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SMITHSONIAN CONTRIBUTIONS TO MUSEUM CONSERVATION • NUMBER 7

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Proceedings of the 2012 MCI Symposium

Edited by
Odile Madden, A. Elena Charola, Kim Cullen Cobb, Paula T. DePriest, and Robert J. Koestler

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ABSTRACT
Madden, Odile, A. Elena Charola, Kim Cullen Cobb, Paula T. DePriest, and Robert J. Koestler. The Age of Plastic: Ingenuity and Responsibility, Proceedings of the 2012 MCI Symposium. *Smithsonian Contributions to Museum Conservation*, number 7, viii + 181 pages, 139 figures, 5 tables, 2017. — This volume brings together papers presented at "The Age of Plastic: Ingenuity + Responsibility," a Smithsonian symposium hosted by the Museum Conservation Institute on June 7–8, 2012. The event was conceived as a cross-disciplinary exploration of plastic as technological material, cultural phenomenon, preservation challenge, and force on the environment. Writers, scientists, conservators, historians, filmmakers, designers, and policy makers offer researched and first-hand accounts from life in the Plastic Age. Papers are organized to highlight the importance and complexity of plastic material culture through juxtaposition of countervailing positive and negative viewpoints. The volume features observations on innovation in plastic with past and contemporary examples of furniture design, failed experiments with proteinaceous fibers before World War II, the transition of celluloid from ivory simulant to unique identity, the space program, and bioplastics in automobiles. Studies of the rise of food packaging further explore how plastic shapes and is shaped by our culture. Preservation challenges that new, often unstable plastic poses for the cultural heritage community are explored through case studies of novel conservation treatments, research into new deterioration phenomena, and knowledge transfer. The relationship between plastic and the environment is probed with perspectives on pollution, advantages of plastic to living zoological collections, and recycling. Intended primarily for the cultural heritage community but also relevant to other fields, this volume demonstrates the importance and challenges of documenting the remarkable ongoing evolution of plastic materials that now are integral to the artifact record as markers of achievement and records of the innovation process.

Cover images, from left to right: Detail of Bernat, Figure 6R; Moggridge, Figure 5; and detail of Biddle, Figure 1.

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Preface

The papers compiled in this volume are based on the symposium "The Age of Plastic: Ingenuity + Responsibility," which was hosted by the Museum Conservation Institute (MCI) in June 2012. The symposium was conceived to document the important relationship between plastic materials and culture from a cross-disciplinary perspective. With previous material ages, the so-called Stone, Bronze, and Iron, robust scholarship links the historical, cultural, and technological developments to the material for which each era is named. In the Age of Plastic, the technological and cultural shifts are ongoing and have been so abrupt that they have yet to be studied through the same lens. Yet plastic has had sufficient impact that we will want to document it, and our knowledge will be richer if we begin the documentation now while it is happening. The papers compiled here can be considered a set of eyewitness accounts.

It is appropriate that this work happen at the Smithsonian, our national museum and arguably the world's greatest repository of plastic artifacts, where we record history in objects, words, images, and sounds. As the Smithsonian's center for specialized technical collection research and conservation, MCI develops our knowledge of materials and the history of technology using scientific techniques and analysis of our collections. Plastics present a challenge for preservation of cultural heritage because the artifacts and plastics used to preserve and manage collections can show material instability over the short, medium, and long term. As these instabilities reveal themselves, we are presented with new opportunities to observe and study deterioration phenomena with which we had little prior experience or had not seen before. One of the priority research areas being developed by the MCI is to understand plastics in order to improve their preservation and conservation.

Many of the plastic objects that we have designated as historical artifacts were not intended to endure in perpetuity—none more so than the disposable plastic containers and cutlery with a functional lifetime of a single meal. Other objects are intended to withstand longer, often extreme use, such as the plastic components of astronaut suits and artificial hearts. And for artwork the desired life span is often indefinite. Once an object is accessioned into a museum collection, the time horizon is extended to centuries. Virtually all Smithsonian collections include plastic objects. Even our live-animal collections at the National Zoo in Washington, D.C. and at the Conservation Biology Institute in Front Royal, VA are impacted by the plastics used in their care.

In this volume we take a broad view that includes not only preservation concerns but also perspectives on history, design, and environmental fate. With this approach, we can explore the history of polymers, the ingenious innovations, and the failures. We can examine how our culture has shaped the materials and objects we choose to create and, conversely,

how the advent of plastic materials has affected our culture. We can weigh how the proliferation of plastic, with its various material properties, affects our health and the environment.

Finally, plastic must be shaped and is therefore inextricable from design. Some synergy of form and function is required for any plastic object to be useful, appealing, and collectable. At the same time, the properties of plastic determine the possibilities of expression. This give-and-take between material and designer is a fundamental concept of the Cooper Hewitt, Smithsonian Design Museum. At our 2012 symposium, we were delighted that the opening presentation was by the museum's director, a visionary designer and pioneer in human-centered design, the late Bill Moggridge, to whom we dedicate this volume.

Odile Madden, Research Scientist,
Museum Conservation Institute
A. Elena Charola, Research Scientist,
Museum Conservation Institute
Robert J. Koestler, Director,
Museum Conservation Institute

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Balancing Ingenuity and Responsibility in the Age of Plastic

Odile Madden

ABSTRACT. This introduction assumes the premise that we are in the midst of a new material age to explore how seemingly disparate perspectives on plastic from history, design, technology, uses, preservation, and effects on culture and the environment can be connected by considering plastic as a physical substance. This chapter examines 15 papers presented at a Smithsonian symposium held in 2012 (including one presented by the author that is excerpted here) and stitches them into a larger discussion of innovation, transformations brought about by plastic, and current struggles to preserve the iconic examples and simultaneously address hazards and disposal of the rest.

INTRODUCTION

Stone Age, Bronze Age, Iron Age, and now the Age of Plastic? The original three-age system was conceived by a Danish gentleman named Christian Jürgensen Thomsen, who in the early nineteenth century proposed that the history of human activity before Christianity could be categorized by the materials people exploited as tools and other implements (Thomsen, 1836; Ellesmere, 1848). If Thomsen were to browse any Smithsonian museum collection or even walk through the back hallways of the National Zoo, what material would define today? I contend that material is plastic.

Thomsen developed his three-age system while studying the antiquities collection of what is now the National Museum of Denmark, noting that the artifacts progressed from found materials—like stones but also bones, horns, and pieces of wood—to copper alloys (e.g., bronze) and then to iron.[1] Over many years, he organized chronologies for these artifacts and established the three material ages that have become fundamental to our understanding of humanity: Stone, Bronze, Iron. Many other Ages of X, Y, or Z have been proposed since then, and describing periods in this way arguably has been overdone, but the three-age construct is useful to this volume because it is based on the idea that materials are transformed through processing into things people can use. This idea can be described more succinctly as materials plus technology: obsidian that has been flaked to shape an arrowhead, copper alloyed with tin and cast into a bronze axe, and iron forged to create a sword. By studying worked materials we can learn how people modified the world around them and how our capabilities have changed over time. We can examine what people have chosen to do with new materials and how priorities evolve in reaction to new technologies.

For example, in the Stone Age, which had begun by 2.6 million years ago, people essentially gathered existing materials that they could use as tools. A round-bottomed rock could be used for pounding, whereas another might be flaked or sharpened so it could cut or pierce animal hide. Choosing a good tool meant understanding what material

Museum Conservation Institute, Smithsonian Institution, 4210 Silver Hill Road, Suitland, MD 20746, USA.
Correspondence: O. Madden, MCIweb@si.edu
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properties would be best suited for the job. The stone for pounding should have a rounded bottom but also be harder than the material being pounded. It should be strong and not fall apart in use. This concept of material properties seems obvious and intuitive, and some of it is, but conscious consideration of physical properties lies at the heart of understanding materials. This is as true for plastic as it is for stone.

The Bronze Age, which began as early as the fourth millennium BCE, differed in that the material did not already exist in the natural world. Copper and tin, or arsenic in the earliest bronzes, were extracted from their respective ores by smelting, and then the smelted copper metal was alloyed with a lesser amount of the other to make a new metal with new properties.[2] Bronze melts at a lower temperature than copper, is easier to cast, and solidifies into a harder metal with a different color.

The Iron Age refers to a period beginning between around 1200 and 600 BCE, when bronze technology was supplanted by the smelting, purifying, and working of iron in much of the world. Like the Bronze Age, iron technology emerged regionally at different times. As with copper, the majority of our iron comes from ore and, in combination with other elements, has been processed into pig, wrought, and cast irons and a range of steels from which we construct bridges, roads, skyscrapers, and machinery. Transmutation of ores was a major accomplishment that at times seemed magical. To the untrained eye, the ores from which we extract metals are just rocks, and turning these into metal was not easily explained until a conceptual framework of redox chemistry was described in the eighteenth century (van der Merwe and Avery, 1986; Budd and Taylor, 1995; Blakely, 2006). Indeed, the Smithsonian Institution was conceived as "an establishment for the increase and diffusion of knowledge" by the eighteenth-century mineralogist and chemist James Smithson, whose broad curiosity about the material world included traveling the globe to collect and study mineral samples, in particular zinc ore, and describe the mining and manufacturing practices he encountered (Rhees, 1881; Ewing, 2007).

Plastic is similar to bronze and steel in that the final product tends to be very different from the starting materials.[3] The earliest plastics, often called semisynthetic (although they could just as easily be called seminatural), had naturally occurring polymers as a starting point. Rubber latex is a sticky sap exuded by certain trees that had little commercial potential until Charles Goodyear and Nathaniel Hayward stiffened it by adding sulfur bonds in around 1847.[4] Arguably, vulcanized rubber may have been recognizable as a tougher version of the natural substance, but other plastics did not resemble their starting products. Cellulose nitrate, a nineteenth-century invention that would come to be known by the popular brand name Celluloid, and its successors cellulose acetate and cellulose acetate butyrate are modifications of natural cellulose that can be dissolved or melted and reformed into blocks, sheets, tubes, threads, and coatings.[5,6] The portfolio of plastic raw materials eventually expanded to include nonpolymeric chemicals obtained from coal processing and petroleum, which bore even less resemblance to the final product. In fact, polyethylene and polypropylene, the most common commodity plastics today, are often created from gases! Given that the transformation is so complete and occurs in chemical factories, away from view, it is not hard to see how plastic engineering could seem like alchemy. Nevertheless, it is not magical, and its discovery and development are one of the most important technological achievements of the nineteenth and twentieth centuries.

In a mere century and a half, advances in plastic technology have made possible equally significant advances in other fields, including aviation, medicine, and packaging, which in turn have transformed the way we move and interact with people and the world around us and our quality and span of life. Some of these transformations have been positive, whereas others—such as the impact on the natural environment—are cause for concern. These transformations, their scale, and the interplay between material innovation and culture are central themes of this volume.

A common refrain of most contributors to this volume is that we are surrounded by plastic. This fact probably was clear to today's reader even before picking up this book. Perhaps less obvious is the idea that the sheer scale of the plastic in our lives and the associated cultural transformations are sufficiently important that we will want to document them. That process will be more successful if we record the information now while in the midst of plastic's development and before many of the early steps have evolved away and the fine-grained detail has been forgotten. One shortcoming of previous material ages is that we started recording them too late, so we have had to rely on the haphazard archaeological record. To this end, in 2012 the Smithsonian's Museum Conservation Institute (MCI) convened a group of historians, scientists, engineers, designers, journalists, artists, and conservators to consider plastic. Each was invited to present a paper at a public symposium, participate in panel discussions, and contribute a chapter to this volume. They brought perspectives based on professional and personal experience, and the result was a broadly based discussion of innovation, driven by counterbalancing principles of ingenuity and responsibility.

Unlike many public discussions of plastic, the underlying motivation was not to brainstorm strategies to do away with the stuff but rather to understand and preserve it in a historical and material sense. Objects that are made of plastic or include plastic elements increasingly are being accessioned into museum collections as art and artifacts, and museums are tasked with interpreting their significance and stewarding them for the long term. This interpretation and stewardship is a mission of MCI, and the responsibility comes with significant challenges. First, it is likely that we are still in the midst of plastic's early development, a time when the technology is evolving quickly and involves a lot of experimentation. (In comparison, the Stone Age lasted millions of years, and the various regional Bronze and Iron Ages lasted millennia or several centuries.) This means there is great variety to document and understand. Perhaps because it is quite a new phenomenon the population at large is only beginning to recognize its evolution as an important historical event. Some notable histories have been written (e.g., DuBois, 1972;

Haynes, 1953; Friedel, 1983; Meikle, 1995; Mulder and Knot, 2001; Freinkel, 2011; Mercelis, 2012), but scholarship in this area is still young and incomplete. We also are discovering that many plastic objects are inherently unstable over the time spans expected by museums. Some categories of objects become sticky, yellow, shrunken, distorted, or cracked and can exude vapors that damage things stored nearby. For conservators, tackling this problem begins with knowing what the artifact is made of, which can be determined analytically but also requires understanding which technologies were available when the object was made. Interpretation and stewardship of artifacts also requires understanding an object's context and the qualities that should be preserved. For example, aesthetic qualities like form, color, and texture might be given priority for a decorative object. On the other hand, the value of an early example of Celluloid might be preserving original material. For these reasons, collecting the various stories of plastic is important from a historical standpoint and for museums as both interpreters and stewards.

But what information should we capture? Given that the body of existing scholarship is less developed for plastic than other traditional artifact materials, it behooves an institution like the Smithsonian to gather these histories. The editors of this volume have taken the perspective that to understand plastic fully, we should extract from it as much information as we can and pursue the question broadly, in the spirit of ethnographer and archaeologist Augustus Henry Lane-Fox Pitt Rivers (1887), who believed that the best archaeology records everything. We have chosen to include vignettes from chemistry, materials science, craft, design, art, industrial processing methods, history, archaeology, anthropology, and ethnology. The result is an intersection of many disciplines, with the substance plastic at the hub. For the overall category of plastic, a multiplicity of perspectives and voices is required to get a sense of the whole.

Of course, some linear organization is required for a volume like this to be a compelling read. The volume is organized along three general themes. The first contributions describe facets of the discovery and innovation process as they relate to plastic technology. The second section highlights instances of adoption and transformation, where plastic spurred innovations that were not envisioned before and that have radically transformed the way we live. As part of the innovation and adoption processes, deficiencies are discovered, either in the material itself or related to social and environmental factors. Stories of material shortcomings and current notions of social responsibility toward plastic, namely preserving our heritage, protecting ecosystems, and dealing with our waste, are described in the third section. Many of the volume's chapters are significant for more than one of these themes and were placed in the category we considered most relevant. However, many different connections between them remain, and the reader may prefer to read the chapters in a different order. When the interplay is most obvious, I have included my comment as an editorial note.

By design, contributions to this volume include many voices and writing styles that are peculiar to each author's discipline, but the language is not highly technical for the most part. However, embedded in each chapter are issues that depend on the physical nature of the plastic. In reading this volume, I encourage the reader to consider the following:

- the background and perspective of each author
- the ways in which new design possibilities have been born from discoveries in plastic processing
- why certain polymers have been innovated and why they were or were not successful
- how material stability affects long-term preservation and our health
- the ways in which our shifting cultural priorities influence the raw materials from which plastic is made

I believe the reader will find that the seemingly disparate contributions offered here can all be related by considering plastic as a physical substance, with unique structures and material properties.

WHAT IS PLASTIC?

Plastic is a category of materials with wide possibilities for composition, processing, and properties. However, the substance is a mystery to most of us. In 1957 Roland Barthes described his experience at an exposition of plastics where an inscrutable machine turned out green plastic trifles:

> An ideally-shaped machine, tubulated and oblong . . . draws, out of a heap of greenish crystals, shiny and fluted dressing-room tidies. At one end, raw, telluric matter, at the other, the finished, human object; and between these two extremes, nothing; nothing but a transit, hardly watched over by an attendant in a cloth cap, half-god, half-robot. (Barthes, 1972:97)

Presumably, the machine is an injection molder, a standard and quite straightforward piece of plastic-forming machinery. At one end, a stock of plastic beads is held in a hopper. The machine draws in a quantity of the beads, melts them with heat, and forces the molten goo into a mold. As the mold cools, the plastic rehardens in its new shape, and the mold is opened to reveal a new hairbrush or a coat hanger. It is hardly magic. One goal of this volume is to demystify plastic, so a primer is offered here.

The greenish crystals Barthes describes are most likely plastic beads, also called nurdles or molding powder, which are a convenient form for measuring out plastic in bulk, transporting it to manufacturers, and achieving even melting (Figure 1). Each bead contains a custom mixture of compounds. At a minimum Barthes's greenish crystals include a polymer and a green colorant, but other substances like plasticizers, heat stabilizers, and fillers could also be present.

A polymer is the defining component of a plastic. It is a long or netlike molecule made of thousands of repeating segments. The vast expanse of these connected, identical segments

FIGURE 1. Cellulose acetate nurdles for injection molding. These colorless nurdles also contain the plasticizer diethyl phthalate. Photo by Odile Madden and Morgan Dundon, Smithsonian Institution, MCI.

is what gives polymers strength, elasticity, and moldability not found in other materials. A polymer's qualities, typically called properties, describe how it behaves and depend on the atoms present, how they are organized within a molecule, and the relationship between individual polymer molecules. These qualities are defined at the molecular scale and translate out to the bulk material.

Polymers typically are based on the element carbon, although inorganic polymers based on silicon, germanium, tin, and other elements also exist.[7] The simplest polymer molecule and most common plastic in the world today is polyethylene, a long chain of carbon atoms (gray) with hydrogen atoms (white) along the sides (Figure 2). It is a very nonpolar molecule, which imparts properties like waxiness, a propensity to absorb oils and repel water, and a resistance to friction and adhesion. A single strand of polyethylene is quite flexible because hydrogen atoms are small and only slightly inhibit the bending and rotating movements of the carbon backbone. This polymer is the material of Tupperware, Hula Hoops, and Frisbees.

Swapping out some hydrogen atoms with chlorine atoms or phenyl groups makes polyvinyl chloride (PVC) and polystyrene, respectively (Figure 3). These side groups are bigger and more electronegative, which restricts the carbon chains' freedom to bend and rotate and hence makes plastics that are more rigid than polyethylene (Lampman, 2003); PVC plumbing pipe and the transparent polystyrene cover of a CD jewel case are examples. The polymer chain can be more complex than a straight chain of carbon and can include other elements, ring structures, double and triple bonds, and branches that influence all sorts of properties, from melting temperature and solubility to flexibility, impact resistance, elastic strength, transparency, and electrical conductivity (Figures 4 and 5).

Individual polymer strands stick together by covalent and ionic bonds, other attractive forces, and entanglements. In *thermoplastic* polymers the strand-like molecules hold to one another by entanglement and with relatively weak attractive forces like hydrogen bonding, dipole-dipole interactions, van der Waals forces, and sometimes ionic bonds. These attractions are not as strong as the covalent bonds that make up a polymer strand, but even the weakest of these becomes significant when it is repeated thousands of times across a polymer's structure. These interchain attractions can often be overcome by heat or liquid solvents, which allow the polymer strands to slip past one another and the plastic to flow. *Thermosetting* polymers are different in that they cure into a network of covalent, and sometimes ionic, bonds rather than strands. Examples include polyurethane, like the Piero Gilardi polyurethane sculpture treated by Thea van Oosten (this volume), the Impranil substance she uses to reinforce the foam, and the Fred Eversley polyester resin sculpture treated by Hugh Shockey (this volume). Once cured, these thermosetting polymers can be softened somewhat with heat or swelled with solvents, but they will not flow again because the network of strong bonds between atoms prevents movement. Bonds also can be induced in existing thermoplastic polymers to create plastics

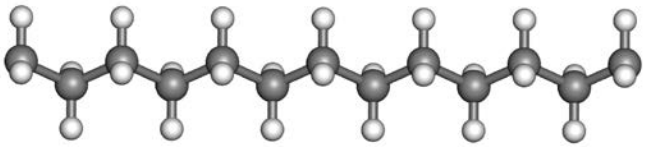

FIGURE 2. Segment of an idealized polyethylene molecule. The entire molecule would be many thousands of carbon atoms long. Image by Odile Madden.

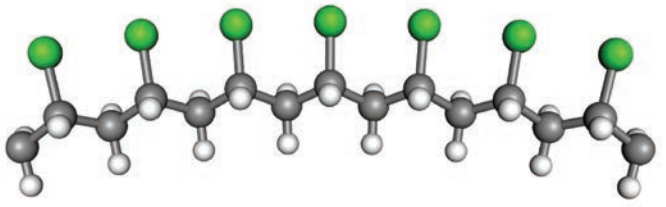

FIGURE 3. Segment of an idealized PVC molecule with chlorine atoms shown in green. Image by Odile Madden.

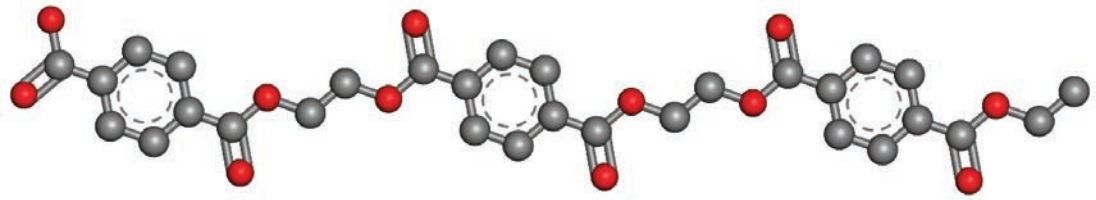

FIGURE 4. Disposable soda bottles and polar fleece are made from polyethylene terephthalate (PET). Oxygen atoms are shown in red. Image by Odile Madden.

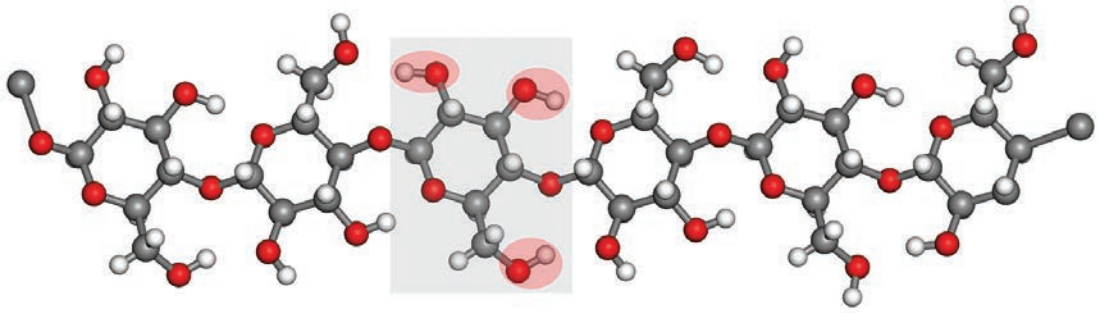

FIGURE 5. Segment of cellulose molecule with the repeating unit shaded in gray and the substitutable –OH sites shaded in red. Image by Odile Madden.

that behave like a thermoset, are stronger and more rigid, and soften at higher temperatures.[8] This kind of bonding, often called cross-linking, can be forced in a factory or occurs spontaneously over time by oxidation. Examples include vulcanized rubber and cross-linked ultrahigh molecular weight polyethylene used in hip replacement surgery.

For interchain attractions to create a cohesive plastic, polymer strands must be aligned enough to have many points of contact between them. The degree of organization and the type and number of contact points between strands influence the properties of the bulk plastic. The extremely long polymer strands in plastic tend toward disorder, and regions of tangles and nonspecific organization are described as amorphous. Amorphousness is yet another way to enhance a bulk polymer's flexibility, solubility, and softening temperature, for example. At the other end of the spectrum, polymer chains that line up well can form highly organized crystalline regions that increase the temperature at which the plastic softens and make the plastic harder and less permeable to solvents. In reality, plastics contain amorphous and crystalline regions, and varying their relative proportions is yet another way in which polymer engineers can intervene to tailor a plastic's properties.

Crystallinity, strength, and high melting temperatures are not always desirable. In fact, we have as much need for plastics that are flexible, soft, or easy to melt or break. One way to induce these qualities is to reduce interstrand attractions by modifying the polymer side groups or by occupying the attraction sites with some intermediate compound. The modification of cellulose is an example of the former (Figure 5). Cellulose is a beautifully constructed molecule that organizes into a highly crystalline structure with strong hydrogen bonds between chains. It technically is a thermoplastic because the chains hold together with hydrogen bonds. However, we know from experience that cellulosic materials like paper, cotton, linen, and wood do not melt when heated or dissolve in water, alcohol, nail polish remover, or paint thinner. Meltable and dissolvable forms of cellulose are made by switching out the –OH side groups with other species. In methyl cellulose, soluble in water, some proportion of the hydroxyl side groups of the cellulose molecule is replaced with $–OCH_3$ (Figure 5). In cellulose nitrate, the substituting group is $–ONO_2$; the amount of substitution determines whether it can be used as a dissolved lacquer, celluloid film or object, or an explosive. In similar fashion, swapping out some proportion of –OH sites with acetyl groups gives cellulose acetate. Acetyl ($–OCHOCH_3$) substitution of 2.0 to 2.5, meaning the average number of cellulose's three –OH sites that are substituted with an acetyl group, can be dissolved readily in acetone (Cowie and Ranson, 1971). In each instance, introduction of some proportion of $–OCH_3$, $–ONO_2$, and $–OCHOCH_3$ side groups transforms crystalline cellulose into a more amorphous, thermoplastic substance. From an

industrial standpoint, tailoring the solubility of the polymer to certain solvents for cost, protection of the processing equipment, safety, and environmental considerations is very important.

Another option to reduce interstrand attraction is to add substances called *plasticizers*. Typical plasticizers are relatively small molecules that are mixed with the polymer during *compounding* and fit between the polymer chains.[9] These molecules reduce the number of secondary bonds that can form between polymer strands and simultaneously have enough attraction to the strands that the plastic coheres. The attractions between polymer and plasticizer and the remaining polymer-polymer attractions can be overcome by heating, adding a solvent, or even stretching the plastic such that the strands slide past one another. Plasticizers are added to facilitate manufacturing by lowering the flow temperature of the plastic and also to change the working properties of the finished product, such as making it more impact resistant, flexible, less brittle, and often weaker. Thus, enhancing one property might require a trade-off in another. A good example of these phenomena is PVC, which historically has been heavily plasticized with certain phthalates that transform the rigid PVC used as plumbing pipe into plastic as flexible as a shower curtain. Because plasticizer molecules are small and held in the plastic with relatively weak attractions, they sometimes migrate out of the plastic over time, resulting in shrinking, distortion, and embrittlement of the plastic and formation of sticky surface slicks. Migration becomes a public health concern when the plasticizer has some toxicity as in the case of some endocrine-disrupting phthalates. It also affects the future legacy of certain plastic artifacts that have been collected by museums but have begun degrading within decades of their manufacture. In this volume, these two perspectives on plasticizers are a focus of Susan Freinkel (this volume) and the contribution by McGath and Madden (this volume).

The discussion above highlights the many ways one can intervene in the process of creating a plastic and explains why such a staggering range of materials is possible. Polymer design and property-modifying additives all influence the finished object and how well it performs. The makers of early plastics did not have these polymer models to interpret rubber and celluloid. Experimentation was the norm, trying combinations of ingredients and processes by trial and error until some usable stuff emerged from the vat. Simultaneously, fabricators of plastic objects were figuring out how to process the various polymers and compounded plastics into usable forms: films, sheets, rods, fibers, paints and coatings, foams, and custom three-dimensional shapes. Increasingly, the fields of materials science and polymer engineering are advancing such that plastic structures can be modeled at the molecular level with a computer and then produced for specific applications. Computer modeling shortens the time needed to get new materials to market because the number of trial-and-error cycles is reduced. In theory, this shortened timeframe results in plastics evolving ever more quickly and should improve product quality. The plastics that are in fashion, being innovated, or becoming obsolete are a quickly shifting landscape.

INNOVATION BEYOND THE $10,000 BILLIARD BALL

How does innovation happen? It should be no surprise that a Smithsonian volume about plastic would look to the past. The first three chapters by Bill Moggridge, Mary Brooks, and Robert Friedel offer perspectives on plastic innovation that are, for the most part, retrospective. Innovation is a complex phenomenon that can be described in many ways. Often, innovation is recounted as an auspicious discovery or happy accident and is attributed to a particular individual, which has certainly been the case with plastic. The end result is a sort of creation myth that highlights the ultimate achievement at the expense of the process. It usually does not tell you much about innovation. In reality, innovation in materials is more complex and can have long developments and many participants, who may work together or separately, within a company or in competition, across national borders and long spans of time. Gradually, they advance the technology through a process of trials.

Take as an example the famous Celluloid billiard ball that John Wesley Hyatt created as a substitute for elephant ivory and is reputed to have won a $10,000 prize (Friedel, 1983; Figure 6). The ball is now in the collection of the Smithsonian's National Museum of American History. Although it captures the imagination, the fabled billiard ball contest of 1868 does not convey the complexity of creating celluloid or a synthetic billiard ball. With such a large prize at stake, many people would have been working on solutions, and most of these would have been unsatisfactory or failed outright. Patent records show that John Wesley Hyatt himself tried multiple ideas. In 1865 he was awarded a patent for a billiard ball made from shellac, a plastic-like lacquer secreted by beetles (Hyatt, 1865).[10] If that ball ever went into production, it does not seem to have been commercially successful. It is also rarely noted that John Hyatt did not work alone on the material that would be named Celluloid. His brother, Isaiah Smith Hyatt, was also named on the original patent and cofounded the Celluloid Manufacturing Company, but he died in 1885 (Hyatt and Hyatt, 1869; Morris, 2012).

Although the Hyatts' Celluloid often is credited as the *first* plastic, other plastic-like substances with similar properties had been molded not only from shellac but also from tree saps, animal blood, and horn for a few decades prior (DuBois, 1972; Pedersen, 2004).[11] The polymer cellulose nitrate—the primary component of Celluloid—was not new either. Nitric acid had been combined with cellulose to make explosive guncotton since the 1830s and plastic-like lacquers known as pyroxylin and collodion since 1846 (Ménard and Florès Domonte, 1846; Pelouze, 1846; Schönbein, 1846). Celluloid was innovative in that the cellulose nitrate polymer was mixed with camphor to form a solid, pliable mass. But the Hyatts' Celluloid was not the earliest example of that material either. Englishman Alexander Parkes had patented his Parkesine a few months earlier (Parkes, 1865), and that venture was continued under the name Xylonite by Daniel Spill, a competitor of the Hyatts. Celluloid was the more successful commercial venture,

FIGURE 6. John Wesley Hyatt's Celluloid billiard ball, National Museum of American History, Smithsonian Institution. Photo by NMAH, Smithsonian Institution.

and the trademark has been a common name for cellulose nitrate plastics and motion picture film ever since. The billiard ball story is historical shorthand for a more complex set of stories about invention that eventually led to the so-called first plastic, and these can be considered from the perspective of a famous lone inventor or as a gradual, competitive effort.

Retracing the innovation journey through milestones like the billiard ball is a natural and effective didactic tool, and it is a typical museum approach to teaching history. The first section of this volume opens with another such contribution by Bill Moggridge, designer and entrepreneur, who also was director of the Cooper Hewitt, Smithsonian Design Museum. Moggridge guides us through a multifaceted design lesson seen through the 60-year evolution of the plastic chair. Chairs are particularly fertile ground for designers and a good challenge. Whereas art need not have a use or be understood, design presupposes that the design object has an intended purpose. A successful chair will invite a person to sit on it and support that person's weight comfortably for a time. It might fall into a certain price window to make it commercially profitable, meet certain aesthetic requirements, or have other special features like stackability so many can be stashed away in a small space. As American industrial designer and social critic George Nelson (1953:9) wrote, "Every truly original idea—every innovation in design, every new application of materials, every technical invention for furniture—seems to find its most important expression in a chair." Moggridge's approach recalls influential chair histories by Nelson (1953) and Charlotte and Peter Fiell (1997) in highlighting examples that are or will surely become iconic. For Nelson, plastic was inevitable, but it was still a minor player in furniture when he wrote the book *Chairs* in 1953. Written 46 years later, the Fiells's *1000 Chairs* includes many plastic examples, some of which overlap with Moggridge's selections. However, the authors tend to approach the materials of which the chairs are made as incidental to the chairs' context and aesthetics. Moggridge's approach differs in that his focus is on the plastic technology, and the chairs are the examples. By spotlighting an everyday object that existed long before plastic and with which we are all intimately familiar he is able to isolate specific design innovations and relate each to an advance in plastic manufacturing that made that innovation

possible. From Bernard Rancillac laying up fiberglass by hand (Moggridge, this volume, fig. 6) to the charming robot that squirts out Dirk Vander Kooij's Endless Flow collection (Moggridge, this volume, figs. 13–14), he treats the technologies by which plastic is worked as artists' tools that can be explored and pushed to create design objects that are unique and yet mass produced. For Moggridge, the materials and craft elevate the result.

