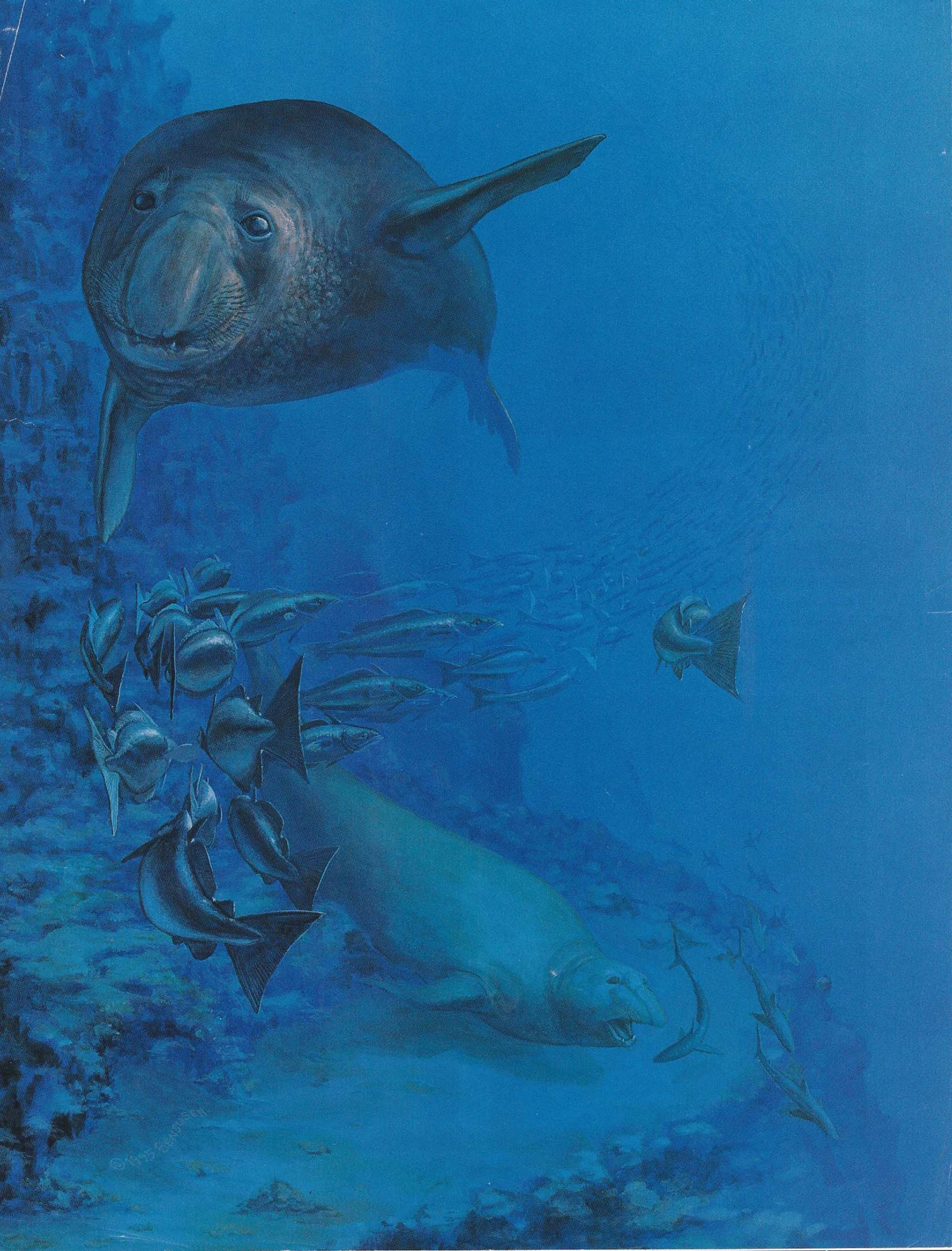
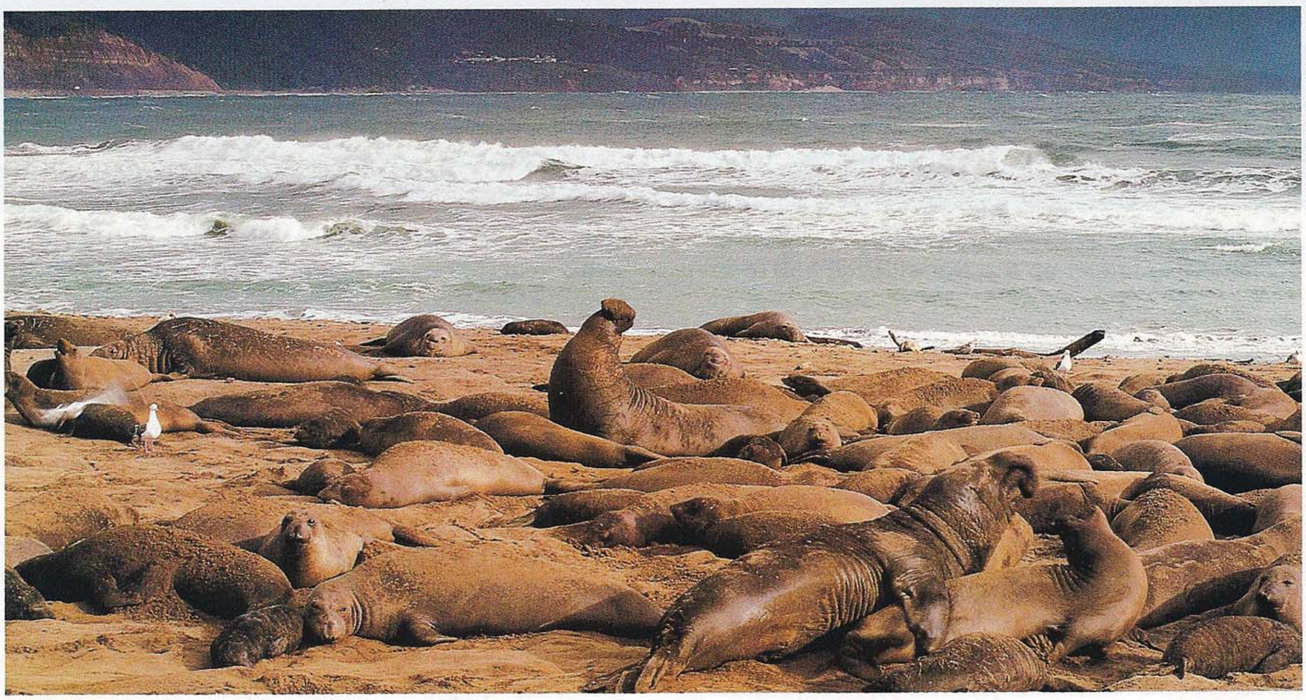


