CHAPTER 9

Polymers Are Forever

THE PORT OF Plymouth in southwestern England is no longer listed among the scenic towns of the British Isles, although prior to World War II it would have qualified. During six nights of March and April 1941, Nazi bombs destroyed 75,000 buildings in what is remembered as the Plymouth Blitz. When the annihilated city center was rebuilt, a modern concrete grid was superimposed on Plymouth's crooked cobbled lanes, burying its medieval past in memory.

But the main history of Plymouth lies at its edge, in the natural harbor formed at the confluence of two rivers, the Plym and the Tamar, where they join the English Channel and the Atlantic Ocean. This is the Plymouth from which the Pilgrims departed; they named their American landfall across the sea in its honor. All three of Captain Cook's Pacific expeditions began here, as did Sir Francis Drake's circumnavigation of the globe. And, on December 27, 1831, H.M.S. *Beagle* set sail from Plymouth Harbor, with 22-year-old Charles Darwin aboard.

University of Plymouth marine biologist Richard Thompson spends a lot of time pacing Plymouth's historic edge. He especially goes in winter, when the beaches along the harbor's estuaries are empty—a tall man in jeans, boots, blue windbreaker, and zippered fleece sweater, his bald pate hatless, his long fingers gloveless as he bends to probe the sand. Thompson's doctoral study was on slimy stuff that mollusks such as limpets and winkles like to eat: diatoms, cyanobacteria, algae, and tiny plants that cling to seaweed. What he's now known for, however, has less to do with

marine life than with the growing presence of things in the ocean that have never been alive at all.

Although he didn't realize it at the time, what has dominated his life's work began when he was still an undergraduate in the 1980s, spending autumn weekends organizing the Liverpool contingent of Great Britain's national beach cleanup. In his final year, he had 170 teammates amassing metric tons of rubbish along 85 miles of shoreline. Apart from items that apparently had dropped from boats, such as Greek salt boxes and Italian oil cruets, from the labels he could see that most of the debris was blowing east from Ireland. In turn, Sweden's shores were the receptacles for trash from England. Any packaging that trapped enough air to protrude from the water seemed to obey the wind currents, which in these latitudes are easterly.

Smaller, lower-profile fragments, however, were apparently controlled by currents in the water. Each year, as he compiled the team's annual reports, Thompson noticed more and more garbage that was smaller and smaller amid the usual bottles and automobile tires. He and another student began collecting sand samples along beach strand lines. They sieved the tiniest particles of whatever appeared unnatural, and tried to identify them under a microscope. This proved tricky: their subjects were usually too small to allow them to pinpoint the bottles, toys, or appliances from which they sprang.

He continued working the annual cleanup during graduate studies at Newcastle. Once he completed his Ph.D. and began teaching at Plymouth, his department acquired a Fourier Transform Infrared Spectrometer, a device that passes a microbeam through a substance, then compares its infrared spectrum to a database of known material. Now he could know what he was looking at, which only deepened his concern.

"Any idea what these are?" Thompson is guiding a visitor along the shore of the Plym River estuary, near where it joins the sea. With a full moonrise just a few hours off, the tide is out nearly 200 meters, exposing a sandy flat scattered with bladderwrack and cockle shells. A breeze skims the tidal pools, shivering rows of reflected hillside housing projects. Thompson bends over the strand line of detritus left by the forward edge of waves lapping the shore, looking for anything recognizable: hunks of nylon rope, syringes, topless plastic food containers, half a ship's float, pebbled remains of polystyrene packaging, and a rainbow of assorted bottle caps. Most plentiful of all are multicolored plastic shafts of cotton ear swabs. But there are also the odd little uniform shapes he challenges people to identify. Amid twigs and seaweed fibers in his fistful of sand are a couple of dozen blue and green plastic cylinders about two millimeters high.

"They're called nurdles. They're the raw materials of plastic production. They melt these down to make all kinds of things." He walks a little farther, then scoops up another handful. It contains more of the same plastic bits: pale blue ones, greens, reds, and tans. Each handful, he calculates, is about 20 percent plastic, and each holds at least 30 pellets.

"You find these things on virtually every beach these days. Obviously they are from some factory."

However, there is no plastic manufacturing anywhere nearby. The pellets have ridden some current over a great distance until they were deposited here—collected and sized by the wind and tide.

In Thompson's laboratory at the University of Plymouth, graduate student Mark Browne unpacks foil-wrapped beach samples that arrive in clear zip-lock bags sent by an international network of colleagues. He transfers these to a glass separating funnel, filled with a concentrated solution of sea salt to float off the plastic particles. He filters out some he thinks he recognizes, such as pieces of the ubiquitous colored ear-swab shafts, to check under the microscope. Anything really unusual goes to the FTIR Spectrometer.

Each takes more than an hour to identify. About one-third turn out to be natural fibers such as seaweed, another third are plastic, and another third are unknown—meaning that they haven't found a match in their polymer database, or that the particle has been in the water so long its color has degraded, or that it's too small for their machine, which analyzes fragments only to 20 microns—slightly thinner than a human hair.

"That means we're underestimating the amount of plastic that we're finding. The true answer is we just don't know how much is out there."

What they do know is that there's much more than ever before. During the early 20th century, Plymouth marine biologist Alistair Hardy developed an apparatus that could be towed behind an Antarctic expedition boat, 10 meters below the surface, to sample krill—an ant-sized, shrimp-like invertebrate on which much of the planet's food chain rests. In the 1930s, he modified it to measure even smaller plankton. It employed an impeller to turn a moving band of silk, similar to how a dispenser in a public lavatory moves cloth towels. As the silk passed over an opening, it filtered plankton from water passing through it. Each band of silk had a sampling capacity of 500 nautical miles. Hardy was able to convince English merchant vessels using commercial shipping lanes throughout the North Atlantic to drag his Continuous Plankton Recorder for several decades, amassing a database so valuable he was eventually knighted for his contributions to marine science.

He took so many samples around the British Isles that only every second one was analyzed. Decades later, Richard Thompson realized that the ones that remained stored in a climate-controlled Plymouth warehouse were a time capsule containing a record of growing contamination. He picked two routes out of northern Scotland that had been sampled regularly: one to Iceland, one to the Shetland Islands. His team pored over rolls of silk reeking of chemical preservative, looking for old plastic. There was no reason to examine years prior to World War II, because until then plastic barely existed, except for the Bakelite used in telephones and radios, appliances so durable they had yet to enter the waste chain. Disposable plastic packaging hadn't yet been invented.

By the 1960s, however, they were seeing increasing numbers of increasing kinds of plastic particles. By the 1990s, the samples were flecked with triple the amount of acrylic, polyester, and crumbs of other synthetic polymers than was present three decades earlier. Especially troubling was that Hardy's plankton recorder had trapped all this plastic 10 meters below the surface, suspended in the water. Since plastic mostly floats, that meant they were seeing just a fraction of what was actually there. Not only was the amount of plastic in the ocean increasing, but ever smaller bits of it were appearing—small enough to ride global sea currents.

Thompson's team realized that slow mechanical action—waves and tides that grind against shorelines, turning rocks into beaches—were now doing the same to plastics. The largest, most conspicuous items bobbing in the surf were slowly getting smaller. At the same time, there was no sign that any of the plastic was biodegrading, even when reduced to tiny fragments.

"We imagined it was being ground down smaller and smaller, into a kind of powder. And we realized that smaller and smaller could lead to bigger and bigger problems."

He knew the terrible tales of sea otters choking on polyethylene rings from beer six-packs; of swans and gulls strangled by nylon nets and fishing lines; of a green sea turtle in Hawaii dead with a pocket comb, a foot of nylon rope, and a toy truck wheel lodged in its gut. His personal worst was a study on fulmar carcasses washed ashore on North Sea coastlines. Ninety-five percent had plastic in their stomachs—an average of 44 pieces per bird. A proportional amount in a human being would weigh nearly five pounds.

There was no way of knowing if the plastic had killed them, although it was a safe bet that, in many, chunks of indigestible plastic had blocked their intestines. Thompson reasoned that if larger plastic pieces were breaking down into smaller particles, smaller organisms would likely be consuming them. He devised an aquarium experiment, using bottom-feeding lugworms that live on organic sediments, barnacles that filter organic matter suspended in water, and sand fleas that eat beach detritus. In the experiment, plastic particles and fibers were provided in proportionately bite-size quantities. Each creature promptly ingested them.

When the particles lodged in their intestines, the resulting constipation was terminal. If they were small enough, they passed through the invertebrates' digestive tracts and emerged, seemingly harmlessly, out the other end. Did that mean that plastics were so stable that they weren't toxic? At what point would they start to naturally break down—and when they did, would they release some fearful chemicals that would endanger organisms sometime far in the future?

Richard Thompson didn't know. Nobody did, because plastics haven't been around long enough for us to know how long they'll last or what happens to them. His team had identified nine different kinds in the sea so far, varieties of acrylic, nylon, polyester, polyethylene, polypropylene, and polyvinyl chloride. All he knew was that soon everything alive would be eating them.

"When they get as small as powder, even zooplankton will swallow them."