Moggridge then moves in for a close-up of his early experiences as an industrial designer working in plastic to create "everyday things" for people to use. Through personal stories, he recounts a designer's experience exploring and struggling with new types of plastic and design tools. For example, there are anecdotes about shaping sticky structural foams and fabricating heat-resistant plastic parts that had to be painted in the colors he wanted because suitable body-colored plastics did not yet exist. His description of "the" CAD draws us right back to the 1970s when Computer Aided Design was still very new and foreign. The result is an eyewitness account from the Plastic Age that captures the flavor of exploring new technology, and what predominates is a delight in the possibilities, both past and future.

Not all possibilities succeed, of course. There are many failures along the way. In the second chapter, Mary Brooks (this volume), historian and conservator of textiles, recounts a failed and largely forgotten category of "azlon" textile fibers innovated from agricultural proteins. Naturally occurring polymers were the earliest source of man-made plastics and a large share of plastic feedstocks through World War II, but the majority came from rubber latex and cellulose rather than proteins. Brooks demonstrates that it was not that proteins were overlooked for plastics but rather that efforts to develop them flopped repeatedly.[12] She traces two trajectories of failure in silk- and wool-like azlon textiles through World Wars I and II and weaves together the physical properties of regenerated protein fibers with complex motivators like market demand, wartime shortages, and national pride. Whereas Moggridge delights in the possibilities of new materials, Brooks introduces the concept of *ersatz*, a German word for a substitute material that tends to connote inferiority (Shurtleff and Aoyagi, 2014). Attitudes toward these ersatz textiles teetered between pride in innovation and disappointment. In times of war, a substitute could be a welcome solution to shortages of food and clothing, but once the scarcity was resolved, juxtaposition with the authentic original highlighted the ersatz's inferiority. Brooks shows how this tension could strongly affect the market success or failure of a new plastic. Azlon fiber did not catch on then because it was an inferior product.

This concept of plastic as a substitute winds through several contributions to this volume and is a central question of historian Robert Friedel's "Is It Real? Imitation and Originality in Plastics" (this volume). In 1983 Friedel published the influential *Pioneer Plastic: The Making and Selling of Celluloid,* in which he discussed why celluloid so often imitated other materials, particularly elephant ivory. In the nineteenth century, biological materials like wood, elephant ivory, other teeth and bones, tortoiseshell, hoof, and horn were used for many objects that we make from plastic today. The natural dimensions of these substances, which limited the size and shape of objects that could be produced from them, and perceived impending shortages motivated innovation of substitutes (Friedel, 1983). Cellulose nitrate plastics like Parkesine, Xylonite, and Celluloid ultimately met these needs and in a sense democratized precious ivory and tortoiseshell objects by making convincing, affordable synthetic imitations.

Friedel (1983) also showed how these precious natural antecedents facilitated celluloid's adoption. By imitating ivory, makers of celluloid were teaching implicitly how the new material ought to be used, namely, for the same purposes as ivory. There is an interesting play on the perception of substitute materials here. On one hand, Mary Brooks shows how plastics could be the poor, ersatz cousin that was not quite as authentic or good as the original. But on the other hand, some plastics like celluloid made quite acceptable substitutes that became popular as lower-budget alternatives.

Through imitation, celluloid also was made more culturally acceptable by association with a known and reputable substance. Friedel described that the prestige of ivory was familiar and that the uses of ivory were familiar. Thus, the chameleon-like nature of celluloid, a substance that excelled at imitating other substances, helped its adoption. He does not go quite so far as to describe familiarity of the *material* as a key to its success. The fact is that celluloid and plastics in general share many material properties with ivory, tortoiseshell, horn, coral, amber, mother of pearl, and the like because they are all based on polymers, some made by nature and some made by people. Their hardness, impact resistance or brittleness, hand feel, carvability, and luster when polished can be very similar, especially when contrasted with glass, ceramics, stone, and metals. By emphasizing the connection to ivory and tortoiseshell, manufacturers of celluloid were also communicating the material properties of the new, unfamiliar substance.

In this volume, some 30 years later, Friedel draws our attention to a period when celluloid showed subtle signs of emerging from an ivory substitute to a material with its own possibilities of form and a distinct economic niche. Celluloid novelties in the Smithsonian's National Museum of American History look like ivory at first glance, but Friedel invites us to go beyond their color and texture and see that they are more than ivory simulants. These objects slip the dimensional and financial constraints of ivory because celluloid is moldable, whereas elephant tusks are not. Yet these celluloid objects continued to be made with the color and texture of ivory. Friedel argues that the ivory look was used to elevate the status of celluloid, which was inexpensive and being used for mass-produced novelty items. I also would argue that the so-called first plastic, a new and foreign substance, *needed* to simulate other materials with which people were more familiar and had experience. The ivory-like appearance persisted as part of celluloid's identity until it became familiar and was freed to find an aesthetic of its own.[13] I base this proposition on ideas proposed by philosopher and early experimental psychologist James Mark Baldwin (1861–1934), who put forth that imitation and gradual adaptation are fundamental truths of human development and society.

> In its nature society is conservative. Its form results from long racial processes of gradual adaptation and compromise. It represents a complex state of equilibrium, a balance of opposing and concurring interests. So every new idea, every project of reform or change, has to fight for its acceptance, to struggle for existence, to show itself adapted to social belief and use. Not all alike are available for social generalization. Those which do show themselves available must not be too antagonistic to the established, or too remote from it. They must be, as it were, children of the present, made of the same material and recognizing the same realities, physical and social, as the thought already adopted and sanctioned in society.
>
> It is, in fact, the slight variations which are more usually fruitful. Seed-thoughts, epoch-making discoveries, are slow in making themselves felt. If they are too abrupt, too radical in the demands they make for change, they rest dead and fruitless, perhaps always—certainly until some moderate thinker restates them in form more assimilable to the social store. (Baldwin, 1911:153–155)

In short, when confronted with something new, it is natural to try to make sense of it through comparisons to things you already know. Baldwin observed that early childhood development proceeds by trials of imitation; we copy behaviors we observe around us, categorize things we sense, and file them away in our minds. For example, the category of birds includes many variations on a bird, but they are all birds and in a sense copies. As humans, we continue our very existence through a process we call reproduction and transmit our culture through tradition. Imitation also is key to the innovation process, whereby changing only a few facets at a time maintains continuity to the past and helps the new aspects to be accepted. Friedel touched on this idea of incremental innovation in *Pioneer Plastic*, but here he fleshes out the idea and describes it with artifacts.[13] Making objects that would not have been made out of ivory or tortoiseshell look like those materials allowed manufacturers to produce objects "in an indisputably acceptable form" (Friedel, 1983:61).

Many chapters in this volume play with the idea of imitation and substitution, from Brooks' faux silks and wools to Jan Vozenilek's heartbreaking account of the Laysan albatross for whom plastic imitates food (Vozenilek, this volume). The imitation that is so widely practiced in plastic can even verge on parody. Bill Moggridge describes the Louis Ghost Chair as Philippe Starck always wanting to make a joke. The play on the historic wooden Louis XV and XVI chair styles of the late eighteenth century, but rendered in plastic by Starck, actively recalls the past. However, by making the chair transparent and naming it "ghost," Starck situates it firmly as a memory, all the while doing nothing to hide its materiality and instead celebrating a new possibility of plastic. Self-awareness of plastic's inauthenticity is so deeply engrained in us that when Moggridge shares that he has a collection of plastic food, meaning the small food sculptures used to advertise the menus of Japanese eateries, it is funny. These are beautifully rendered plastic sculptures that he valued for their craftsmanship and probably their irony. Implicit are plays on plastic and food, synthetic versus natural, and the freshly prepared versus the industrially packaged.

TRANSFORMATIVE PLASTICS OPEN NEW HORIZONS

There came a point in the development of plastic when expectations flipped; plastic began to open up new vistas. These new vistas are the focus of the volume's second section. The most incredible feat, and of special importance to the Smithsonian, is the evolution of human flight and space exploration. Here Bill Ayrey and Linda Hewes (this volume) recount the creation of space suits for the NASA Apollo and Space Shuttle programs (Figure 7). On May 25, 1961, President John F. Kennedy announced his goal "of landing a man on the moon and returning him safely to the earth" before the decade's end (Kennedy, 1961). Given the new space program's tight timeframe and modest budget, known plastics were chosen and tasked for new, demanding applications. These included nylon, polyester, PVC, and neoprene to name a few. A space suit would not have been possible without plastic, for what were the alternative materials?

Ayrey and Hewes's firsthand accounts of designing successful space suits are rich with details that are valuable as historical knowledge and for the suits' long-term preservation. Again, there is the sense of an incremental process of product development whereby improvement came about through repeated discovery of inadequacies. For these authors, the focus is not the extraordinary finished space suit—the marvel of which is self-evident—but rather the long, even plodding development process, as if we are asked to focus not on the birth of sun god Apollo but rather on his mom Leto's grueling 9-day labor (Figure 7). They convey beautifully that to innovate is to persevere.

The advent of synthetic polymers has also contributed to astounding medical breakthroughs. With plastic we have extended our life quality and expectancy worldwide and can literally outlive our bodies. A stand-out example in the Smithsonian's National Museum of American History is the Liotta-Cooley artificial heart, the first artificial heart implanted in a human being (Figure 8). It kept patient Haskell Karp alive in 1969 for sixty-four hours until a human heart became available for transplant. The heart incorporates textiles of Dacron, a polyester textile fiber created by DuPont, and Silastic, a silicone elastomer from Dow Corning (Cooley, 1969). In fact, many temporary and permanent plastic prosthetics now sustain us after our physical bodies fail. This trend is likely to grow with 3-D printing technology.

Blood bags and other disposable intravenous equipment are another consequence of plastic. Early blood transfusion attempts in the seventeenth century were direct from one living being to another through goose quills or tubes of silver or brass

FIGURE 7. Pressure suit worn by Neil Armstrong on the Apollo 11 mission. Transferred from NASA to the National Air and Space Museum. Photo by Mark Avino, NASM, Smithsonian Institution.

(Tucker, 2012). This sounds nightmarish today because we have better options. By World War II, the ability to store blood for a period of time had been developed but was limited by the available materials: glass bottles and rubber tubing (Elliott, 1936; Elliott and Nesset, 1940). Glass is heavy and breaks easily, which made the blood supply insecure. It also is rigid and cannot be squeezed, so blood flowed to the patient by gravity with the bottle lifted high. This was particularly problematic in battle as the person holding the bottle could become a target for enemy fire. Plastic eventually revolutionized blood transfusion and intravenous medicine. Plasticized PVC was made into blood bags in 1950 as an alternative to glass bottles and has since replaced rubber tubing as well (Walter and Murphy, 1952; Walter, 1955, 1984). The risk of contamination is reduced as is the incidence of air bubbles. The bags can be squeezed and so do not need to be held up high in a combat situation. According to the American Red Cross (2017), nearly 21 million blood components are transfused in the United States each year! And yet there are challenges. Fluids, nutrients, medicines, and blood are administered intravenously to patients through plastic bags, tubing, syringes, cannulae, and catheters, and there is valid concern that components of the plastic, including phthalate plasticizers, can migrate into the solution and be delivered into the patient (Center for Devices and Radiological Health, 2001; Calafat et al., 2004; Koch et al., 2006). But with so many lives saved by intravenous treatments, we are unlikely to give up that technology. As Pierre Comizzoli (this volume) describes, veterinary and reproductive medicine have been transformed by plastic supplies that are more convenient, less expensive, and safer than glass. Comizzoli, a gamete biologist and veterinarian, gives us a peek at the requirements of curating and preserving endangered animal species. He shows that plastic is vital to his work and draws a distinction with the plastic pollution that threatens those same animals and their habitats. In so doing he draws attention to a paradox of plastic and what it means to use mass production and disposability responsibly.[15]

In the following chapter, Cory Bernat describes another important transformation made possible by plastic, namely the rise of plastic food packaging after World War II. Bernat describes the war as a time when assembly-line manufacturing flourished and food production was industrialized. At the war's close in 1945 resources began to flow from public uses to private ones, and consumer goods including plastics proliferated (Meikle, 1995). This adoption has led to indisputably beneficial transformations. Food wrapped in plastic can be preserved longer, protected from contamination, and distributed widely in regular measured quantities. Much of the world no longer needs to live near the cow or the farm to eat safely. Yet despite its great promise, the proliferation of packaging has downsides. Drawing on her dual expertise in history and graphic design, Bernat describes the evolution of food packaging through visual and written marketing messages that reprogrammed wartime frugality into a culture of postwar "consumers" who could afford to use cups once and throw them away. She then ties the rise of these single-use

FIGURE 8. Liotta-Cooley artificial heart. National Museum of American History. Division of Medicine and Science, NMAH, Smithsonian Institution.

convenience items to the explosion of plastic that pollutes our land and waterways today.

A great deal of angst exists in our society about plastic, waste, the environment, and pollution, but the root of that angst can be difficult to articulate. We worry about the scale of plastic manufacturing and the fate of natural resources that are not renewable or are being used at rates that outpace their renewal. Discarded plastics put pressure on landfills, pollute our land and waterways, and pose hazards to people, flora, fauna, and ecosystems. Being wasteful, with disposable single-use plastic items for example, is philosophically distressing in many cultures. This discomfort is spurring action that is transforming the types of plastics available to us and the ways in which we interact with them.

One reaction has been to revitalize research into *bioplastics*, the current term for plastics that are made wholly or partly from agricultural inputs, like soybean oil and wheat straw, rather than petroleum and natural gas. Debbie Mielewski (this volume) leads the plastics technology research program at Ford Motor

Company, where she develops new bioplastic materials for use in their automobiles. Like Bill Moggridge, Bill Ayrey, and Linda Hewes, she and her team offer a fine-grained, firsthand account of their research experience, which includes creation of a commercially successful seating foam from soybeans that finally transcends the ersatz soy products chronicled by Mary Brooks (this volume). Mielewski too is a designer, but in chemical engineering, and has focused her career on resource management and sustainability rather than design aesthetics. Her perspective is an interesting blend of environmentalism, chemistry, and the large corporate paradigm.

Mielewski's team showcases the development of a few of their most successful products, including fairly technical, behind-the-scenes accounts of soy-based polyurethane foam, wheat straw–reinforced polypropylene (WSPP), and polylactic acid. Although the polymers are different, this must be how creators of Brooks' azlon fibers would have worked, except Mielewski's foam and WSPP have been commercial successes. The products they make must meet stringent requirements. Because the materials will end up in an automobile, they must perform well in terms of safety and over an extreme range of temperatures from below freezing to more than 100°F. Their foams must be resilient to the sitting and bouncing of many riders over many years. Her team's innovations must be cost-effective, competitive with traditional alternatives, and scalable to the size of Ford's fleet.

Mielewski and her team's work in bioplastic highlights some important distinctions in today's bioplastic debate. As discussed earlier in this introduction and in the chapters by Brooks and Friedel, plastics derived from plants are not new but rather were fundamental to the birth of plastic. Ford Motor Company's history with plant-based plastics stretches back to the 1920s when Henry Ford became interested in *chemurgy*, a synergy of agriculture and chemical processing to create profitable industrial products (Shurtleff and Aoyagi, 2004). For two decades he invested in research into the possibilities of soy in paints, plastic panels, and textile fibers that he incorporated into automobiles and food products like soymilk and textured vegetable protein. This research faded away after World War II as petroleum extraction and distribution expanded across the United States. The postwar shift to fossil fuels has been so complete that plastics and petroleum are now seen to go hand in hand, and the early history with plant-based feedstocks has been largely forgotten. Mielewski and her team have revived this kind of research at Ford Motor Company with different motivation. From a corporate perspective, diversifying the portfolio of raw materials to include more domestic agricultural products stands to reduce Ford Motor Company's vulnerability to petroleum price volatility and dependence on foreign oil. Although they do not state it explicitly, the authors also imply a personal desire to move plastic manufacturing toward more environmentally sustainable and less wasteful models. For example, straw is essentially a waste product of wheat cultivation that they have used as reinforcement for some plastic parts. In fact, Mielewski's earnest research seems to have been a novelty at Ford until fairly recently, when the global sustainability movement became mainstream. Perhaps for these reasons, Mielewski and her team consider their research to be postplastic and the beginning of a new technological paradigm.

RESPONSIBILITY: PLASTIC WE VALUE AND PLASTIC WE DON'T

> By the culture of improvement I mean the ascendancy of values and beliefs permeating all levels of society that "things could be done better." Friedel (2010:2)

With ingenuity comes responsibility. New ideas, things, and technologies can be exciting at the outset, and the flaws, deficiencies, and disappointments become apparent only with time and experience. Robert Friedel posited that innovation happens by a culture of improvement, whereby the next new thing is some kind of improvement of the status quo. This certainly has been the case with synthetic polymers, and the third section of this volume looks at some of the current concerns.

When natural rubber was first exploited in Europe and the United States, it was both marvelous and vexing. It could erase pencil marks and make coats waterproof, but it was sticky in warm weather and rock hard in the cold and was prone to foul-smelling rot. Then it was discovered that heating the rubber with a mixture of white lead and sulfur transformed the latex into a highly elastic, stable substance that was "'cured' of its problems" (Loadman, 1998). Two centuries later it remains one of the world's most important industrial and commercial polymers.

Figuring out how to stabilize rubber took a decade or so, but in hindsight the solution was straightforward. Correcting other plastic deficiencies has required more complex solutions, even when the problem was a glaring public safety risk.

> We learn from a Connecticut paper that while a little girl in Norwich was combing her hair the other day with a celluloid band comb, near an open gas-jet, she accidentally brought her head too near the flame and the comb took fire. The frightened child had presence of mind enough to throw it from her head, and escaped with her hair considerably singed. The comb burned on the floor until it was entirely consumed. (*Baltimore Underwriter*, 1880:198)

Cellulose nitrate combs were even more hazardous to manufacture. Errant sparks from a buffing machine, celluloid dust collected on hot steam pipes, and carelessly discarded cigarettes all started factory fires that gutted buildings, destroyed tons of inventory, and killed and disfigured people working inside (Bureau of Surveys of New York Board of Fire Underwriters, 1909; Figure 9).

Cellulose nitrate motion picture film was another notorious hazard. Around the world, movie theaters were scenes of conflagration, mass injuries, and deaths by burning, stampede, and jumping from buildings. Months before the fire at Robert

FIGURE 9. On November 8, 1909, at least 10 people died when Robert Morrison & Son's Fiberloid comb factory caught fire in Brooklyn, New York. Underwriters speculated that two young men were sneaking a cigarette while nailing shut a crate of celluloid merchandise or maybe their hammer sparked when it struck a nail. Photo: *Brooklyn Daily Eagle*, 1909:1.

Morrison's Brooklyn comb factory, a celluloid film reel caught fire in Acapulco, and more than 200 persons burned to death in the wooden theater (*Hopkinsville Kentuckian*, 1909; *Insurance Press*, 1909). Cellulose nitrate film's flammability was so notorious that it has become an enduring movie plot device used by Alfred Hitchcock (*Sabotage*, 1936), Giuseppe Tornatore (*Cinema Paradiso*, 1988), and Quentin Tarantino (*Inglourious Basterds*, 2009).

The public health hazards posed by celluloid were clear as soon as it came to market, but its dangers and solutions were still being debated into the 1920s (e.g., Jenkins, 1918; Cook, 1919; Richardson, 1919). What should one do with a plastic that can explode into flames when heated, supplies its own oxygen, and therefore cannot be smothered, even under water? The obvious answer would be to ban cellulose nitrate outright, which did not happen, or substitute it with a noninflammable polymer, which did not happen until the early 1950s (Cricks, 1949). A cellulose acetate substitute called Cellit was introduced by Bayer in the first years of the twentieth century, but production of this product and its subsequent competitors ramped up slowly (Stannett, 1950; Coleman, 1975). In the United States, the available stock of noninflammable motion picture film was directed to the portable projector market, whereas commercial movie houses relied on engineering and regulatory controls (Victor, 1918; Cook, 1919). For example, the British Cinematograph Act of 1909 and subsequent regulations enacted licensing requirements for projection houses, mandated the use of enclosed, fireproofed projection rooms with self-closing doors, and forbade smoking in the projection room (Hart, 1949; Williams, 1997). Movie projectors were redesigned to expose minimal lengths of film at a time, and the "projectionist" became a recognized professional with standards set by professional societies (Society of Motion Picture Engineers, 1916). The projectionist's vigilance was further ensured by the installation of a toilet and wash basin in the projection room so that no film would be left unattended (Richardson, 1919). Regulations also extended beyond the theater. For instance, municipal regulatory agencies and insurance companies set strict construction and storage standards for facilities that housed any form of nitrocellulose (*Insurance Engineering*, 1912). In Britain it was forbidden to transport celluloid film by rail unless enclosed in sturdy galvanized iron cases (Hart, 1949). The problem of inflammable cellulose nitrate was ultimately solved with these and many other administrative, engineering, and regulatory controls, along with hiked insurance rates, development of fire-retardant additives, and, finally, a shift in polymer from cellulose nitrate to cellulose triacetate by the early 1950s. It was more than 70 years from the little girl with the burning comb to a permanent resolution of the cellulose nitrate problem.

Today's plastic problems are different. We no longer accept plastics that burn down buildings or singe children, but we do have serious issues with which to contend.

The first issue we examine is the preservation of cultural heritage. Plastics have been so successful—socially, technologically, and artistically—that they are now important historically as well. Plastic artifacts and artworks are being collected by museums in increasing numbers. These objects have a wide range of intended *service life*. For example, each space suit for the Apollo mission was intended for a single flight. A McDonald's polystyrene foam clamshell box was intended to last long enough to keep a hamburger warm until it was eaten (see Bernat, this volume, fig. 13). When an object enters a museum collection, its intended purpose and service life changes. It will not travel to the moon again or hold any more food. Its new purpose is to represent itself in perpetuity. What representing entails varies, but typically, the object should look like itself and remain chemically and physically stable, and for objects that have moving parts or have a time-based element like physical motion or video, it might be desirable to keep that function intact.

However, museums are discovering that many plastic objects show signs of chemical degradation quite quickly relative to other more traditional artifact materials like stone, glass, or wood. They shrink, discolor, distort, crack, and become sticky.

Some become brittle or weak and no longer support their own weight. Our experience with plastic is relatively short, and long-term degradation is something we are learning to understand. Conservators must prolong the survival of these objects and deal with routine damages that occur in storage, handling, and exhibition. Scientists working in this area are actively trying to decipher the chemical processes that underlie deterioration and to come up with solutions to entropy. Three chapters illustrate some of this problem.

Hugh Shockey is an objects conservator who has encountered many sculptures made of plastic or that include plastic elements. He describes some of the issues that face a conservator of modern and contemporary art and three novel conservation treatments of objects in the collection of the Smithsonian American Art Museum.

Thea van Oosten is a conservation scientist emeritus at the Netherlands Cultural Heritage Agency and a recognized expert in the stability of historic plastics. She is particularly well known for her work with polyurethane foam and here offers her account of treating a colorful and pliable foam sculpture by Italian artist Piero Gilardi. In this instance the object has become brittle and structurally unsound, and she intervenes by applying another polymer to strengthen the foam and restore flexibility.

The third paper in this group is offered by materials scientists Molly McGath and Odile Madden, working at the Museum Conservation Institute on a collection of model airplanes from the National Air and Space Museum. We describe a catastrophic form of deterioration in objects made of cellulose acetate, which became popular during World War II through the early 1960s, when it was largely supplanted by other polymers like ABS. This deterioration has no known cure, but we present the case study as a potential model for dealing with waste plastics we would like to recycle.

Although the museum community grapples with plastics that break down, the general public has formed a contradictory impression that plastic never goes away. Most often, this opinion is heard in relation to the plastic pollution that clogs our landfills and litters our cities, landscapes, and waterways. Although we are still learning how long individual pieces of plastic will last under a range of conditions, it is clear that plastic is an increasing proportion of our waste stream and that the garbage often ends up in places where we do not want it to be.

The related problems of waste management and plastic pollution are a recurrent theme in this volume, but three contributions in this section address them expressly. The section opens with a photographer's personal memoir of documenting the plight of Laysan albatrosses on Midway Island. These majestic and charismatic birds have been popularized in recent years for their ingestion of plastic garbage floating on the ocean. Jan Vozenilek gives a moving account of his time spent on Midway as part of a documentary film crew. By painting a picture of suffering, he shows that even the remotest islands are not immune to our consume-and-discard culture and irresponsible attitude toward garbage. Given that we live on a watery sphere with a growing population and such large-scale pollution, there can be no more "away."

Vozenilek's account is deeply personal, and his suggested solutions are geared toward individual behavior. Solutions also must be sought at a much larger scale. The U.S. government response to marine pollution, the official policy term for which is *marine debris*, is described by Nancy Wallace and Dianna Parker (this volume), the director and communications specialist of the Marine Debris Group of the National Oceanic and Atmospheric Administration. They offer a macroperspective in more formal and dispassionate terms. Pollution is a phenomenon as old as civilization itself, and our solid pollution today includes the colorful plastic we see in the albatrosses and other materials like concrete and metal (Markham, 1994). Wallace and Parker contextualize the plastic problem in the larger scheme of marine debris and show how the federal government is addressing the problem. Wallace and Parker and Jan Vozenilek are at two ends of a spectrum, but they tell similar stories. Like flaming celluloid, the solutions to our pollution crisis are likely to involve cultural solutions at the individual, community, national, and global levels.

End-of-life belief systems for plastic are not so different from our scheme for humans: we inter it in a designated place, burn it, let it go back to nature, or reincarnate it. Debbie Mielewski's team offered bioplastic as a sustainable solution to our natural resource woes. However, their chapter does not touch on what should happen to the plastic after its time in a car.[16] In the third paper of this series Mike Biddle, founder and CEO of MBA Polymers, draws our attention to the commercial challenges of reincarnating discarded plastic through recycling. Biddle (this volume) takes the perspective that existing plastic is a valuable resource that can be mined to create tomorrow's plastics. He points out that plastic is more valuable than steel on a weight-to-weight basis, but we recycle 90% of our steel, copper, and aluminum and less than 10% of our plastic waste. By offering a reliable supply of recycled polypropylene, polyethylene, polystyrene, and other plastic nurdles for injection molding and extrusion, valuable plastic waste can be diverted from landfills or incineration, and we can save energy and CO_2 we would otherwise expend to create virgin plastics. The obstacle he faces is not technological but rather cultural. To mine our discarded electronics, refrigerators, and other refuse on an industrial scale, those resources must be aggregated, and this requires the will and cooperation of governments, communities, and individuals alike. It is telling that his company's headquarters and research facility are in California, where the company was started, but the production facilities are located in England, Austria, and China rather than the United States.

We chose to end this volume with an essay by Susan Freinkel, author of *Plastic: A Toxic Love Story*. For her, the toxic in the title has dual meaning. There are the toxic chemicals that can leach out of plastic into the environment or directly into our bodies, and there is our unhealthy relationship with plastic. Her metaphor of a love story going awry is apt for our current

situation. We are at a crossroads where we must learn to understand plastic not as an evil villain but rather as an evolving substance made by people. The papers in this volume show that the innovation trajectory of plastic is complex, with some progress dependent on iterative material discoveries and other less obvious elements rooted deep in our human nature. Nevertheless, Freinkel (this volume) draws our attention to aspects of plastic objects that are quite within our control: we create plastic, choose how to use it, and choose how we value it. Currently, we expect plastic things to perform well and be durable, but we designate too many of them as cheap and disposable. Much of the innovation in plastics today focuses on solving this problem with technological solutions. Yet our relationship to plastic is tricky, and detangling it will also require changes in our behavior and attitudes—cultural changes. We know from Cory Bernat that our transition to disposable convenience was not that long ago, and hence, it is not inevitable. Freinkel describes that we can choose to follow our higher selves and prioritize achievement and betterment of our condition—and many noble examples are examined in this volume—or we can choose to use this magical substance carelessly to the detriment of ourselves and the planet on which we live. If we accept the premise that we are in the midst of a plastic age, its central challenge is to balance our drive to innovate and transform with our responsibility for the repercussions.

NOTES

1. Interestingly, bones, horns, and wood are examples of naturally occurring polymeric materials. Plastics are synthetic polymeric materials.
2. It is widely accepted that the arsenic in early arsenical bronzes was a contaminant in the copper ore. It is debated whether arsenic was intentionally added in some cases (Lechtman, 1996; Thornton et al., 2009). Regardless, the resultant metal is derived from ore.
3. Plastic also is similar to bronze in that multiple substances are often blended to tailor properties of the material to specific applications.
4. The vulcanization of rubber by American chemist Charles Goodyear and businessman Nathaniel Hayward in around 1847 is one of the earliest examples of a category of plastics called elastomers. As is so often the case in recorded history, this was not a new discovery. Mesoamerican cultures are believed to have vulcanized natural rubber latex with the sulfur-rich juice of *Ipomoea alba*, a species of morning glory, more than 3,000 years ago. Goodyear and Hayward's work is associated with the beginning of plastics because it was coincident with the burgeoning Industrial Revolution, the beginnings of organic chemistry, and commercial production of synthetic polymeric materials in the Western world. Thus, rubber vulcanization was one event in a flow of innovation that would come to be called plastic.
5. Cellulose is a major structural component of plants and is worked into materials that include cotton and linen threads, basketry, tapa cloth, papyrus, and wooden objects. It is the world's most abundant natural polymer.
6. Throughout this volume, celluloid is used to describe moldable cellulose nitrate plastics, whereas the proper name Celluloid describes Hyatt's specific brand and their company, the Celluloid Manufacturing Company.
7. Of these, carbon and silicon polymers are made into plastics. Common silicon examples include caulk that seals our bathtubs and showers, flexible silicone cooking tools, and Silly Putty.
8. Controlled cross-linking can be desirable in manufacturing, but spontaneous cross-linking over the long term is also a common cause of insolubility, shrinkage, and embrittlement in historic plastics.
9. Compounding is the process of formulating a plastic by mixing polymer(s) and additives in a molten state. In industry the end result is usually nurdles, beads, or molding powder. Thus, raw plastic is often a mixture of more than one compound that has already gone through a round of factory processing. Mielewski et al. (this volume) give an excellent example of the complexities of compounding in their description of formulating wheat straw–reinforced polypropylene.
10. The patent process is another means by which inventions are recognized and attributed to specific individuals. A patent officially documents the invention being patented but does not typically describe the innovation process.
11. Examples include vulcanite, gutta-percha, and bois durci.
12. One notable exception is casein, a moldable milk-based plastic that was developed in Europe beginning in 1897 and today is known best by the brand Galalith. It was a popular material for buttons, knickknacks, and costume jewelry, but even it had poor moisture resistance.
13. Susan Freinkel, in the closing chapter of this volume, describes that the change in aesthetic came in 1907 with a new phenol formaldehyde plastic known best by the brand name Bakelite.
14. Discussed in Friedel (1983:60–61).
15. In the symposium, the order of oral presentations was different, and Comizzoli's was juxtaposed with Jan Vozenilek's account of albatrosses on Midway Island. Reading the written versions together highlights that contradiction even more strongly than Comizzoli's account alone.
16. Bioplastic and biodegradability are often used interchangeably, but they have different meanings. Bioplastics describes the raw materials of which a plastic is made. The feedstock material may have been alive recently and would have returned to the earth by nature's own recycling scheme if it had not become a plastic. Biological beginnings do not necessarily mean that the resultant plastics are more likely to break down in a speedy or benign way. Biodegradable refers to the likelihood that a plastic will be degraded by living organisms but does not presuppose that a biodegradable plastic was made from a biological source.