Sept 1995

By Kathleen McAuliffe

Elephant seals, the champion divers of the deep

These ponderous pinnipeds continually set new records for diving to crushing depths; researchers are hard at work to discover just how they do it



A herd of elephant seals relaxes on the beach at the Año Nuevo State Reserve in California (above). As at home at depths of nearly a mile as on land, they hunt along seawalls for Pacific hake, dogfish (opposite).

The California bathers do not welcome a truck on the beach overlooking Monterey Bay. Annoyance quickly gives way to curiosity, however, when a coffin-shaped cage on the back of the flatbed becomes the center of activity. As parents and children gather round for a closer view, marine biologist Burney Le Boeuf signals a team of six to unload the crate at the water's edge. Out rolls Camille, a juvenile northern elephant seal with a video camera attached to her back. Big brown eyes blinking in the noonday sun, she circles once, snarls at her human abductors and then galumphs toward the ocean. Moments later, the world's first video-shooting elephant seal disappears under a big wave.

Le Boeuf, a professor at the nearby University of California at Santa Cruz, is gambling that the animal's homing instincts will guide it back to a beach on the mainland behind the island of Año Nuevo, a popular spring gathering ground of elephant seals 18 miles up the coast. "Let's hope by tomorrow afternoon we'll be sitting back with a beer, watching the first rushes," he enthuses. "You never know—the film might just reveal something we didn't expect." A moment later, his jubilant spirit falls prey to realism. "Or it might just be all murk."