Two sources of tiny plastic particles hadn't before occurred to Thompson. Plastic bags clog everything from sewer drains to the gullets of sea turtles who mistake them for jellyfish. Increasingly, purportedly biodegradable versions were available. Thompson's team tried them. Most turned out to be just a mixture of cellulose and polymers. After the cellulose starch broke down, thousands of clear, nearly invisible plastic particles remained.

Some bags were advertised to degrade in compost piles as heat generated by decaying organic garbage rises past 100°F. "Maybe they do. But that doesn't happen on a beach, or in salt water." He'd learned that after they tied plastic produce bags to moorings in Plymouth Harbor. "A year later you could still carry groceries in them."

Even more exasperating was what his Ph.D. student Mark Browne discovered while shopping in a pharmacy. Browne pulls open the top drawer of a laboratory cabinet. Inside is a feminine cornucopia of beauty aids: shower massage creams, body scrubs, and hand cleaners. Several are by boutique labels: Neova Body Smoother, SkinCeuticals Body Polish, and DDF Strawberry Almond Body Polish. Others are international name brands: Pond's Fresh Start, a tube of Colgate Icy Blast toothpaste, Neutrogena, Clearasil. Some are available in the United States, others only in the United Kingdom. But all have one thing in common.

"Exfoliants: little granules that massage you as you bathe." He selects a peach-colored tube of St. Ives Apricot Scrub; its label reads, *100% natural exfoliants*. "This stuff is okay. The granules are actually chunks of ground-up jojoba seeds and walnut shells." Other natural brands use grape seeds, apricot hulls, coarse sugar, or sea salt. "The rest of them," he says, with a sweep of his hand, "have all gone to plastic."

On each, listed among the ingredients are "micro-fine polyethylene granules," or "polyethylene micro-spheres," or "polyethylene beads." Or just polyethylene.

"Can you believe it?" Richard Thompson demands of no one in particular, loud enough that faces bent over microscopes rise to look at him. "They're selling plastic meant to go right down the drain, into the sewers, into the rivers, right into the ocean. Bite-size pieces of plastic to be swallowed by little sea creatures."

Plastic bits are also increasingly used to scour paint from boats and aircraft. Thompson shudders. "One wonders where plastic beads laden with paint are disposed. It would be difficult to contain them on a windy day. But even if they're contained, there's no filter in any sewage works for material that small. It's inevitable. They end up in the environment."

He peers into Browne's microscope at a sample from Finland. A lone green fiber, probably from a plant, lies across three bright blue threads that probably aren't. He perches on the countertop, hooking his hiking boots around a lab stool. "Think of it this way. Suppose all human activity ceased tomorrow, and suddenly there's no one to produce plastic anymore. Just from what's already present, given how we see it fragmenting, organisms will be dealing with this stuff indefinitely. Thousands of years, possibly. Or more."

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IN ONE SENSE, plastics have been around for millions of years. Plastics are polymers: simple molecular configurations of carbon and hydrogen atoms that link together repeatedly to form chains. Spiders have been spinning polymer fibers called silk since before the Carboniferous Age, whereupon trees appeared and started making cellulose and lignin, also natural polymers. Cotton and rubber are polymers, and we make the stuff ourselves, too, in the form of collagen that comprises, among other things, our fingernails.

Another natural, moldable polymer that closely fits our idea of plastics is the secretion from an Asian scale beetle that we know as shellac. It was the search for an artificial shellac substitute that one day led chemist Leo Baekeland to mix tarry carbolic acid—phenol—with formaldehyde in his garage in Yonkers, New York. Until then, shellac was the only coating available for electric wires and connections. The moldable result became Bakelite. Baekeland became very wealthy, and the world became a very different place.

Chemists were soon busy cracking long hydrocarbon chain molecules of crude petroleum into smaller ones, and mixing these fractionates to see what variations on Baekeland's first man-made plastic they could produce. Adding chlorine yielded a strong, hardy polymer unlike anything in nature, known today as PVC. Blowing gas into another polymer as it formed created tough, linked bubbles called polystyrene, often known by the brand name Styrofoam. And the continual quest for an artificial silk led to nylon. Sheer nylon stockings revolutionized the apparel industry, and helped to drive acceptance of plastic as a defining achievement of modern life. The intercession of World War II, which diverted most nylon and plastic to the war effort, only made people desire them more.

After 1945, a torrent of products the world had never seen roared into general consumption: acrylic textiles, Plexiglass, polyethylene bottles, polypropylene containers, and "foam rubber" polyurethane toys. Most world-changing of all was transparent packaging, including self-clinging wraps of polyvinyl chloride and polyethylene, which let us see the foods wrapped inside them and kept them preserved longer than ever before.

Within 10 years, the downside to this wonder substance was apparent. *Life Magazine* coined the term "throwaway society," though the idea of tossing trash was hardly new. Humans had done that from the beginning with leftover bones from their hunt and chaff from their harvest, whereupon other organisms took over. When manufactured goods entered the garbage stream, they were at first considered less offensive than smelly organic wastes. Broken bricks and pottery became the fill for the buildings of subsequent generations. Discarded clothing reappeared in secondary markets run by ragmen, or were recycled into new fabric. Defunct machines that accumulated in junkyards could be mined for parts or alchemized into new inventions. Hunks of metal could simply be melted down into something totally different. World War II—at least the Japanese naval and air portion—was literally constructed out of American scrap heaps.

Stanford archaeologist William Rathje, who has made a career of studying garbage in America, finds himself continually disabusing waste-management officials and the general public of what he deems a myth: that plastic is responsible for overflowing landfills across the country. Rathje's decades-long Garbage Project, wherein students weighed and measured weeks' worth of residential waste, reported during the 1980s that, contrary to popular belief, plastic accounts for less than 20 percent by volume of buried wastes, in part because it can be compressed more tightly than other refuse. Although increasingly higher percentages of plastic items have been produced since then, Rathje doesn't expect the proportions to change, because improved manufacturing uses less plastic per soda bottle or disposable wrapper.

The bulk of what's in landfills, he says, is construction debris and paper products. Newspapers, he claims, again belying a common assumption, don't biodegrade when buried away from air and water. "That's why we have 3,000-year-old papyrus scrolls from Egypt. We pull perfectly readable newspapers out of landfills from the 1930s. They'll be down there for 10,000 years."

He agrees, though, that plastic embodies our collective guilt over trashing the environment. Something about plastic feels uneasily permanent. The difference may have to do with what happens outside landfills, where a newspaper gets shredded by wind, cracks in sunlight, and dissolves in rain—if it doesn't burn first.

What happens to plastic, however, is seen most vividly where trash is never collected. Humans have continuously inhabited the Hopi Indian Reservation in northern Arizona since AD 1000—longer than any other site in today's United States. The principal Hopi villages sit atop three mesas with 360° views of the surrounding desert. For centuries, the Hopis simply threw their garbage, consisting of food scraps and broken ceramic, over the sides of the mesas. Coyotes and vultures took care of the food wastes, and the pottery sherds blended back into the ground they came from.

That worked fine until the mid-20th century. Then, the garbage tossed over the side stopped going away. The Hopis were visibly surrounded by a rising pile of a new, nature-proof kind of trash. The only way it disappeared was by being blown across the desert. But it was still there, stuck to sage and mesquite branches, impaled on cactus spines.

South of the Hopi Mesas rise the 12,500-foot San Francisco Peaks, home to Hopi and Navajo gods who dwell among aspens and Douglas firs: holy mountains cloaked in purifying white each winter—except in recent years, because snow now rarely falls. In this age of deepening drought and rising temperatures, ski lift operators who, the Indians claim, defile sacred ground with their clanking machines and lucre, are being sued anew. Their latest desecration is making artificial snow for their ski runs from wastewater, which the Indians liken to bathing the face of God in shit.

East of the San Francisco Peaks are the even taller Rockies; to their west are the Sierra Madres, whose volcanic summits are higher still. Impossible as it is for us to fathom, all these colossal mountains will one day erode to the sea—every boulder, outcrop, saddle, spire, and canyon wall. Every massive uplift will pulverize, their minerals dissolving to keep the oceans salted, the plume of nutrients in their soils nourishing a new marine biological age even as the previous one disappears beneath their sediments.