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Designing Plasticity

*Bill Moggridge**

I called my talk "Designing Plasticity" because, as a designer, plastics are a wonderful thing to use and manipulate. When I graduated from college with an industrial design education, I thought that my whole career would be trying to create everyday things, made in metals and plastics, for people to use. Now we find that design can be applied in a much broader way, but I certainly did not think at that time that I would end up at the Cooper Hewitt, National Design Museum, and be working with the Smithsonian.

Roland Barthes described plastic in *Mythologies* in 1957 as "the first magical substance which consents to be prosaic" (Barthes, 1972:98). The prosaic part of it is something I really like as a designer thinking of everyday things. I thought it would be interesting to take a single product category and look at a few examples as a first thing.

PLASTIC DESIGN AS SEEN THROUGH THE CHAIR

The film *Objectified* by Gary Hustwit (2009) is about industrial design. In the initial sequence he shows the manufacture of a modern plastic chair:[1]

> When you see an object, you make so many assumptions about that object, in seconds. What it does. How well it's going to do it. How heavy it is. How much you think it should cost. The object testifies to the people that conceived it, thought about it, developed it, manufactured it, ranging from issues of form to material, to its architecture, to how it connects to you, how you touch it, how you hold it. Every object, intentional or not, speaks to who put it there.

The narrator, Jony Ive, is the senior vice president of design at Apple, so he is responsible for all of the Apple design in the last 15 to 20 years, although not going back as far as the Apple II, which was designed by Jerry Manock. Jony Ive has just been knighted, actually. I think next time I see him I'm going to have to decide whether to call him "Jony" or to call him "Sir Jony." That's a rather embarrassing decision.

The Air Chair being made in that scene comes from a company Magis in Italy and was designed by Jasper Morrison (Figure 1). It is gas-injected polypropylene, so it has the ability to have a thick wall because it has gas squirted on the inside, whereas most injection-molded plastics require a constant wall thickness. That's why you see all those shapes with edges, whereas this has that rather enjoyable solidity. It is an innovative material.

Let's go back a bit to the Cooper Hewitt collections from 1948. Charles Eames, of course, was the most dramatic of innovators in terms of materials, and he and Ray and their team at the design office experimented with new materials, yielding this chair in "fiberglass" glass reinforced plastic (GRP; Figure 2). That was a very innovative thing in

Cooper Hewitt, Smithsonian Design Museum, 2 East 91st Street, New York, New York 10128, USA.

* Deceased. Transcribed and edited by Odile Madden, Kim Cullen Cobb, and A. Elena Charola. Correspondence: O. Madden, MCIweb@si.edu

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FIGURE 1. Jasper Morrison Ltd product: Air Chair, 1999. Produced by: Magis. Photo: Walter Gumiero.

FIGURE 2. RAR Rocking Chair, ca. 1948–1950; designed by Charles Eames (American, 1907–1978); USA; molded fiberglass-reinforced polyester, bent metal rods, wood, rubber; H × W × D: 69.5 × 62 × 66 cm (27 3/8 × 24 7/16 × 26 in.); gift of Barry Friedman and Patricia Pastor; 1986-99-46, Cooper Hewitt, Smithsonian Design Museum.

1948 and an interesting design. We have an original one in our collection, but you can still buy them today in the same form, although some of the details are a little different, from many design outlets.

A little bit later, we find George Nelson, also for Herman Miller, designing also in GRP this rather beautiful swan chair, Swag Leg (Figure 3). The shape of the legs and the curved form of the plastic material give it a very interesting individual quality.

The Danish designer Verner Panton designed one of the first stackable injection-molded chairs for Herman Miller in 1960 (Figure 4). It is stackable by having its shape repeatable. The form allows comfortable seating with a little elasticity, so when you sit, you bend back a little bit, but at the same time it has that stacking quality.

Joe Colombo designed another stacking chair in injection-molded ABS in 1965 (Figure 5). The legs look rounded because there are additional parts added to the bottom. The bottom of each leg is a separate molding that is plugged into the chair, such that only a hair line join is visible. You get a sense that the chair is a very complete form.

The Elephant Chair is an experimental form from Bernard Rancillac (Figure 6). I think it is a one-piece and probably a hand laid-up polyester.[2] Called the elephant chair, quite obviously why, it has that rather fascinating shape.

Pastil by Eero Aarnio is also one from our collections (Figure 7). This is a two-part molded GRP. You can see again that split line around the center, which allows it to be this sort of very single, pastil-shaped object, but it is made of the two parts to complete the underside.

Of course, you can separate your plastics into little bits, so the beanbag was an interesting invention in the 1960s and became very popular, in fact, when I was at college. This was one

FIGURE 3. Swag Leg Chair, 1958; designed by George Nelson (American, 1907–1986); USA; molded fiberglass, swaged tubular steel, rubber composite; H × W × D: 78 × 71.5 × 67 cm (30 11/16 × 28 1/8 × 26 3/8 in.); gift of Barry Friedman and Patricia Pastor; 1986-99-45, Cooper Hewitt, Smithsonian Design Museum.

FIGURE 4. Panton Stacking Side Chair, designed 1960, manufactured 1972; designed by Verner Panton (Danish, 1926–1998); United States; injection molded luran s thermoplastic; H × W × D: 82.5 × 49.5 × 55 cm (32 1/2 × 19 1/2 × 21 5/8 in.); gift of Robert Blaich; 1977-1-1, Cooper Hewitt, Smithsonian Design Museum.

of the original leather and polystyrene pellets version of it where the polystyrene pellets inside allow it to move around, and as you sit they firm up (Figure 8). They use a lot of things of that nature now in hospitals, when you're going for a CAT scan or something. They'll put a bed underneath and allow the weight of your body to hold your neck, head, or whatever is being scanned in a constant position during the process. This was designed by a lot of collaborators: Pietro Gatti, Cesare Paolini, and Franco Teodoro.

The Herman Miller Work Chair by Don Chadwick and Bill Stumpf was a great breakthrough in terms of work seating, and the pellicle really made the difference (Figure 9). Previously, work seating had adjustments for up and down, leaning back, and all those things, but they had always been a bit sticky because there was a solid back and seat. The idea of this pellicle, which is a woven synthetic fiber with elastomers, allows you to have a transparent-to-air seat and back that makes it much less sticky when you are sitting on it. You can sit and be warm and not find that the sweat accumulates, which is very enjoyable. The chair has been incredibly successful, and still a lot of them are being sold.

Philippe Starck always wants to make a joke, and this joke was about Louis XIV, I suppose (Figure 10).[3] The idea of this injection-molded chair is that the transparency makes it become ghostlike. You hardly notice the chair as it picks up the environment around it. This is a single-molded injection molding in polycarbonate, but the thickness of the walls is constant here, so the edges define the form. Being broader at the front than at the back, it also allows vertical stacking.

Patrick Jouin is an interesting designer who designed the show *Set in Style: The Jewelry of Van Cleef & Arpels* that we had at the museum in 2011. He experimented with single pieces of epoxy, which are laid over the top of each other (Figure 11). It looks like a printed chair, but it's not actually. Strips of epoxy are

FIGURE 5. 4860 Side Chair, 1967; designed by Joe Colombo (Italian, 1930–1971); Italy; injection-molded ABS plastic, rubber; H × W × D: 72 × 43.3 × 43 cm (28 3/8 × 17 1/16 × 16 15/16 in.); 1986-115-1, Cooper Hewitt, Smithsonian Design Museum.

FIGURE 6. Elephant Chair, 1967; designed by Bernard Rancillac; France; molded polyester, bent metal; overall: 109 × 143 × 156.6 cm (42 15/16 in. × 56 5/16 in. × 5 ft. 1 5/8 in.); museum purchase from Decorative Arts Association Acquisition Fund; 1991-47-6-a,b, Cooper Hewitt, Smithsonian Design Museum.

FIGURE 7. Pastilli Rocking Chair, 1968; designed by Eero Aarnio (Finnish, b. 1932); Finland; molded fiberglass-reinforced polyester; H × diam.: 52 × 92 cm (20 1/2 × 36 1/4 in.); gift of The Lake St. Louis Historical Society; 2001-31-2, Cooper Hewitt, Smithsonian Design Museum.

FIGURE 8. Sacco Chair, 1968; codesigner: Piero Gatti (Italian, b. 1940); Italy; leather, polystyrene pellets; 103.0 × 85.0 × 94.0 cm (40 9/16 × 33 7/16 × 37 in.); gift of International Contract Furnishings, Inc.; 1981-59-1, Cooper Hewitt, Smithsonian Design Museum.

FIGURE 9. Aeron Office Chair, 1992; codesigner: William Stumpf (American, 1936–2006); USA; die-cast aluminum, molded glass-reinforced polyester, hytrel polymer, polyester, lycra; H × W × D: 91.3 × 75.5 × 57 cm (35 15/16 × 29 3/4 × 22 7/16 in.); gift of the employee-owners of Herman Miller, Inc.; 1997-73-1, Cooper Hewitt, Smithsonian Design Museum.

FIGURE 10. Louis Ghost from Kartell by Philippe Starck, 2002. Image courtesy of Kartell.

FIGURE 11. Solid C2 Chair, 2009; designed by Patrick Jouin (French, b. 1967); Belgium; stereolithography-formed epoxy resin; H × W × D: 76.8 × 40 × 54 cm (30 1/4 × 15 3/4 × 21 1/4 in.); museum purchase from the Members' Acquisitions Fund of Cooper Hewitt, Smithsonian Design Museum; 2009-8-1.

FIGURE 12. Sayl Chair designed by Yves Béhar for Herman Miller, 2011. Image courtesy of fuseproject.

laid together and welded together, which forms this very natural look and gives it a unique quality, but in fact it's made very much by hand.

Yves Béhar, who runs the design company fuseproject and designs for Herman Miller, had an opportunity to research an alternative to the pellicle. He found that using an injection-molded polyurethane, which has flexibility and a rubbery quality, he could just hang a single molding across the back of an armature, which avoids having a big frame around it like the Herman Miller Aeron chair, and get the same sort of comfort and feel that the pellicle had (Figure 12). The Sayl Chair is available now and seems to be doing very well because it is made quite economically.

We see a lot of ideas of printing now. In the same way that in the 1980s desktop publishing allowed everybody to make nice graphics for their picnic or whatever it was, now we have everybody with their little robots able to print nice objects at home. Dutch designer Dirk Vander Kooij has managed to raise the scale of the printing so that you could actually print a chair (Figure 13a,b). An article by Suzanne LaBarre of Co.Design, the online version of Fast Company, includes a video that shows the chair is made of plastics recycled from the inside of fridges that are printed by a robot (LaBarre, 2010, 2012; Vander Kooij, 2012a; Figure 13c).

On this idea of responsibility versus ingenuity, this is a clearly ingenious design, in my opinion. Is it responsible? You maybe think that it is more responsible because it uses the recycled interiors of fridges. On the other hand, you could have made the Air Chair out of recycled material, but you could not have made this beautiful yellow version of it because you would lose the purity of color.[4] The choice here was to use an unrecycled material in order to get that pure color. So, I think this idea of responsibility related to sustainability is always a more complex choice than first is obvious. The more of it the better, clearly, but at the same time one wants to think about the value proposition of both recycling and not recycling.

PERSONAL STORIES

I want to tell a few personal stories because I think it's interesting to go back and think about how plastics have affected one in a direct way. As a designer, I was always fascinated by them. They give the freedom to do design in a way that wasn't there until the plastics industries emerged and made the opportunity to create lots of forms that have functionality and value. Here I am in my first studio in 1969 (Figure 14). Yes, that's the same guy, the one on the right there. Not the same color of beard, I have to admit. One of the first design competitions I won using plastics was a television design competition from Rank Bush Murphy, which was the big TV producer in Britain at that time (Rowlands, 1972; Figure 15). Of course, most TVs at that time were in wooden cabinets, so the idea was to try and do something a little bit more revolutionary that would use the tactile qualities of self-skinned polyurethane (PU) foam, which is squashy and forms a skin on the outside that would give it a surface quality. We also designed a mechanism so that you could lean it back at different angles by pushing on the front.

Because I won the competition we were given the budget to develop a full-size prototype. The instrumentation in the center, which was made with conventional ABS-type materials, looks very crisp, but the self-skinned part is a little bit uneven and has a little bit of a wobble down the edges. It is very difficult to make models out of flexible foam. It is much easier to cut things that are rigid than it is to cut things that are flexible. For this foam, you use an electric carving knife and then a very, very fast sanding disc. I managed to get it fairly even but not perfect. Also, there's something rather disgusting about the model because it was made with an existing piece of foam with a sprayed on covering rather than the actual self-skinning of PU that would have been used in production. The prototype had a slightly soapy quality so when you pushed it was a little icky. So apologies for lack of model-making ability.

The first product that I designed completely myself that went into full production was a toaster for the UK company

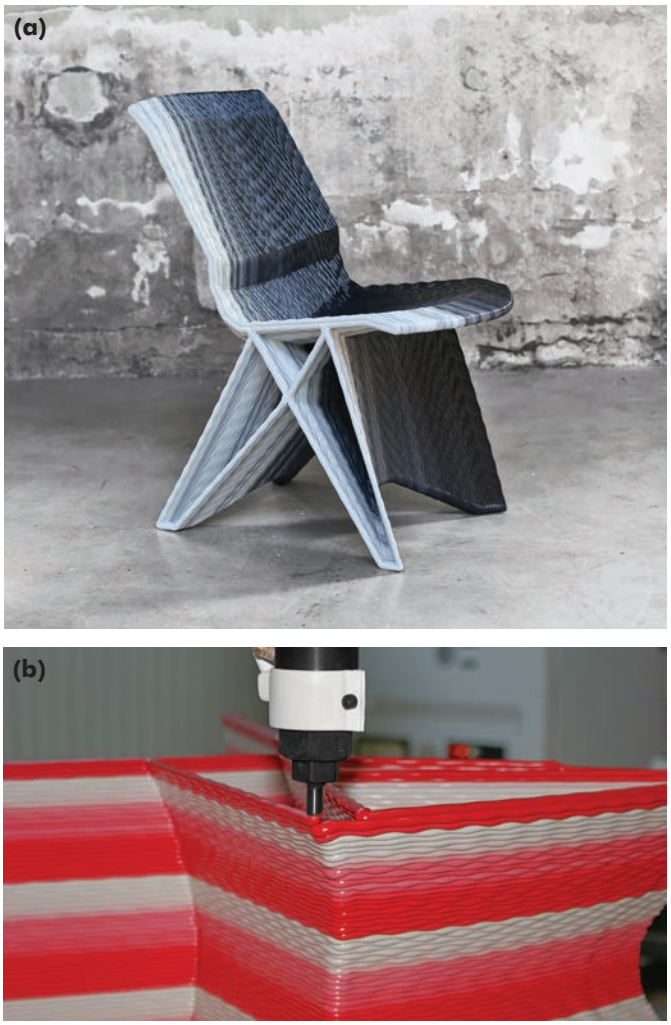

FIGURE 13. (a) Endless Chair by Dirk Vander Kooij, 2011. (b) Detail of robot printing an Endless Chair by Dirk Vander Kooij, 2011. (c) Robot printing an Endless Chair. Images courtesy of Studio Dirk Vander Kooij.

FIGURE 14. Bill Moggridge (foreground) in studio, 1969. Image courtesy of IDEO and the Moggridge estate.

FIGURE 15. Soft TV designed by Bill Moggridge for Rank Bush Murphy, 1969. Image courtesy of IDEO and the Moggridge estate.

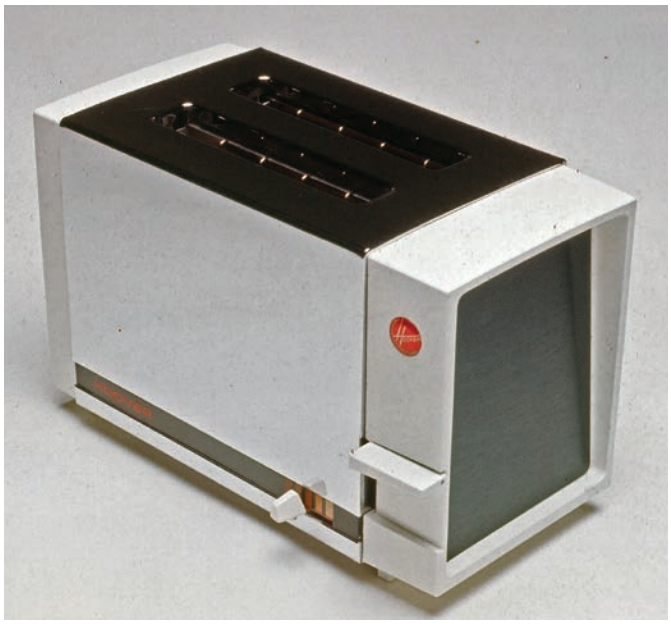

FIGURE 16. Toaster designed by Bill Moggridge for Hoover UK, 1970. Photograph courtesy of IDEO and the Moggridge estate.

FIGURE 17. Prototype for Domestic Space Heater (England), 1973; designed by Bill Moggridge (English, 1943–2012); sheet metal, extruded aluminum, compression molded phenolic plastic, wood; H × W × D: 15.2 × 38.1 × 27.9 cm (6 × 15 × 11 in.); gift of Bill Moggridge; 2010-22-2, Cooper Hewitt, Smithsonian Design Museum.

belonging to Hoover (Figure 16). Interestingly, the front and back end moldings are made of phenolic, a thermosetting resin, rather than a thermoplastic because of the temperature of the heating elements inside. Phenolic, of course, is black, so in order to make a white version as well as a black version they painted the phenolic. Although it was good paint that didn't chip off easily, it seemed ironic to me that you had to have a black plastic that was painted white in order to get that effect. Today, you could get high-temperature injection-molded material, probably a melamine, without any problem.

This space heater was the first design that I created that was put on the front cover of a design magazine, so it was a kind of triumph (Figure 17). The idea is it sucks the air in from the sides, then compresses, heats, and pushes the air out into the room. I was trying to express that in the form of the design, which is probably why it got the notoriety. I was disappointed that Hoover never produced it. The combining of materials was interesting. The top is a piece of sheet metal, and the front is an aluminum extrusion. Both those two components are painted. Then the sides are injection-molded phenolic, again painted. The whole thing is put together to look like a single form but is actually made of multiple materials. I think this is pretty normal for good design. If it is going to work properly, one has to be so

FIGURE 18. Data Entry Workstation, designed by Bill Moggridge for ITT, Spain, 1974. Bill Moggridge, *Designing Interactions*, photograph, page 9, © 2006 Massachusetts Institute of Technology, by permission of The MIT Press.

aware of the possibilities of materials and to always think of and work with them.

The first computer I designed that went into full production was a large data entry workstation that people would sit at and enter information on the keyboard (Figure 18). A display down in a hole in front of you was a reflection trap, and you also could use the surface without the display for different tasks. This was made in big structural foam moldings, rigid structural foam in polyurethane. The whole top is one molding, and then the whole of the chassis is a second molding, with sheet metal at the back. It was very much made up of large plastic components.

This marine radiotelephone is a relatively small structural foam design (Figure 19). The front panel is designed in typical injection-molded ABS, but the two-part surrounding body component is a molded, self-skinned structural foam that is smaller and more dense than that used for the desk and ABS rather than polyurethane. Another secret of design is to always find out what it's really like for the people who use these things. In order to discover how fishing boats would use these marine radiotelephones, we went to Hull, which is a fishing town up north in Britain, got on the boats, and went out into the North Sea with them. We found out what it was really like to have to try and use these things in cramped cabins full of instrumentation for their fish finders and all that stuff. If you can think of materials and people in prototyping, those are key to understanding design.

FIGURE 19. Marine radiotelephone designed by Bill Moggridge for SRT Sweden, 1977. Photograph courtesy of IDEO and the Moggridge estate.

FIGURE 20. Telenova Station Set Desktop Telephone, 1982; designed by Bill Moggridge and ID Two; USA; plastic housing; overall: 6.2 × 28 × 21.2 cm (2 7/16 × 11 × 8 3/8 in.); gift of Arango Design Foundation; 1994-31-126-a/c, Cooper Hewitt, Smithsonian Design Museum.

FIGURE 21. Word processor designed by Bill Moggridge for Minolta, 1984. Photograph courtesy of IDEO and the Moggridge estate.

When I started the second office in Silicon Valley, I designed an office telephone of molded ABS using computer-aided design (CAD). We were just trying to learn how to use CAD systems, which were very expensive in the early 1980s. A unit cost about $150,000, so instead of buying one, initially, we went to a service. An operator would do the operation, and you'd sit next to that person and say, "Please, put a line here and a radius there," et cetera. It was a very bad user interface. I was rather delighted one day when I was going around the collections in Newark with Odile Madden. We were winding the handles in the compact storage and peering and seeing the rows of things, and I found this telephone was in our collection (Figure 20).

And so was this word processor! It was the first I knew about it, and I felt very lucky. We developed the word processing system from Minolta in collaboration with a company in Boston (Figure 21). We had taken training in using these difficult CAD systems and were doing it ourselves without the skill of the operator. It was a nightmare! We were working 12 hours a day, and these guys from Minolta were looking over our shoulders to see how we did the CAD, and we weren't very competent at it. It was just very, very difficult, although we did get it done in the end.

ON INGENUITY AND RESPONSIBILITY

With all things plastic the idea of ingenuity plus responsibility is a complicated issue. Examples that I feel are on the ingenuity side include Adaptive Eyecare for self-prescription of eyeglasses, from a British inventor (Figure 22). There is a plastic frame, and in each of the circular lenses are two pieces of Mylar,

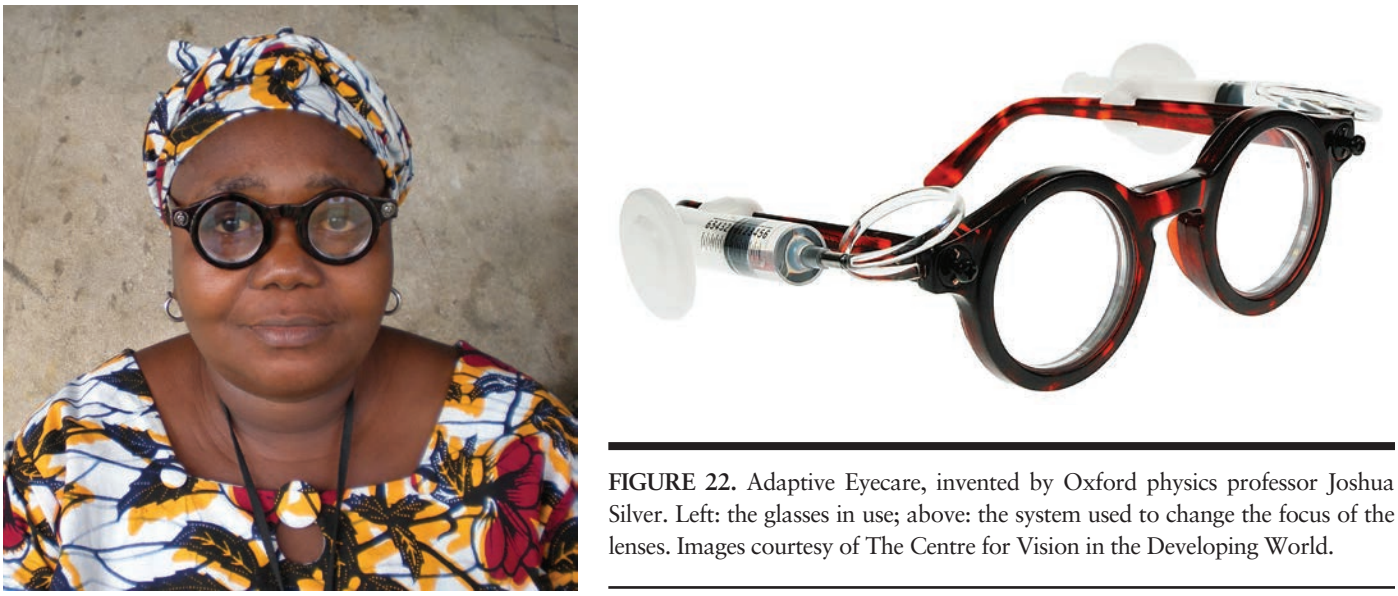

FIGURE 22. Adaptive Eyecare, invented by Oxford physics professor Joshua Silver. Left: the glasses in use; above: the system used to change the focus of the lenses. Images courtesy of The Centre for Vision in the Developing World.

FIGURE 23. Game controller designed at IDEO for Logitech, 1996. Image courtesy of IDEO.

front and back. Two cylinders of gel with dials are attached to the arms. To fix your eyesight, you close one eye and then wind the dial on the other one until it expands the lens and you can see. If you go too far, just wind it back a bit. Then close the other eye, and do the same. You don't need any opticians. You can do it in Africa. You can do it wherever, and you can do it very inexpensively without the infrastructure that we have here in the West. Of course, the system deals with magnification and not aberration, but as such it is pretty magical and very ingenious.

A colleague of mine at IDEO designed a game controller for Logitech that looks like carbon fiber but is really made of ABS (Figure 23). These printed techniques where you can float any form onto a complex surface is a false kind of ingenuity. In fact, most of the cars that you drive in have some sort of texture, often wood, on the dashboard that use these printed techniques. Only very expensive cars like Bentleys and Ferraris use real wood nowadays. There is a long history of simulation in plastics of real materials. Sometimes they come out as nicer. Sometimes they

FIGURE 24. iMac Computer with Keyboard and Mouse, 1999; designed by Apple Industrial Design Team and Jonathan Ive; China; molded plastic, rubber, glass, metal, electronic components; H × W × D (a: computer/monitor): 38 × 38.5 × 42.5 cm (14 15/16 × 15 3/16 × 16 3/4 in.) H × W × D (b: keyboard): 4 × 39.2 × 14 cm (1 9/16 × 15 7/16 × 5 1/2 in.) H × diam. (c: mouse): 42.5 × 8 cm (16 3/4 × 3 1/8 in.); gift of Apple Computer; 2000-63-1-a/c, Cooper Hewitt, Smithsonian Design Museum.

come out as just awful copies. Sometimes they are as good as this carbon fiber texture, and you really can't tell the difference. I am fascinated by that. Personally, I have a collection of Japanese plastic food, which is a way of representing food in plastic. They are lovely for their really excellent calligraphy. Cast in very accurate shapes, the shape and color and details are put back with brushes in a very beautiful way. My wife also has a collection of Lucite purses from the 1950s, so between us we are kind of crazy about the old plastics, which are mostly simulating something else.

The first iMacs were ingenious by the use of transparency and one of Jony Ive's first designs that struck a big chord with the public (Figure 24). The first typewriter to be obviously portable and obviously accessible using a plastic molded, colorful surround is another excellent example of ingenuity, designed by Ettore Sottsass and Perry King in 1969 (Figure 25).

Now when it comes to responsibility, I don't think it is very responsible the way we use so many plastic water bottles for drinking. I would far rather have something traditional and simple like a glass, thank you. It also would be perhaps more responsible if we could think of materials that wear in rather than wearing out. I mean, there is nothing like an old boot, is there? The leather quality is absolutely wonderful, and the more you've well worn it, the more you've kicked it about, the better it seems to look. There are a few plastics that ding nicely, often with textures, things that don't mind when they get knocked about, that get nicer, and you get more fond of them. That's a wonderful thing to do if you can.

Ecovative's Mushroom® Materials is an example of replacing wicked materials with wonderful materials (Figure 26).[5] It is the equivalent of expanded polystyrene that is used in construction

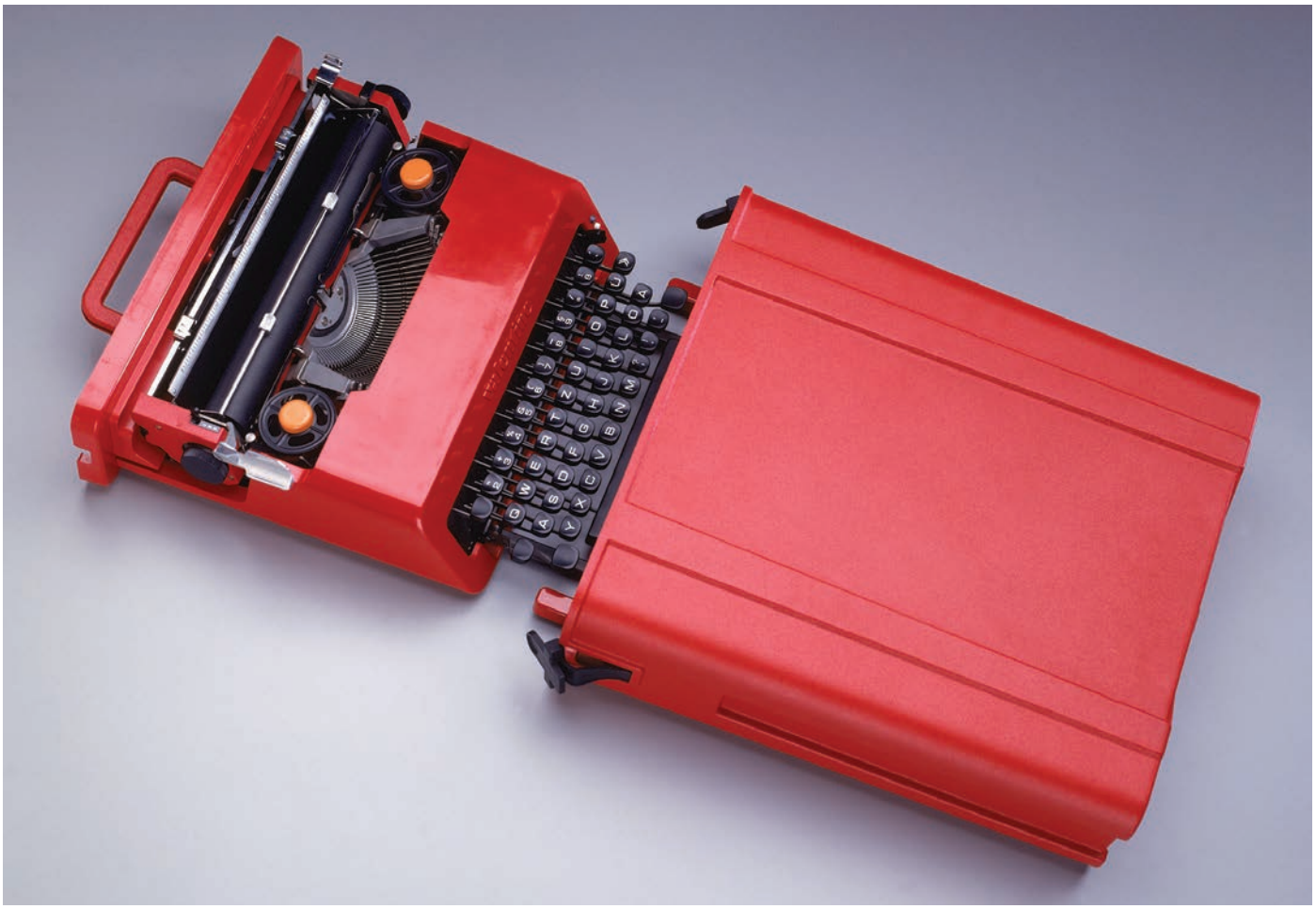

FIGURE 25. Valentine Typewriter and Case, ca. 1969; designed by Ettore Sottsass and Perry A. King; Italy; molded ABS plastic, metal, rubber; H × W × D (a): 10.3 × 33 × 34 cm (4 1/16 in. × 13 in. × 13 3/8 in.) H × W × D (a, b: with case): 11.5 × 34.5 × 35.5 cm (4 1/2 in. × 13 9/16 in. × 14 in.); gift of Barry Friedman and Patricia Pastor; 1986-99-40-a,b, Cooper Hewitt, Smithsonian Design Museum.

for two purposes: fire protection and insulation. Mushroom® Materials have exactly the same properties in both those characteristics, but it is actually made of mycelium. Mycelium grows, and when it gets to the right density you kill it and use it like expanded polystyrene. Pretty nice.