Such are the risks of animal trials with undersea technologies. But the hope is that Camille will return from the deep with clues to how elephant seals have evolved

Illustrations by Sally J. Bensusen

Photographs by Frans Lanting

A team of researchers from University of California at Santa Cruz angles up to a tranquilized bull to keep him from reentering the water. Next they will attach instruments to him to record dive depth and duration.

into the greatest diving champions on Earth. These blimp-shaped creatures plunge to record-breaking depths—more than 4,000 feet—and stay down long enough to defy our understanding of physiological limits. They accomplish this feat with dizzying regularity, demonstrating an ease and endurance that no other marine mammals, not even the great whales, can match.

A self-professed "blubber lover," Le Boeuf is tall and rangy—proportions accentuated beside the rotund mounds of his favorite subjects. At 61, he is youthful of feature, especially when his face lights up in contemplation of the mystifying behavior of elephant seals. His infatuation with these creatures spans more than three decades, and it's easy to see why. Whether on land or at sea, almost everything about these animals is exceptional, bizarre, barely believable (SMITHSONIAN, April 1978).

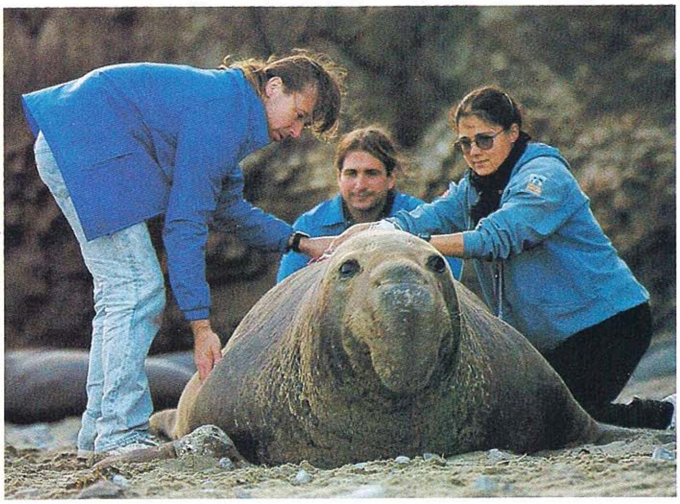
To behold the behemoth bulls is to be transported back to the age of mammoths. Sporting trunklike proboscises and necks as thick as chimney stacks, they typically stretch from 16 to 18 feet in length and weigh from two to four tons. During the mating season, the bulls bellow and charge one another on the beach, delivering bloodletting bites to the neck. The winners of these macho contests command among the largest harems of any mammal, with a single victor sometimes inseminating as many as 100 cows. No less wondrous, females fast the entire month that they nurse their pups. Says Le Boeuf, "You can only talk about these animals in superlatives."

Scientists had no inkling of their extraordinary diving feats until the introduction of portable depth-recording equipment in the early 1960s. The earliest prototypes were tested on Antarctica's Weddell seals, which returned from the frigid depths registering dives of nearly 2,000 feet. Awestruck, scientists launched a series of studies that led them to revise radically their theories of how marine mammals withstand oxygen deprivation and crushing depths. The first elephant seal to dive with recording equipment immediately broke the record set by Weddell seals. Then, in 1988, results of a new pilot study sent the biologists reeling back to the blackboard. Three northern elephant seals made such steep descents that the recording stylus went right off the charts. The animals had exceeded depths of 3,300 feet. "Our theories were blown clear out of the water," recalls Le Boeuf. "They were breaking every record in the book."