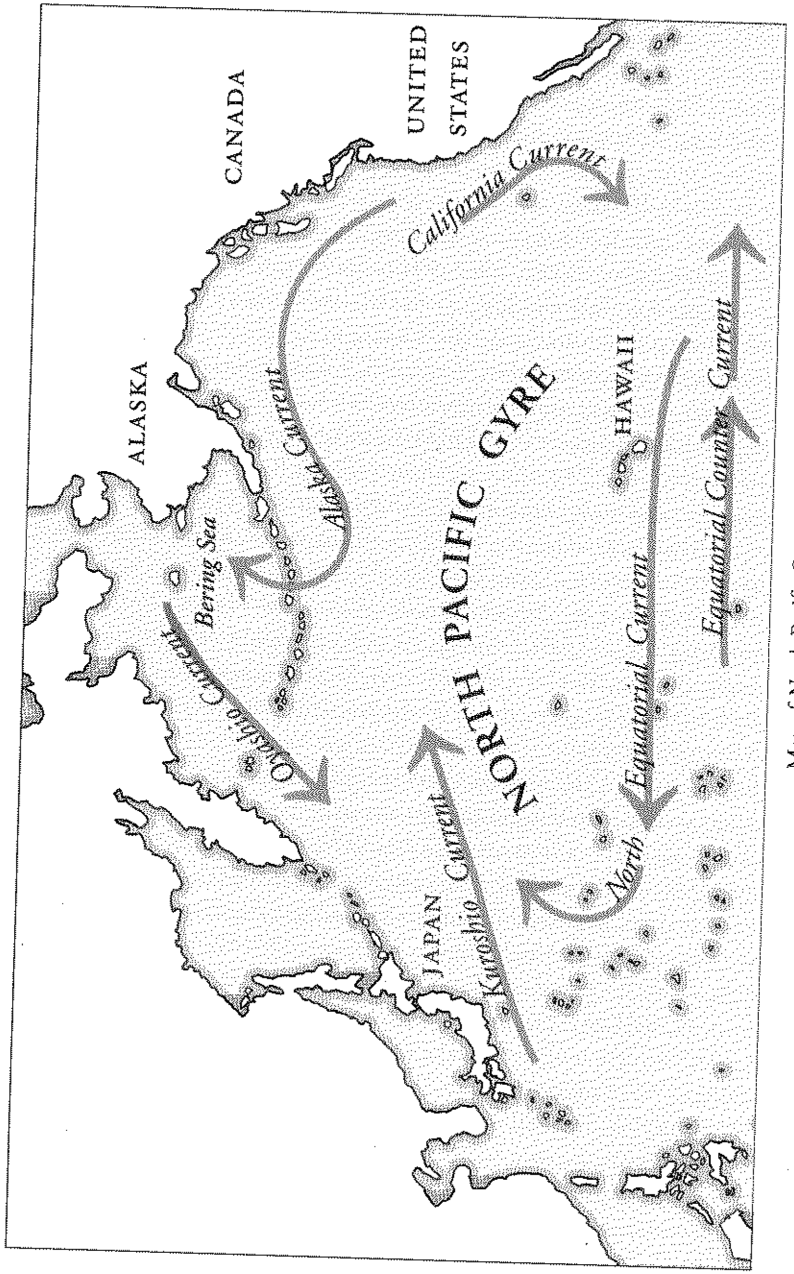
Long before that, however, these deposits will have been preceded by a substance far lighter and more easily carried seaward than rocks or even grains of silt.

Capt. Charles Moore of Long Beach, California, learned that the day in 1997 when, sailing out of Honolulu, he steered his aluminum-hulled catamaran into a part of the western Pacific he'd always avoided. Sometimes known as the horse latitudes, it is a Texas-sized span of ocean between Hawaii and California rarely plied by sailors because of a perennial, slowly rotating high-pressure vortex of hot equatorial air that inhales wind and never gives it back. Beneath it, the water describes lazy, clockwise whorls toward a depression at the center.

Its correct name is the North Pacific Subtropical Gyre, though Moore soon learned that oceanographers had another label for it: the Great Pacific Garbage Patch. Captain Moore had wandered into a sump where nearly everything that blows into the water from half the Pacific Rim eventually ends up, spiraling slowly toward a widening horror of industrial excretion. For a week, Moore and his crew found themselves crossing a sea the size of a small continent, covered with floating refuse. It was not unlike an Arctic vessel pushing through chunks of brash ice, except what was bobbing around them was a fright of cups, bottle caps, tangles of fish netting and monofilament line, bits of polystyrene packaging, six-pack rings, spent balloons, filmy scraps of sandwich wrap, and limp plastic bags that defied counting.

Just two years earlier, Moore had retired from his wood-furniture-finishing business. A lifelong surfer, his hair still ungrayed, he'd built himself a boat and settled into what he planned to be a stimulating young retirement. Raised by a sailing father and certified as a captain by the U.S. Coast Guard, he started a volunteer marine environmental monitoring group. After his hellish mid-Pacific encounter with the Great Pacific Garbage Patch, his group ballooned into what is now the Algalita Marine Research Foundation, devoted to confronting the flotsam of a half century, since 90 percent of the junk he was seeing was plastic.

What stunned Charles Moore most was learning where it came from. In 1975, the U.S. National Academy of Sciences had estimated that all oceangoing vessels together dumped 8 million pounds of plastic annually. More recent research showed the world's merchant fleet alone shamelessly tossing around 639,000 plastic containers every day. But littering by all the commercial ships and navies, Moore discovered, amounted to mere



Map of North Pacific Gyre.
MAP BY VIRGINIA NOREY

polymer crumbs in the ocean compared to what was pouring from the shore.

The real reason that the world's landfills weren't overflowing with plastic, he found, was because most of it ends up in an ocean-fill. After a few years of sampling the North Pacific gyre, Moore concluded that 80 percent of mid-ocean flotsam had originally been discarded on land. It had blown off garbage trucks or out of landfills, spilled from railroad shipping containers and washed down storm drains, sailed down rivers or wafted on the wind, and found its way to this widening gyre.

"This," Captain Moore tells his passengers, "is where all the things end up that flow down rivers to the sea." It is the same phrase geologists have uttered to students since the beginning of science, describing the inexorable processes of erosion that reduce mountains to dissolved salts and specks small enough to wash to the ocean, where they settle into layers of the distant future's rocks. However, what Moore refers to is a type of runoff and sedimentation that the Earth had hitherto never known in 5 billion years of geologic time—but likely will henceforth.

During his first 1,000-mile crossing of the gyre, Moore calculated half a pound for every 100 square meters of debris on the surface, and arrived at 3 million tons of plastic. His estimate, it turned out, was corroborated by U.S. Navy calculations. It was the first of many staggering figures he would encounter. And it only represented *visible* plastic: an indeterminate amount of larger fragments get fouled by enough algae and barnacles to sink. In 1998, Moore returned with a trawling device, such as Sir Alistair Hardy had employed to sample krill, and found, incredibly, more plastic by weight than plankton on the ocean's surface.

In fact, it wasn't even close: six times as much.

When he sampled near the mouths of Los Angeles creeks that emptied into the Pacific, the numbers rose by a factor of 100, and kept rising every year. By now he was comparing data with University of Plymouth marine biologist Richard Thompson. Like Thompson, what especially shocked him were plastic bags and the ubiquitous little raw plastic pellets. In India alone, 5,000 processing plants were producing plastic bags. Kenya was churning out 4,000 tons of bags a month, with no potential for recycling.

As for the little pellets known as nurdles, 5.5 *quadrillion*—about 250 billion pounds—were manufactured annually. Not only was Moore finding them everywhere, but he was unmistakably seeing the plastic resin bits trapped inside the transparent bodies of jellyfish and salps, the ocean's most prolific and widely distributed filter-feeders. Like seabirds, they'd taken brightly colored pellets for fish eggs, and tan ones for krill. And now God-knows-how-many quadrillion little pieces more, coated in body-scrub chemicals and perfectly bite-sized for the little creatures that bigger creatures eat, were being flushed seaward.

What did this mean for the ocean, the ecosystem, the future? All this plastic had appeared in barely more than 50 years. Would its chemical constituents or additives—for instance, colorants such as metallic copper—concentrate as they ascended the food chain, and alter evolution? Would it last long enough to enter the fossil record? Would geologists millions of years hence find Barbie doll parts embedded in conglomerates formed in seabed depositions? Would they be intact enough to be pieced together like dinosaur bones? Or would they decompose first, expelling hydrocarbons that would seep out of a vast plastic Neptune's graveyard for eons to come, leaving fossilized imprints of Barbie and Ken hardened in stone for eons beyond?

Moore and Thompson began consulting materials experts. Tokyo University geochemist Hideshige Takada, who specialized in EDCs—endocrine-disrupting chemicals, or "gender benders"—had been on a gruesome mission to personally research exactly what evils were leaching from garbage dumps all around Southeast Asia. Now he was examining plastic pulled from the Sea of Japan and Tokyo Bay. He reported that in the sea, nurdles and other plastic fragments acted both as magnets and as sponges for resilient poisons like DDT and PCBs.

The use of aggressively toxic polychlorinated biphenyls—PCBs—to make plastics more pliable had been banned since 1970; among other hazards, PCBs were known to promote hormonal havoc such as hermaphroditic fish and polar bears. Like time-release capsules, pre-1970 plastic flotsam will gradually leak PCBs into the ocean for centuries. But, as Takada also discovered, free-floating toxins from all kinds of sources—copy paper, automobile grease, coolant fluids, old fluorescent tubes, and infamous discharges by General Electric and Monsanto plants

directly into streams and rivers—readily stick to the surfaces of free-floating plastic.

One study directly correlated ingested plastics with PCBs in the fat tissue of puffins. The astonishing part was the amount. Takada and his colleagues found that plastic pellets that the birds ate concentrate poisons to levels as high as 1 million times their normal occurrence in seawater.

