladium, and examined at various magnifications in an ISI-DS 130 high resolution scanning electron microscope.

![Figure 3. Schematic top and side views of oil containment barrier structure](image)

![Figure 4. A schematic representation of a sectioned Acropora branch stained with Alizarin Red S (stippled area). New growth is represented by the clear area.](image)
Table 1. Summary of dissolved oxygen monitoring data (mg/liter) presented as averages

<table>
<thead>
<tr>
<th>Plot type</th>
<th>24-hour experiment</th>
<th>120-hour experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil-plus-dispersant plots</td>
<td>4.75</td>
<td>4.75</td>
</tr>
<tr>
<td>Oil-only plots</td>
<td>5.00</td>
<td>4.85</td>
</tr>
<tr>
<td>Dispersant-only plots</td>
<td>5.10</td>
<td>5.15</td>
</tr>
<tr>
<td>Control plots</td>
<td>5.20</td>
<td>5.00</td>
</tr>
</tbody>
</table>

Results

Physical test environment. Water temperature and salinity were stable throughout both studies, exhibiting few differences between experimental and control plots. Both parameters remained well within tolerances for corals. These data are summarized in Table 1.

The dissolved oxygen concentrations varied somewhat through the experiments. A range of 2.5 to 7 mg/liter was noted in the 24-hour experiment, which seems quite large, but this resulted from the normal diurnal variation caused by day vs. night differences in photosynthetic activity. This pattern existed outside the OCBs as well as inside. Little difference was noted among plots; the range of individual plot averages was only 4.7 to 5.2 mg/liter. The same pattern was noted in the 120-hour experiment, where the range of individual plot averages was again 4.7 to 5.2 mg/liter.

Despite the narrow range of differences among plots, a pattern emerged (Table 2). The plots containing dispersed oil consistently exhibited slightly lower dissolved oxygen levels, while the plots containing only oil had slightly higher values, but still less than the remaining plots. In no case, however, did the average dissolved oxygen levels approach the tolerance limits for corals.

Hydrocarbons in water. Figure 5 illustrates total hydrocarbon concentrations in the 24-hour test plots. The only plots exhibiting elevated levels were the oil-plus-dispersant plots, which peaked immediately after toxicants were administered, and subsequently tapered to control plot concentrations. In comparing data from the oil-only vs. oil-plus-dispersant plots, it is readily apparent that the dispersant greatly enhanced the dispersal of oil through the water column, so that it reached the water sampling tube located approximately 15 cm above the coral.

The same pattern was noted in the 120-hour experiment (Figure 6). Elevated hydrocarbon concentrations occurred only in the oil-plus-dispersant plots; concentrations occurring in the oil-only and dispersant-only plots were not significantly different from the background levels occurring in the control plots.

Biological observations. Visual inspection for indicators of stress was made immediately after the exposure experiments were terminated and the OCB skirts had been raised. At that time, no indication of damage or stress was observed, and the corals in all plots appeared normal. During the five-day experiments, the oil-only plots were briefly entered and the corals inspected. Corals appeared normal and several reef fishes were in the contained area. The dispersant-only and oil-plus-dispersant plots were not entered while the experiments were in progress. Unlike the clear seawater characteristic of all other plots, the seawater in oil-plus-dispersant plots was clouded and brown in color. The response of the corals to the dispersed oil could not be observed until after the dispersed oil had been removed, at which time the corals appeared normal. The dispersant-only plots were not entered for reasons of safety.

Changes in the corals and reef structure were gradual and became increasingly apparent throughout the one-year monitoring period. One of the most pronounced changes in the corals was a seasonal phenomenon, which occurred uniformly among all study plots as well as over the entire study area reef. This was a seasonal increase in bleaching, or loss of coral color, due either to a decrease in the number of zooxanthellae or to polyp degeneration. Bleaching was noted during the December inspection, but was more extensive and severe during the following March inspection. Corals gradually regained their color over the warmer months, and by the following September appeared normal. *Acropora* spp. were the most severely affected by bleaching, and most colonies exhibited some loss of color over the winter months, especially from terminal branches.