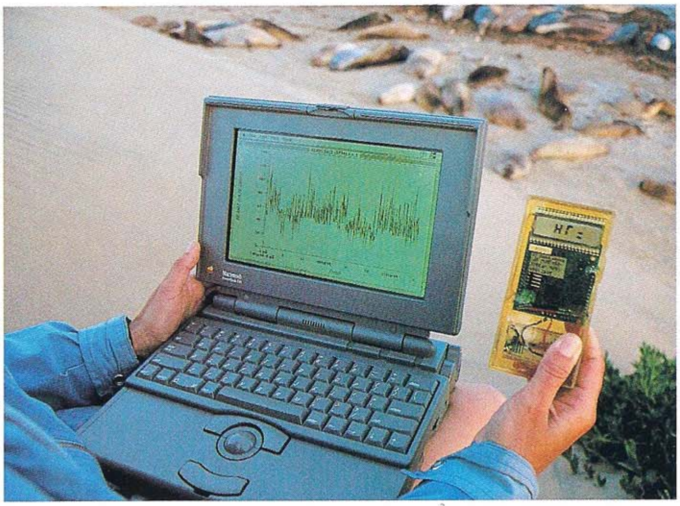
Today Le Boeuf still can't say for sure just what their true limit is. Although a northern elephant seal recently reached slightly more than 5,000 feet—just under a mile—he doubts that that record will go unchallenged for long. "It seems like every time we put a dive recorder on an elephant seal it breaks a new record," he laughs.

A mile below the surface, water crushes with a pres-

Kathleen McAuliffe lives in Florida and writes frequently about marine science. Her deepest recorded dive, however, is nine feet, to the bottom of a pool.



A subdued bull submits as Russ Andrews, Dan Crocker and Susanna Blackwell prepare mount on his back.



The seal's heart rate will be monitored with a tiny recorder and charted with the aid of a laptop computer.

Susanna Blackwell tracks a radio-equipped juvenile in the vast throng of sleeping seals at the tideline.

sure of more than a ton per square inch. "Things just implode at those depths," says Le Boeuf. "Many of our earliest instruments were made of metal and looked really tough, but after being deployed on animals, they came back all pushed in from the pressure." Many animals do live at such depths, but they die when pulled to the surface. Elephant seals appear to be equally at home at depth and at the surface—environments as different as Earth is from the moon.

To appreciate their tours de force, Le Boeuf asks us to imagine four Empire State Buildings stacked one on top of the other. An elephant seal is capable of descending from the uppermost floor of the top building to the base of the bottom building in about 20 minutes. It then ascends at the same speed, making the round-trip journey of almost two miles in just 40 minutes.

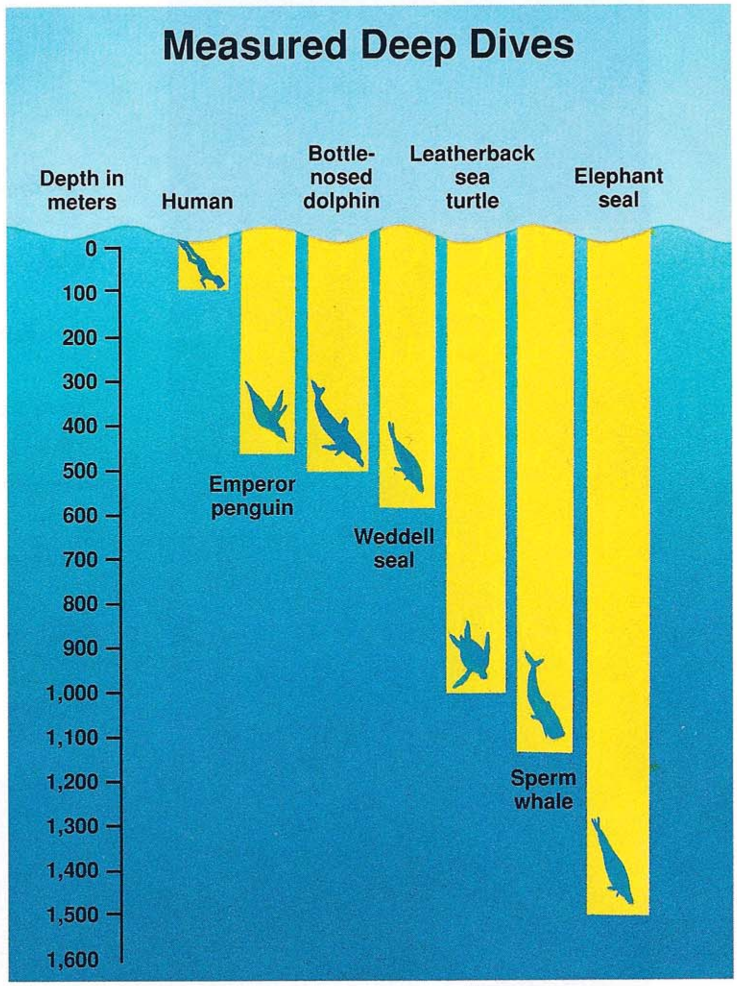
Any human scuba diver foolish enough to attempt such exploits would soon fall unconscious from nitrogen narcosis ("rapture of the deep") on the way down or die of decompression sickness, a frothing of the nitrogen in the blood associated with "the bends," on the way back up. The unfortunate diver could also writhe in convulsions from oxygen toxicity below 300 feet or from high-pressure nervous syndrome (HPNS). The bane of deep-sea divers, HPNS occurs in most mammals at depths below 600 feet when mounting pressure on the body triggers an increased excitability of nerve cells, culminating in possibly fatal seizures.