By 2005, Moore was referring to the gyrating Pacific dump as 10 million square miles—nearly the size of Africa. It wasn't the only one: the planet has six other major tropical oceanic gyres, all of them swirling with ugly debris. It was as if plastic exploded upon the world from a tiny seed after World War II and, like the Big Bang, was still expanding. Even if all production suddenly ceased, an astounding amount of the astoundingly durable stuff was already out there. Plastic debris, Moore believed, was now the most common surface feature of the world's oceans. How long would it last? Were there any benign, less-immortal substitutes that civilization could convert to, lest the world be plastic-wrapped evermore?

That fall, Moore, Thompson, and Takada convened at a marine plastic summit in Los Angeles with Dr. Anthony Andrady. A senior research scientist at North Carolina's Research Triangle, Andrady is from Sri Lanka, one of South Asia's rubber-producing powers. While studying polymer science in graduate school, he was distracted from a career in rubber by the surging plastics industry. An 800-page tome he eventually compiled, *Plastics in the Environment*, won him acclaim from the industry and environmentalists alike as the oracle on its subject.

The long-term prognosis for plastic, Andrady told assembled marine scientists, is exactly that: long-term. It's no surprise that plastics have made an enduring mess in the oceans, he explained. Their elasticity, versatility (they can either sink or float), near invisibility in water, durability, and superior strength were exactly why net and fishing line manufacturers had abandoned natural fibers for synthetics such as nylon and polyethylene. In time, the former disintegrate; the latter, even when torn and lost, continue "ghost fishing." As a result, virtually every marine species, including whales, is in danger of being snared by great tangles of nylon loose in the oceans.

Like any hydrocarbon, Andrady said, even plastics "inevitably must biodegrade, but at such a slow rate that it is of little practical consequence. They can, however, photodegrade in a meaningful time frame."

He explained: When hydrocarbons biodegrade, their polymer molecules are disassembled into the parts that originally combined to create them: carbon dioxide and water. When they *photodegrade,* ultraviolet solar radiation weakens plastic's tensile strength by breaking its long, chain-like polymer molecules into shorter segments. Since the strength of plastics depends on the length of their intertwined polymer chains, as the UV rays snap them, the plastic starts to decompose.

Everyone has seen polyethylene and other plastics turn yellow and brittle and start to flake in sunlight. Often, plastics are treated with additives to make them more UV-resistant; other additives can make them more UV-sensitive. Using the latter for six-pack rings, Andrady suggested, might save the lives of many sea creatures.

However, there are two problems. For one, plastic takes much longer to photodegrade in water. On land, plastic left in the sun absorbs infrared heat, and is soon much hotter than the surrounding air. In the ocean, not only does it stay cooled by water, but fouling algae shield it from sunlight.

The other hitch is that even though a ghost fishnet made from photodegradable plastic might disintegrate before it drowns any dolphins, its chemical nature will not change for hundreds, perhaps thousands of years.

"Plastic is still plastic. The material still remains a polymer. Polyethylene is not biodegraded in any practical time scale. There is no mechanism in the marine environment to biodegrade that long a molecule." Even if photodegradable nets helped marine mammals live, he concluded, their powdery residue remains in the sea, where the filter feeders will find it.

"Except for a small amount that's been incinerated," says Tony Andrady the oracle, "every bit of plastic manufactured in the world for the last 50 years or so still remains. It's somewhere in the environment."

That half-century's total production now surpasses 1 billion tons. It includes hundreds of different plastics, with untold permutations involving added plasticizers, opacifiers, colors, fillers, strengtheners, and light stabilizers. The longevity of each can vary enormously. Thus far, none has disappeared. Researchers have attempted to find out how long it will take polyethylene to biodegrade by incubating a sample in a live bacteria culture. A year later, less than 1 percent was gone.

"And that's under the best controlled laboratory conditions. That's not what you will find in real life," says Tony Andrady. "Plastics haven't been around long enough for microbes to develop the enzymes to handle it, so they can only biodegrade the very-low-molecular-weight part of the plastic"—meaning, the smallest, already-broken polymer chains. Although truly biodegradable plastics derived from natural plant sugars have appeared, as well as biodegradable polyester made from bacteria, the chances of them replacing the petroleum-based originals aren't great.

"Since the idea of packaging is to protect food from bacteria," Andrady observes, "wrapping leftovers in plastic that encourages microbes to eat it may not be the smartest thing to do."

But even if it worked, or even if humans were gone and never produced another nurdle, all the plastic already produced would remain—how long?

"Egyptian pyramids have preserved corn, seeds, and even human parts such as hair because they were sealed away from sunlight with little oxygen or moisture," says Andrady, a mild, precise man with a broad face and a clipped, persuasively reasonable voice. "Our waste dumps are somewhat like that. Plastic buried where there's little water, sun, or oxygen will stay intact a long time. That is also true if it is sunk in the ocean, covered with sediment. At the bottom of the sea, there's no oxygen, and it's very cold."

He gives a clipped little laugh. "Of course," he adds, "we don't know much about microbiology at those depths. Possibly anaerobic organisms there can biodegrade it. It's not inconceivable. But no one's taken a submersible down to check. Based on our observations, it's unlikely. So we expect much-slower degradation at the sea bottom. Many times longer. Even an order of magnitude longer."

An order of magnitude—that's 10 times—longer than what? One thousand years? Ten thousand?

No one knows, because no plastic has died a natural death yet. It took today's microbes that break hydrocarbons down to their building blocks a long time after plants appeared to learn to eat lignin and cellulose. More recently, they've even learned to eat oil. None can digest plastic yet, because 50 years is too short a time for evolution to develop the necessary biochemistry.

"But give it 100,000 years," says Andrady the optimist. He was in his native Sri Lanka when the Christmas 2004 tsunami hit, and even there, after those apocalyptic waters struck, people found reason to hope. "I'm sure you'll find many species of microbes whose genes will let them do this tremendously advantageous thing, so that their numbers will grow and prosper. Today's amount of plastic will take hundreds of thousands of years to consume, but, eventually, it will all biodegrade. Lignin is far more complex, and it biodegrades. It's just a matter of waiting for evolution to catch up with the materials we are making."

And should biologic time run out and some plastics remain, there is always geologic time.

"The upheavals and pressure will change it into something else. Just like trees buried in bogs a long time ago—the geologic process, not biodegradation, changed them into oil and coal. Maybe high concentrations of plastics will turn into something like that. Eventually, they will change. Change is the hallmark of nature. Nothing remains the same."

CHAPTER 10

The Petro Patch

WHEN HUMANS DEPART, among the immediate beneficiaries of our absence will be mosquitoes. Although our anthropocentric worldview may flatter us into thinking that human blood is essential to their survival, in fact they are versatile gourmets capable of supping at the veins of most warm-blooded mammals, cold-blooded reptiles, and even birds. In our absence, presumably plenty of wild and feral creatures will rush to fill our void and set up house in our abandoned spaces. Their numbers no longer culled by our lethal traffic, they should multiply with such abandon that humanity's total biomass—which the eminent biologist E. O. Wilson estimates wouldn't fill the Grand Canyon—won't be missed for long.

At the same time, any mosquitoes still bereaved by our passing will be consoled by two bequests. First, we'll stop exterminating them. Humans were targeting mosquitoes long before the invention of pesticides, by spreading oil on the surfaces of ponds, estuaries, and puddles where they breed. This larvicide, which denies baby mosquitoes oxygen, is still widely practiced, as are all other manners of antimosquito chemical warfare. They range from hormones that keep larvae from maturing into adults, to—especially in the malarial tropics—aerial spraying of DDT, banned only in parts of the world. With humans gone, billions of the little buzzers that would otherwise have died prematurely will now live, and among the secondary beneficiaries will be many freshwater fish species, in whose food chains mosquito eggs and larvae form big links. Others will be flowers:

Canal was completed. As Lake Gatún filled, some mountains ended up as islands. The biggest, 3,000-acre Barro Colorado, became a research laboratory for the Smithsonian's Tropical Studies Institute. Wills began to study foraging antbirds and ground cuckoos—until suddenly they were gone.

"Three thousand acres weren't enough to sustain a population of species that won't cross open water," says Steve Hilty. "In forest islands separated by pastures, it's the same."

The birds that manage to survive on islands, as Charles Darwin momentously observed among finches in the Galápagos, can adapt so tightly to local conditions that they become species unto themselves, found nowhere else. Those conditions explode, however, once humans arrive with their pigs, goats, dogs, cats, and rats.

In Hawaii, all the roast feral pig devoured in luaus can't keep up with the mayhem their rooting wreaks on forests and bogs. To protect exotic sugarcane from being eaten by exotic rats, in 1883 Hawaiian growers imported the exotic mongoose. Today, rats are still around: the favorite food of both the rat and the mongoose is the eggs of the few native geese and nesting albatrosses left on Hawaii's main islands. In Guam, just after World War II, a U.S. transport plane landed bearing stowaway Australian brown tree snakes in its wheel-wells. Within three decades, along with several native lizards, more than half the island's bird species were extinct, and the rest designated uncommon or rare.

When we humans become extinct ourselves, part of our legacy will live on in the predators we introduced. For most, the only constraints on their rampant proliferation have been the eradication programs with which we've tried to undo our damage. When we go, those efforts go with us, and rodents and mongooses will inherit most of the South Pacific's lovely isles.