Evaluation of sequential photographs indicates that although bleaching was a seasonal phenomenon unrelated to the exposure experiments, recovery of corals was a bit less aggressive in the two five-day plots containing oil-plus-dispersant. Some *Acropora* colonies that were partially dead and bleached before and during exposure to dispersed oil in September continued to die over the winter months. By the following March, the bleached tissue appeared dead. In con-

Table 2. Summary of water temperature and salinity data taken during the experiments

<table>
<thead>
<tr>
<th>Water temperature</th>
<th>24-hour experiment</th>
<th>120-hour experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall average</td>
<td>32.0</td>
<td>32.8</td>
</tr>
<tr>
<td>Overall range</td>
<td>31.0–33.5</td>
<td>31.0–34.0</td>
</tr>
<tr>
<td>Range of individual plot averages</td>
<td>31.9–32.9</td>
<td>32.7–32.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Salinity (ppt)</th>
<th>24-hour experiment</th>
<th>120-hour experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall average</td>
<td>38.1</td>
<td>36.4</td>
</tr>
<tr>
<td>Overall range</td>
<td>36.4–40.0</td>
<td>30.3–38.8</td>
</tr>
<tr>
<td>Range of individual plot averages</td>
<td>37.8–38.3</td>
<td>36.1–36.6</td>
</tr>
</tbody>
</table>
The corals that appeared normal at the time of the exposure experiments seemed unaffected by exposure to dispersed oil and were able to survive the winter season, appearing normal at the end of the study. In contrast, corals that appeared normal at the time of the exposure experienced delayed effects on a small percentage of stressed corals; that is, the growth form of the corals apparently was not affected by the exposure experiments. The implication for this study is that simple measurements of coral growth do not necessarily reflect coral “health” or “vigor” as affected by environment, as had been commonly believed.

Representative stained specimens from the five-day exposure, oil-only, dispersant-only, and oil-plus-dispersant plots were examined by SEM to determine if calcification was interrupted by the exposure experiment. Using the stained/unstained interface of the skeleton as a marker for the skeletal surface at the time the exposure experiments were made one year earlier, the skeletal microarchitecture was examined at two levels: The microarchitecture was examined for discontinuity between and among the major skeletal structures (including septa, dissepiments, and voids), and the skeletal ultrastructure was examined at 2,000 to 10,000 magnifications for discontinuity in the crystallization pattern. Neither the microarchitecture of the skeletons nor the shape and arrangement of aragonite crystals comprising the skeletons exhibited any unusual features. It was presumed that any severe interruption of calcification, either from stress induced by staining with Alizarin Red S or by exposure to suspected pollutants, would result in a recognizable interface between the coral skeleton surface exposed to the stress event and the skeleton excreted after the event. The lack of such interface indicates either that a severe interruption in calcification did not occur, or that growth was resumed after a period of non-growth without any recognizable physical trace of the hiatus.

### Conclusions

The conclusions resulting from this study are summarized below. They apply to Arabian Gulf reef corals exposed to specific toxicants under the experimental conditions described previously.

- During a one-year observation period, no visible effects were exhibited by Arabian Gulf corals exposed to the following toxicants for 24 hours: floating crude oil corresponding to a slick thickness of 0.25 mm; dispersant in an amount equivalent to 5 percent of the crude oil volume; and a combination of the above as dispersed oil.
- Corals exposed for five days to floating crude oil corresponding to a slick thickness of 0.10 mm exhibited no visible effects during a one-year observation period. Similarly, corals exposed for five days to dispersant in an amount equivalent to 5 percent of the crude oil volume showed no effects.
- Corals exposed to dispersed oil for five days exhibited some delayed effects on a small percentage of stressed corals; that is, those corals that exhibited bleaching (an indicator of stress) prior to and during the exposure experiment, were unable to survive the stress of the subsequent cold winter season. Estimates are that less than 5 percent of the Acropora in the five-day exposure plots was affected.
- Coral growth and colonization in the study plots appeared unaffected by exposure to crude oil, dispersant, or dispersant-plus-oil mixtures in both the one-day and five-day exposure plots. This field study implies that healthy reef corals can tolerate relatively short (one to five days) exposure to floating oil and to dispersed oil with no observable effects. In the Arabian Gulf, some coral mortality is likely to result from the prolonged use of dispersant on oil slicks; effects are likely to be minimal during the warm season in areas where water temperature is optimal for coral vitality, and most severe during the winter, when most reef corals appear to be stressed by the low water temperatures.
References


Bibliography