By contrast, the elephant seal shows no signs of distress. Within minutes of surfacing, it pushes its big schnozz back under the waves and repeats the same miracle all over again. What's more, this virtuoso diver can remain submerged for seemingly impossible durations. A southern elephant seal recently logged two hours down under. How do they do it?

Marine biologists have been trying to coax the secret from these Olympian divers for more than a decade. Aware that colleague Randall Davis, chairman of the department of marine biology at Texas A&M University at Galveston, was studying Weddell seals by attaching video cameras to their backs, Le Boeuf proposed a collaboration. The rationale of recruiting the elephant seals to spy on themselves was irresistible and the men quickly reached an accord: Le Boeuf would supply the animal and Davis would supply the camera.

From the start, neither scientist expected this first-of-a-kind trial to yield a bonanza of new information about deep-diving mammals. Rather, the main goal was to test the basic feasibility of the concept. Could a video camera be securely attached to an elephant seal? At what angle should the lens be positioned? How would the animal react to the camera? How would the camera be retrieved at the end of the experiment?

Because of the logistical problems involved, Davis immediately nixed the idea of risking a still-in-develop-



A human holding its breath can reach only a fraction of the depth of other divers. Elephant seal limits are still unknown; new records are often set—and broken.

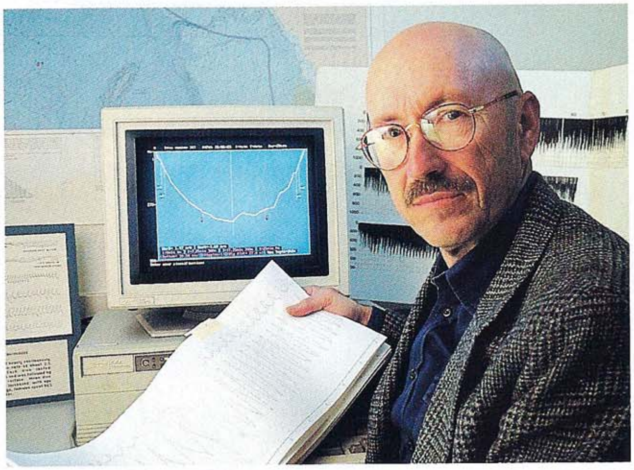
ment, $24,000 state-of-the-art underwater video camera for the pilot study. The $1,500 conventional camcorder he brought instead would function down to only 60 or 70 feet. Below that, the picture would fade to complete blackness, and worse, below 1,000 feet the pressure on the camera's housing might cause it to crack, permitting water to seep in and destroy the tape.