Although albatrosses spend most of their lives on their majestic wings, they still must land in order to breed. Whether they will still have enough safe places to do so is uncertain, whether we're gone or not.

CHAPTER 15

Hot Legacy

1. The Stakes

AS BEFITS A chain reaction, it happened very fast. In 1938, a physicist named Enrico Fermi went from Fascist Italy to Stockholm to accept the Nobel Prize for his work with neutrons and atomic nuclei—and kept going, defecting with his Jewish wife to the United States.

That same year, word leaked that two German chemists had split uranium atoms by bombarding them with neutrons. Their work confirmed Fermi's own experiments. He had guessed correctly that when neutrons cracked an atomic nucleus, they would set more neutrons free. Each would scatter like a subatomic shotgun pellet, and with enough uranium handy, they would find more nuclei to destroy. The process would cascade, and a lot of energy would be released. He suspected Nazi Germany would be interested in that.

On December 2, 1942, in a squash court beneath the stadium at the University of Chicago, Fermi and his new American colleagues produced a controlled nuclear chain reaction. Their primitive reactor was a beehive-shaped pile of graphite bricks laced with uranium. By inserting rods coated with cadmium, which absorbs neutrons, they could moderate the exponential shattering of uranium atoms to keep it from getting out of hand.

Less than three years later, in the New Mexico desert, they did just the opposite. The nuclear reaction this time was intended to go completely out of control. Immense energy was released, and within a month the act was repeated twice, over two Japanese cities. More than 100,000 people died instantly, and the dying continued long after the initial blast. Ever since, the human race has been simultaneously terrified and fascinated by the double deadliness of nuclear fission: fantastic destruction followed by slow torture.

If we left this world tomorrow—assuming by some means other than blowing ourselves to bits—we would leave behind about 30,000 intact nuclear warheads. The chance of any exploding with us gone is effectively zero. The fissionable material inside a basic uranium bomb is separated into chunks that, to achieve the critical mass necessary for detonation, must be slammed together with a speed and precision that don't occur in nature. Dropping them, striking them, plunging them in water, or rolling a boulder over them would do nothing. In the tiny chance that the polished surfaces of enriched uranium in a deteriorated bomb actually met, unless forced together at gunshot speed, they would fizzle—albeit in a very messy way.

A plutonium weapon contains a single fissionable ball that must be forcibly, exactly compressed to at least twice its density to explode. Otherwise, it's simply a poisonous lump. What *will* happen, however, is that bomb housings will ultimately corrode, exposing the hot innards of these devices to the elements. Since weapons-grade plutonium-239 has a half-life of 24,110 years, even if it took an ICBM cone 5,000 years to disintegrate, most of the 10 to 20 pounds of plutonium it contained would not have degraded. The plutonium would throw off alpha particles—clumps of protons and neutrons heavy enough to be blocked by fur or even thick skin, but disastrous to any creature unlucky enough to inhale them. (In humans, 1 millionth of a gram can cause lung cancer.) In 125,000 years, there would be less than a pound of it, though it would still be plenty lethal. It would take 250,000 years before the levels were lost in the Earth's natural background radiation.

At that point, however, whatever lives on Earth would still have to contend with the still-deadly dregs of 441 nuclear plants.

2. Sunscreen

When big, unstable atoms like uranium decay naturally, or when we rip them apart, they emit charged particles and electromagnetic rays similar to

the strongest X-rays. Both are potent enough to alter living cells and DNA. As these deformed cells and genes reproduce and replicate, we sometimes get another kind of chain reaction, called cancer.

Since background radiation is always present, organisms have adjusted accordingly by selecting, evolving, or sometimes just succumbing. Anytime we raise the natural background dosage, we force living tissue to respond. Two decades prior to harnessing nuclear fission, first for bombs, then for power plants, humans had already let one electromagnetic genie loose—the result of a goof we wouldn't recognize until nearly 60 years later. In that instance, we didn't coax radiation out but let it sneak in.

That radiation was ultraviolet, a considerably lower energy wave than the gamma rays emitted from atomic nuclei, but it was suddenly present at levels unseen since the beginning of life on Earth. Those levels are still rising, and although we have hopes to correct that over the next half century, our untimely departure could leave them in an elevated state far longer.

Ultraviolet rays helped to fashion life as we know it—and, oddly enough, they created the ozone layer itself, our shield against too much exposure to them. Back when the primordial goo of the planet's surface was being pelted with unimpeded UV radiation from the sun, at some pivotal instant—perhaps sparked by a jolt of lightning—the first biological mix of molecules jelled. Those living cells mutated rapidly under the high energy of ultraviolet rays, metabolizing inorganic compounds and turning them into new organic ones. Eventually, one of these reacted to the presence of carbon dioxide and sunlight in the primitive atmosphere by giving off a new kind of exhaust: oxygen.

That gave ultraviolet rays a new target. Picking off pairs of oxygen atoms joined together—O_2 molecules—they split them apart. The two singles would immediately latch onto nearby O_2 molecules, forming O_3: ozone. But UV easily breaks the ozone molecule's extra atom off, reforming oxygen; just as quickly, that atom sticks to another pair, forming more ozone until it absorbs more ultraviolet and spins off again.

Gradually, beginning about 10 miles above the surface, a state of equilibrium emerged: ozone was constantly being created, pulled apart, and recombined, and thus constantly occupying UV rays so that they never reached the ground. As the layer of ozone stabilized, so did the life on Earth it was shielding. Eventually, species evolved that could never have tolerated the former levels of UV radiation bombardment. Eventually, one of them was us.

In the 1930s, however, humans started undermining the oxygen-ozone balance, which had remained relatively constant since soon after life began. That's when we started using Freon, the trademark name for chlorofluorocarbons, the man-made chlorine compounds in refrigeration. Called CFCs for short, they seemed so safely inert that we put them into aerosol cans and asthma-medication inhalers, and blew them into polymer foams to make disposable coffee cups and running shoes.

In 1974, University of California–Irvine chemists F. Sherwood Rowland and Mario Molina began to wonder where CFCs went once those refrigerators or materials broke down, since they were so impervious to combining with anything else. Eventually, they decided that hitherto indestructible CFCs must be floating to the stratosphere, where they would finally meet their match in the form of powerful ultraviolet rays. The molecular slaughter would free pure chlorine, a voracious gobbler of loose oxygen atoms, whose presence kept those same ultraviolet rays away from Earth.

No one paid Rowland and Molina much heed until 1985, when Joe Farman, a British researcher in Antarctica, discovered that part of the sky was missing. For decades, we'd been dissolving our UV screen by soaking it with chlorine. Since then, in unprecedented cooperation, the nations of the world have tried to phase out ozone-eating chemicals. The results are encouraging, but still mixed: Ozone destruction has slowed, but a black market in CFCs thrives, and some are still legally produced for "basic domestic needs" in developing countries. Even the replacements we commonly use today, hydrochlorofluorocarbons, HCFCs, are simply milder ozone-destroyers, scheduled to be phased out themselves—though the question of with what isn't easily answered.

Quite apart from ozone damage, both HCFCs and CFCs—and their most common chlorine-free substitute, hydrofluorocarbons, HFCs—have many times the potential of carbon dioxide to exacerbate global warming. The use of all these alphabetical concoctions will stop, of course, if human activity does, but the damage we did to the sky may last a lot longer. The best current hope is that the South Pole's hole, and the thinning of the ozone layer everywhere else, will heal by 2060, after destructive

substances are exhausted. This assumes that something safe will have replaced them, and that we'll have found ways to get rid of existing supplies that haven't yet drifted skyward. Destroying something designed to be indestructible, however, turns out to be expensive, requiring sophisticated, energy-intensive tools such as argon plasma arcs and rotary kilns that aren't readily available in much of the world.

As a result, especially in developing countries, millions of tons of CFCs are still used or linger in aging equipment, or are mothballed. If we vanish, millions of CFC and HCFC automobile air conditioners, and millions more domestic and commercial refrigerators, refrigerated trucks and railroad cars, as well as home and industry air-cooling units, will all finally crack and give up the chlorofluorocarbonated ghost of a 20th-century idea that went very awry.

All will rise to the stratosphere, and the convalescing ozone layer will suffer a relapse. Since it won't happen all at once, with luck the illness will be chronic, not fatal. Otherwise, the plants and animals that remain in our wake will have to select for UV tolerance, or mutate their way through a barrage of electromagnetic radiation.

3. Tactical and Practical

Uranium-235, with a half-life of 704 million years, is a relatively insignificant fraction of natural uranium ore—barely .7 percent—but we humans have concentrated ("enriched") several thousand tons of it for use in reactors and bombs. To do that, we extract it from uranium ore, usually by chemically converting it to a gas compound, then spinning it in a centrifuge to separate the different atomic weights. This leaves behind far less potent ("depleted") U-238, whose half-life is 4.5 billion years: in the United States alone, there's at least a half-million tons of it.

One approach to what to do with some of it involves the fact that U-238 is an unusually dense metal. In recent decades it has proved useful, when alloyed with steel, for fashioning bullets that can pierce armor, including the walls of tanks.