Another thing to think about a lot if we are going to be responsible is how we recycle and how we handle our materials once we have used them. I came across an example in Belmont, which is a suburb of San Francisco close to Silicon Valley where they seem to have a really good way of getting effective recycling. An informational piece gets delivered to every household with instruction about how to position three containers with different contents outside when they are getting ready for pickup. A sign on the top of each container tells you what goes inside. Lovely trucks with a little robot on the side come along and pick them up in three sweeps, one for each of the containers. The robot lifts the container up, pops it over the top, and empties it. It's done with a nice piece of robotics, and the driver never has to leave the cab. Then they give you more information about how to deal with it as you move forward. I think that's an interesting example of trying to deal with the information needed to get people to really recycle rather than just paying lip service to it, in a way that is supported by a system of infrastructure.

Secretary Clough put together a strategic group that he was kind enough to invite me to participate in, about a year and a half ago, for looking at a strategic plan for sustainability at Smithsonian.[6] Our team found that you could really think of sustainability in three different sections. There is the knowledge we can create, and the Museum Conservation Institute could be a great place to do that. Then the way we communicate and get the knowledge out there. And then there are actions that we take ourselves to be more sustainable as an institute.

FIGURE 26. Ecovative's Mushroom® Packaging made from mycelium and agricultural materials. Image courtesy of Ecovative.

NOTES

1. The film score plays as an automated gas-assisted injection molding apparatus sucks up polypropylene nurdles and melts them unseen. The machinery slides in to push the melt into the mold. The mold then opens, revealing a complete white plastic chair that is picked up with suction cups by a robotic arm and placed at the end of a row of identical chairs. Jonathan Ive narrates in voice-over.
2. The chair seat probably is polyester reinforced with fiberglass, which is one form of glass-reinforced plastic (GRP). Polyester, fiberglass, and GRP are commonly used terms that describe the same material.
3. In fact, the style of the Louis Ghost Chair is more reminiscent of the Louis XV and Louis XVI styles.
4. The color palette of recycled plastics has expanded in the time since this presentation was first conceived. In 2012 Dirk Vander Kooij claimed that his pigment manufacturer has found a way to make bright colors, such as yellow. This expanded palette is evidenced in the designer's printed products since then (Vander Kooij, 2012b).
5. In his original presentation, Bill Moggridge called this mycelium-based biomaterial by an earlier product name, "Greensulate," that has since been changed to Mushroom® Materials. http://www.ecovativedesign.com/ (accessed March 15, 2016).
6. G. Wayne Clough was the twelfth Secretary of the Smithsonian Institution and served from 2008 to 2014.

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"Astonish the World with . . . Your New Fiber Mixture": Producing, Promoting, and Forgetting Man-Made Protein Fibers

Mary M. Brooks

ABSTRACT. This paper explores the background and development of a largely forgotten group of regenerated protein fibers made from vegetable and animal proteins such as corn, peanuts, soybeans, milk, and egg white in Europe, America, and Japan. Two generations of these fibers are identified. The first group, produced around the turn of the nineteenth century, was trying to emulate silk. The second, intended to emulate wool, was produced under wartime political and economic pressures during and after World War II and only had a brief commercial life. Their complex but short-lived trajectory is bound up with different—and shifting—attitudes to the synthetic and to ersatz materials. Their changing status from exciting, modernist, patriotic, and fashionable fibers to failed, forgotten fibers is mapped and analyzed using Thompson's rubbish theory. This theory explores the practices of value creation and is here used to illuminate their slippage from cultural memory and their consequent representation—or the lack of it—within museum collections.

INTRODUCTION

In 1942, the renowned agricultural chemist George Washington Carver wrote to Henry Ford expressing his admiration for the latter's experimental "chemurgy" (biochemical engineering):

> Possibly the thing that I believe you're going to astonish the world with is your new fiber mixture . . . as trial mixtures perfect it I am expecting to see from your looms not only finer cloth, but rugs equal to the best Axminster, Wilton, etc. . . . I can see unlimited possibilities here. (George Washington Carver to Henry Ford, 1942, as summarized in Shurtleff and Aoyagi, 1994:70–71)

The fiber causing such enthusiasm was made by Ford's research chemists from soybeans and was one of a number of man-made fibers developed as substitutes for wool or silk from a variety of protein sources known as regenerated protein fibers, or azlons. At about the same time, three very different men were wearing suits made with regenerated protein fibers. Both Thomas McInnerney of National Dairy Products Corporation and Dino Grandi, the Italian ambassador to Great Britain, were sporting milk fiber suits, while Henry Ford had himself photographed in his soybean/wool fiber suit (Mielewski et al., this volume). The transformation of sources such as soybeans, milk, peanuts, or corn into a viable fiber involved complex processing and has intriguing overlaps with the development of some plastics. However, the fibers were not technically successful and enjoyed a restricted commercial life only under the unusual political and economic

Department of Archaeology, Durham University, Durham DH1 3LE, UK
Correspondence: M. M. Brooks, mary.brooks@durham.ac.uk
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circumstances of World War II. This chapter will review the definition, production, and promotion of these fibers in the late nineteenth and early twentieth centuries and the mid-twentieth century; these distinct groups are categorized as the first and second generations, respectively. Their links with plastic technologies are examined, and their complex but short-lived trajectory is analyzed together with different—and shifting—attitudes to substitute materials often described by the German word *ersatz*. Their changing status from exciting, modernist, patriotic, and fashionable fibers to a failed and rapidly forgotten technical experiment makes them a classic exemplar of Michael Thompson's rubbish theory (Thompson, 1979).

DEFINING A REGENERATED PROTEIN FIBER

Researchers and chemists alike found it difficult to define and characterize the fibers they were striving to develop. Fibers are traditionally categorized by source, whether animal, vegetable, mineral, or man-made, which encompasses both the truly synthetic fibers such as nylon and regenerated fibers from natural sources. Regenerated fibers are situated on the boundary between the natural and synthetic, being made from artificially manipulated natural materials. Francis Atwood, who led the mid-twentieth-century development of Atlantic Research Associates' (ARA) casein fiber Aralac, acknowledged this difficulty: "This confusion of words is disconcerting to a chemist who approaches this field of man-made fibers. . . . What is he to call the product when he starts with casein from milk or soybean and ends with a textile fiber, and why?" (Atwood, 1940:1547).

In a definition that reflects the nature of the regenerated cellulosic fibers such as rayon made from plant sources, on which some of these fibers were modeled and from which they derived some of their production technology, the 1958 U.S. Textile Fiber Products Identification Act defined an azlon fiber as "a manufactured fiber in which the fiber forming substance is composed of any regenerated, naturally occurring protein." However, unlike cellulosics, proteins have extremely diverse structures. They may be completely fibrous or globular. This diversity contributed to the challenges encountered by researchers and manufacturers seeking to create regenerated protein fibers and also influenced the debate over defining and naming the resulting fibers. R. L. Wormell, a Courtaulds chemist who dedicated many years to the study of these proteins and their fiber-forming potential, argued that the term "regenerated protein fiber" masked a fundamental physical inaccuracy:

> Regenerated protein fibers are not at all like regenerated cellulose fibers. Regeneration means being born new, and in this sense is correctly applied to cellulose, because the cellulose originates in nature as fibers; it is dispersed and regenerated in fiber form. Proteins come into existence as corpuscles; they remain corpuscular when dispersed, and are still corpuscular when dispersed, and still corpuscular when they are strung together into fibers with the aid of some extraneous agent such as formaldehyde. Their fibers are thus fundamentally different from those of cellulose. (Wormell, 1954:v)

This distinction is significant and indicates the importance of the growing understanding of protein chemistry in comprehending the behavior of regenerated protein fibers and the need to cross-link protein filaments so as to produce a fiber. A regenerated protein fiber is essentially a nonfibrous globular protein (noncrystalline random copolymer) that has been reconfigured to achieve crystallized sequences that can take up and retain a fibrous form.

PRODUCING A REGENERATED PROTEIN FIBER

To be suitable for use as fibers, source proteins, whether animal or vegetable, needed to be readily available in large quantities at an economically viable cost, be either color free or bleachable, and, most importantly, be capable of forming at least a relatively effective fiber.

Almost all soluble proteins may be turned into fibers when they are considered as orientated assemblies of linear macromolecules. Whether they are useful fibers or not is another matter; as Cook (1959:228) noted, "wherever there is a source of cheap, waste protein, there is potential textile fibre." In order of descending importance, milk casein and proteins from soybeans, peanuts, and zein (derived from corn/maize) were the most common sources of protein used for making fibers. Other proposed sources included blood, collagen, egg white, feathers, fish albumen, gelatin, hair, hemoglobin (horse serum), silk and wool waste or rags, hooves, horns, and whalebone, as well as seeds, including castor oil, cotton, pumpkin, hemp, linseed, and tobacco (Traill, 1951:262; Stout, 1965:163). This list indicates both the scope of the initial research and possibly the randomness of some of the experimentation, fueled by the urgency of the search for replacement fibers in the mid-twentieth century. To be capable of forming a useful fiber, polymers need to be pure and stereochemically regular so they can crystallize once oriented to the fiber axis, to have large molecules (molecular weight not less than 12,000), and to possess a high degree of polarity to give intermolecular cohesion. The degree of crystallinity is critical as this gives strength to a fiber. The process of transforming a nonfibrous protein into a stable fibrous protein is complex. Traill summarized it with beautiful simplicity, noting where the process diverged from that of the production of regenerated cellulose fibers:

> In general, regenerated protein fibers are made by dissolving the protein starting materials, usually in a suitable alkaline solution, and extruding through a spinneret into a coagulating bath. Thus far the process is similar to viscose [regenerated cellulose fiber] spinning. The protein fibers, however, require a hardening or tan-

> ning process, in order to render them resistant to the wet processing which they encounter during dyeing, finishing, laundering etc. (Traill, 1951:262)

There were, of course, more stages in this process. Fats and oils first had to be removed from the source protein, often leaving a solid, usually called a curd, which then had to be washed, dried, and redissolved to form a solution with a high solids content. Often referred to in contemporaneous literature as a "spinning" solution, a term derived from regenerated cellulose production, this was actually a colloidal dispersion. Aging was required prior to forcing the solution under pressure through fine spinnerets into the coagulation bath. This step was often described as air or wet spinning but was actually an extrusion process. The vital cross-linking process took place at this stage using a variety of chemicals, including formaldehyde. Other "hardening" treatments followed, including both chemical baths and stretching to increase physical orientation and hence fiber quality. The threads thus formed were then gathered together, washed, dried, cut, and processed using standard textile machinery. The fibers were often blended with other natural, man-made, or synthetic fibers to overcome problems with wet strength.

Who Made Them and When?

Fibers to blend with, bulk out, or substitute for wool were developed from animal and vegetable protein sources in Europe, America, and Japan in two main phases (Table 1).

TABLE 1. Production dates (when known), trade names, and manufacturers of first- and second-generation regenerated protein fibers.

Fiber source	Trade names	Manufacturer, country, and date (when known)
Gelatin	Vanduara	Adam Millar, Vanduara Silk Company, Scotland, 1890s
Milk	casein sellwolle	Frederick Todtenhaupt, Deutsche Kunstseidenfabrik, Germany, 1904–1909
	Lanital and Merinova	SNIA Viscosa and Leumann, Italy, 1936; Under license Les Textiles Nouveaux, Belgium
	Cisalfa	Probably SNIA Viscosa, Italy, 1930–1940s
	Caslen	Rubberset, USA, 1949
	Cargan	Belgium
	Casenka (Enkasa)	Nederlandsche Kunstzijde Fabriek, Netherlands (Dutch Enka, later AKU)
	Casolana	Condensfabriek, Netherlands
	Lactofil	Nederlandsche Kunstzijde Fabriek, Netherlands
	Tiolan/Thiolan	VEB Thuringisches Kunstfaserwerk, Germany
	Thiozell	State Factory and VEB Thuringisches Kunstfaserwerk, Germany; Lodzkie Zaklady Wlokien Sztucznych, Poland; still in production in 1960s
	Silkool	Kanebo, Japan, 1938
	Fibrolane A, B, BC, BX	Courtaulds, UK
	Lactofil	Nederlandsche Kunstzijde Fabriek, Netherlands
	Lactron	Unknown
	Aralac and Aralac R-53	Atlantic Research Associates, USA, 1939/1942–1946/1948
	Caslan	Monofilament; possibly Atlantic Research Associates, USA
	Wipolan	Lozkie Zaklady Wlokien Sztucznych, Poland
	Polan	Poland
Feathers	No known trade name	Possibly United States Rubber Co., USA, 1940s
Egg white	Zealon	Northern Regional Laboratory, USA, 1940s
Corn (maize)	Vicara	Virginia-Carolina Chemical Corp., USA, 1948–1957/1958
	Zycon	
Peanuts	Ardil	Imperial Chemical Industries, UK, 1935–1957
	Fibrolane C	Courtaulds, UK
	Sarelon	U.S. Department of Agriculture, USA
Soybeans	No known trade name	Ford Motor Company, USA, 1939?–1943
	No known trade name	Drackett Company, USA, 1943–1949
	Provis	Teikoku Seni, Japan; 1940s
	Tammo	Teikoku Seni, Japan; 1940s
	Silkool	Showa Sangyo, Japan, 1940s

First-Generation Fibers

The first generation of these fibers was produced by around the turn of the nineteenth and twentieth centuries with the aim of producing imitation silk. These pioneering manufacturers and inventors explored the potential of a regeneration process applied to "proteid" sources, by which they meant egg albumen, blood, gelatin from seaweed, and milk, to produce threads with chemical composition and physical properties comparable to the animal fibers silk, wool, and hair. Patentees often seem to have regarded these sources as comparable and interexchangeable (Figure 1).

Gelatin Fibers

Both Marie-Paul Emile Gerard in the 1880s in France and the Scottish manufacturer Adam Millar in the 1890s were interested in the fiber-forming potential of gelatin produced by solubilizing ground-up bone, cartilage, and fibrous tissue in boiling water or dilute acid. Gerard patented a "spinning solution" of gelatin and nitrocellulose spun into glacial acetic acid (Koch 1972:27). Although not commercially exploited (Koch, 1972), Génin considered this the birth of "l'industrie moderne des fibres de protéine" (1954:521). Adam Millar worked for the firm of William Cross, a shawl and tartan manufacturer, and was also managing director of Vanduara Silk Company, named for the Celtic word for Paisley, where he had his factory. He was interested in producing artificial silk using gelatin and devised a method of extruding a liquid solution on to a traveling belt, resulting in "a proteid strand" that he claimed was "insoluble in water" (Millar, 1899a). The importance of Millar's process is his use of formaldehyde to harden the fiber in order to achieve some degree of insolubility. He acknowledged he was inspired by "chemicals frequently employed in various photographic processes" including "the recently introduced material called formic-aldehyde" (Millar, 1895). "Vanduara silk" was apparently produced commercially, but although praised for its luster and elasticity when dry, it had little wet strength (Barker, 1919:59).

Milk Casein Fibers

Millar (1899b) was also interested in the fiber-forming potential of milk, although he does not seem to have produced a viable fiber. At almost the same time in Germany, Dr. Friedrich Todtenhaupt (1904–1905) was experimenting with fiber made from milk casein. With a background in artificial silk made from cellulosic sources, he produced a viable but not very successful fiber, sinking all his private resources into his company Deutsche Kunstseidenfabrik. Wormell noted this was an "enlarged experimental plant rather than full commercial production" (1954:xv). The equipment and spinning technique were primitive, producing

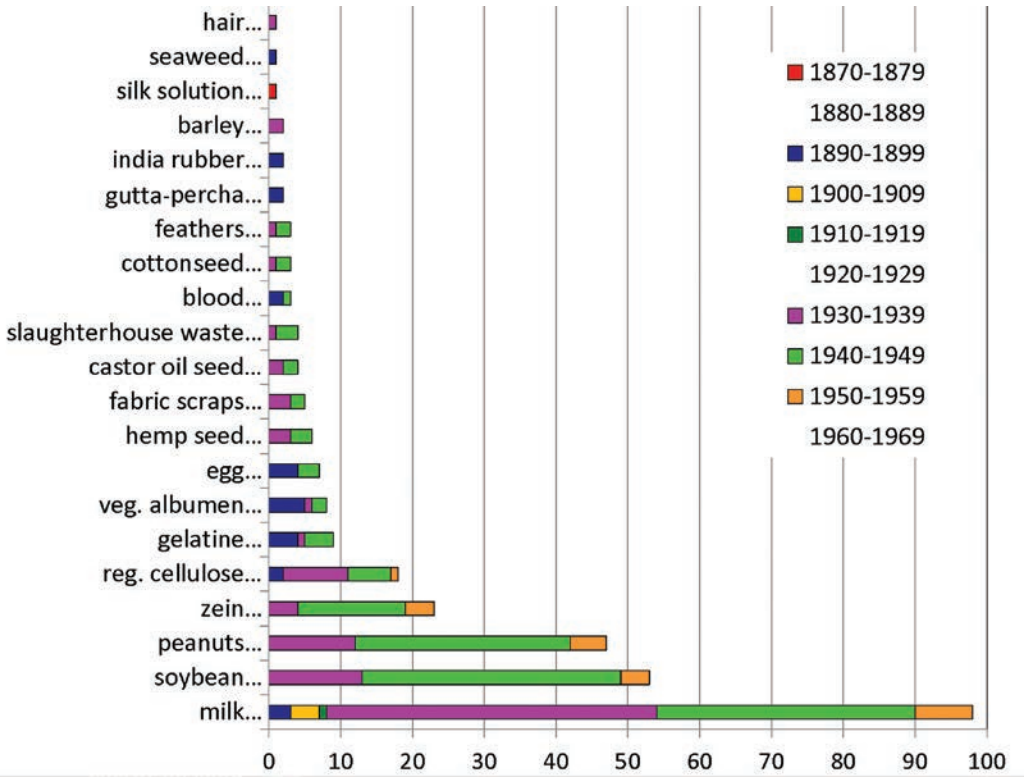

FIGURE 1. Sources used for producing regenerated protein fibers showing date of patent application. Note that no applications were made in the decades 1880–1889, 1920–1929, and 1960–1969.

uneven fibers of variable width that were hard and brittle (Peterson et al., 1945:492) but would also swell, soften, and stick together during dyeing, making processing highly problematic (Fletcher, 1942:34). Despite the failure of his business, Todtenhaupt made some crucial advances in processes for solubilizing and extruding casein and hardening the resulting fiber.

Serious interest in producing azlon fibers appears to have lapsed after this, despite some Dutch interest in casein fibers. Hermann Timpe (1911–1912) patented a method of producing fibers drawn from a solid casein curd. In the 1920s, the American Arthur D. Little Laboratories explored this technology simply to demonstrate the value of scientific research. In order to disprove the proverb "You can't make a silk purse out of a sow's ear," they extracted gelatin from pigs' ears and formed fibers using a method similar to Millar's. They admitted that their gelatin fiber was "frankly . . . not very strong or good silk" (Arthur D. Little Inc., 1921:8).

Second-Generation Fibers

Little successful production seems to have been carried out until the 1930s, when the opposing forces of surplus (excess milk by-products) and actual or perceived lack due to war (threatened wool imports) encouraged manufacturers to develop the second generation of regenerated protein fibers. Researchers in America, Europe, and Japan explored the fiber and film-forming potential of various proteins, the most successful being milk, soybeans, peanuts, and corn, although egg white and feathers were also seriously studied.

The potential of milk casein fibers was followed up by many researchers and manufacturers. Antonio Ferretti, an Italian chemist, had been researching casein fibers since 1924, registering at least 15 patents in Europe and America. It seems likely Ferretti modified Todtenhaupt's method, using different quality casein and altering the composition of the coagulating baths to improve the fiber's wet strength, resulting in a reasonably satisfactory commercially viable casein fiber named Lanital produced by SNIA Viscosa, a renowned producer of regenerated cellulosic fabrics, and widely licensed across Europe. Dutch casein curd producers sold over 4 million pounds of casein to SNIA Viscosa (Génin, 1940:156) as well as producing their own milk fibers, often using Ferretti's method licensed to them by SNIA Viscosa. These Dutch fibers were sold under different trade names, such as Lactofil produced by H. Timpe Nammlooze. Despite the interest shown by American adhesive and paint companies, it was National Dairy Products Corporation (NDPC), the dairy conglomerate formed by Thomas McInnerney in 1923, that was successful in producing and marketing the American milk fiber named Aralac. The American government's interest and involvement in alternative fiber sources is demonstrated by the public service patents issued by Earle O. Whittier and Stephen P. Gould, chemists working for the Bureau of Dairy Industry, U.S. Department of Agriculture (USDA). Somewhat unexpectedly, casein fiber patents were also filed by American manufacturers of regenerated cellulosic fibers, such as the Celanese Corporation (1942), and of synthetic fibers, such as DuPont (1940).

Soybean Fibers

The ready availability of soybeans in America spurred on considerable investigation into their use as the source of food, materials, and fibers. Soy had huge potential to supply wartime requirements: "There is no farm crop that the test tube has turned into more industrial products than soy beans . . . from gunstocks for guns to a good substitute for butter; from vitamin K for our blood to a handkerchief for tears" (R. L. Holman, "A Chemurgic Fantasy," *Yale Review,* 1945, as summarized in Shurtleff and Aoyagi, 1994:86).

In Japan, Ryohei Inouye apparently built on Ferretti's work with milk fibers, replacing casein with soy protein (Génin, 1940:157–158). Several companies, including Mitsubishi, are reported to have produced soybean fiber commercially, although the fiber was not very successful (Wickliffe Rose, 1946:103). From the 1930s onward, intensive research was undertaken in America into both the plant and its potential products. The Regional Soybean Industrial Products Laboratory (which became the National Soybean Research Laboratory) was established in Urbana, Illinois, in 1936. The laboratory researched soybean varieties, genetic engineering, disease management, and different end uses. Objectives included "finding as many end uses for this farm product as possible," including plastics (Brother, 1939:147). Many of the major players filed patents for soybean fiber in 1942, including Atwood (1942a, 1942b) for Atlantic Research Associates in America, Huppert (1943, 1945) for the Glidden Company in Chicago, Wormell and Knight (1942) for Courtaulds in England, and Ferretti (1942) in Italy. It was Henry Ford who took up soybean fiber with undiminished enthusiasm, although with mixed results (Brooks, 2005). His interest in the potential of soybeans was part of his wider vision to use chemurgy to link industry with agriculture (cf. Mielewski et al., this volume). Ford wanted to address the agricultural decline of the Great Depression, but his vision seems surprisingly prophetic in its environmental ambitions:

> Stalks and straw garbage are being made to yield valuable products, such as fibers, gas and fertilizers. . . . I foresee the time when Industry shall no longer denude the forests which require generations to mature, nor use up the mines which were ages in making, but shall draw its material largely from the annual produce of the fields. (Simonds, 1938:217—219)

During 1932 and 1933 Ford is reported to have spent about $1,225,000 researching potential applications of soy in food and industry, including plastics and fibers (J. Sweinhart, *The Industrialized American Barn: A Glimpse of the Farm of the Future. Dearborn, Michigan. Ford Motor Co.,* 1934, as summarized in Shurtleff and Aoyagi, 1994:23). His researchers, including Robert Boyer, first filed soybean protein fiber patents on behalf of Ford Motor Company in the 1940s. It was this fiber, together with beans, soybean-based paint, and coated paper, that had elicited Carver's enthusiastic response (Carver, 1942:70–71; Frank Campsall to George Washington Carver,

1942, as summarized in Shurtleff and Aoyagi, 1994:68). By 1942, the Ford Motor Company reported that the pilot plant at Highland Park, Detroit, was producing about 1,000 pounds of fiber per day. Another large plant at the Rouge River works was planned, capable of producing 5,000 pounds of soybean fiber. The War Production Board granted Ford permission to acquire equipment for air-conditioning in the factory because it was hoped the resulting fiber could be used for military purposes (Stouffer, 1942). One of Ford's original goals had been to reduce dependence on imported wool for car upholstery, but the company's experiments never seemed to have achieved a viable and commercially competitive soybean fiber that could be woven into a useful fabric, and the armed forces were not interested in using it. Ford sold the process and the soy fiber processing machinery to the Drackett Company, which had expertise in soybean processing for oil and cattle feed, in November 1943. Key Ford staff with soy fiber expertise, including Boyer, Calvert, Atkinson, and Robinette, moved to Drackett (C. Butke, "The Drackett Company's Work with Soy Proteins," interview, 1993, as summarized in Shurtleff and Aoyagi, 1994:199) and sought to improve the quality of the soy curd and experimented with soybean plastics, wallboards, and paint as well as fiber. An Azlon Research Facility with a laboratory and spinning facilities was set up (W. Shurtleff, "Dave Perkins: Update on The Drackett Co.," interview transcript, 1993, as summarized in Shurtleff and Aoyagi, 1994:205). In 1944, Boyer reported to a National Forecast Council meeting that "this new source of protein from soybeans marks the start of a new industry which promises to be not only-worldwide in scope, but fundamentally important to the future of the nation" (*Rayon Textile Monthly*, 1944b:114). Suits and hats containing "Soybean Azlon" were made for the sales team (Butke, 1993). Commercial production apparently started on 2 December 1944 but was limited by difficulties in obtaining equipment and machinery under wartime conditions. Approximately 1,000–1,500 pounds of Soybean Azlon were made per day, cut into 2½″-3½″ fibers for hat feltings, and sold mainly to the American Hat Corporation (Butke, 1993). However, technical problems were never overcome, and by 1947 the company acknowledged that their fiber, which never acquired a trademarked name, was only viable under wartime conditions: "We realized from the time that we began to sell Azlon in the war period that the shortage of textile fibers was to some degree responsible for its acceptance" (Drackett Company Annual Report, 1947, as summarized in Shurtleff and Aoyagi, 1994:97). Drackett ceased their fiber spinning operation in 1949 (W. Shurtleff, "Robert Boyer: Work with Henry Ford and Soybeans III," interview transcript, 1980, as summarized in Shurtleff and Aoyagi, 1994:151).

Zein (Corn) Fibers

Unusually, fibers formed from corn (maize) are generally referred to by the name of the protein, zein, rather than that of the originating plant. Ostenberg filed the earliest patent for zein fibers in 1919, but no viable fiber seems to have been developed until the 1930s, when there was an "explosion of research" (Lawton, 2002:1–2). Research into zein fiber production was carried out by the USDA Northern Regional Research Laboratory in Peoria, Illinois; several commercial companies, particularly Lloyd Swallen at the Corn Products Refining Company; and an independent laboratory, the Harris Research Laboratory (Stout, 1965:165). There were close links between researchers and industry; DuPont and Calco Chemical Division carried out experimental dyeing work for the Peoria Laboratory (Evans et al., 1947), while other work was carried out by the Virginia-Carolina Chemical Corporation of Richmond, Virginia. DuPont was also interested. In 1947, DuPont's Electrochemicals Department announced "a process for making nylon intermediates from corn cobs and other agricultural by-products," although this may have been a mechanical rather than a regeneration process (E. I. du Pont de Nemours & Company, 1980:10). Their 1940 patent proposed methods for stretching zein and casein fibers, implying familiarity with both the product and production methods (DuPont, 1940). DuPont argued that combining compatible proteins and synthetic linear polyamides resulted in strong, flexible films and fibers, proposing a "new and valuable composition of matter comprising intimate mixtures of proteins and synthetic linear polyamides or interpolyamides." They filed two patents with a remarkably wide-ranging list of proteins, including albumins (egg), collagen (cartilage, bone, fibrous connective tissue), edestin, elastin (protein of animal elastic fibers), gelatin, globulins (blood hemoglobin, serum, and soya), hordein (barley), oryzenin (rice), keratins (wool, hair, and horn), phosphoproteins (casein), prolamins (zein), scleroprotein (fibroin from waste silk), vitellin (egg yolk), and wheat gliadin, although zein was preferred (DuPont, 1941, 1942). However, their zein/polyhexamethylene adipamide fiber does not seem to have been produced commercially. The Virginia-Carolina Corporation proved to be the most successful producers of zein fibers. Vicara (a registered trade mark), usually as a blended fiber, was made until well after the war. Virginia-Carolina bought National Dairy's redundant Aralac plant in Taftville, Connecticut, in 1948 (National Dairy Products Corporation, 1948), aiming to increase their initial capacity of about 12 million pounds per year to 20 million pounds by 1954. Despite some commercial success, increasing competition from other man-made fibers caused production to cease in 1957 or 1958.

Peanut (Groundnut) Fibers

Interest in peanuts as a fiber source was second to interest in milk and almost equal to that in soybeans. In America, the USDA Southern Regional Laboratory researched peanut protein, but no commercial fiber resulted. In the United Kingdom, Imperial Chemical Industries (ICI) and Courtaulds both contributed to the understanding of the peanut fiber. Courtaulds' scientist Wormell furthered understanding of both the protein and fiber production, writing an important book on the subject (Wormell, 1954). Partly as result of the complex and conflicted relationship between these industrial giants, only ICI produced it in any quantity. Professor William Astbury (Department of Textile Industries, University of

Leeds) and Professor Albert C. Chibnall and Kenneth Bailey (Imperial College of Science and Technology) were the first to file patents. After acquiring their process, ICI proceeded to file patents of their own (Imperial Chemical Industries, 1937). Imperial Chemical Industries' chemists in Ardeer, Scotland, included David Traill, Robert Seddon, William Sever, and George Simpson, who all filed patents; Traill also published on the subject. Imperial Chemical Industries announced Ardil's arrival just before the start of World War II and planned to start commercial production in 1938, but this plan was suspended for the duration of the war (Brooks, 1993). A pilot plant, also possibly at Ardeer, was set up in 1939 because, of all ICI's divisions, their Scottish plants had the most experience of fiber spinning and weaving. This pilot plant had the capacity to produce 400 pounds of protein and 200 pounds of fiber per week (Byrne and Johnstone, 1987:21). After the war, ICI urgently needed to diversify, particularly seeking replacement activities for their newly—and happily—redundant Scottish Explosion Division factories. Using these for the production of Ardil seemed the ideal solution. A 1947 internal memo noted that ICI invested capital of £2.1 million in Ardil for an expected return of 7% when the full plant was operating at half capacity (Reader, 1970:389). In 1949 ICI built a dedicated factory at Dumfries, Scotland, with a maximum capacity of 22 million pounds. Production commenced in 1951 (Coleman, 1980:70), just in time for the early 1950s slump in the worldwide textile market. This slump reduced the economic viability of Ardil as a blending fiber, which needed both to be cheaper than natural or synthetic fibers and to be produced in sufficiently large quantities to achieve economies of scale. Imperial Chemical Industries was caught in a vicious economic circle: while costs were high, it was difficult for the sales force to build up the bulk orders, which meant cost-effective production and hence a lower price. Of the 316 firms indicating an interest in the fiber in 1947, only 76 placed small trial orders in 1951 (Reader, 1975:380). Despite internal divisions and marked skepticism from the influential Dyestuffs Division, which had extensive experience of the British wholesale textile market (Reader, 1975:379), ICI set up a new division called Group F in 1956 to develop their man-made fibers, including Ardil and Terylene. Cautious, but misplaced, optimism was expressed: "Sales of Ardil were disappointing, but work is in hand to evaluate an Ardil fibre with improved properties, samples of which are in the hands of potential consuming bodies" (Imperial Chemical Industries, 1956:21). The hoped-for improvements never materialized. Trading losses reached £3.7 million between 1951 and 1957 (Craik, 1957). In 1957, Ardil production ceased after an effective commercial life of only six years.