Given these limitations, the optimal conditions would be in shallow, well-lit waters. But restricting a free-roaming creature in an aquatic habitat is easier said than done. The solution the scientists ultimately lit upon was far from fail-safe. Rather than releasing the seal miles out at sea, they would set it free from the Monterey shoreline during the spring molting season, when seals taken from Año Nuevo usually make a beeline back to their colony to complete the shedding of their coats on land. The camera mount would be attached with—of all things—epoxy. The camera could be retrieved at the trial's end, and when the seal molted, the mount would simply fall off, and the seal would be none the worse for wear. In the parlance of scientists, this would be a "shotgun study." As Le Boeuf explains, "We're not pursuing precise goals. There's so much we don't understand about these animals that we're trying to cast as broad a net as possible."

Elephant seals do not rely on oxygen from the lungs to sustain them during long dives (as diving birds and turtles do), Le Boeuf explains. Rather, the oxygen is stored in blood and muscle. The lungs of Weddell seals actually collapse at from 30 to 40 meters on the way down and reinflate at the same level on the ascent. Biologists believe this also happens in elephant seals.

Marine mammals bring down a vast auxiliary supply of oxygen in their blood. That is possible, according to Le Boeuf, because blood constitutes as much as 20 percent of their body weight, in comparison with only 7 percent in humans. What's more, research by Jesper Qvist of Herlev Hospital in Copenhagen suggests that the spleen of Weddell seals may double as a scuba tank. According to this theory, the organ serves as a reservoir of oxygen-rich red blood cells which, under pressure, are squeezed into the circulatory system. Qvist and collaborators discovered that the organ is abnormally large in Weddell seals, equaled only in southern elephant seals. The idea is not unprecedented: racehorses also use the spleen to shunt oxygen-rich cells into circulation during exertion. Adding to the seals' reserve, a molecule known as myoglobin enables them to store oxygen in their muscles.

Though masters at hoarding oxygen for their submarine plunges, aquatic mammals cannot carry down an infinite supply. Consequently these animals conserve oxygen by lowering their metabolic rate. At Long Marine Lab, where Le Boeuf's team does most of its indoor work, graduate student Russell Andrews shows off a



Dr. Burney Le Boeuf charts an elephant seal dive in his Santa Cruz lab; video data (below) were collected by attaching a camcorder to a diving seal's back.

sophisticated new probe no bigger than a Walkman. "This," he says, "goes way beyond the standard depth recorder. In addition to measuring how deep the seals go, it also tracks their swim velocity, heart rate and body temperature."

By charting these physiological measurements, researchers in Le Boeuf's lab have documented a number of startling changes in metabolism during diving. Elephant seals lower their temperature by from 5 to 6 degrees F before long dives. At depth, they shut off circulation to the kidneys, stomach and other organs, conserving more oxygen. Meanwhile, their heart rates slow from 120 beats per minute at the surface to as low as 6 per minute on the bottom. For brief spells, elephant seals have even been clocked at 2 beats per minute. That's 30 seconds in between pulses—an acute case of cardiac arrest by human standards.

If the Weddell seal is a source of wonderment to scientists, the elephant seal is downright mystifying. Not only does it dive deeper and longer, but it does so again and again, barely pausing at the surface. While Weddell seals rest from 11 to 13 hours out of every 24, the elephant seal never seems to sleep. In the mid-1980s, using a long-running time-depth recorder, Le Boeuf's team made a discovery that shook him more than any other finding of his career. The recorder revealed that elephant seals were diving continuously, 24 hours a day, week after week, for as much as eight months at a time. "No one could believe they were doing this," says Le Boeuf. "Think about it," he beckons. "These mammals spend more than 90 percent of their lives in the utter darkness, at crushing depths, with their lungs collapsed and their hearts barely beating. Floating along in this state of suspended animation, they are probably alert only to their prey."

How do these animals stay submerged for so long? And why do they dive so relentlessly? Is it to hunt for food? Or to escape becoming food themselves? Finally, when—if ever—do they get a wink of sleep?