With so much surplus depleted uranium lying around, this is far cheaper for U.S. and European armies than buying the non-radioactive alternative, tungsten, which is mainly found in China. Depleted uranium projectiles range from 25-millimeter bullet size to three-foot-long, 120-millimeter darts with their own internal propellants and stabilizing fins. Their use kindles outrage over human health issues, on both the firing and receiving end. Because depleted uranium ordnance bursts into flames when it strikes, it leaves a pile of ash. Depleted or not, there's enough concentrated U-238 in the bullet points that radioactivity in this debris can exceed 1,000 times the normal background level. After we're gone, the next archaeologists to appear may unearth arsenals of several million of these super-dense, modern versions of Clovis spear points. Not only will they look considerably more fearsome, but—possibly unbeknownst to their discoverers—they'll emit radiation for more years than the planet likely has left.

There are far hotter things than depleted uranium that will outlast us, whether we're gone tomorrow or 250,000 years from now. It's a big enough problem that we contemplate hollowing out entire mountains to store them. Thus far the United States has only one such site, in salt dome formations 2,000 feet below southeastern New Mexico, similar to the chemical-storage caverns below Houston. The Waste Isolation Pilot Plant, or WIPP, operating since 1999, is the boneyard for detritus from nuclear weapons and defense research. It can handle 6.2 million cubic feet of waste, the equivalent of about 156,000 55-gallon drums. In fact, much of the plutonium-drenched scrap it receives is packaged just that way.

WIPP isn't designed to store spent fuel from nuclear generating plants, which in the United States alone increases by 3,000 tons each year. It is a landfill only for so-called low- and midlevel waste—stuff like discarded weapons-assembly gloves, shoe coverings, and rags soaked in contaminated cleaning solvents used in fashioning nuclear bombs. It also holds the dismantled remains of machines used to build them, and even walls from rooms where that happened. All this arrives on shrink-wrapped pallets containing hot hunks of pipe, aluminum conduits, rubber, plastic, cellulose, and miles of wiring. After its first five years, WIPP was already more than 20 percent full.

Its contents come from two dozen high-security warrens across the country, such as the Hanford Nuclear Reservation in Washington, where plutonium for the Nagasaki bomb was made, and Los Alamos, New Mexico, where it was assembled. In 2000, large wildfires hit both sites. Official reports say that unburied radioactive wastes were protected—but in a world without firefighters, they won't be. Except for WIPP, all U.S. nuclear waste-storage containment is temporary. If it remains that way, fire will eventually breach it and send clouds of radioactive ash billowing across the continent, and possibly across the oceans.

The first site to begin shipping to WIPP was Rocky Flats, a defense facility on a foothills plateau 16 miles northwest of Denver. Until 1989, the United States made plutonium detonators for atomic weapons at Rocky Flats with somewhat less than a lawful regard for safety. For years, thousands of drums of cutting oil saturated with plutonium and uranium were stacked outside on bare ground. When someone finally noticed they were leaking, asphalt was poured over the evidence. Radioactive runoff at Rocky Flats frequently reached local streams; cement was swirled into radioactive sludge in absurd attempts to try to slow seepage from cracked evaporation ponds; and radiation periodically escaped into the air. A 1989 FBI raid finally closed the place. In the new millennium, after several billion dollars' worth of intensive cleanup and public relations, Rocky Flats was transmuted into a National Wildlife Refuge.

Simultaneously, similar alchemy was recasting the old Rocky Mountain Arsenal next to Denver International Airport. RMA was a chemical-weapons plant that made mustard and nerve gas, incendiary bombs, napalm—and during peacetime, insecticides; its core was once called the most contaminated square mile on Earth. After dozens of wintering bald eagles were found in its security buffer, feasting on the prodigious prairie dog population, it, too, became a National Wildlife Refuge. That required draining and sealing an Arsenal lake where ducks once died moments after landing, and where the bottoms of aluminum boats sent to fetch their carcasses rotted within a month. Although the plan is to treat and monitor toxic groundwater plumes for another century until they're considered safely diluted, today mule deer big as elk find asylum where humans once feared to tread.

A century, however, would make little difference to uranium and plutonium residues whose half-lives start at 24,000 years and keep going. The weapons-grade plutonium from Rocky Flats was shipped to South Carolina, whose governor was enjoined from lying in front of trucks to stop it. There, at the Savannah River Site's Defense Waste Processing

Facility, where two huge buildings ("reprocessing canyons") are so contaminated that no one knows how they might be decommissioned, high-level nuclear waste is now melted in furnaces with glass beads. When poured into stainless steel containers, it turns into solid blocks of radioactive glass.

This process, called vitrification, is also used in Europe. Glass being one of our simplest, most durable creations, these hot glass bricks may be among the longest-lasting of all human creations. However, in places like England's Windscale plant, scene of two nuclear accidents before it was finally closed, vitrified waste is stored in air-cooled facilities. One day, should power go off permanently, a chamber full of decaying, glass-embedded radioactive material would get steadily warmer, with shattering results.

The Rocky Flats asphalt where drums of radioactive oil spilled was also scraped and shipped to South Carolina, along with three feet of soil. More than half its 800 structures were razed, including the infamous "Infinity Room," where contamination levels rose higher than instruments could measure. Several buildings were mostly underground; after the removal of items like the glove boxes used to handle the shiny plutonium disks that triggered A-bombs, the basement floors were buried.

Atop them, a mix of native bluestem tall grass and side-oats grama grass has been planted to assure a habitat for resident elk, mink, mountain lion, and the threatened Preble's meadow jumping mouse, which have impressively thrived in the plant's 6,000-acre security buffer despite the evil brewing at its center. Regardless of the grim business that went on here, these animals seem to be doing fine. However, while there are plans to monitor the human wildlife managers for radiation intake, a refuge official admits doing no genetic tests on the wildlife itself.

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"We're looking at human hazards, not damage to species. Acceptable dose levels are based on 30-year career exposures. Most animals don't live that long."

Maybe not. But their genes do.

Anything at Rocky Flats too hard or too hot to move was covered with concrete and 20 feet of fill, and will remain off-limits to hikers in the wildlife preserve, though how they'll be deterred hasn't been decided. At

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WIPP, where much of Rocky Flats ended up, the U.S. Department of Energy is legally required to dissuade anyone from coming too close for the next 10,000 years. After discussing the fact that human languages mutate so fast that they're almost unrecognizable after 500 or 600 years, it was decided to post warnings in seven of them anyway, plus pictures. These will be incised on 25-foot-high, 20-ton granite monuments and repeated on nine-inch disks of fired clay and aluminum oxide, randomly buried throughout the site. More-detailed information about the hazards below will go on the walls of three identical rooms, two of them also buried. The whole thing will be surrounded by a 33-foot-tall earthen berm a half-mile square, embedded with magnets and radar reflectors to give every possible signal to the future that *something* lurks below.

Whether who-or-whatever finds it someday can actually read, or heed, danger in those messages may be moot: the construction of this complex scarecrow to posterity isn't scheduled until decades from now, after WIPP is full. Also, after just five years, plutonium-239 was already noticed leaking from WIPP's exhaust shaft. Among the unpredictables is how all the irradiated plastic, cellulose, and radionuclides below will react as brine percolates through the salt formations, and as radioactive decay adds heat. For that reason, no radioactive liquids are allowed lest they volatilize, but many interred bottles and cans contain contaminated residues that will evaporate as temperatures rise. Head space is being left for buildup of hydrogen and methane, but whether it's enough, and whether WIPP's exhaust vent will function or clog, is the future's mystery.

4. Too Cheap to Meter

At the biggest U.S. nuclear plant, the 3.8-billion-watt Palo Verde Nuclear Generating Station in the desert west of Phoenix, water heated by a controlled atomic reaction turns to steam, which spins the three largest turbines General Electric ever manufactured. Most reactors worldwide function similarly; like Enrico Fermi's original atomic pile, all nuke plants use moveable, neutron-sopping cadmium rods to dampen or intensify the action.

In Palo Verde's three separate reactors, these dampers are interspersed among nearly 170,000 pencil-thin, 14-foot zirconium-alloy hollow rods stuffed end to end with uranium pellets that each contain as much power as a ton of coal. The rods are bunched into hundreds of assemblies; water flowing among them keeps things cool, and, as it vaporizes, it propels the steam turbines.