REGENERATED PROTEIN FIBERS AND PLASTICS

Although the development of these fibers and that of the early plastics may seem very far apart, there is, in fact, a link—the casein curd. Lebriel and Desgorge's (1916) patent for a silk-like fiber refers to preparing "plastic casein." It seems likely that Millar's development of casein fiber was linked to the development of casein plastics in the late 1890s, but no evidence exists to support this. The word "plastic" appears in some of his fiber patents but as a description of a material quality rather than a material in its own right. In one patent Millar (1899c) took a rather scattergun approach, listing gutta-percha, India rubber, and nitrocellulose alongside protein sources such as gelatin and albumen as well as "any substance which can be made plastic or liquid and which may subsequently be made non-plastic and tenacious." Millar appeared to have used the lactic casein used in cheese making and was not overly concerned about its production method. Todtenhaupt was clearly aware of the differences between various commercial caseins and the implications of their use in fiber production. It is possible that he used a casein similar to that used for casein plastics. His experimentation was supported by Galalith Gesellschaft, who produced the casein-based plastics Galalith from 1904 in Germany and Erinoid from 1914 in Britain. It was gradually realized that the process of extracting the protein and the nature of the curd had a critical impact on the quality of the resulting fiber. Ferretti's understanding of the need to use a curd especially developed for fiber production was critical to his fiber's success. He believed it was "necessary to devise a method for obtaining a textile casein, namely a casein which is suitable for the regular manufacture of artificial fibers" (Ferretti, 1938). He rejected the casein used for plastics:

> Galalith is rendered insoluble by dipping it into water baths of formaldehyde, but this product is formed by paracasein, which, among other features, is not soluble in alkalis and is a plastic material. . . . Casein, on the contrary, differently from paracasein, is not plastic material; it must be dissolved in alkali and water. (Ferretti, 1942)

Ferretti (1942) was clear that processes used in the production of casein plastics could not be simply transferred to the production of casein fibers, criticizing other researchers for trying "simply to apply to protein fibers the already known method for insolubilizing the so-called Galalith in water solutions of formaldehyde" and for not understanding the differences between casein and paracasein. He experimented with methods for forming satisfactory casein for fibers through acid coagulation, rejecting lactic casein because it was insoluble in alkalis and demineralized caseins because they were liable to stick together when extruded from the spinnerets, resulting in hard and brittle fibers. However, Whittier and Gould (1939:374), although noting that the Lanital process used a special casein that was subjected to acid treatment at pH 2.9, stated that their unnamed milk fiber could be made using any high-grade commercial acid-precipitated casein.

QUALITY ISSUES

The second-generation regenerated protein fibers had a wool-like warmth and softness with high moisture absorption and high heat of wetting, making them warm and comfortable to wear. As the fibers had no scales, they did not felt, nor did they

shrink like wool in hot water (Dirks, 2000:81). However, they had poor abrasion resistance, could be damaged by concentrated acids, and, most critical of all, had poor tenacity when wet, with a marked tendency to dissolve in hot water and shrink in boiling water (Maueersberger, 1940:37; Patterson, 1945:83–84; Scull and De Witt Smith, 1945:137–138; Dirks, 2000:81). The NDPC advised consumers that Aralac could be washed like wool using mild soap suds without rubbing and should be dried flat without wringing. However, these fibers had a distinctive and regrettable property: they tended to smell when wet, an obvious drawback for consumers. Lanital was said to smell like cheese (Traill, 1951:263), whereas Aralac had "an odour similar to that of spoiled milk" (Dirks, 2000:81). Others contest this. Moncrieff (1970:297) argued that Lanital smelled "cheesy" when wet but, because Aralac had undergone an acetylation process known as "Aratherming," it did not smell when wet. There were other problems. Micol Fontana, an Italian couturier, recalled how her sister called Lanital the "mozzarella fabric, because when you ironed it threads came up like tiny threads of cheese" (Paulicelli, 2004:162).

Zein had many attractive qualities—good wet strength, hand (the way a textile feels when touched), elastic resistance, and better abrasion resistance than regenerated cellulosic fibers—but lower tensile strength than other fibers, and dyeing was problematic. Despite these problems, the zein fiber Vicara had a longer commercial life than other regenerated protein fibers; Lawton (2002:13) suggests this success was simply because of the lack of better alternatives in the 1950s. The behavior of garments containing Ardil when washed is indicative of the sort of problems these fibers presented. Freda Moody's father worked in the commercial and distribution department of ICI's Dumfries factory where Ardil, their peanut fiber, was manufactured. Her mother was asked to "fill in questionnaires about the wearability, washability [*sic*] etc. of the various clothes my father brought home for us to try out." Sadly, she remembers, "the hems always dropped. I had a pretty floral patterned dress which I loved wearing. However, after several washes, it lost its shape and eventually my mother cut it up" (F. Moody, personal communication, 2001).

WHY RESEARCH AND PRODUCE A REGENERATED PROTEIN FIBER?

What lay behind this intellectual and economic investment in fibers that were problematic to produce and had poor qualities in use? The first-generation fibers were intended as substitutes for silk or for the silk substitutes made from regenerated cellulose. Millar (1899b) noted that his fibers would be "similar in chemical composition to silk, wool, hair, and other insoluble animal products." Todtenhaupt (1906) was clearly interested in the potential of casein to create substitute silk and hair fibers, arguing his fibers "possess[ed] qualities similar to those of natural silk." By the late 1930s things had changed: most researchers were focusing on creating wool-type fibers alone. As war loomed, European and American politicians and planners were increasingly anxious about the availability of wool for military purposes and actively encouraged research into substitutes for use in fashion at a time when synthetics such as nylon were in their infancy. When Ferretti filed British Patent 483,731 in 1935, his emphasis was clearly on finding a wool substitute. He rejected the regenerated cellulosic fibers precisely on account of their cotton-like characteristics: "These fibers are cold like cotton, are inflammable, are not adapted to be dyed with the dye stuffs employed with textile fibers of animal origin, such as wool and animal hair generally, and do not contain nitrogen" (Ferretti, 1938). His goal was therefore to produce "an artificial fiber consisting solely of a substance of animal character containing nitrogen and having an elementary composition almost identical to that of natural wool" (Ferretti, 1938).

The need for a wool substitute was driven by threats to wool imports by the spread of World War II. A cheaper fiber that, unlike regenerated cellulose, had wool's warmth, handle, and hydrophobicity was clearly desirable and lay behind research in America and Europe. Britain was in a different position. Exploiting the special relationship with the Dominions and Dependencies, the government bought the entire Australian and New Zealand wool clip and negotiated an agreement to acquire these clips for the war's duration plus one subsequent year (Hurstfield, 1953:57–58). Such farsighted planning resulted in Britain holding surplus wool stocks at the war's end (Hurstfield, 1953:174). This agreement may be a significant factor behind ICI's and Courtaulds' relative disinterest in developing their milk and peanut fibers as alternatives to wool during the war.

PROMOTING SUBSTITUTE FIBERS

Educating the consumer to accept substitute products in a controlled wartime economy was vital. Governments and manufacturers sought to promote these substitute fibers as desirable and patriotic alternatives to wool, which was increasingly unavailable either through genuine lack or because its use was restricted to the armed forces. Whether undertaken by manufacturers or as part of a political strategy, the underlying aim was to convince consumers of the value and utility of unknown—and poor quality—fibers.

Axis countries appear to have started implementing strategies to develop substitute materials earlier than Allied countries in order to develop economic self-sufficiency or autarchy as preparation for war. From this flowed new attitudes toward the morality of buying and wearing certain types of fibers and fabrics. The Nazi propaganda machine lauded the development of new man-made fibers. Hitler visited the 1937 Düsseldorf exhibition *Industrious People* and saw Vistra, a spun rayon, being produced. In 1935, the Spinnstoffgesetz (Textile Act) legally regulated textile production; fabrics had to contain a certain amount of man-made fibers (Guenther, 2004:234). The 1936 Four Year Plan, developed by Goring's Office of Raw Materials

and Synthetics and the War Ministry's economic division, had the overt goal of developing raw materials, thus saving foreign exchange; its covert aim was autarchy and rearmament (Macrakis, 1993:102). Increased restrictions were placed upon the textile industry in order to engineer a shift from foreign to domestic raw materials for civilian garments. Domestic textile production increased, but quality fell. Eventually, demand was controlled by the introduction of rationing in November 1939. Substitute materials became vital, essential, and desirable. *Life* magazine reported that "Germans live substitute lives": "In Germany's delicately balanced internal economy, the word ersatz has lately increased in importance. Ersatz or substitute products are the Reich's answer to the problem of living at home on home-grown materials" (*Life*, 1939:40). Olaf Nissen's book *Germany: Land of Substitutes*, published in Britain in 1944, argues that German innovation and technical ability in producing ersatz materials would enable the country to win the war. It may be black propaganda, but Leslie considers many of its claims to be plausible (Leslie, 2005:265). In the same vein, I. G. Farben published a celebratory history of the "science of synthetics" under the Third Reich (Leslie, 2005:167, 170–182).

In Italy, substitute materials were initially seen as modernist and futurist, a way of defining Italian identity and national pride. However, celebrations of national identity through the use of new materials became an urgent search for economic self-sufficiency, especially after the 1935 sanctions imposed by the League of Nations following Italy's transgressions in Ethiopia. Finding substitutes for restricted materials was a matter of urgency, expressed politically through autarkic policies. Mussolini lauded politically correct substitutes. The Ente Tessile Nazionale (National Textile Board) was set up in 1937 to establish self-sufficiency in the textile industry and to promote the resulting autarchic fibers and fabrics. In 1939 the composition of an autarchic fabric was regulated by law; imported wool or cotton had to be less than 20%, with the remainder comprising either indigenous natural or man-made fibers (Paulicelli, 2004:107–108). A series of exhibitions celebrated these fabrics as achievements of Fascist Italy, including those at the Circo Massimo, Rome (1937–1938), and the Palazzo Giustiniani, Venice (1941; Paulicelli, 2004:117).

SNIA Viscosa was strongly committed to the development of autarkic fibers. The image of their Torviscosa rayon factory with the word AUTARCHIA blazoned above the roof vividly demonstrated the merging of politics, industry, and national identity. SNIA Viscosa's Propaganda Office commissioned the futurist—and fascist—poet Filippo Marinetti (1937) to write *Il Poema del Vestito di Latte* in praise of Lanital. A striking, if brutal, fusion of visual and textual war imagery with fibers and fashion, the poem was, significantly, dedicated to Mussolini, who had been involved in supporting SNIA Viscosa through various financial crises. This theme of a modern fiber securing the country's future was articulated in the promotional song "Il Miracolo dalla Lana," put out on an HMV record complete with the image of a milk bottle top on the label (Renzo Mori Orchestra, 1937). This song praises Lanital as the miraculous patriotic fiber that answered each Italian mother's prayer—while her husband is away fighting for his country's glory, their child sleeps in a knitted nest made from the "wool of Italy." Advertisements and promotional literature stressed the fiber's modernity; one advertisement establishes this by linking Lanital with fast cars and elegant women—who establish their contemporary credentials by daring to smoke—set in a distinctive Italian landscape. Leumann stressed the fiber's patriotic appeal through stylized imperial imagery. Smart suits of Lanital, bamboo, and grass fibers were shown off by models at the 1939 New York World's Fair, but reality was rather different. Lanital was used not only for women's clothing, probably as an extender in blends, but also for "army uniforms and overcoats" (Simpich, 1939:604).

O'Brian's article "Wartime Textile Adjustments" makes American concerns about wool, military requirements, and the need for substitute fibers in the domestic market very clear:

> At the opening of the war, wool caused perhaps more concern than any other fiber . . . it is a vital necessity in war—almost as precious as ammunition. . . . Every ounce of this valuable fiber is needed for our men in the front lines. . . . few recognise that warm clothes may become as essential as either food or guns. (O'Brian, 1942:512)

A Pepperell Fabrics advertisement "Mud to You…" makes the link between consumer shortages and military needs explicit: "Clothes, Clothes, Clean Clothes, War Orders Must Come First!" (*Life*, 1942:3). Promotional leaflets reveal how consumers were wooed to accept the new substitute fibers by arguments linking nature, via agriculture, with the laboratory. Fashion magazines such as American *Vogue*, *Harper's Bazaar*, *California Stylist*, and *International Textiles* introduced the new fibers in enthusiastic editorials, often only one step away from advertisements. These nevertheless provided the consumer—and the retail trade—with enticing, often rather overoptimistic information, thus creating social confidence about the acceptability of substitute fibers. The excitement generated by these fibers is demonstrated by their selection by the American Science Service (ASS) for their campaign popularizing science. This not-for-profit organization promoted news coverage of "useful scientific information 'to the masses' by developing and disseminating stories about chemistry" (America Science Services, 1939; LaFollette, 2006). The development of man-made and synthetic fibers, including milk fibers alongside nylon and vinyon, came ninth in ASS's list of the 10 most significant scientific innovations of 1939. Whittier did a radio interview for ASS discussing "Wool from Milk," and listeners could request a free leaflet and a "synthetic" wool sample (interview script, American Science Service, 1939; LaFollette, 2006). The ASS developed a nationwide traveling exhibition on man-made fibers during 1939–1940. Displays in department store windows were sponsored by local newspapers, which published concurrent articles written by Robert D. Potter, a *New York Herald Tribune* science editor and a founder of the U.S. National Association of Science Writers who joined the ASS in 1934 (LaFollette,

FIGURE 2. Women admiring the ASS display of man-made and synthetic fibers, including Lanital, in the window of Woodward & Lothrop, a Washington, D.C., store, ca. 1938–1939. Courtesy Smithsonian Institution Archives, image 2005-10444.

2006). For example, the *Washington Daily News* supported the display in Woodward & Lothrop, a Washington store (Figure 2). A Lanital garment was flanked by nylon stockings and rayon fabric lengths together with samples of chemicals. The spiderweb design on the window signified the spinning of artificial fibers (LaFollette, 2006), again linking nature and science. The ASS authors argued that war had been a spur to American ingenuity and invention, ensuring the country would be "liberated from foreign imports that might fail in time of war" (LaFollette, 2006). Ironically, the fiber used in the exhibition is more likely to have been imported Italian Lanital as ARA's fiber was not yet available (*Rayon Textile Monthly*, 1939:304).

Although no evidence has yet been found for ARA's involvement in this project, their promotion strategy was similar. Aralac was modeled as "The Wonder Protein Fiber," thus overlaying its substitute aspects with technological excitement and converting substitution into modernism and futurism. Atlantic Research Associates might use quirky puns and humorous images, but their underlying point was serious—innovative, modernistic, and patriotic fibers were needed at a time of crisis. Dirks (2000) argued that the early sales campaigns for Aralac promoted it as a wool replacement, but this changed after the start of the war when its separate identity as a new "wonder fiber" was the important factor. The NDPC's promotional leaflet *The Cow, the Milkmaid and the Chemist* exemplifies this approach:

> Aralac identifies a completely new fiber. Nothing like it has ever before existed. Though it has many of the properties of wool—it is *not* a wool . . . Aralac is itself—a fiber standing on its own merits—possessing characteristics distinctly its own—and is *not* a substitute for something else. Neither is Aralac a mere "duration" material. Its development was well under way when war struck. It came into being because from the first—it gave promise of being a material that could be used advantageously—under all conditions—and at all times. (Aralac, Inc., n.d.)

In contrast to the visual sophistication of Aralac's logo linking agriculture, science, and fashion (Figure 3), this leaflet has naïve cartoonlike drawings with a smiling cow (Figure 4). The

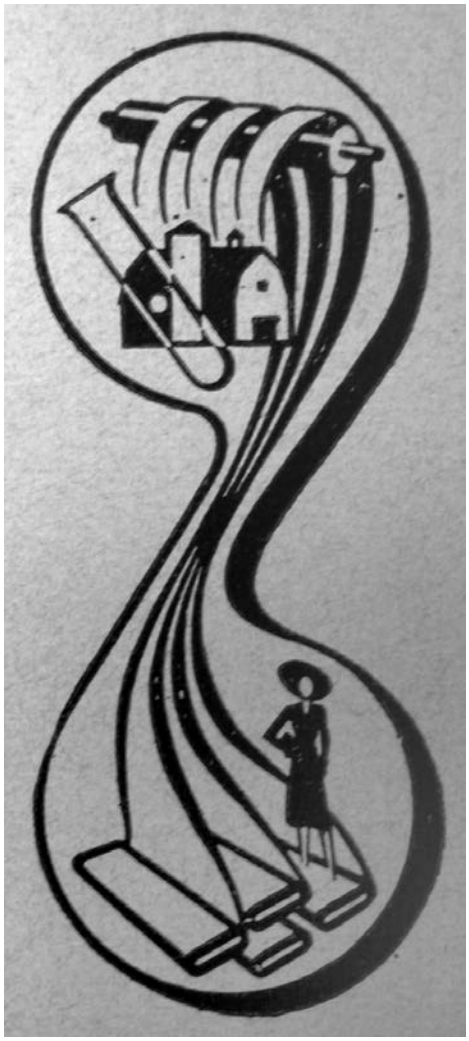

FIGURE 3. One version of the Aralac logo. Aralac, Inc., a division of National Dairy Products Corporation.

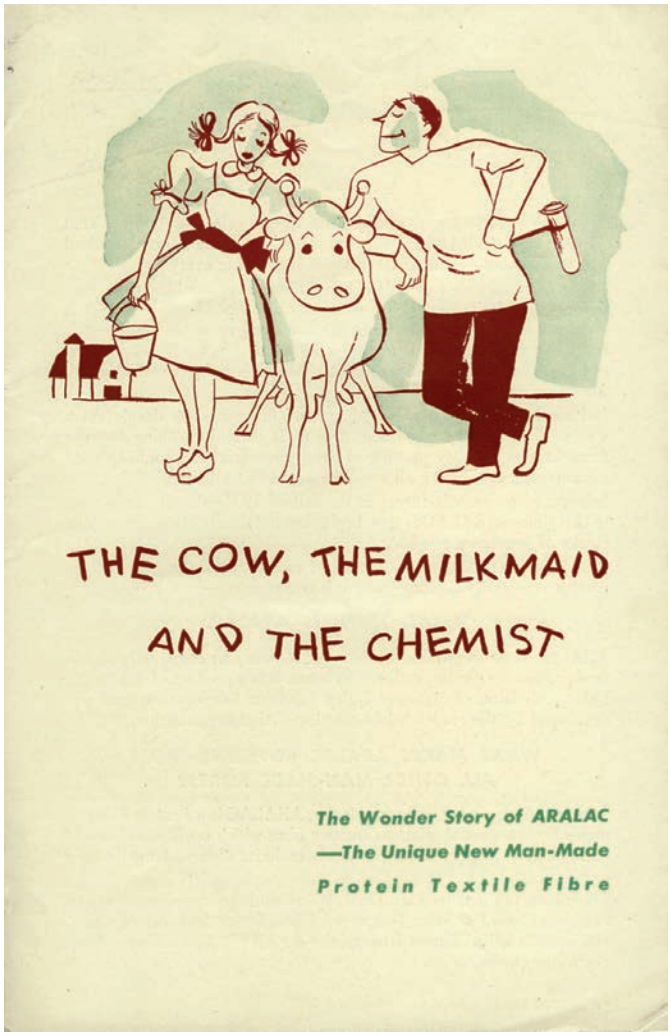

FIGURE 4. Aralac promotional leaflet *The Cow, The Milkmaid and the Chemist*. National Dairy Products Corporation.

childish milkmaid is contrasted with a stereotypical white-coated male scientist. The light tone explaining the fiber's chemistry and extolling its virtues was aimed at overcoming resistance to the unknown by enthralling potential purchasers with the fiber's innovative, scientifically created qualities with a strong nationalist undertone: "Attempts have been made in other countries to produce a similar fiber—but it remained for American ingenuity to perfect it" (Aralac, Inc., n.d.).

Aralac was marketed through press and advertising campaigns, supported with displays in department stores such as Macy's (*Rayon Textile Monthly*, 1942:549). The "It's Aralac" series of advertisements features sophisticated garments made by American designers, suggesting a promotional campaign on the part of NDPC to raise the fashionable status of the fiber. Only Claire McArdle seems to have been interested in using the fiber in its own right. This interest would have been in character as she was famous for her innovative application of "unpretentious materials, such as denim, cotton calico, and industrial fastenings for fashion clothes" (Steele, 2000:190). Despite this positioning of Aralac as a fashionable fiber associated with Hollywood film stars such as Jane Wyman and Dorothy Lamour, who promoted the "Vitamin Coat" costing $22.75, it seems likely that the majority of sales were mass market. Mail-order catalogs such as Sears and Montgomery Ward offered coats containing Aralac fiber priced at a much more modest $9.98.

Other manufacturers also tried to satisfy consumers' conflicting desires for fashionable and the economical. After the war, Vicara fibers were promoted as possessing "Uniformity, Beauty, Versatility, Economy, Ease in Use" while demonstrating their chic by associating them with garments designed by French

couturiers such as Fath, which interestingly contrasts with the anti-Paris fashion rhetoric of some of NDPC's Aralac promotion. Imperial Chemical Industries, promoting Ardil in postwar Britain in the grip of rationing and economic restrictions, did not attempt to evoke the fervid futurism and patriotic modernism seen in the American or Italian rhetoric. Although the journalist Chapman Pincher's excited vision of "Synthetic Man," clad in man-made and artificial materials, including a "ground nuts, rayon and nylon suit" (Pincher, 1952:6), was certainly modernistic and the *News of the World* (1956) welcomed Ardil as "among the wonders of the post-war world," ICI's tone was generally much more muted, reflecting austerity, changing attitudes to women's role and, possibly, the concerns within the company over the fiber's technical and economic viability.

Their advertisements in women's magazines and newspapers sought to convince consumers that Ardil was similar to, if not surpassing, natural fibers while being more economical: "warm and absorbent, like wool. Comfortable because it is soft and smooth—like cashmere and silk: clothes with Ardil cannot irritate even the most sensitive skins" (*Good Housekeeping*, 1955:16). Great play was made of its ability to "give clothes the unmistakable touch of luxury at prices you can afford" (*Woman's Journal,* 1956:4).

Although his unnamed fiber does not appear to have been advertised to consumers, Ford was a brilliant publicist. The Ford Motor Company's "Textiles from Soybean Protein" exhibit at the 1939 New York World Fair demonstrated the production process with the spinning solution dyed blue so that the thread would be visible as it formed. Ford had two soybean fiber ties made and wore one to his seventy-fifth birthday celebrations in Detroit, providing journalists with ample copy. Posing in a field wearing his famous soybean fiber suit was a perfect photo opportunity, enabling Ford to promote both his chemurgic vision and his fiber. According to his employees, this suit was far from being an entirely successful garment. Crump recalls the fabric was so itchy that Ford wore it only for photo calls (C. Crump, "Soy Coffee, Soy Cookies: Buffet Salutes Virtues of Ford's Beloved Bean," *Ann Arbor News,* 1988, as summarized in Shurtleff and Aoyagi, 1994:174), whereas Boyer apparently acknowledged that its strength was so poor that Ford was forced to move extremely cautiously (F. R. Bryan, *Henry's Lieutenants*, 1993, as summarized in Shurtleff and Aoyagi, 1994:184–185).

CHANGING ATTITUDES TO THE ERSATZ

Analyzing the rhetoric associated with regenerated protein fibers shows complex shifts from excitement to disillusionment. The representation of regenerated protein fibers reflected changing financial and political contexts as well as the availability of other new fibers. Initially, many expected great things from these fibers:

> Fibers have been formed from the proteins of milk, soybeans, peanuts, corn, fish, chicken feathers and eggs. All of these materials are potentially abundant and cheap, and the quantities going to waste throughout the world, if made into fibers, would probably be sufficient to keep every man, woman and child well clothed. (Sherman and Sherman, 1946:191)

They were modeled as futuristic and utopian, free of limiting historical traditions, and linked with ideas of democracy, health, and emancipation, an accessible symbol of the modernistic project (Schnapp, 1997). The ASS highlighted the futuristic aspects of these scientific advances, linking patriotism and financial benefits with patriotic self-sufficiency—a democratic version of autarky. Science was magic that, through wizardry, alchemy, and ingenuity, transformed waste materials into essential war fabrics for the fashionable woman. Research chemists became unlikely heroes: "In this period of nationalistic tendencies, economic uncertainty, and surplus agricultural crops, research chemists have an unusual opportunity to be of real and lasting service to society" (Brother, 1939:148).

But the idea of the ersatz was constantly challenging and potentially undermining. Manufacturers themselves sometimes exhibited ambivalent attitudes toward being perceived as producers of substitute—and by implication—inferior fibers. This profound ambivalence about the value of ersatz materials and their desirability (or otherwise) meant that creating a strong and positive commercial identity for regenerated protein fibers was vital through the development of distinctive names, logos, and dramatic marketing campaigns (Brooks, 2006). Their chosen names reveal both the fibers' inherent status as substitutes and the strategies used to overcome this perceived inferiority and invisibility. Subtlety of language and carefully constructed arguments were needed to convince people that ersatz materials were worthwhile. Thyssen observed,

> The Nazis go about trumpeting to the world everything that they think is a discovery. They have made much ado about the so-called new raw materials invented under the Four-Year Plan. Ingeniously, they have called them neue Werkstoffe—new production materials—so as to avoid the word ersatz which has had so bad a sound ever since the last war. (Thyssen, 1941:185)

Underestimating the potential of the ersatz was also a risk. Hurstfield (1953:351) noted that German research into substitute materials "was insufficiently understood in the democracies while the very term for substitutes, ersatz, acquired in the West a derisory connotation." However, misreading innovative substitutes as inferior products was a mistake as it underestimated the technical and scientific expertise they represented: "these materials were characteristic of the most advanced practice of the contemporary chemical industry" (Reader, 1975:33).

However, the utopian scientific vision for regenerated protein fibers quickly became dystopian, and the image of modernity failed under the pressure of the twin realities of the fibers' poor performance and the development of better-performing

synthetics. Margaret Atwood evokes this rejection in her novel *The Blind Assassin* (2000:275):

> Richard had been approached to make an investment in a new fabric the Italians were developing—very hush-hush—made out of heated milk protein. But if the stuff got wet, said Richard, it smelled horribly of cheese, and the ladies in North America would therefore never accept it.

FORGETTING REGENERATED PROTEIN FIBERS

Fiber reputations undoubtedly go through cycles (Schneider, 1994). After the war, the reputation of regenerated protein fibers plummeted rapidly: "What had appeared as an unattractive wartime substitute for natural fibers and the industry had to consider whether improvements in quality and reductions in cost could present it as a desirable fiber for commercial use" (Coleman, 1969:185). With the exception of work such as that of Koch (1972) and Dirks (2000), relatively little published research into these fibers exists. They disappeared quickly from standard textile handbooks. Earlier books from the 1940s, 1950s, and 1960s tended to include enthusiastic and relatively detailed reviews, but these dwindled down to paragraphs and then sentences before ceasing altogether. By the 1960s, phrases such as "of historical interest only" or "obsolete" become common. If these fibers slip out of written histories, it would seem reasonable to expect to find identified examples of regenerated protein fibers surviving in museums. Surprisingly, they are rare, and there are few collections with examples of complete garments, although collections of fiber and fabric samples do survive, notably at the University of Leeds International Textiles Archive (ULITA; Walsh, 1987); the Whitworth Art Gallery, Manchester; the Smithsonian Institution, Washington D.C.; and the Power House Museum, Sydney. A survey of over 50 costume, textile, local, technical, and industrial museums in America carried out in 2002 produced positive results in terms of curatorial interest but no information on identified artifacts in the collections. The difficulty in identifying and cataloguing such pieces is possibly because, unless manufacturers' names or labels provide a clue, there is little physically to suggest the presence of an unusual fiber. Even when a name is present, it can remain unrecognized or give rise to uncertainty, not to say confusion, further contributing to azlons' disappearance from cultural memory. Regenerated protein fibers may have literally disappeared from material culture or been cut up because of their technical weaknesses. Freda Moody recalled that Ardil garments her father brought home performed so badly that "few of our clothes were kept and [they] ended up as dusters." Her mother cut up garments containing Ardil to use as patches to repair a quilt (Moody, pers. comm.). However, there are deeper reasons why these fibers have been forgotten within the span of a generation. In postwar Britain, with rationing still in force, using protein for fibers seemed wrong. Wormell (1954:xiii) asked, "Why use good food to make poor wool?" Moncrieff (1970:295) made the same point: "As to whether it is ethically justifiable to convert a valuable foodstuff into a fibre is open to question." Azlons became remodeled as inferior substitutes and commercial failures—an experiment to forget rather than remember. Association with these fibers had a depressing effect on some key researchers' careers. After leaving Drackett, Boyer, a pioneer researcher into soybean fibers for both Ford and Drackett, suffered a long "wilderness period" before turning the technical difficulties in creating a viable textile fiber to advantage and, somewhat ironically, developing spun soy protein for food.

Rubbish Theory and the Status of Azlon Fibers

The trajectory of the twentieth-century azlon fibers is thus one of physical loss, and textual loss which fits well into the "rubbish theory" model developed by Michael Thompson. A social anthropologist with a keen interest in material culture, Thompson applied mathematical analysis to exploring why some artifacts are considered valuable or valueless in particular cultures at certain times and how and why this status changes. Rubbish theory tracks shifting values applied to objects and the changing "relationship between status, the possession of objects, and the ability to discard objects" (Thompson, 1979:1). This theory enables a systematic understanding of how and why some things lose not only their commercial value but also their cultural values and meanings and why it is thus possible for them to become physically discarded and culturally lost. Of course, the alternative journey to recovery is also possible. Under certain conditions, some artifacts may be shifted from the literal and/or metaphorical rubbish heap to become revalued both financially and commercially and thus desirable and collectable again. Thompson used the categories of "transient" and "durable" to categorize these contrasting destinies. Objects in the transient category decrease in value over time and have finite life spans. Objects in the durable category increase in value over time and, conceptually at least, have infinite life spans (Thompson, 1979:7). This model is particularly relevant to the changing values placed on substitute and/or synthetic materials and shifting attitudes towards the ersatz and, by extension, to the changing values placed on other materials such as man-made plastics. It helps us to understand the cultural shifts that meant ersatz materials were at first seen as desirable but became tainted and undesirable. In Thompson's terms, fibers that had been intended as durable became transient and could thus be literally and metaphorically discarded and so slipped from cultural memory.

CONCLUSIONS

There is considerable evidence of the importance of regenerated protein fibers used as substitute fibers in both the Allied and Axis war economies and the efforts that were made to make these

FIGURE 5. New York fashion show (*Rayon Textile Monthly*, 1944a:543).

fibers acceptable to consumers in increasingly restricted marketplaces. For a brief moment, regenerated protein fibers seemed to be the fibers of the future. At a 1944 New York fashion show to promote new fibers, the elegantly dressed mannequins are shown stepping out of stylized test tubes wearing garments made from both azlons and synthetic fibers (Figure 5). In the battle of the fibers, the synthetics won, but there was a moment when both fiber types held equal sway. Technical problems meant that regenerated protein fibers could not compete effectively with either natural fibers or the newly developed synthetic fibers. They lost economic viability after the war when wool prices slumped. The tension between manufacturers' attempts to create a high-fashion image for these fibers and their more likely role as mass-market fashion fibers probably helps to explain why, after the war, these fibers were rejected, associated in some countries with reduced choices, legal restrictions, and even with fascism. Their status changed from exciting, modernist, patriotic, and fashionable fibers to failed, forgotten fibers, associated with a period of deprivation and substitute materials. The negative image of the ersatz returned to dominance as these fibers became perceived as imitations of desirable and unobtainable natural fibers. They failed to become mainstream, and despite the extensive time, energy, investment, and promotion lavished upon them, by the first decade of the twenty-first century they had been largely forgotten by manufacturers, consumers, and textile historians. Nevertheless, these unusual fibers played a part in creating a unique wartime fashion and have extraordinary social, cultural, and political resonance. The third generation of regenerated protein fibers, combined with synthetics using biochemistry, may yet "astonish the world."