Alas, research on an animal as large and unwieldy as an elephant seal presents special challenges. The males are particularly difficult to study. Given their feisty tempers and massive size, obtaining the simplest measurements can require legions of people—and not a little ingenuity. To weigh a two-ton bull, Le Boeuf's students lure the animal toward an electronic scale on the beach, using a life-size decoy of a female. The model has a wagging tail and a speaker that blares the sounds a cow makes when being mounted.

Happily, the comparatively docile and diminutive cows are more cooperative subjects. Better still are juveniles like Camille. Weighing from 300 to 350 pounds, they can usually be hoisted from the beach to the lab by a small posse of researchers with a truck. When agitated, however, even these youngsters can be trouble. And seals of all sizes can bite when least expected. Stitches are usually the worst repercussions of such attacks.

From analyzing the depth recordings of hundreds of elephant seals, Le Boeuf now believes that the vast majority of their dives are foraging expeditions. After leaving Año Nuevo and other rookeries along the California coast, the cows migrate to an area west of Washington State and north of Hawaii, consuming about 40 pounds of seafood per day on the way. They find an abundant supply by plunging to the "deep scattering layer." (The name comes from its effect on the sound waves used to measure depth in the ocean.) This is actually a collection of bands, each populated by particular fish and other marine creatures, that is found at depths of from 1,500 to 2,400 feet during the day. At night, some of the bands rise to within 300 feet of the surface. Most of the fish in the deep scattering layer are small, fierce-looking and bioluminescent. "They're generally not diving to

A contest for a position at the outer edge of a dominant bull's harem pits two young bulls against each other; they will bellow and bite until one surrenders.

the bottom," Le Boeuf emphasizes. "They're just diving down as far as this floating patch of food."

The larger bulls follow a similar foraging strategy en route to their primary feeding ground farther north, near the Aleutian Islands. Once there, they dive to the tops of seamounts, where they lie in wait for prey. Among the animals whose remains have been recovered from their stomachs are skates, rays and sharks—some as long as six feet.

Why they dive so deep when they could make a far easier living nearer the surface is an evolutionary puzzle. Le Boeuf is not even sure how well they can see their prey, for they descend so quickly that their eyes have little time to adjust to the inky blackness. By venturing where no other large competitors dare to go, however, elephant seals have gained a virtual monopoly on some of the richest marine waters off the continental United States. And by spending so little time at the surface, they reduce their risk of being devoured by two formidable predators that patrol shallower water: the great white shark and the killer whale.

Elephant seals present another mystery: why the animals never seem to doze at sea. No mammal so far studied is known to forgo sleep for weeks—much less months—at a stretch. The only seals that can even come close to these perpetual-motion machines are a few species of sea lions, which dive for three days before coming ashore to sleep. Even sperm and humpback whales regularly alternate diving and resting on the surface for 30 minutes to several hours.

Could elephant seals once again be breaking all the rules? Le Boeuf wouldn't doubt it, but in this instance he subscribes to a still more radical belief. The animals, he speculates, sleep submerged. One likely time that they may be dozing, he proposes, is during drift dives, when they float down and up rather than actively swim. "My guess is that they don't sleep like us—but they reduce their level of vigilance once they're outside the range of predators below 130 feet," says Le Boeuf. "That would give them about ten minutes' rest on the way down and ten minutes on the way up."

Le Boeuf points out that elephant seals sometimes hold their breath while sleeping on land. "The analogue at sea would be that the animal sleeps while diving," he argues. Graduate student Susanna Blackwell used a stopwatch to time the breathing rate of animals as they slumbered on the beach. She measured bouts of suspended respiration, known as sleep apnea, typically lasting 10 minutes and sometimes stretching up to 23 minutes, interspersed by 2 to 3 minutes of regular breathing. "We call this 'terrestrial diving,'" she says, "because during sleep apnea their heart rate goes down, and they lower their metabolism in ways that parallel what happens during diving."

Not everyone believes that elephant seals doze thousands of feet beneath the waves. Dan Crocker, another graduate student of Le Boeuf's, argues that these nonstop diving machines don't need sleep. "One of the major theories as to why sleep evolved in land mammals is to conserve energy for several hours each day," he observes. "Yet here we have an animal that can actively swim and forage at about what it costs it in energy to lie around on the beach and rest. So the physiological adaptations of diving may have taken care of the evolu-

Champion deep-diving elephant seals

tionary requirements that sleep would normally fulfill."