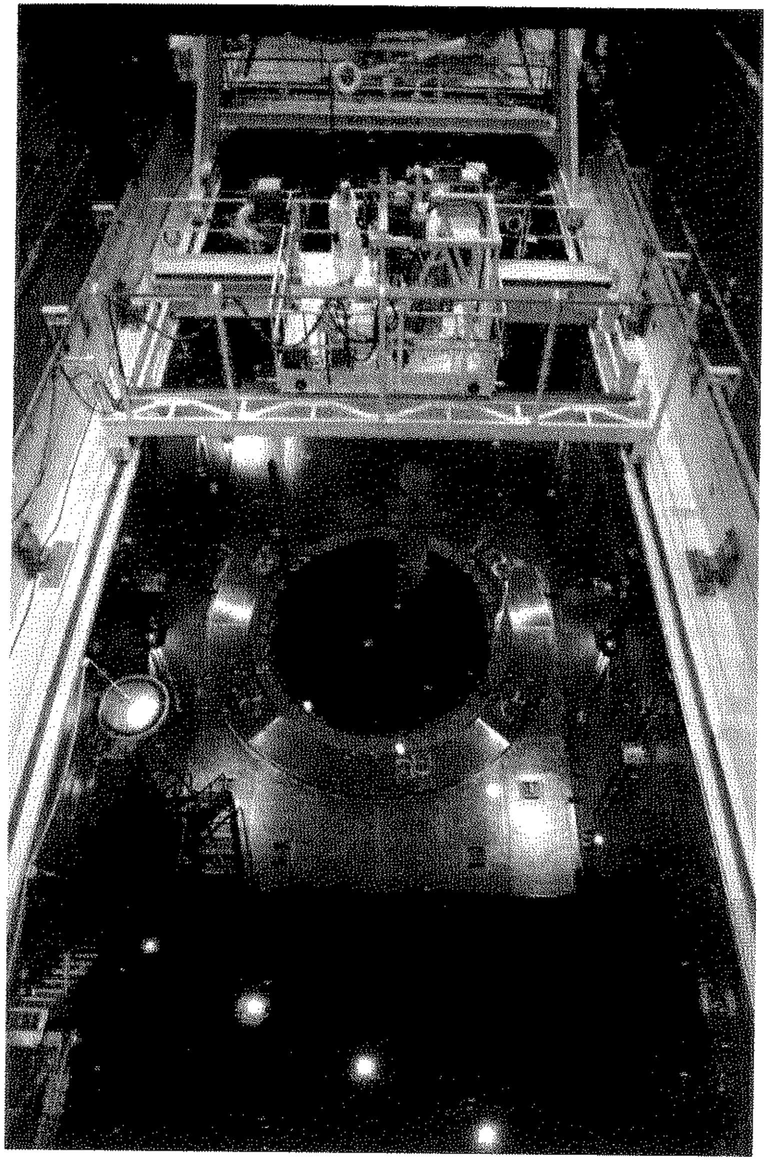
Together, the nearly cubical reactor cores, which sit in 45-foot-deep pools of turquoise water, weigh more than 500 tons. Each year, about 30 tons of their fuel is exhausted. Still packed inside the zirconium rods, this nuclear waste is removed by cranes to a flat-roofed building outside the containment dome, where it is submerged in a temporary holding pond that resembles a giant swimming pool, also 45 feet deep.

Since Palo Verde opened in 1986, its used fuel has been accumulating, because there's nowhere else to take it. In plants everywhere, spent fuel ponds have been re-racked to squeeze in thousands of more fuel assemblies. Together, the world's 441 functioning nuclear plants annually produce almost 13,000 tons of high-level nuclear scrap. In the United States, most plants have no more pool space, so until there's a permanent burial ground, waste-fuel rods are now mummified in "dry casks"—steel canisters clad in concrete from which the air and moisture have been sucked. At Palo Verde, where they've been used since 2002, these are stored vertically, and resemble giant thermos bottles.

Every country has plans to permanently entomb the stuff. Every country also has citizens terrified of events like earthquakes that could unseal buried waste, and of the chance that some truck carrying it will have a wreck or be hijacked en route to the landfill.

In the meantime, used nuclear fuel, some of it decades old, languishes in holding tanks. Oddly, it is up to a million times more radioactive than when it was fresh. While in the reactor, it began mutating into elements heavier than enriched uranium, such as isotopes of plutonium and americium. That process continues in the waste dumps, where used hot rods exchange neutrons and expel alpha and beta particles, gamma rays, and heat.

If humans suddenly departed, before long the water in the cooling ponds would boil and evaporate away—rather quickly in the Arizona desert. As the used fuel in the storage racks is exposed to air, its heat would ignite the cladding of the fuel rods, and radioactive fire would break out. At Palo Verde, like other reactors, the spent-fuels building was intended to be temporary, not a tomb, and its masonry roof is more similar to a big-box discount store's than to the reactor's pre-stressed containment



Reloading nuclear fuel: Unit 3, Palo Verde Nuclear Generating Station.

PHOTO BY TOM TINGLE, ARIZONA REPUBLIC, 12/29/98.
(USED WITH PERMISSION. PERMISSION DOES NOT IMPLY ENDORSEMENT.)

dome. Such a roof wouldn't last long with a radioactive fire cooking below it, and much contamination would escape. But that wouldn't be the biggest problem.

* * *

Resembling giant enoki mushrooms, Palo Verde's great steam columns rise a mile over the desert creosote flats, each consisting of 15,000 gallons of water evaporated per minute to cool Palo Verde's three fission reactors. (As Palo Verde is the only U.S. plant not on a river, bay, or seacoast, the water is recycled Phoenix effluent.) With 2,000 employees to keep pumps from sticking, gaskets from leaking, and filters back-washed, the plant is a town big enough to have its own police and fire departments.

Suppose its inhabitants had to evacuate. Suppose they had enough advance warning to shut down by jamming all the moderating rods into each reactor core to stop the reaction and cease generating electricity. Once Palo Verde was unmanned, its connection to the power grid would automatically be cut. Emergency generators with a seven-day diesel supply would kick in to keep coolant water circulating, because even if fission in the core stopped, uranium would continue to decay, generating about 7 percent as much heat as an active reactor. That heat would be enough to keep pressurizing the cooling water looping through the reactor core. At times, a relief valve would open to release overheating water, then close again when the pressure dropped. But the heat and pressure would build again, and the relief valve would have to repeat its cycle.

At some point, it becomes a question of whether the water supply is depleted, a valve sticks, or the diesel pumps cut out first. In any case, cooling water will cease being replenished. Meanwhile, the uranium fuel, which takes 704 million years to lose just half its radioactivity, is still hot. It keeps boiling off the 45 feet of water in which it sits. In a few weeks at the most, the top of the reactor core will be exposed, and the meltdown will begin.

If everyone had vanished or fled with the plant still producing electricity, it would keep running until any one of thousands of parts monitored daily by maintenance personnel failed. A failure should automatically trigger a shutdown; if it didn't, the meltdown might occur quite quickly. In 1979 something similar happened at Pennsylvania's Three Mile Island Plant when a valve stuck open. Within two hours and 15 minutes, the top of the core was exposed and turned into lava. As it flowed to the bottom of the reactor vessel, it started burning through six inches of carbon steel.

It was a third of the way through before anyone realized. Had no one discovered the emergency, it would have dropped into the basement, and 5,000°F molten lava would have hit nearly three feet of water flooded from the stuck valve, and exploded.

Nuclear reactors have far less concentrated fissionable material than nuclear bombs, so this would have been a steam explosion, not a nuclear explosion. But reactor containment domes aren't designed for steam explosions; as its doors and seams blow out, a rush of incoming air would immediately ignite anything handy.

If a reactor was near the end of its 18-month refueling cycle, a meltdown to lava would be more likely, because months of decay build up considerable heat. If the fuel was newer, the outcome might be less catastrophic, though ultimately just as deadly. Lower heat might cause a fire instead of a meltdown. If combustion gases shattered the fuel rods before they turned to liquid, uranium pellets would scatter, releasing their radioactivity inside the containment dome, which would fill with contaminated smoke.

Containment domes are not built with zero leakage. With power off and its cooling system gone, heat from fire and fuel decay would force radioactivity out gaps around seals and vents. As materials weathered, more cracks would form, seeping poison, until the weakened concrete gave way and radiation gushed forth.

* * *

If everyone on Earth disappeared, 441 nuclear plants, several with multiple reactors, would briefly run on autopilot until, one by one, they overheated. As refueling schedules are usually staggered so that some reactors generate while others are down, possibly half would burn, and the rest would melt. Either way, the spilling of radioactivity into the air, and into nearby bodies of water, would be formidable, and it would last, in the case of enriched uranium, into geologic time.

Those melted cores that flow to the reactor floors would not, as some believe, bore through the Earth and out the other side, emerging in China like poisonous volcanoes. As the radioactive lava melds with the surrounding steel and concrete, it would finally cool—if that's the term for a lump of slag that would remain mortally hot thereafter.

That is unfortunate, because deep self-interment would be a blessing to whatever life remained on the surface. Instead, what briefly was an exquisitely machined technological array would have congealed into a deadly, dull metallic blob: a tombstone to the intellect that created it—and, for thousands of years thereafter, to innocent nonhuman victims that approach too closely.

5. Hot Living

They began approaching within a year. Chernobyl's birds disappeared in the firestorm when Reactor Number Four blew that April, their nest building barely begun. Until it detonated, Chernobyl was almost halfway to becoming the biggest nuclear complex on Earth, with a dozen one-gigawatt reactors. Then, one night in 1986, a collision of operator and design mistakes achieved a kind of critical mass of human error. The explosion, although not nuclear—only one building was damaged—broadcast the innards of a nuclear reactor over the landscape and into the sky, amid an immense cloud of radioactive steam from the evaporated coolant. To Russian and Ukrainian scientists that week, frantically sampling to track radioactive plumes through the soil and aquifers, the silence of a birdless world was unnerving.