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Is It Real? Imitation and Originality in Plastics

Robert Friedel

ABSTRACT. It is a commonplace that the first artificial plastics were used largely to imitate more precious materials. The best example is the widespread imitation of ivory in celluloid products between the material's introduction in about 1870 and its declining popularity in the second or third decade of the twentieth century. On the basis of extensive examination of the Perlov Collection of celluloid acquired by the National Museum of American History, this chapter challenges the characterization of this ivory appearance as simply an imitative effect. The ivory look became, in fact, the hallmark of celluloid's own appearance. When the plastic was used for a variety of purposes, from pocket calculators to notepads to advertising signs, the ivory effect given to celluloid was meant to enhance the value and recognition of the plastic, not to imitate or mimic the traditional material.

INTRODUCTION OR THE VALUE OF IMITATION OR . . .

About 30 years ago, I coined the term "pioneer plastic" to refer to celluloid, the first generally used synthesized plastic material. When celluloid was introduced in about 1870 by a manufacturer in Newark, New Jersey, no other materials had the properties of being easily molded and readily available in a range of colors and visual effects while at the same time being tough and flexible. The "natural plastics," themselves largely new to most craftsmen and manufacturers in the mid-nineteenth century, were materials like shellac and hard rubber, and these were far less versatile. Celluloid, as a pioneer, established technical, economic, and cultural norms for myriad plastics to come.

A representative array of celluloid articles conveys some specific images to the modern viewer. The material is usually shiny, even polished, in appearance. In most uses its ready moldability is obvious, as many objects display complex shapes, chasing, and other forms that would be very laborious to apply otherwise. Most prominent, however, are the surface effects. There would be, in a large collection of materials (such as represented by the Perlov Collection, recently acquired by the Smithsonian's National Museum of American History, NMAH), a wide range of colors and decorations. Most prominent among a typical collection would be objects looking, at least superficially, like ivory. Ivory objects of almost every size and description dominate—toilet sets, letter openers, party favors, toys, even signs, badges, and advertising cards. Ivory may be joined by other visual effects, simulating coral, tortoiseshell, or amber. Above all, the basic impression celluloid conveys is imitation.

For several decades, scholars (me included) have largely characterized celluloid's role as imitating finer and more expensive materials. The prevalence of the ivory form, in particular, supports this characterization (Figure 1).

The sort of elaborate toilet sets shown in Figure 1 has long stood as the prototypical example of celluloid and its role of democratizing luxury through astonishingly good and convincing imitation of pricier materials (although it could be argued that this particular pink mother-of-pearl might be pretty hard to find in nature, at whatever price). This long-lasting and convincing imitative role has been one basis for a kind of dichotomy

Department of History, University of Maryland, College Park, Maryland 20742, USA.
Correspondence: R. Friedel, friedel@umd.edu
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FIGURE 1. Examples of toilet sets imitating ivory and mother of pearl. National Museum of American History, Smithsonian Institution; photo by Ann Seeger.

that has colored the historical interpretation of plastic for decades. My own interpretations of celluloid included it (Friedel, 1983:86–89), and Jeffrey Meikle, as he so often does, has put the case even more clearly:

> Mid-twentieth-century design critics tended to judge plastic by strict either-or categories. On the one hand, "regressive" manufacturers imitated traditional materials with ever more convincing results, hoping to gain by reducing processing costs without alienating naïve consumers who demanded clearly "domestic" surroundings. On the other hand, "enlightened" consumers preferred artificial objects whose plastic forms suggested the outlines of a future technological environment. A split earlier defined by celluloid collars and Bakelite radios survived decades later as an almost schizoid aesthetic. (Meikle, 1996:183–184)

Meikle went on to admit, however, that "to argue about imitative plastic versus plastic-as-plastic was to ignore a vast excluded middle." He pointed to all sorts of explicitly plastic objects that have vaguely imitative elements—like plastic daisies on a wastebasket—as occupying this middle ground. But in the "flood" of plastics appearing in the mid-twentieth century, he saw this ground as an aesthetic desert: "Although some artifacts did evoke modernity, most remained stylistically 'rubbish,' too anonymous and ephemeral to do more than add to a vague consciousness of an ever greater flow of plastic" (Meikle 1996:185–186).

This class of the "anonymous and ephemeral" deserves more attention, however. These objects need to be appreciated for what, in even the earliest plastics, they can tell us about material, design, and originality. To be sure, the finer pieces represented by celluloid, such as the "tortoiseshell" comb, are indeed spectacular examples of imitation and even deception (Figure 2).

FIGURE 2. Celluloid comb imitating tortoiseshell. National Museum of American History, Smithsonian Institution.

Victorian critics, such as John Ruskin or Charles Eastlake, commented on both the dangers and virtues of imitation. On the one hand, imitation was a threat to one of the core values of art—sincerity—and the machine-oriented imitation of celluloid manufactures was a fundamental threat to the values of craftsmanship. On the other hand, Ruskin maintained that skillful imitation was a source of real aesthetic pleasure, particularly when it stopped just short of true counterfeit, that is, when it gave evidence of its real intentions: to honor the natural by imitating it but not going so far as to be "fake."

It is in this "middle ground" between imitation and an avowedly plastic aesthetic that the question "Is it real?" becomes more central to our appreciation of the material and its uses. In some cases, as in the picture frames from the current display of the NMAH's Perlov Collection shown in Figure 3, there is still a high aesthetic in the uses of celluloid at the same time that the imitative effects become a bit more ambiguous.

But it is really to the truly ephemeral that we need to turn—the host of objects that were never expected to have a future or any long-term use, objects never supposed to have even an "aesthetic value." The Perlov Collection has not hundreds, but thousands, of these items, and this abundance is something that few historians have paid any attention to.

FIGURE 3. Two examples of plastic picture frames from the Perlov Collection. National Museum of American History, Smithsonian Institution.

Many of these objects go by the name "novelties," which is, in itself, a curious kind of terminology. Consulting the *Oxford English Dictionary* doesn't help, as it refers only to "some things that are new." The term comes to mean, in the nineteenth century, small objects of modest value, typically given out as premiums or souvenirs or advertising or possibly sold for very small amounts. As such, novelties were expected to be manufactured in quantity, in multiple, identical copies. There are actually two historical roots for this trade, and to understand the significance for plastics, it is worth taking just a quick historical look at both.

BRIEF HISTORICAL BACKGROUND

One of these roots lies back in the seventeenth century, in what came to be known as the "toy trades." The classic locus of this was the English town of Birmingham, where iron and brass workers took advantage of new materials and novel ways of working them, as well as of emerging forms of marketing, to set up hundreds of shops for turning out small goods, not all of them, of course, "toys" in the literal sense but most aptly recognized by small devices of cast or sheet metal. Tellingly, many of these were painted so that they came to look more valuable than they actually were. The most famous form of these painted and decorated items went by the term "japanware," after the shellac composition used to coat sheet iron or tin and make the result look more like fine Oriental lacquer work (Figure 4).

Later, papier-mâché became a favorite material for such elaborate objects as tea trays. Manufacturers like Matthew Boulton, who became James Watt's indispensable partner in the steam engine, made their fortunes in making buttons, buckles, and other small objects. Toy soldiers were another large seller for the toy makers. The lineage from these mass-produced items to the late nineteenth century celluloid novelty makers is not a hard one to construct (Friedel, 2007:247–251).

The other primary historical root for these articles lies with printers. From the first presses in the mid-fifteenth century, printers had produced by the hundreds and the thousands identical small handbills, cards, prayer sheets, and other ephemera. Here, too, the linkage to the mass production of small manufactured

FIGURE 4. A painted tinware tray. Photo R. Friedel.

articles in the late nineteenth century is readily apparent. It is curious, therefore, how little attention has been paid to this linkage. Another NMAH collection, printed items from the shop of Baldwin & Gleason of New York, found in the graphic arts collections, illustrates some of the connections that can be made (Figure 5). Baldwin & Gleason made printing on celluloid one of their specialties, and they appear to have enjoyed some success (Figure 6).

The significance of some aspects of the Smithsonian collections can now be seen in a different light. Printed objects of a great variety are everywhere. Even objects that are not simple cards, like the score keeper shown in Figure 7, are handsomely printed. The most dominant impression they give, however, is that of being "ivory." Of course, they are not ivory in any convincing sense, but they, and many, many objects like them, particularly in the category of novelties, do appear to be ivory;

FIGURE 5. Front and back of printed celluloid card from Baldwin & Gleason, Graphic Arts Collection, National Museum of American History, Smithsonian Institution.

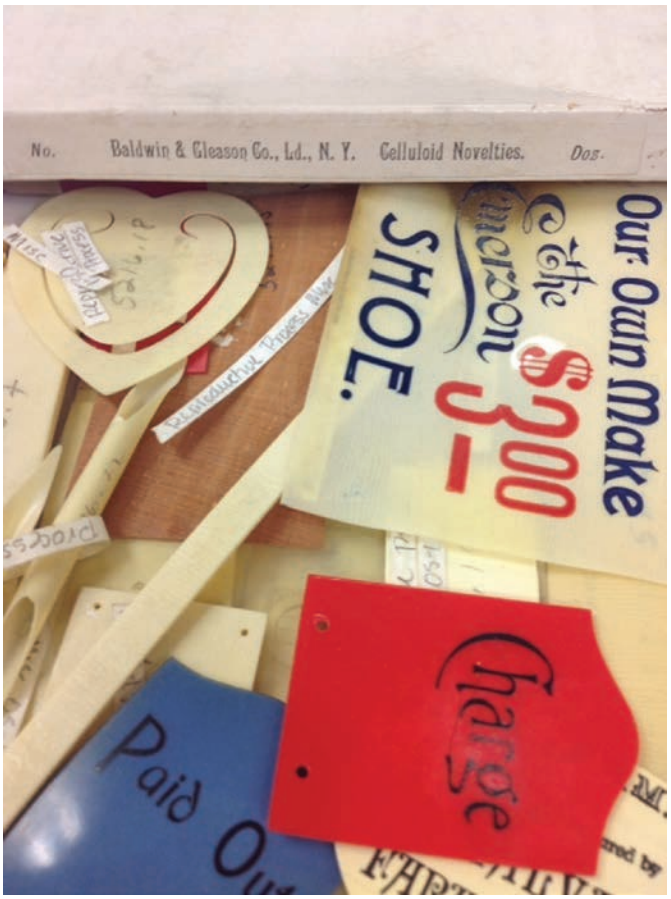

FIGURE 6. Celluloid cards and signs printed by Baldwin & Gleason. National Museum of American History, Smithsonian Institution.

further, these items are not simply an ivory white—the striations of true ivory, complete with their waviness and imperfections, are produced in the most convincing way.

Devices intended for practical applications, although often given out as what we might call "specialized novelties," maintain the same aesthetic that dominates the printed ware and the familiar giveaways. It is the series of very practical, utilitarian calculators for things like drill bits and ball bearings rendered in perfectly reproduced ivory celluloid shown in Figure 8 that is perhaps the most startling to contemplate. It has been remarked before that celluloid's imitation ivory was used for many things that would never have been ivory, but the phenomenon deserves greater scrutiny. The strict division between plastics as imitation and the modern plastics aesthetic is simply inadequate to describe fully the way in which early plastics made their way into the world of everyday objects and design.

The ivory form, in particular, constituted a fundamental identity for celluloid. That materials capable of a wide range of appearances tend to settle into only a small number of widely accepted forms is a common but often overlooked phenomenon. Thus hard vulcanized rubber—naturally a muddled brown or amber color—becomes unshakably associated with jet black.

FIGURE 7. Mock ivory score keeper, front and back. National Museum of American History collection, Smithsonian Institution.

The same happens later to Bakelite, although with a few exceptions. Polymethyl methacrylate—Lucite or Plexiglas to use the most common trade names—is firmly associated with glass-like transparency, although it lends itself readily to colorful effects. Rarely, however, do such instances include the identity with an appearance that requires the extra effort, with no technical benefit, that making imitation ivory involves.

To be sure, the celluloid makers were ready and even eager to make the association between their material and substitution for precious substances central to the material's identity: "As petroleum came to the relief of the whale," the Celluloid Manufacturing Company declared in an oft-quoted passage, "[so] has celluloid given the elephant, the tortoise, and the coral insect a respite in their native haunts" (Meikle, 1996:12; Freinkel, 2011:17). This idea of celluloid as fundamentally a substitute has so strongly colored its image in modern interpretations that an issue of *Chemical Heritage* features a cover story on "Celluloid—the Eternal Substitute." Here once again we see the characterization of celluloid as a "second-class material," valued only as "a substitute, a plausible counterfeit of natural materials" (Boyd, 2011/2012), until it was rescued from this fate by the development of photographic and movie film at the end of the century.

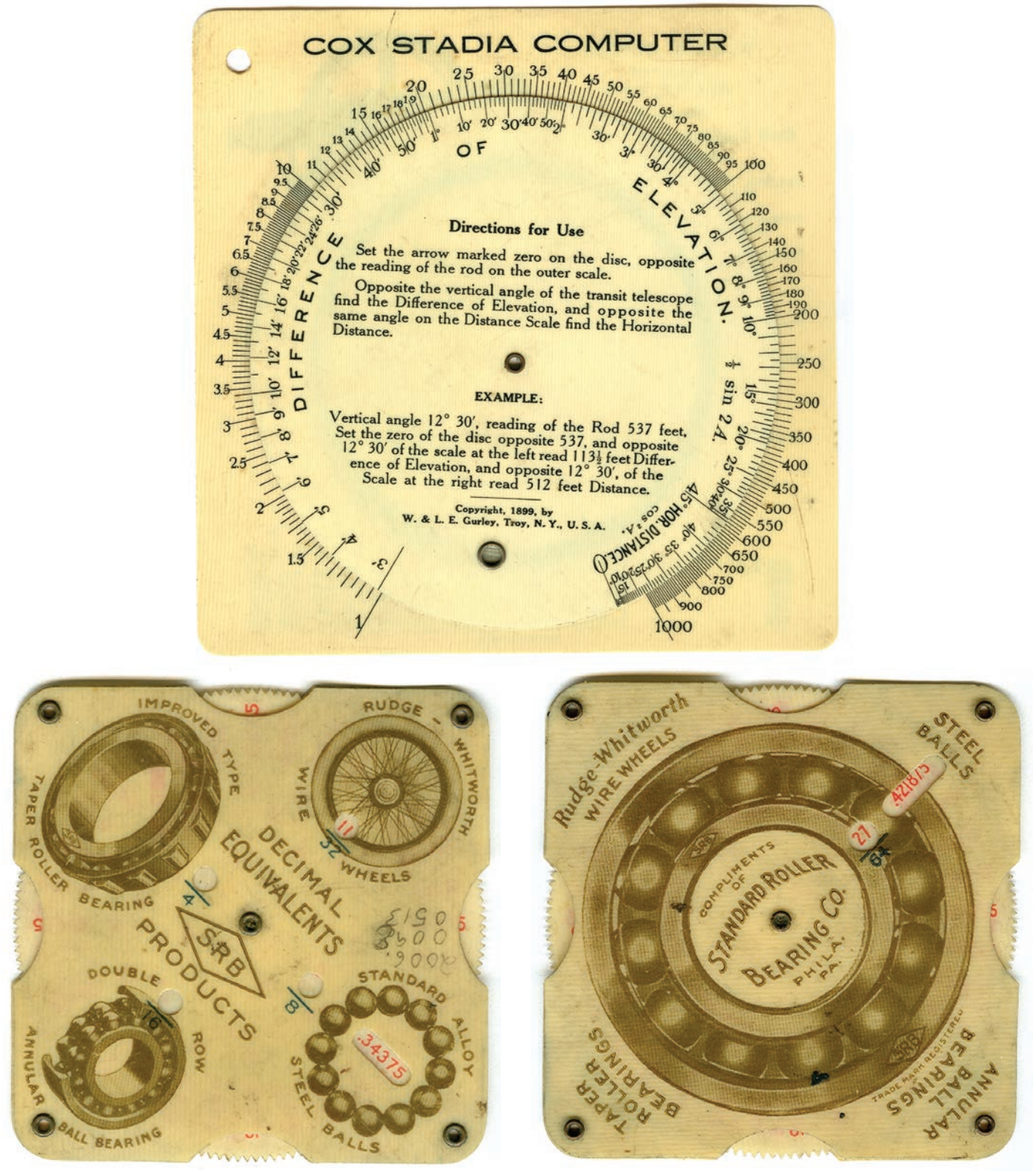

FIGURE 8. Practical calculators in celluloid. Note the high quality of the mock ivory for the item on the top. The back and front of a ball bearing equivalence calculator are shown on the bottom. National Museum of American History collection, Smithsonian Institution.

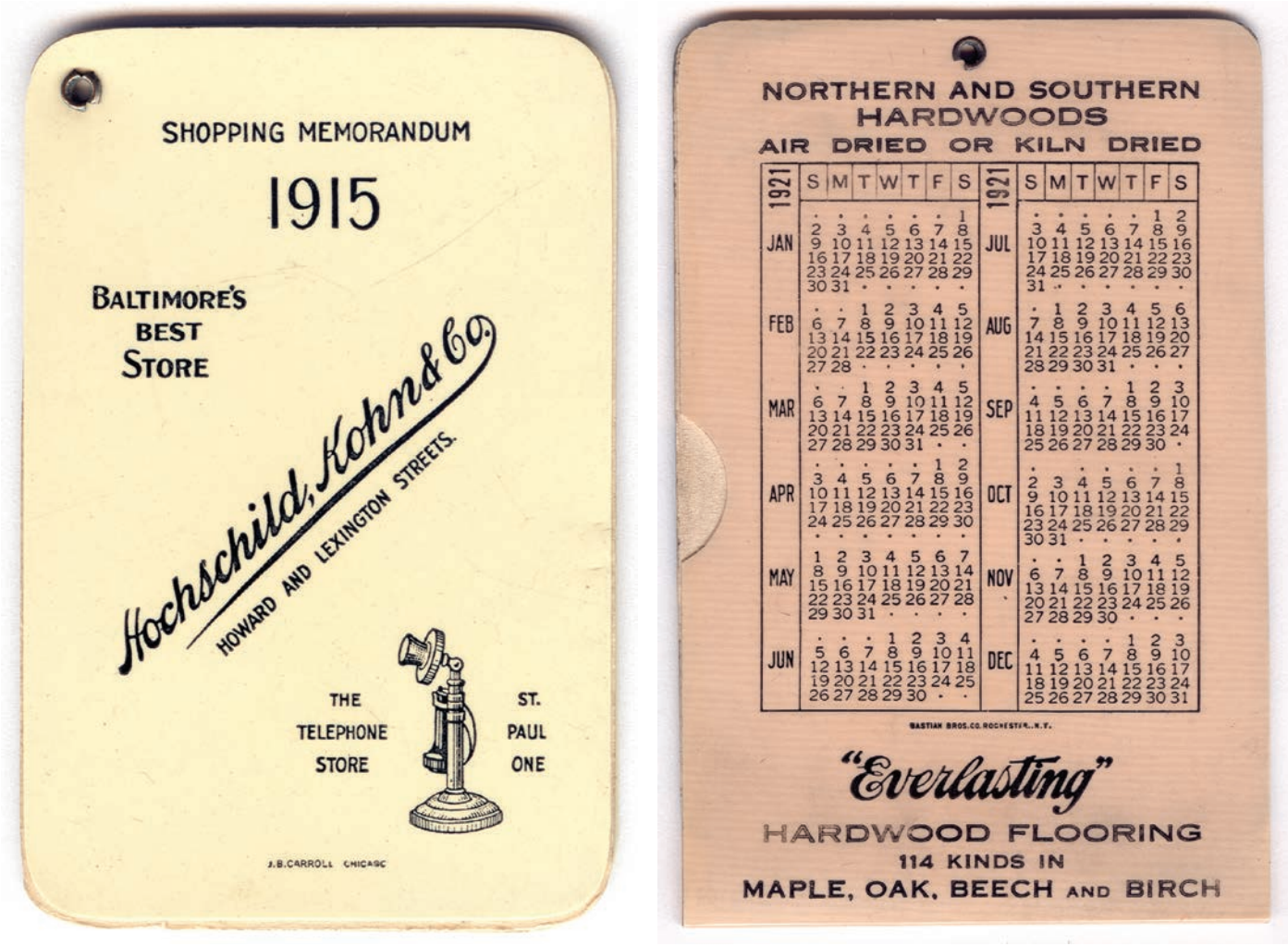

FIGURE 9. Two celluloid objects from the National Museum of American History that are actually replacing paper objects. National Museum of American History, Smithsonian Institution.

What was celluloid actually substituting for in the objects shown in Figure 9? More than anything else, it is, in fact, paper or cardboard. In other words, we are substituting a clearly more expensive plastic for a cheaper, familiar alternative. In addition, of course, as has been noted, the plastic—the celluloid—has been given the fancy appearance of artificial ivory, even though it is abundantly clear that one would never use, or ever want, ivory in these articles.

One detail worth pointing out here is the great range of dates covered by these items. The calendars allow us, of course, particularly easy dating, so there are pieces ranging from the 1880s to the mid-1920s. Presumably, by 1926, when the Baltimore department store Hochschild, Kohn & Co. gave out the note holders for "shopping memoranda" in Figure 9, celluloid was a somewhat old-fashioned material. Nonetheless, the habit of producing and distributing novelties of the material and of using the ivory form dominantly persisted.

Note also that celluloid can, indeed, still be deemed a "substitute," but it is substituting not for more expensive materials, such as ivory (despite the appearance) or shell or the like, but for cheaper materials, like paper or cardboard or, perhaps, thin sheet metal.

More complicated novelties persisted as well, from score keepers (Figure 7) to cigar cutters and reminders of trump suits (Figure 10). It is harder to say just what celluloid is substituting for in the trump suit reminder. Indeed, some of these items might simply not be made at all without the plastic, although it is hard to claim that celluloid is somehow uniquely suited for these uses. There is, in fact, a real level of originality in the uses of this first plastic.

FIGURE 10. A cigar cutter and a trump suit reminder in celluloid. National Museum of American History, Smithsonian Institution.

As mere novelties, it is easy to overlook these objects, to see them not only as ephemera, in the technical sense, but as ephemeral and unworthy of notice. But perhaps here is where we see some of the material's real significance, even in its earliest days.

FINAL CONSIDERATIONS

Celluloid, perhaps above all, did in its gentle, and sometimes subtle way, usher in different principles of design and good taste. Charles Eastlake could declare in a work first published in 1868 on the eve of celluloid's invention and then reprinted throughout the nineteenth century in both Britain and America that "every material . . . is obviously restricted by the nature of its substance to certain conditions of form. . . . Whenever . . . the material is allowed to assume in design an appearance which is foreign to its own peculiar attributes, the result is invariably inartistic and vulgar" (Eastlake, 1969:185–186). But celluloid ushered in new possibilities, not only in manufactures and effects but in conceptions of design itself.

The ivory that seems so blatantly to announce imitation in celluloid is also an announcement of its own identity. We should not blame the material's users for what seems in hindsight to be a remarkable conservatism of appearance but instead celebrate the originality with which they exploited the material's virtues and possibilities.

Indeed, the observers of early plastics might well ask "Is it real?" when encountering a host of products, from brushes to fans to souvenir knives. But the uses of the material, over the course of more than half a century, particularly in the obscure little bits of life, made it very clear that it was as real as any material and opened up new opportunities for design, originality, and profit.

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Advanced Materials Used in Space Suit Construction

Bill Ayrey and Linda Hewes*

ABSTRACT. The materials used in space suits are very diverse and serve multiple purposes. They protect against the known hazards of space such as solar and galactic radiation along with micrometeoroid impacts, but they also need to ensure that the occupants are securely encapsulated within a pressurized system that provides a constant flow of oxygen, body cooling, and all of the mobility they need to safely and efficiently carry out their tasks. The development of early space suits came at a time when DuPont was producing many advanced materials for common use that would ultimately find their way into these suits. Materials such as Mylar worked to reflect the radiation, whereas Nomex and then Beta cloth provided protection against high temperatures. Nylon helped to hold the suits together under internal pressures without elongating, whereas spandex did elongate and comfortably encapsulated the wearer with 300 feet of polyvinyl tubing that contained the flow of cold water for the removal of body heat. This miniature space ship had to allow the elbows to flex and the lower torso to walk. Current space suits still use many of these materials, and improved versions of these are used in advanced space suits.

INTRODUCTION

Plastics became popular around the time the earliest space suits were being developed. Their engineers relied on plastics to provide the strength needed to support the internal pressures and also guard the wearers against the hostile environment of space. The first evidence of pressurized suits appears in this country around the 1930s, almost at the same time one was being developed by a Soviet inventor. The original, crude pressure suits did their job helping to set new altitude records while also ensuring that the wearers could safely land their aircraft on earth. From the start, special materials had to be used that would contain the internal air pressure without catastrophically ripping apart. At the same time these suits had to permit some degree of mobility that initially was very limited. Early on, the main materials of choice typically consisted of simple rubber-coated parachute fabrics. When looking at the names of the companies who developed the first suits, one can immediately guess what the main ingredient was. Companies such as B. F. Goodrich, the Arrowhead Rubber Company, and Goodyear Tire and Rubber all entered into the competition along with others. Even the later contributor to the Apollo space suit, International Latex Corporation, brought along many years of experience working with rubber blends used to develop bras, girdles, and other rubber-based products for World War II such as rafts and canteens.

Between 1948 and the early 1960s, DuPont contributed to a major advancement in fiber development by what can best be described as a "substitution of materials." During this period, DuPont created many new materials that improved upon thermal properties and provided flame resistance, higher elasticity, and strength (Gabara, 2010). Although initially made for earthbound purposes, the timing for providing these materials

ILC Dover, LP, One Moonwalker Road, Frederica, Delaware 19946, USA.

* Correspondence: B. Ayrey, ayreyb@ilcdover.com

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could not have been better as far as the manned space race was concerned. These advanced materials contributed greatly to increased mobility and provided protection from possible fire as well as from radiation and impacts from micrometeoroids traveling at 30,000 miles per hour. One interesting note is the fact that none of the advanced materials used in space suits to date were developed specifically for the suits. The space suit industry along with NASA looked for advanced materials that were available on the market at the time. A DuPont advertisement from the late 1960s demonstrates this fact (Figure 1).

The majority of the space suit materials were developed by very well respected chemists such as Wallace Carothers, Roy Plunkett, and others over a period of many years leading up to the manned space program. The list of materials includes the following, along with the approximate discovery dates:

- neoprene, 1930
- Teflon, 1938
- nylon, 1940
- polyester (PET), 1941
- Mylar, 1955
- spandex, 1959
- Kapton, 1962
- Nomex, 1962

WHAT IS A PRESSURE SUIT?

Space suits are also known as full-pressure suits. They encapsulate the wearer and rely on a pressure source to inflate the suit with 100% oxygen and maintain this pressure around the entire body. Although the history of full-pressure suits is relatively long, the most noted example of this style of suit was the one worn by Wiley Post in the mid-1930s. Post was an aviation record setter who knew that flying at 50,000 feet or higher meant that he could fly faster since there was less air, thus reducing drag on the airplane. As a result, Post worked with engineers at B. F. Goodrich to design a full-pressure suit to protect him as he flew for long durations in his unpressurized plane. The result was "a suit made of parachute silk, rubberized and doubled on the bias to give light weight minimum diffusivity and ease of fabrication

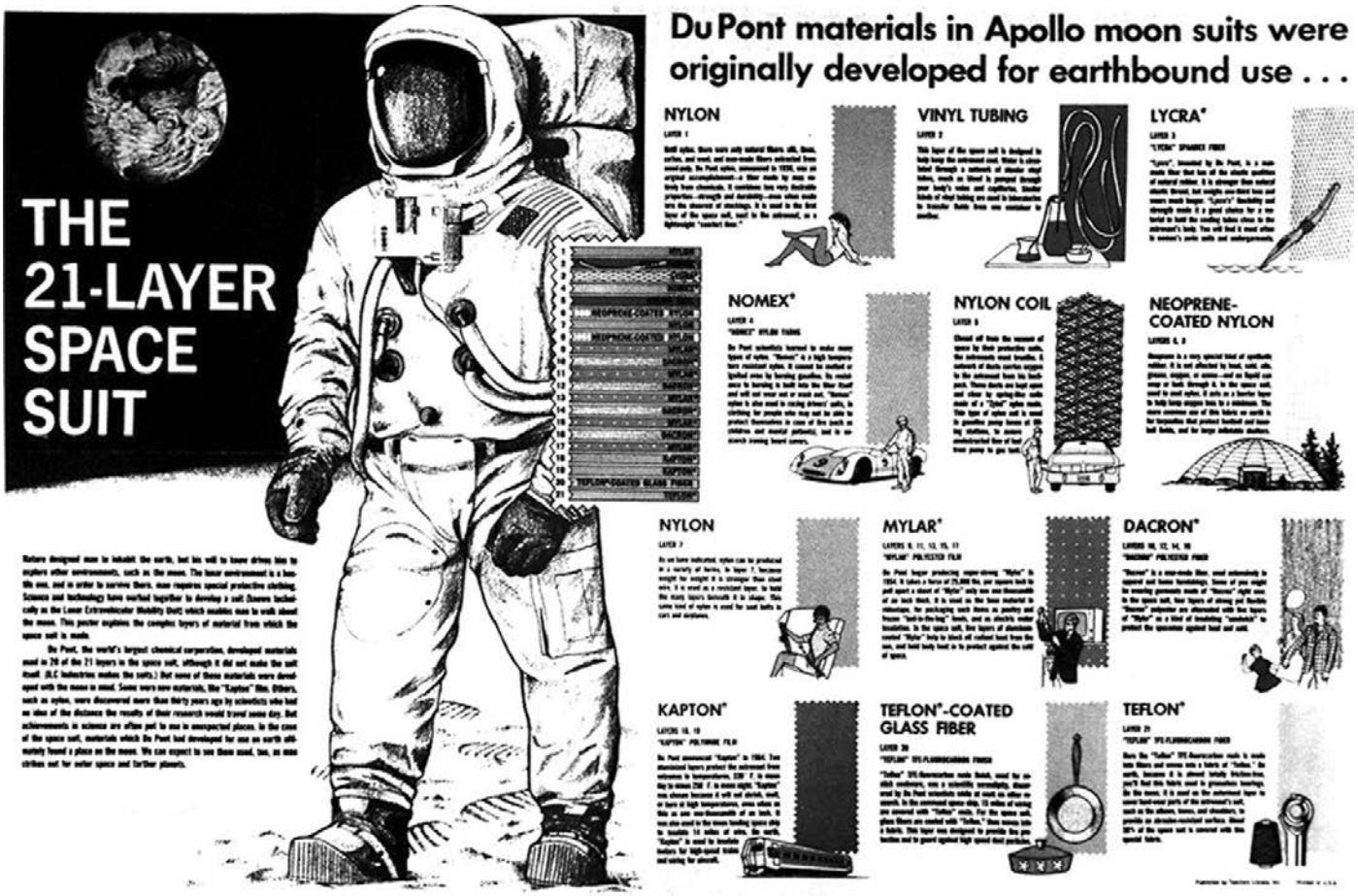

FIGURE 1. Early DuPont materials advertisement. Courtesy of DuPont.

on the sewing machines" (Mallan, 1971:27). Post went through three different suits during the development efforts. Both the first and second versions were made from only a single layer of rubberized silk that leaked excessively and ballooned beyond an acceptable range, thus providing very poor performance. The third suit featured an inner neoprene rubber layer to retain the pressure with an outer layer of heavy three-ply cotton cloth intended to hold shape and provide some limited mobility. This concept of a bladder within a restraint layer is still used today. Several records were set by Post, and the full-pressure suit that he wore proved the value of such a device (Figure 2).

FIGURE 2. The Wiley Post suit. Photo by Eric F. Long, National Air and Space Museum, Smithsonian Institution, SI 98-15012.