As to why the animal sometimes drifts, rather than swims, up and down, Crocker believes the animals stop swimming during some dives to digest food, so that oxygen that would ordinarily be channeled to the muscles can be rerouted to the gut. "This is a classic response to feeding," he points out. "You wouldn't want to swim or exercise after a big meal either."

After a heated debate in which all the participants have worked up a sweat defending their positions, Le Boeuf loves to rock back on his heels and then pose to his team a devastating question. "Now that's a good story," he begins enthusiastically. "But can we prove it?"

For all the reams of data and rich abundance of theories, the most basic answers are not yet in hand. The question of whether the seals sleep while diving remains open. The species' resistance to high-pressure nervous syndrome also remains a profound enigma. Most problematic of all, no matter how the scientists tweak the equations, they can't explain how an elephant seal can stay submerged for as long as two hours. Taking into account all the animal's marvelous adaptations for conserving fuel, it should still run out of oxygen within 50 minutes at most. Yet there's no evidence that the animal switches to anaerobic (without free oxygen) pathways of energy production at the end of a long dive. Consequently, scientists have been forced to conclude that elephant seals must parcel out their oxygen by suppressing their metabolism further than anyone has yet measured. And therein lies the central paradox of diving. In their cold, torpid state, with their heartbeat suspended, they are supposed to be stalking highly mobile prey—an activity normally associated with rigorous exercise.

The answer to these riddles is not just of academic interest. The Navy, among others, is eager to know how the animal protects itself against nervous convulsions at depth, for this deadly reaction is the single greatest impediment to scuba divers who want to go deeper than they now can. At the University of Alaska, marine biologist Robert Elsner is keen to study how seals regulate their heartbeat, with the goal of uncovering new strategies for controlling arrhythmic human hearts. He is also fascinated by how they lower their temperature and other metabolic functions during dives because these adaptations, he believes, could help to shed light on how young children sometimes survive being submerged in icy water for more than half an hour. Still other researchers are scrutinizing both Weddell and elephant seals for clues to the cause of sudden infant death syndrome, which occurs when babies stop breathing during sleep.

Clearly, marine biologists have their work cut out for them. Camille proved maddeningly unpredictable in her pioneering trial. Expected back at Año Nuevo within two days of her release, she instead took a detour that delayed her return by a week. But after apparently wandering off the continental shelf into deep water, she did return to land. The camera housing held up to depths of 2,600 feet, and the film was retrieved undamaged. Le Boeuf and Davis declared the mission a success.

"There's a great shot where you can actually see the cliffs off the coast where the seal came up," reports Le Boeuf. "Then it quickly heads toward the twilight zone of blue water. You feel like you're in a space odyssey with jellyfish screaming by like asteroids. Mostly though, the animal is in pitch-black water."

Davis, on the other hand, seems to be more excited by the technical aspects of the production than the film itself. He offers rave reviews of the technique used to secure the camera to the animal's back. "The attachment work was dynamite," he enthuses. "I was afraid the camera might fall off, but it held rock-solid."

All in all, not bad for a pilot study. But virtually everyone agrees that the real potential of this approach lies just around the corner, as Le Boeuf, Davis and other scientists get ready to outfit animals with a new generation of pressure-resistant cameras equipped with lights that will allow taping but are invisible to the animals. In theory, such equipment should have no trouble penetrating the oppressive darkness and the crushing forces of the abyss. Of course, the technology doesn't come cheap. But while the risk is great, so too are the potential rewards. With luck, the scientists might catch these champions of the deep slurping down a squid, wrestling with a six-foot-long shark or perchance sleeping. Through the lens of the camera, their theories could be confirmed . . . or dissolved in a flurry of bubbles.

One flip of the tail, and a sand shower rains down on a molting female; sand may protect new skin from hot sun.