But the following spring the birds were back, and they've stayed. To watch barn swallows zip naked around the carcass of the hot reactor is discombobulating, especially when you are swaddled in layers of wool and hooded canvas coveralls to block alpha particles, with a surgical cap and mask to keep plutonium dust from your hair and lungs. You want them to fly away, fast and far. At the same time, it's mesmerizing that they're here. It seems so normal, as if apocalypse has turned out to be not so bad after all. The worst happens, and life still goes on.

Life goes on, but the baseline has changed. A number of swallows hatch with patches of albino feathers. They eat insects, fledge, and migrate normally. But the following spring, no white-flecked birds return. Were they too genetically deficient to make the winter circuit to southern Africa? Does their distinctive coloring make them unappealing to potential mates, or too noticeable to predators?

In the aftermath of Chernobyl's explosion and fire, coal miners and subway crews tunneled underneath Number Four's basement and poured a second concrete slab to stop the core from reaching groundwater. This probably was unnecessary, as the meltdown was over, having ended in a 200-ton puddle of frozen, murderous ooze at the bottom of the unit. During the two weeks it took to dig, workers were handed bottles of vodka, which, they were told, would inoculate them against radiation sickness. It didn't.

At the same time, construction began on a containment housing, something that all Soviet RMBK reactors like Chernobyl lacked, because they could be refueled faster without one. By then, hundreds of tons of hot fuel had already blown onto the roofs of adjacent reactors, along with 100 to 300 times the radiation released in the 1945 bombing of Hiroshima. Within seven years, radioactivity had eaten so many holes in the hastily built, hulking, gray five-story concrete shell, already patched and caulked like the hull of a rusting scow, that birds, rodents, and insects were nesting inside it. Rain had leaked in, and no one knew what vile brews steeped in puddles of animal droppings and warm, irradiated water.

The Zone of Alienation, a 30-kilometer-radius evacuated circle around the plant, has become the world's biggest nuclear-waste dump. The millions of tons of buried hot refuse include an entire pine forest that died within days of the blast, which couldn't be burned because its smoke would have been lethal. The 10-kilometer radius around ground zero, the plutonium zone, is even more restricted. Any vehicles and machinery that worked there on the cleanup, such as the giant cranes towering over the sarcophagus, are too radioactive to leave.

Yet skylarks perch on their hot steel arms, singing. Just north of the ruined reactor, pines that have re-sprouted branch in elongated, irregular runs, with needles of various lengths. Still, they're alive and green. Beyond them, by the early 1990s, forests that survived had filled with radioactive roe deer and wild boars. Then moose arrived, and lynx and wolves followed.

Dikes have slowed radioactive water, but not stopped it from reaching the nearby Pripyat River and, farther downstream, Kiev's drinking supply. A railroad bridge leading to Pripyat, the company town where 50,000 were evacuated—some not quickly enough to keep radioactive iodine from ruining their thyroids—is still too hot to cross. Four miles south, though, you can stand above the river in one of the best birding areas today in Europe, watching marsh hawks, black terns, wagtails, golden and white-tailed eagles, and rare black storks sail past dead cooling towers.

In Pripyat, an unlovely cluster of concrete 1970s high-rises, returning poplars, purple asters, and lilacs have split the pavement and invaded buildings. Unused asphalt streets sport a coat of moss. In surrounding villages, vacant except for a few aged peasants permitted to live out their shortened days here, stucco peels from brick houses engulfed by untrimmed shrubbery. Cottages of hewn timbers have lost roof tiles to tangles of wild grapevines and even birch saplings.

Just beyond the river is Belarus; the radiation, of course, stopped for no border. During the five-day reactor fire, the Soviet Union seeded clouds headed east so that contaminated rain wouldn't reach Moscow. Instead, it drenched the USSR's richest breadbasket, 100 miles from Chernobyl at the intersection of Ukraine, Belarus, and western Russia's Novozybkov region. Except for the 10-kilometer zone around the reactor, no other place received so much radiation—a fact concealed by the Soviet government lest national food panic erupt. Three years later, when researchers discovered the truth, most of Novozybkov was also evacuated, leaving fallow vast collective grain and potato fields.

The fallout, mainly cesium-137 and strontium-90, by-products of uranium fission with 30-year half-lives, will significantly irradiate Novozybkov's soils and food chain until at least AD 2135. Until then, nothing here is safe to eat, for either humans or animals. What "safe" means is wildly debated. Estimates of the number of people who will die from cancer or blood and respiratory diseases due to Chernobyl range from 4,000 to 100,000. The lower figure comes from the International Atomic Energy Agency, whose credibility is tinged by its dual role as both the world's atomic watchdog agency and the nuclear power industry's trade association. The higher numbers are invoked by public health and cancer researchers and by environmental groups like Greenpeace International, all insisting that it's too early to know, because radiation's effects accumulate over time.

Whatever the correct measure of human mortality may be, it applies to other life-forms as well, and in a world without humans the plants and animals we leave behind will have to deal with many more Chernobyls. Little is still known about the extent of genetic harm this disaster unleashed: genetically damaged mutants usually fall to predators before scientists can count them. However, studies suggest that the survival rate of Chernobyl swallows is significantly lower than that of returning migrants of the same species elsewhere in Europe.

"The worst-case scenario," remarks University of South Carolina biologist Tim Mousseau, who visits here often, "is that we might see extinction of a species: a mutational meltdown."

"Typical human activity is more devastating to biodiversity and abundance of local flora and fauna than the worst nuclear power plant disaster," dourly observe radioecologists Robert Baker, of Texas Tech University, and Ronald Chesser, of the University of Georgia's Savannah River Ecology Laboratory, in another study. Baker and Chesser have documented mutations in the cells of voles in Chernobyl's hot zone. Other research on Chernobyl's voles reveals that, like its swallows, the life-spans of these rodents are also shorter than those of the same species elsewhere. However, they seem to compensate by sexually maturing and bearing offspring earlier, so their population hasn't declined.

If so, nature may be speeding up selection, upping the chances that somewhere in the new generation of young voles will be individuals with increased tolerance to radiation. In other words, mutations—but stronger ones, evolved to a stressed, changing environment.

Disarmed by the unexpected beauty of Chernobyl's irradiated lands, humans have even tried to encourage nature's hopeful bravado by reintroducing a legendary beast not seen in these parts for centuries: bison, brought from Belarus's Belovezhskaya Pushcha, the relic European forest it shares with Poland's Białowieża Puszcza. So far, they're grazing peacefully, even nibbling the bitter namesake wormwood—*chornobyl* in Ukrainian.

Whether their genes will survive the radioactive challenge will only be known after many generations. There may be more challenges: A new sarcophagus to enclose the old, useless one, isn't guaranteed to last, either.

Eventually, when its roof blows away, radioactive rainwater inside and in adjacent cooling ponds could evaporate, leaving a new lode of radioactive dust for the burgeoning Chernobyl menagerie to inhale.

After the explosion, the radionuclide count was high enough in Scandinavia that reindeer were sacrificed rather than eaten. Tea plantations in Turkey were so uniformly dosed that Turkish tea bags were used in Ukraine to calibrate dosimeters. If, in our wake, we leave the cooling ponds of 441 nuclear plants around the world to dry and their reactor cores to melt and burn, the clouds enshrouding the planet will be far more insidious.

Meanwhile, we are still here. Not just animals but people too have crept back into Chernobyl's and Novozybkov's contaminated zones. Technically, they're illegal squatters, but authorities don't try very hard to dissuade the desperate or needy from gravitating to empty places that smell so fresh and look so clean, as long as no one checks those dosimeters. Most of them aren't simply seeking free real estate. Like the swallows who returned, they come because they were here before. Tainted or not, it's something precious and irreplaceable, even worth the risk of a shorter life.

It's their home.

CHAPTER 16

Our Geologic Record

1. Holes

ONE OF THE largest, and probably longest-lasting, relics of human existence after we're gone is also one of the youngest. As the gyrfalcon flies, it lies 180 miles northeast of Yellowknife, Northwest Territories, Canada. If you flew over it today, it would be the very round hole half a mile wide and 1,000 feet deep. There are many huge holes here. This is the dry one.

Though, within a century, the rest may be, too. North of the 60th parallel, Canada contains more lakes than the rest of the world combined. Nearly half of Northwest Territories isn't land at all, but water. Here, ice ages gouged cavities into which icebergs dropped when the glaciers retreated. When they melted, these earthen kettles filled with fossil water, leaving countless mirrors that sequin the tundra. Yet the resemblance to an immense sponge is misleading: because evaporation slows in cold climates, little more precipitation falls here than in the Sahara. Now, as the permafrost thaws around these kettles, glacial water held in place by frozen soil for thousands of years is seeping away.

Should northern Canada's sponge dry out, that would also be a human legacy. For now, the hole in question and two recent smaller ones nearby comprise Ekati, Canada's first diamond mine. Since 1998, a parade of 240-ton trucks with 11-foot tires, owned by BHP Billiton Diamonds, Inc., has lugged more than 10,000 tons of ore to a crusher 24 hours a day, 365 days a year, even at −60°F. The daily yield is a handful of gem-quality diamonds, worth well over $1 million.