THE HAZARDS OF SPACE

Although there have been many varieties of full-pressure suits used by aviators over the years that have used advanced materials, the focus of this chapter is on space suits. Before proceeding, it is a good idea to explain the challenges of space travel. Simply put, human space travel exposes astronauts to the following hazards:

- total vacuum/no oxygen
- solar radiation and galactic cosmic radiation
- high- and low-temperature exposure due to radiant heat gain or loss
- exposure to high-velocity micrometeorites traveling up to 64,000 miles per hour
- touch temperatures between 302°F and –292°F (+150°C and –180°C)

Space suits come in two different styles. One is called the intravehicular activity suit. The best example of this is the space suit worn by the Mercury astronauts and the crew of the space shuttle as they launched and landed aboard the shuttle vehicles. These astronauts were pressurized within the capsule or the space shuttle and were protected by the environmental control systems on board the spacecraft and during normal conditions would never need a space suit. The intravehicular activity suits are typically never pressurized, but they are capable of pressurization should the spacecraft develop a severe problem where it cannot hold pressure. The other suit is referred to as the extravehicular activity (EVA) suit, which is designed specifically to protect the astronaut against significant outside hazards encountered during space walks. These suits rely on constant pressurization in order to keep the astronaut alive.

The suits need to protect against the hazards outlined above, but other problems come about as a direct result. The suit needs to be pressurized to keep the dissolved gases within the body from expanding, thus resulting in what is known as the bends. The resultant effect is a series of pressurized joints that wrap around critical body flex points such as the elbows, knees, and waist. These joints need to allow the wearer to flex their limbs naturally without compressing the cylinder, thus increasing the pressure as a result of the gas compression. This "compression" causes the muscles to have to work much harder, leading to fatigue. A convoluted joint or one that does not significantly change volume eliminates or greatly reduces the compression, so that less muscle energy is expended. These are sometimes referred to as "constant-volume joints."

Another challenge is that the wearer is encapsulated within a suit while they are typically working hard and generating a lot of heat and humidity brought about by sweating. In addition, they are likely to abrade skin areas against parts of the suit and need a comfort layer to provide abrasion protection. Other factors must be taken into account such as the fit. Assuming that an astronaut is sized perfectly within the suit, it is necessary that they maintain this perfect fit with the suit under pressure; otherwise,

their hands may not be properly positioned inside their gloves once the suit begins to "balloon" out and away from them. This effect was demonstrated by the earlier Wiley Post suits when the rubberized fabrics could not restrain the expansion or growth under pressure.

INTRODUCTION OF ADVANCED MATERIALS TO THE AEROSPACE WORLD

As newer aircraft were being manufactured to fly much higher, newer pressure suits were needed that provided better flexibility when pressurized. When the X-15 was being developed in the early to mid-1950s, the National Advisory Committee for Aeronautics was in need of advanced pressure suits since the X-15 was expected to break new records by flying to altitudes beyond 300,000 feet. The pressure suits at that time allowed extremely poor mobility, which had to be improved. As a result, Wright-Patterson's Aero Medical Laboratory released a contract to develop an entirely new suit. Several companies provided suits designated as models XMC-2. The David Clark Company was the eventual winner with their model XMC-2-DC suit.

ILC Industries (previously known as the International Latex Corporation) entered that competition with the first pressure suit they ever made using state-of-the-art manufacturing facilities that helped them create latex-dipped convolutes that made flexing of the joints much easier. This design was further evolved as the Air Force continued to provide development contracts to ILC until the late 1950s. By 1962, the further developed ILC suit was in a prime position to enter the competition for the Apollo space program. David Clark went on to make the Gemini space suits, whereas B.F. Goodrich provided the Mercury suits.

Mercury Space Suits

Development of the Mercury space suits began in January of 1959. The B. F. Goodrich Mercury suits were derived from the Navy Mark IV high-altitude aircraft suit with some minor modifications. The most notable was the silvery outer cover that was added to help reflect heat generated during reentry. This outer silver layer was made of aluminized nylon. The inner layers consisted of a neoprene-coated nylon fabric to hold the pressure. When the suit was pressurized, the nylon offered reduced elongation versus the rubber used in much earlier suits, thus helping maintain shape and conformity to the body. Since the Mercury suits were never intended for EVA use, there was little need to further develop this suit to withstand more extreme space-like conditions. In addition, the Mercury suits were never inflated during use. They were attached to oxygen tanks on board the capsule, and if pressure were lost at any time during the mission, the suits would instantly pressurize. Fortunately, such an event never occurred (see Figure 3).

FIGURE 3. The Mercury space suit. Courtesy of NASA.

Gemini

The David Clark Company designed and manufactured the Gemini space suit using their own funding. It was based somewhat on their successful X-15 suit. The greatest challenge this suit faced was the fact that it would be the first one to perform an EVA from the Gemini capsule and be directly exposed to the hazards of outer space. Three versions of the Gemini suits were made, each containing different combinations of fabric layers necessary to meet specific mission goals. An interesting fact is that the Gemini astronauts faced the possibility of having to use ejection seats to evacuate their capsule in the event of a catastrophic incident at launch. If this occurred, they likely had to eject through a fireball of ignited rocket fuel, which meant that the space suits had to stand up to a significant challenge. This possibility no doubt was taken into account during the development of the suit and throughout the materials selection process.

The outer layer consisted of the uncoated, high-temperature-resistant polyamide fabric called HT-1, or Nomex as it is now referred to. The name Nomex was first announced by DuPont in 1963 when pilot plants began production. DuPont marketed this material as retaining 50% of its strength at 285°C (545°F). In addition, it retained its dimensional stability and resistance to chemical and solvent attack (McCune, 1962). The rate of material decomposition and charring is high only after the temperature greatly exceeds 350°C (660°F); however, the material does not melt (DuPont, 2016).

The first U.S. astronaut to perform an EVA was Ed White on Gemini 4. The suit he used, the model G4C suit, contained the HT-1 outer layer followed by a felt layer made up of the HT-1 Nomex and also contained a thermal layer of aluminized Mylar. Another felt layer of the HT-1 was further inside to absorb any potential impacts from micrometeorites. The pressure bladder was made of neoprene-coated nylon and was surrounded by a restraint layer made up of link-net woven from Dacron and Teflon cords (Figure 4). The link-net design, which resembled an open-weave net, was patented and used extensively by David Clark as a way to promote flexibility in the various limb joints while retaining the shape of the suit when pressurized. One of Dacron's advantages is its resistance to stretching under load (low elongation) even when wet, and as a result, Dacron is a prime candidate for use in space suits in which elongation is not a desired property.

The main purpose of the Gemini missions was to learn as much as possible about human space flight and the required systems so that we could successfully venture to the moon in Apollo. On Gemini 9A, astronaut Eugene Cernan was scheduled to take a space walk that required him to transit to the aft end of the capsule and strap on a rocket pack called the Astronaut Maneuvering Unit, or AMU. This was the first true U.S. space walk that required extensive energy to carry out a task. Previously, Ed White simply drifted in free space for about 30 minutes, expending very little energy. Cernan, however, soon discovered that he had to work much harder than was expected. His heart rate went

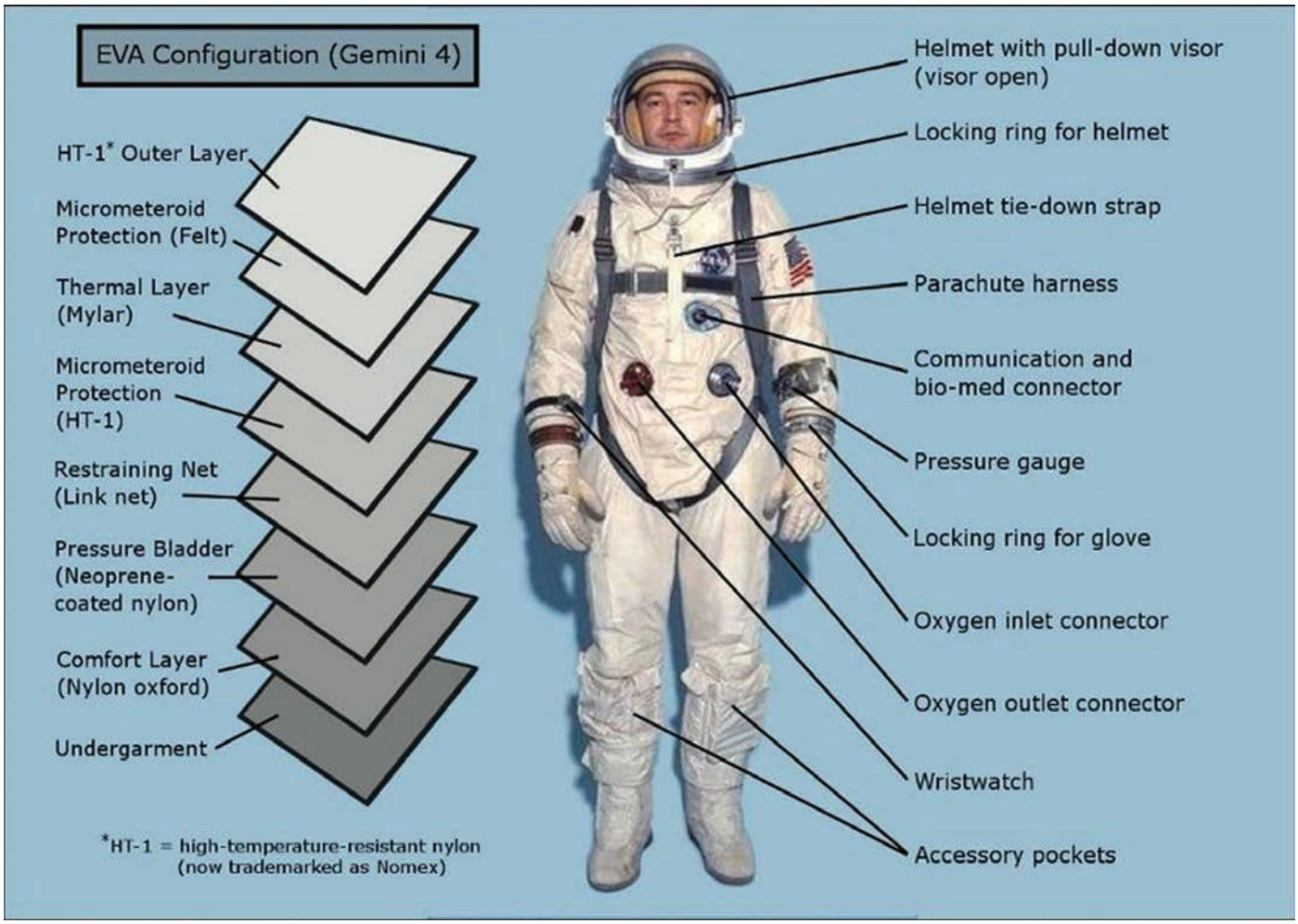

FIGURE 4. The Gemini space suit, showing the various layers it contains. Courtesy of NASA.

up to 155 beats per minute, and his perspiration overwhelmed the air circulation system inside the suit to the point that his visor fogged up and he could not see without wiping his nose against the visor to clear it. This discovery would drive a change to the design of the Apollo suit.

The Apollo Space Suit

While David Clark was busy manufacturing the Gemini space suits and flying them on missions in the early to mid-1960s, ILC was deeply immersed in the development of its Apollo suit. Having won the contract in 1962, ILC was building on its earlier pressure suits from the 1950s. Between 1962 and the first flight of Apollo 7 in 1968, the ILC pressure garments took several twists in their design path and development, but the essential material ingredients remained the same. What few people realize is that between each of the Apollo missions, from Apollo 7 all the way through to Apollo 17, small changes took place to improve the performance and reliability of the suits, but once again, the materials essentially remained the same. Figure 5 provides insight into the various DuPont materials selected for the Apollo program.

During the development of the Apollo suits, ILC continuously worked closely with NASA engineers to determine what material combinations had to be used in order to provide the necessary life support for an astronaut expected to perform as much as a 7-hour walk on the moon. In a worst-case scenario, the sun angle would be at 70°, and there would be solar reflection from a close-by crater. Heat loss or gain to the suit was measured in Btu leakage per hour, and the solar loading could certainly not exceed the capability of the backpack. The leakage limit was

FIGURE 5. DuPont advertisement detailing the various materials used in the Apollo suit. Courtesy of DuPont.

250 Btus per hour. Thanks to the multilayered combinations of modern plastics, the suit fell within the required specifications.

The Apollo suit began its design from the inside out, meaning that the pressure garment and supporting hardware were developed first, followed by the outside layers that make up the thermal micrometeoroid garment (TMG). The following sections outline the major components that made up the Apollo suits.

Liquid Cooling Garment

As proven during Eugene Cernan's Gemini 9A space walk, much needed to be improved in terms of removing body heat that was significant during any physical activity. It was estimated from previous studies that the Apollo astronauts would be required to expend between 1,200 and 1,600 Btus per hour of heat and possibly upward of 2,000 Btus while walking about on the moon, and an air-cooled suit alone would not be able to compensate these loads. The solution to this problem came about once again by way of advanced materials. In 1963, Hamilton Standard engineers working with NASA developed a liquid cooling suit based on a Royal Air Force design to keep their fighter pilots cool while they sat in their aircraft on hot runways. The final result for the Apollo suit was an open-weave nylon spandex garment with approximately 300 feet of polyvinyl chloride (PVC) tubing through which cool water would flow from the backpack. This PVC tubing was sold under the trade name of Tygon, which is a registered trademark of the Saint-Gobain Corporation. It also featured a thin, lightweight nylon chiffon liner for comfort. Spandex is a manufactured fiber based on a long-chain synthetic polymer composed of at least 85% of a segmented polyurethane (American Fiber Manufacturers Association, 1997–2012). The spandex provided the ability to be stretched repeatedly with almost total recovery; thus, when it is worn close to the body, the cooling tubes are held close to the skin and remove the body heat (Figure 6).

One of the key issues investigated during the Save America's Treasures program was the fact that the dioctyl phthalate (DOP) was leaching out of the vinyl tubing, thus resulting in brittle and brown-colored tubes covered with the wet and tacky DOP. In addition, over time PVC will release hydrogen chloride (HCl) that further goes on to attack any metal suit hardware nearby (V. Gabara, DuPont Fellow, personal communication, May 7, 2012). Nothing can be done to reverse these conditions, and the items in the collection that have the potential to create these problems must be isolated from contact with other artifacts. Figure 7 shows the Apollo liquid cooling garment (LCG) and its current state with the brown vinyl tubing.

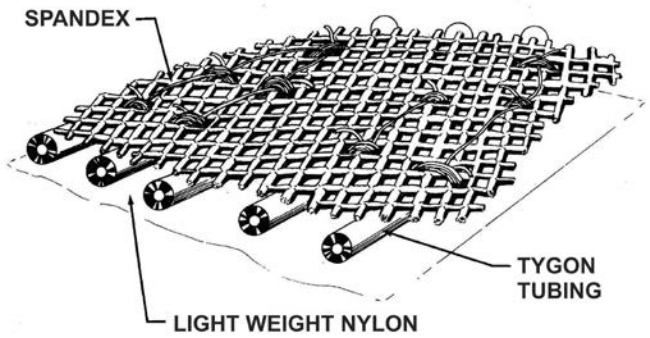

FIGURE 6. Liquid cooling garment. Courtesy of NASA.

FIGURE 7. Apollo liquid cooling garment. Courtesy of ILC Dover, LP.

Pressure Garment Assembly

Working our way out from the cooling garment, we have the beginning of what it called the pressure garment assembly (Figure 8). The first layer consists of a lightweight Nomex liner. This liner not only serves as a comfort barrier, but it also aids the astronaut when donning the suit and protects the bladder layer. Getting into the suit was not an easy task since: you had to fold your body and slip in between the tight zipper assembly while working your arms and legs into their respective openings. The thin Nomex layer helped provide this continuous, slippery surface for the arms and feet to slide along until the suit was fully donned.

The next layer is the neoprene-coated nylon fabric used as the barrier to retain the pressurized oxygen. Neoprene is a synthetic rubber also known as polychloroprene. This layer was certainly one of the most critical barriers of the suit, and it did serve to prevent any leakages. Various cut panels were spliced together using a two-part neoprene adhesive and similar neoprene/nylon cover tape to form this bladder layer. This rubber-coated layer had to be installed into the garments within one year of manufacture and had only a three-year shelf life from the installation date. Most of the Apollo suits were manufactured with the intent of using them within three years of installation. Unfortunately, many of the suits now in the care of the National Air and Space Museum are well beyond the three-year installation date, and the results of the aging process show by way of brittle rubber particles that fall out of the suit openings during handling.

To prevent the bladder layer from being stressed when under the internal pressure or loads (as when walking, reaching, bending, etc.), the next layer toward the outside consisted of a blue colored 7.0 ounce per yard oxford nylon called the *restraint layer* that maintained the shape of the suit. Integrated throughout several areas of this layer were the accordion-style convolutes that allowed the joints to flex. These convolutes were latex dipped and contained a tricot fabric throughout the inside layer to retard growth under pressure. In addition, within the valley of each band of the convolute was a nylon webbing to further help prevent expansion. From the earlier Apollo missions up to Apollo 14, a couple of the suits had to have their bellow joints surgically removed and replaced with new units just prior to their flights because the rubber was beginning to turn brittle as it reached the end of its relatively short shelf life. An investigation was begun to find possible solutions to extend the life of the rubber. Leading experts were brought in, and two significant changes were made on the basis of the findings. It was found that the reason for the accelerated aging of the rubber was the presence of copper alloy traces in the tank used for the latex dipping process of the bellows that originated from the copper pipes feeding the tank. As a result, all copper pipes were eliminated from the process. The second improvement was the addition of an antioxidant, called Agerite White (N, N′-di-2-naphthyl-p-phenylene diamine), still used currently throughout the industry to prolong the life of the rubber. That these improvements served their purpose was validated during the Save America's Treasures program when it was apparent that all of the suits prior to Apollo 14 had convolutes that were seriously degraded, whereas the later suits had convoluted joints that still appeared to be in good condition. The inner restraint and bladder layer also contained air ducts made of nylon to aid in the circulation of the air throughout the suit.

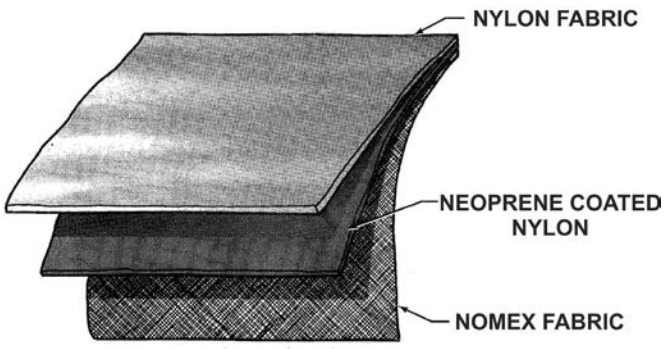

FIGURE 8. Pressure garment assembly layers. Courtesy of NASA.

Thermal Micrometeoroid Garment

Following the Apollo 1 fire in February of 1967 that killed astronauts Gus Grissom, Ed White, and Roger Chaffee, safety review findings determined that more work was needed on crew protection in the event of a similar situation. With regard to the suit design, much, if not all of this change affected the outer TMG layer of the suit. The purpose of this multilayered garment was to provide protection from possible fire as well as to defend against radiant heat energy from the sun and micrometeoroid impacts when performing space walks. In addition, it provided abrasion resistance and significantly reduced conductive heating and cooling through the layers. It was found that the fire actually melted the outer Nomex layers of the suits in the Apollo 1 incident, so NASA immediately began looking for improved performance.

Prior to the fire, the initial version of the ILC Apollo suit was the model A6L. This first model of the actual flight suit was initially designed to have a slip-on TMG with a cover layer of Nomex similar to the Gemini one. The intent was to reduce bulk by being able to remove this outer TMG layer during noncritical phases of the mission. This design was taking shape in 1967 when the fire occurred. As a result of the many findings that came out of the NASA Review Board investigating the incident, it was decided that the TMG of the suit should be redesigned using improved materials so that it could protect crewmembers against even higher temperatures and, in addition, not be removable but rather be integrated onto the suit as a permanent part of it. This ultimately led to the model A7L suit that was used in most of the Apollo missions. New requirements were set in place so that astronauts might have a chance to escape onboard fires provided they could exit the command module (such as when on the launch

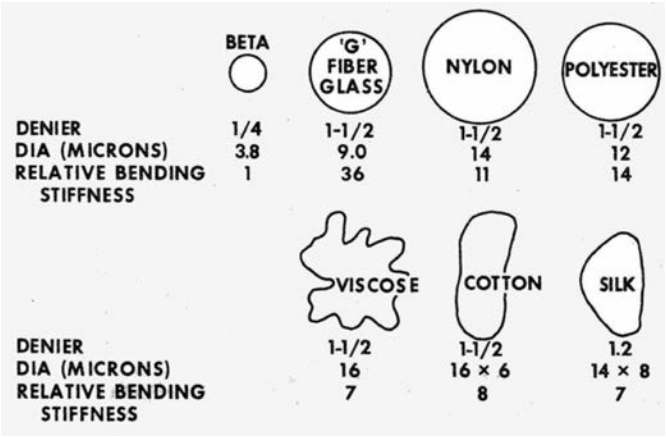

FIGURE 9. Relative fiber diameters and bending stiffness (Naimer, 1970). Courtesy of NASA.

pad). The goal was to provide a TMG layer that could offer the following benefits: (1) provide crewmembers 45 s of time to exit the spacecraft once flame impingement began and (2) ensure that the inner bladder layer of the pressure garment did not exceed 250°F (122°C) within the 45-s time period. This estimation was all based on a flame temperature of 1,800°F (982°C) in an oxygen environment (McBarron and Poradek, 1968).

NASA engineers quickly began work with both Owens Corning and DuPont to develop a new combination of existing fibers to create a cover layer that would ultimately become known as Beta cloth. It was a noncombustible fabric that had a melting point of over 1,200°F (650°C). The main component was an ultrafine glass filament that was twisted into yarns and woven as a fabric. Figure 9 shows the size of the Beta fiber relative to other fibers in addition to its relative bending stiffness (Naimer, 1970). Its small diameter afforded good bending qualities and provided high tensile strength.

The next step was to coat the fabric with a DuPont polytetrafluoroethylene more commonly known as Teflon. One of the earlier findings during the development of this Beta cloth material was that the glass-fiber threads alone did not stand up well during the sewing operations. To increase their mechanical resistance, the glass fibers were coated with Teflon. This robust combination of fibers was then covered with a layer of Teflon cloth that provided excellent abrasion and additional fire resistance.

The TMG consisted of many layers of different insulating materials under the Teflon and Beta cloth that made up what was known as "superinsulation." They were assembled in a very precise order so as to provide maximum insulating capacity. Figure 10 shows the arrangement of the materials typical of the Apollo

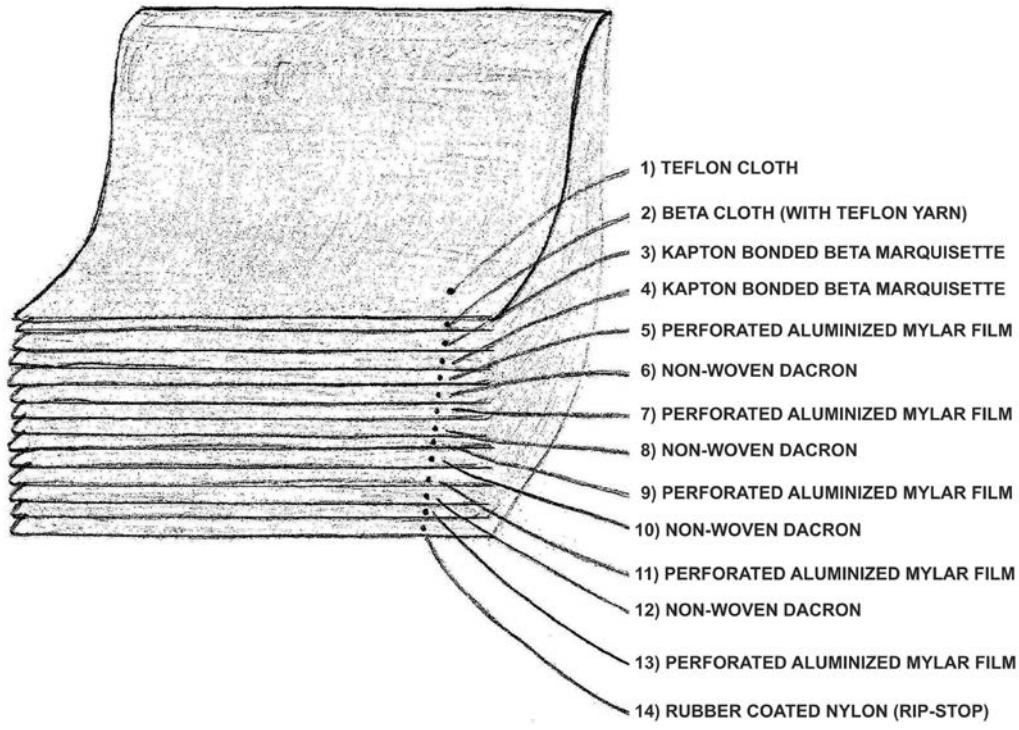

FIGURE 10. Layers of the Apollo A7L thermal micrometeorite garment. Please note that layers 3 and 4 are aluminized Kapton bonded to Beta Marquisette. Courtesy of ILC Dover, LP.

missions. Under the Beta cloth, the combinations included the following:

- Aluminized Kapton provided the capability to reflect the solar radiant energy away from the inner layers.
- Beta marquisette/laminated aluminized Kapton consisted of a Teflon-coated silica fiber laminated to Kapton. This layer provided a spacer material between the aluminized Kapton so that conductive heat gain or loss was kept to a minimum.
- Aluminized Mylar film was a plastic film consisting of polyethylene terephthalate (also referred to as PET) with a vaporized metallic layer. This material provided further reflective capability to reduce heat gain or loss through radiant means. It is capable of reflecting up to 99% of the light, including much of the infrared spectrum.
- Nonwoven polyester Dacron also acted as a spacer material and reduced conductive heat gain or loss.
- Neoprene-coated nylon ripstop was the inner liner that helped sandwich all the layers together. It acted as a protective layer and gave a firm base cloth in which to sew.

Once flame testing was performed on the final design of the TMG, it was found that the bladder layer took 54 s to reach the 250°F (121°C) temperature with an 1,800°F (982°C) flame impingement. This time was 9 s over the minimum requirement. All of the above materials remained very stable at the expected lunar temperatures of between +350°F (+415°C) and –180°F (–292°C). The end result was a TMG garment that weighed less than 20 pounds and had 454 individual piece parts taped or sewn together to form the single garment.

Helmet: Extravehicular Visor Assembly

The helmet for Apollo consisted of two main sections. First was the pressure helmet proper that provided the pressure sealing integrity and strength and allowed good visibility. It was made from a high-optical-quality polycarbonate plastic and made by Air-Lock, Inc. A synthetic elastomer foam vent pad was mounted inside the back of the helmet to provide a comfort headrest for the astronauts during the launch and reentry phases.

The extravehicular visor assembly was mechanically attached over the pressure helmet and provided protection while the astronauts were exposed to direct sunlight. The white shell was made of fiberglass that also had three opaque sun shades. Two were on the sides, and one was located in the center and could be pulled down to block direct sun at low angles. The extravehicular visor assembly contained two separate visors. The outer gold-coated sun visor was made of a high-temperature polysulfone plastic. The inner visor was made of ultraviolet stabilized polycarbonate plastic. The outer visor filtered visible light and rejected most ultraviolet and infrared rays while the inner visor also aided in filtering these radiations. Together they also provided a thermal barrier. All of these materials worked together to ensure that if a crewmember were to fall and strike his head against the surface, the helmet would stand up to the impact with minimal damage while ensuring pressure integrity. The outer surface of the helmet (top, sides, and back) was covered with Beta cloth and plied-up insulation as in the suit cover for additional thermal protection (Figure 11).

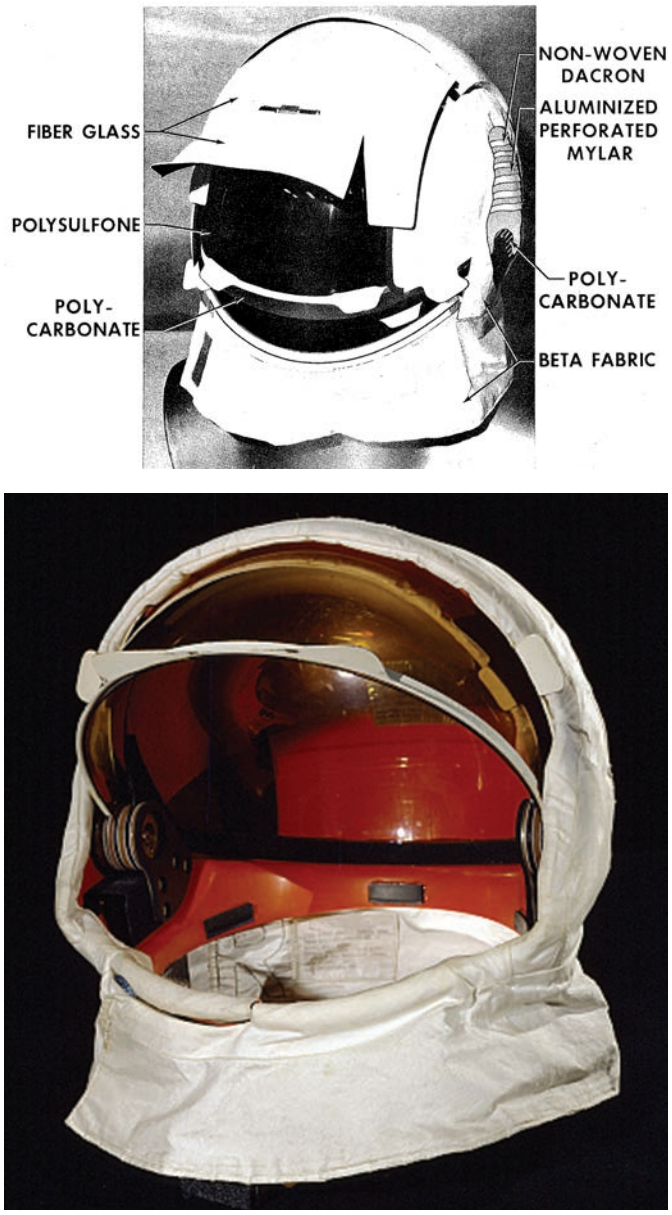

FIGURE 11. Extravehicular visor assembly. Courtesy of NASA.

Gloves

The gloves started with the dipping of a hand-shaped mold into neoprene rubber. The mold was custom made on the basis of over 20 hand dimensions from each astronaut. Following the

first dipping, a thin nylon restraint layer was wrapped over the mold, and the dipping process continued until 10 mils (a thousandth of an inch, approximately 25 μm) of neoprene coating were applied. Several layers of the superinsulation were formed on top of this, similar to the TMG construction, where alternating layers of nonwoven Dacron were sandwiched between aluminized Mylar. Nylon was provided as a cover layer over this. The gauntlet, which in terms of space suit gloves is defined as the cuff below the palm area, consisted of a layer of Beta cloth together with Chromel-R fabric, which was a woven chromium steel fiber to provide puncture and abrasion resistance. (At the cost of over $3,000 per yard in the 1960s this Chromel-R material was locked up in a vault at ILC when not being cut for parts.) The fingertips had a silicone rubber cover to protect it as well as aid in picking objects up (Figure 12).

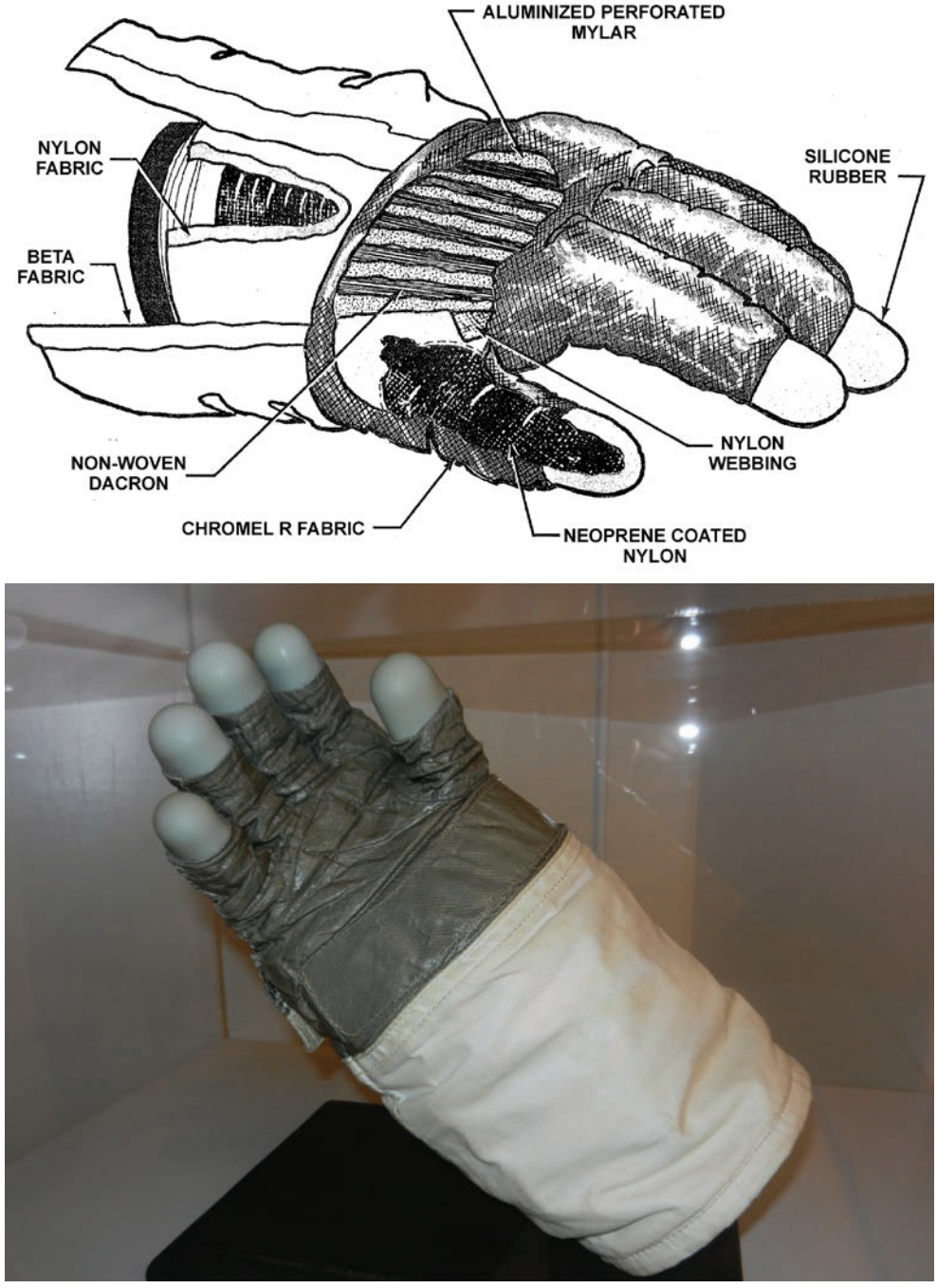

FIGURE 12. The Apollo EVA glove. Courtesy of NASA.

Lunar Boots

The soles of the lunar boots—famous for the prints left on the moon—were molded using silicone rubber. The upper portions of the boots contained the similar makeup of Beta cloth and plied-up insulation. The sole of the boots contained two layers of 0.125″ Nomex felt to provide added insulation. Because of the concerns of the astronauts cutting into the boots because of abrasion from sharp rocks, the Chromel-R steel fabric was used as a cover layer around most of the outer surface.

The Apollo 17 mission was the last mission to the moon; ILC continued making many more suits for Skylab and then the Apollo–Soyuz Test Project. These suits remained essentially the same with some minor changes resulting in fewer insulating layers, which were all driven by mission requirements. However, the basic materials remained the same.

As a result of the Save America's Treasures program, the effort to preserve the Apollo space suits in the National Air and Space Museum collection, an extremely helpful and instructive report was published (Young and Young, 2001). Along with general care and display practices, this report summarized the issues related to the decay of the older space suits and the challenges associated with it. This publication was used in preparing the Smithsonian Institution *Suited for Space* traveling exhibition that opened in 2011 at the Museum of Science and Industry in Chicago, Illinois, and closed in 2105 at the Stauth Memorial Museum in Montezuma, Kansas, after touring nine other states.

The Space Shuttle/Space Station Suit

When NASA announced the new Space Shuttle Program in the early 1970s, new requirements were called for, including those related to space suits. No longer could suits be custom made since significantly more astronauts would need to do space walks. In addition, the suits would be used only in a no-gravity environment. By the late 1970s as the plan was coming together for the shuttle EVA suit, it was decided to assemble the suits from a modular design where parts could be reused, and modularity would also increase sizing capability. This meant that the suit had to be robustly designed. It also meant taking advantage of more advanced materials that provided longer life and could stand up to repeated abrasion and cycling. Both NASA and industry learned a lot from the Apollo program, and this new program was a good time to start with a fresh design that eliminated the perceived weak areas of the Apollo suits.

There were a number of design-related concerns with the Apollo suits:

- the use of rubber that was readily susceptible to age-related degradation mechanisms such as UV light exposure, moisture, or oxidation
- closure zippers that had the potential to open under extreme stress (but fortunately never did)
- the need to replace the steel restraint cables that had the potential to fail where tied off

By the time ILC had won the contract to make the Space Shuttle/Station Suit Assembly (SSA) in 1977, newer advanced materials were on the market, and once again, the focus was on using industry material advancements to lead the way.

For the new shuttle program the LCG design remained relatively unchanged except for two important design changes: (1) a change to the tubing material and (2) removing the vent system from the pressure garment itself and adding it to the cooling garment. The addition of the vents resulted in the newer garment being called the liquid cooling and ventilating garment (LCVG; Figure 13). The DOP plasticizer that leached out of the vinyl tubing was a serious concern for the portable life support system (PLSS). The DOP had the potential for blocking filters in the PLSS, causing it to malfunction. Ethylene vinyl acetate copolymer (EVA resin) was used to replace the vinyl for the tubing. The EVA resin does not contain migratory additives such as plasticizers, and when partially cross-linked through irradiation, it develops sufficient strength to allow the use of thermal sealing

FIGURE 13. The shuttle-station LCVG. Courtesy of ILC Dover, LP.

methods in manufacture. The vent system consisted of urethane-coated springs that are covered with Dacron for abrasion protection. These ducts run down the arm to the elbow and along the outside of each leg. They come together at the plenum located in the small of the back on the LCVG. The combination of materials used provides for air retention without the risk of crushing or blocking off one of the tubes.

Perhaps one of the biggest material substitutions was the change to urethane for the air-retaining bladder material. The availability of urethane-coated fabrics ushered in a chance to streamline suit manufacture while increasing reliability and reducing the need for adhesive bonding. Urethane-coated fabrics were being used in the life raft industry and provided an ideal material for replacing the neoprene-coated nylon that required cement bonding for use in the air- and pressure-retaining bladders. With urethane-coated materials came the capability to use heat-sealing techniques that provided reliable and robust bonds. In addition, the urethane-coated materials exhibited better adhesion between the polymers and fabric, increased abrasion resistance, increased damage tolerance, increased air retention properties, and perhaps most importantly, increased resistance to age-related degradation, all of which contributed to better wear characteristics and longer life. Early on in the program only solution-coated fabric technology provided the fabric with the film adhesion needed in the bladder cloth as it came to be known. The downside was that solution-coated fabric was more prone to flex cracking. To solve this problem, an additional layer of urethane film was applied to the individual parts as they were being assembled. This application provided protection against any flex cracking if it were to occur as well as a layer of abrasion resistance. However, this process was very time-consuming from a manufacturing perspective and made the bladders thicker and less flexible. A new bladder cloth was developed by ILC Dover that incorporated a laminate structure providing abrasion resistance and adhesion while maintaining material thickness and weight of the solution-coated material. This material development program significantly reduced cost and schedule for suit manufacture, increased flexibility, and significantly increased reliability by virtually eliminating delamination, a problem that plagued the solution-coated material, especially once the abrasion layer had been applied.

Urethanes in general also provided the versatility for different use applications, including pressure seals. Early on in the program, however, ester urethanes were used throughout the system because of their durability and availability relative to ether urethanes. Ester urethanes are particularly prone to hydrolytic degradation, which limited the life of suit components. Compounding the hydrolysis degradation is the fact that the material degrades to form carboxylic acid, which becomes a catalyst for the degradation reaction. Degradation rates accelerate, and physical properties drop off nonlinearly. To address this issue, hydrolytic stabilizers were incorporated into ester urethanes used in the space suit assembly as the shuttle program matured, but the principal course of action was to gradually replace them with ether urethanes. Although ether urethanes are also degraded by hydrolysis and oxidation, ether urethanes are far more stable, and testing performed at ILC shows that their service life can be nearly twice as long as that of ester urethanes given standard storage conditions. Examples of the different degradation between the two types of urethanes can be seen when comparing the glove bladders of the 1000 series to the 4000 series, made of ester and ether urethane, respectively. Within a three-year period the ester bladders began to embrittle and quickly disintegrated, and very little remains of these original bluish-colored bladders. Conversely, ether urethane glove bladders older than 15 years exist in fairly good condition, and testing of samples from these bladders shows that material properties begin to deteriorate at about this age.

For restraint layer applications, Dacron fabric offered improved abrasion resistance and durability over the nylon used in the Apollo restraints. The Dacron fabric also replaced the rubber convolutes, which dramatically increased the usable life of the restraint from both an age-related degradation aspect and wear. Dacron also offers lower elongation than nylon and provides more design flexibility and control with the restraint. In addition, since Dacron is versatile in that it can be used in webbing form and is not prone to flex fatigue as metals are, it was used to replace the steel restraint cables previously used with the Apollo suit.

In the early 1990s a major suit redesign was undertaken to add on-orbit sizing change out, increased mobility, and increased reliability by improving safety factors and adding redundant systems. With the arrival of Spectra, an ultrahigh-molecular-weight polyethylene, replacement of the Dacron restraint lines with Spectra increased restraint line strength, effectively increasing safety factors without additional bulk or weight. The Spectra fibers possess a tenacity (that is fiber strength) over three times that of Dacron (26 g/denier for the former and 8 g/denier for the latter). However, Spectra has a lower melting temperature and creeps at relatively low temperatures over time. For space suit applications it was determined that the Spectra could be used only in applications where the temperature would not exceed 160°F (71°C). For those applications for which higher temperature resistance was required, the use of Dacron would continue. Figure 14 shows the waist subassembly section with the oxygen retention (bladder) layer with the restraint fabric and restraint webbings.

Another significant design change from Apollo to shuttle suits was the use of a hard upper torso (HUT) made using a composite material consisting of epoxy-impregnated fiberglass (Figure 15). The rigid composite HUT provides a good supporting structure for the PLSS and Display Control Module that are now consolidated on the space suit to eliminate the myriad of hoses that were in the Apollo suit. The modular design of the SSA allowed for the rigid structure that could not be used economically with the customized suit design of the Apollo suits. Also, with the zero-gravity shuttle missions, the extra weight could be afforded. In the early to mid-1990s the HUT was redesigned to eliminate the single point of failure at the arm pivots. This design also removed the need for the neoprene-coated fabric bellows. This change paved the way for extending the life of the HUT significantly.

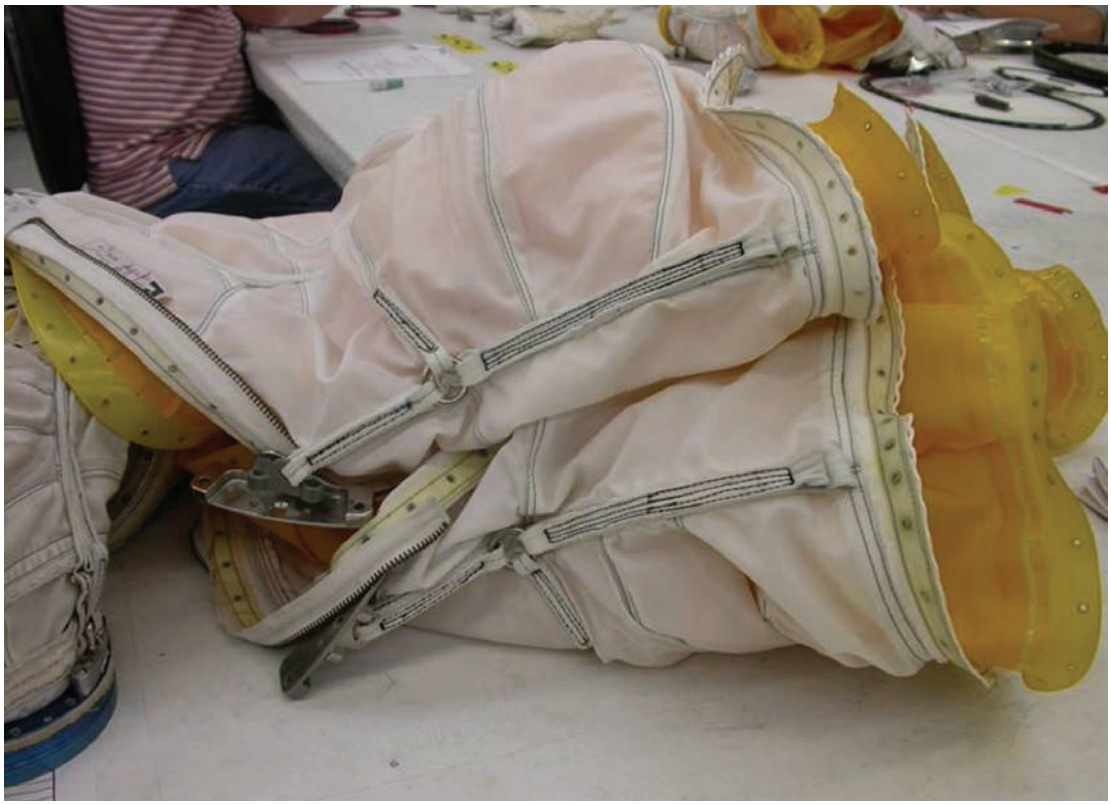

FIGURE 14. Waist subassembly including the bladder, restraint fabric, and webbings. Courtesy of ILC Dover, LP.

FIGURE 15. The shuttle/space station hard upper torso (HUT). Courtesy of ILC Dover, LP.

The new shuttle missions did not require extensive mobility below the waist, and the lack of gravity did allow for some weight gain, but as the shuttle missions evolved, it became apparent that the gloves would play perhaps the most critical role. Early on in the shuttle program, EVAs typically consisted of deploying satellites, which required some increased dexterity over the Apollo program, but it was the assembly of the International Space Station and missions to repair on-orbit hardware like the Hubble Space Telescope that really challenged and drove glove design improvements. The material changes in the glove from Apollo to the beginning of the shuttle program focused on increased wear life and age as well as increased flexibility and function. The monolayer rubber bladders wore out quickly because the material aged poorly and by simple abrasion. In addition, as a fabric-reinforced rubber, the Apollo glove bladder material was not as flexible, nor did it have the tactility that the shuttle program astronauts would come to demand. The first shuttle glove design, the 1000 series, consisted of the ester urethane bladder that resisted wear and was more flexible because it was unreinforced but still aged poorly, as previously mentioned. In the 2000 series, the glove bladder material was changed to the ether urethane. This ether urethane has very good aging characteristics and is flexible as well as tough. It is more damage resistant, having a high tear propagation strength, and has the ability to "self-heal" in that small punctures can close themselves.

Beginning in 1996, very significant changes to the glove design came about with the Phase VI gloves still in use today. The improvements required at the beginning of the SSA called for higher mobility and torque, and the new joint designs demanded materials with increased strength to keep the bulk down in the glove. Spectra cords and webbings could handle the higher loads without having to increase material usage. The low coefficient of friction also allowed improved movement through the range of motion in certain locations. The development and use of Vectran (a multifilament yarn spun from a liquid crystal polymer fibers made by Honeywell, now Kuraray) was also an important event for glove design. Vectran had been used for the Pathfinder Airbag program at ILC.

Early on in the design development Kevlar (a heat-resistant fiber related to Nomex) had been evaluated for use in areas where higher-strength materials were needed at elevated temperatures that Spectra cannot withstand, like the glove TMG palm. However, Kevlar would wear quickly with the amount of flexing typical of glove use. Although not as strong as Kevlar, Vectran possesses high strength with tenacity approximately at 22 g/denier. More importantly, Vectran exhibits better flex fatigue resistance than Kevlar in glove cycle testing, allowing the glove to be used longer. In 2005, a cut to an EVA glove TMG highlighted the fact that glove mission models were changing. Not only were EVAs becoming more hand intensive, but the work environment was changing too. Sharp edge requirements are levied on all space hardware, but as the International Space Station continued to be exposed to the space environment, the space hardware could change. This change became evident when damage from micrometeoroid/orbiting debris (MMOD) was identified on the International Space Station handrails. At their high energy level, MMOD impact with metal can create sharp edges. The hole in the TMG drove a design change that added Vectran TurtleSkin developed by Warwick Mills for ILC Dover. The material weave construction combined with the high tenacity and cut resistance of the Vectran fiber produced a puncture- and cut-resistant material that would protect the underlying glove materials from sharp edges.

At the start of the shuttle program, it was understood that the Apollo Beta cloth TMG materials had to be replaced. Although the fiberglass in the Beta cloth did not degrade with exposure to environmental factors, fiberglass exhibits particularly poor flex properties over time. The Beta cloth was replaced by a Gore-Tex/Kevlar/Nomex double woven that became known as Ortho-Fabric because the weave looked orthogonal in nature. This material is nonflammable, and the Gore-Tex is chemically inert. The outer Gore-Tex shell provides for thermal and abrasion protection and acts as a fire-resistant and chemical-resistant barrier for the materials underneath. The Apollo era Kapton film was removed from the insulation ply up and replaced where needed with aluminized Mylar since the Mylar has higher tear strength and folding endurance. In addition, scrim material was added to the aluminized Mylar to provide standoff and avoid thermal conduction through the layers. Reinforcing the aluminized Mylar also increased tear and made manufacture easier by decreasing the number of layers in the ply up (separation of Mylar layers was accomplished using nonwoven Dacron in the Apollo suit). Figure 16 provides a view of the various layers of the current suit materials.

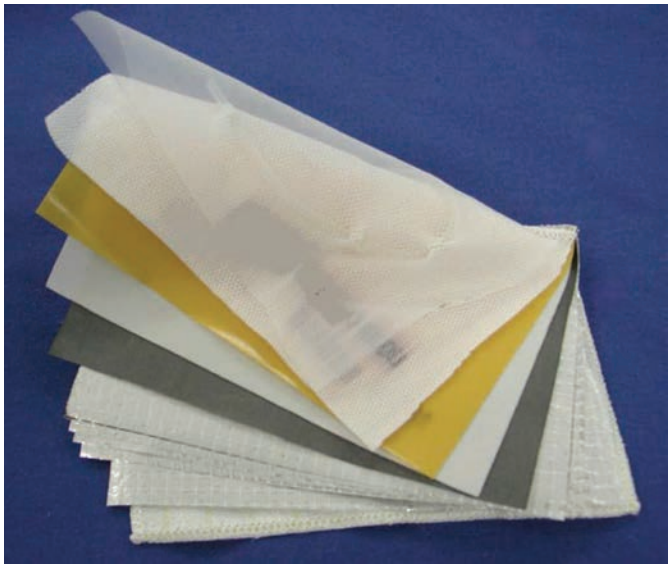

FIGURE 16. The shuttle/space station suit layers. Courtesy of ILC Dover, LP.

CONCLUSION

In conclusion, the plastics used in the current SSA significantly extend their life span and reliability compared with the earlier Apollo space suits. The future development suits now being fabricated by ILC Dover use advanced plastics and provide a springboard for long-duration missions to the moon or Mars. Objectives for suit advancement include adding more sizing capability and continued improvement to comfort, durability, mobility, and functionality. For those future interplanetary missions, some of the objectives include greater protection against long-term exposure of solar and galactic radiation. Plastics that contain a high concentration of hydrogen may be a nonmetallic solution, for example. Other advances may include the addition of electronic devices such as GPS and navigational control using plastic materials for enclosures and integration into the suits. For long-term missions lasting over a year, treated plastics will play a role in helping to prevent or limit microbial growth that occurs because of the inability to thoroughly launder the space suit garments after use. Plastics will likely be used to replace heavy metal bearings used in the arms and legs and ensure increased mobility and possibly seal out lunar or Martian dust. If we are to protect suited humans on Mars someday, we have to provide plastics that are cut resistant since there will be no sewing machines or other resources needed to perform repairs.

Companies such as ILC Dover continue to depend on plastics for the fabrication of many other future space-related devices such as habitats necessary to provide long-term protection on the moon or on Mars. ILC currently fabricates high-altitude airships and other space inflatables such as aerodynamic decelerators that are constantly challenged by the severe environments. Whether protecting humans or machinery, plastics will always be a key ingredient in finished goods.

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Separating Good Plastic from Bad Plastic in Conservation Biology

Pierre Comizzoli

ABSTRACT. Conservation biology aims at understanding and maintaining the biological diversity that is critical for the sustainability of entire ecosystems while benefiting human societies. Plastic materials have brought many improvements in human daily life but also have many positive or negative impacts on conservation efforts. They include obvious detrimental effects on the environment (plastic pollution of lands and seas) as well as positive or even irreplaceable roles in animal care and biological research. Specifically, plastic enables us to save species from extinction by providing tools (including medical and laboratory supplies) and allowing technologies (assisted reproduction or genomic studies) that would be impossible to implement otherwise. Conversely, the presence of plastic waste in the environment threatens wildlife species that eat or become entangled by debris. In addition, plastic polymers are leaching out chemicals (mostly plasticizers) that can be transferred to wildlife and humans through simple contact or by ingestion. With controversial and sometimes contradictory reports on issues related to plastic, the difference between good plastic and bad plastic in conservation biology still needs to be thoroughly explored. The objective of this paper is twofold: first, to review the current interactions of plastic with natural habitats and animal populations either in the wild or in captive conditions and, second, to propose the design of systematic studies and wildlife monitoring to better identify and then mitigate the most significant, detrimental effects of plastic.

INTRODUCTION

Natural selection has resulted in millions of different plant and animal species, each with its own genetic makeup and each adapted to its own environment. However, extinction of species is now occurring at a much higher rate than speciation because of human activities, such as habitat destruction, overhunting, and competition with introduced or invasive plants or animals. As a result, some animal populations have become small and fragmented in nature, with little or no genetic exchange between them. The poor genetic diversity (homozygosity or inbreeding) then leads to a poor adaptive capacity of individuals to any environmental changes, risks of transmission of inherited diseases, congenital defects, and fertility problems (Reed and Frankham, 2003). The aim of conservation biology is to understand and maintain the biological diversity that is critical for the sustainability of entire ecosystems while also benefiting current and future human societies (Soule, 1985). Natural habitat preservation is virtually the best way to conserve biodiversity because in situ efforts enable live populations of animals in their adaptive environments to be maintained. However, these approaches have to be complemented by ex situ conservation efforts to establish viable populations in captivity as well as preserving animal genetic resources (gametes, embryos, gonadal tissues, DNA samples) for eventual reinforcements or reintroductions of wild populations into their natural habitat. Successful field conservation and captive breeding management also depend on different research areas aiming at a better understanding of the biology of entire species

Center for Species Survival, Smithsonian Conservation Biology Institute, National Zoological Park, P.O. Box 37012, MRC 5502, Washington, D.C., 20013, USA.

Correspondence: P. Comizzoli, comizzolip@si.edu

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and populations. These scientific areas include field ecology, population genetics, behavior, nutrition, husbandry, reproductive physiology, endocrinology, and veterinary medicine. Thus, a multidisciplinary and interdisciplinary strategy is the only efficient way to aid in the survival or recovery of species and their habitats as well as to ensure the health and well-being of animals in captivity and in the wild.

In this context, man-made plastic polymers often appear to be the most artificial materials having negative interactions with the protection of species. Plastic polymers have transformed human daily life since the 1940s with an increased usage and an annual production now exceeding 300 million tons. The omnipresence of plastic in human society has also become true for the environment (Freinkel, 2011). Interestingly, animal populations and natural habitats are involuntarily exposed to plastic, whereas some protection efforts in situ and ex situ extensively use plastic on purpose to save species. If anyone wonders about the positive aspects of plastic, there is an impressive list of benefits, including the enhancement of technological and medical advances and the limited amount of energy required to produce and transport plastic compared with other materials (Table 1). Unfortunately, plastic also is well known for its lack of biodegradability, being difficult to recycle, and not being sustainable since production depends on the extraction of fossil fuels (Table 1). Last, it can be toxic, which is really a generic term including all the negative impacts that plastic can have on organisms and ecosystems (Andrady and Neal, 2009).

Plastics are composed of chains of hydrocarbon polymers (Table 2) that are rarely used by themselves and typically are mixed with various additives to improve performance. These supplements can be inorganic fillers such as carbon and silica that reinforce the material, plasticizers to render the material flexible, thermal and ultraviolet stabilizers, flame retardants, and colorings. Many additives are used in substantial quantities and in a wide range of products (Meeker et al., 2009). Some added chemicals are potentially toxic (e.g., lead, tributyltin, antimonium, phthalates, and bisphenol A), but there is considerable controversy about the extent to which additives can leach out from plastic products and have toxic effects on animal or human populations. The main issue is to link the types and quantities of additives present in plastics to real uptake and accumulation by living organisms (Andrady and Neal, 2009; Oehlmann et al., 2009). Given the increasing usage and presence of plastic in our lives and our environment, separating good plastic from bad plastic in conservation biology has become a priority. The objective of this paper therefore is to review the current interactions

TABLE 1. Positive and negative roles of plastic (from Andrady and Neal, 2009).

Why is plastic good?	Why is plastic bad?
Producing plastics saves energy: 20%–40% less energy consumption than other materials	Not biodegradable
Producing plastics saves our fresh air: between 63% and 73% fewer emissions than the alternatives	Not easily recyclable
Producing plastics saves our waterways: 90% less waterborne waste than those created during the manufacture of alternatives	Production is not sustainable
Plastics save transport costs: easy deliveries	Toxic
Plastics save landfill space: plastics represent only 7% of total solid waste (by weight)	
Plastics help health care via no cross contamination: disposable blood bags, tubing, catheters, syringes, protective gloves, artificial limbs, lifesaving valves	
Plastics help agriculture: greenhouses and ground film	
Plastics safely insulate: almost 100% of electrical energy insulation is provided by plastics (lowest thermal conductivity)	
Plastics reduce food and water wastage: optimized food and water storage	

TABLE 2. Example of plastics used for human consumption and in conservation biology.

Type of polymer	Human use	Medical or laboratory use
Polyethylene	Good for beverage containers	Good for medical tubing
Polypropylene	Good for food containers	Bad for in vitro culture (embryotoxic)
Polystyrene	Very bad because of potential toxicity	Optimal in its hard form for in vitro culture (not embryotoxic)
Polyvinyl chloride	Very bad	Gold standard for semen straws

of plastic with natural habitats and animal populations either in the wild or in captive conditions and suggest systematic studies to better address the questions of good or bad plastic in conservation biology.

PLASTIC AND NATURAL HABITATS

As previously mentioned, the protection of animal populations and their natural habitats is the highest priority in conservation biology. The presence of plastic in the wild is recognized as a major issue because its biodegradation is extremely slow compared to other natural materials (being degraded by physical or microbial processes). Recent studies have revealed that the vast majority of plastic waste and debris that are found in the marine environment are made of polyethylene or polypropylene. Interestingly, 80% of the plastic present in the sea originates from land pollution. It is transported by rain waters, rivers, flood events, winds, and streams (Thompson et al., 2005). As a result, plastic can be found really far from the continental coasts. Once debris is in the sea, it can slowly fragment into small pieces of <5 mm by the combined effect of the sun, the sea salt, and the water movements. This fragmentation creates a suspension of small plastic pieces that can be found from the water surface down to 30 m. This process is known to be bad for wildlife because of physical problems caused by ingestion or entanglement (Thompson et al., 2009). Investigations also have demonstrated that a high proportion of animal species ingests plastic debris (86% of sea turtles, 44% of seabirds, and 43% of marine mammals; Derraik, 2002). Even though most animals will be able to process the small plastic pieces through their entire digestive system, leaching out of additives and their potential transfer to the organisms are not known. Studies on annelids, mollusks, crustaceans, insects, fish, and amphibians have shown that phthalates and bisphenol A can affect reproduction in all studied animal groups. It also impairs development in crustaceans and amphibians and induces genetic aberrations (Oehlmann et al., 2009). Toxic effects seem to be species specific because mollusks, crustaceans, and amphibians appear to be especially sensitive to plasticizers at environmentally relevant exposures (ranging from nanograms to micrograms per liter). In contrast, most negative effects in fish (except for disturbance in spermatogenesis) occur at higher concentrations (Oehlmann et al., 2009). Interestingly, floating plastic could have some indirect beneficial impacts on the environment. It appears that more phytoplankton can stay at the surface instead of sinking by getting attached to plastic debris. This addition of floating phytoplankton could lead to increased photosynthesis by CO_2 absorption and oxygen production at the surface of the oceans (Tara Expeditions, 2013).

Regarding terrestrial ecosystems, there is still a need for more research on the quantities and effects of plastic debris in natural habitats, on agricultural land, and in freshwater. Stomach obstructions caused by plastic bags have been described in several animal species, but no toxic effects have been measured so far. There also are a few reports about the contamination of soils with small plastic fragments as a consequence of spreading sewage sludge (Zubris and Richards, 2005) or fragments of plastic contaminating compost prepared from municipal solid waste (Brinton, 2005). Plastic therefore appears to represent more of a problem than an advantage in its interaction with natural habitats.

PLASTIC AND BIOLOGICAL STUDIES OF ANIMAL POPULATIONS

Understanding the biology of animal populations in the wild (in situ) or in captivity (ex situ) is another critical component of conservation biology that interacts with plastic in many ways. Animal populations managed in zoos or research centers are surrounded by plastic devices (toys, gates, water reservoirs), but safety committees always try to check the innocuousness of any plastic devices that are supposed to be in direct contact with the animals.

Preventive or curative veterinary medicine in situ and ex situ now extensively uses plastic (e.g., disposable syringes, tubing, catheters, and physiological fluid bags) that is irreplaceable, as already mentioned for human medicine (Table 1). In these specific conditions, plastic is needed and is good. Even if it can be hypothesized that it is too good to be true, the potential harmful or toxic impact of "medical" plastic has not been reported yet. Besides animal care, conservation projects include biological research in laboratories or in the field. Over the past few decades, there has been a switch from glassware to convenient plasticware that is sterile and disposable (thus avoiding cross contamination of pathogens or reagents). Plastic supplies now are the gold standard in molecular biology and in vitro culture of cells and embryos (Figure 1). However, laboratory plastics are exposed to different stress conditions (e.g., autoclave, gas sterilization, UV lights, sonication, microwaves) that have unknown impacts on the integrity of the plastic polymer or the leaching out of additives.

For several decades, biologists and veterinarians have been collecting and storing frozen biological materials, including samples of DNA, somatic cells, tissues, blood products, germplasm (sperm and eggs), and embryos, as well as other animal, plant, and soil products. The value of systematic and organized frozen biorepositories extends far beyond ensuring the protection of the world's unique animal and plant species. When collected, stored, and used properly, these frozen biological materials can significantly enhance the pursuit of scholarly knowledge, enable biodiversity preservation and thus understanding, and contribute to the improvement of human health and well-being. The fact that some of the samples currently stored are no longer available in the natural world reflects the critical importance of properly preserving and managing these rare and growing biological collections. This critical resource relies heavily on plastic (tubes and straws; Figure 1d,e) because glass is not reliable and is

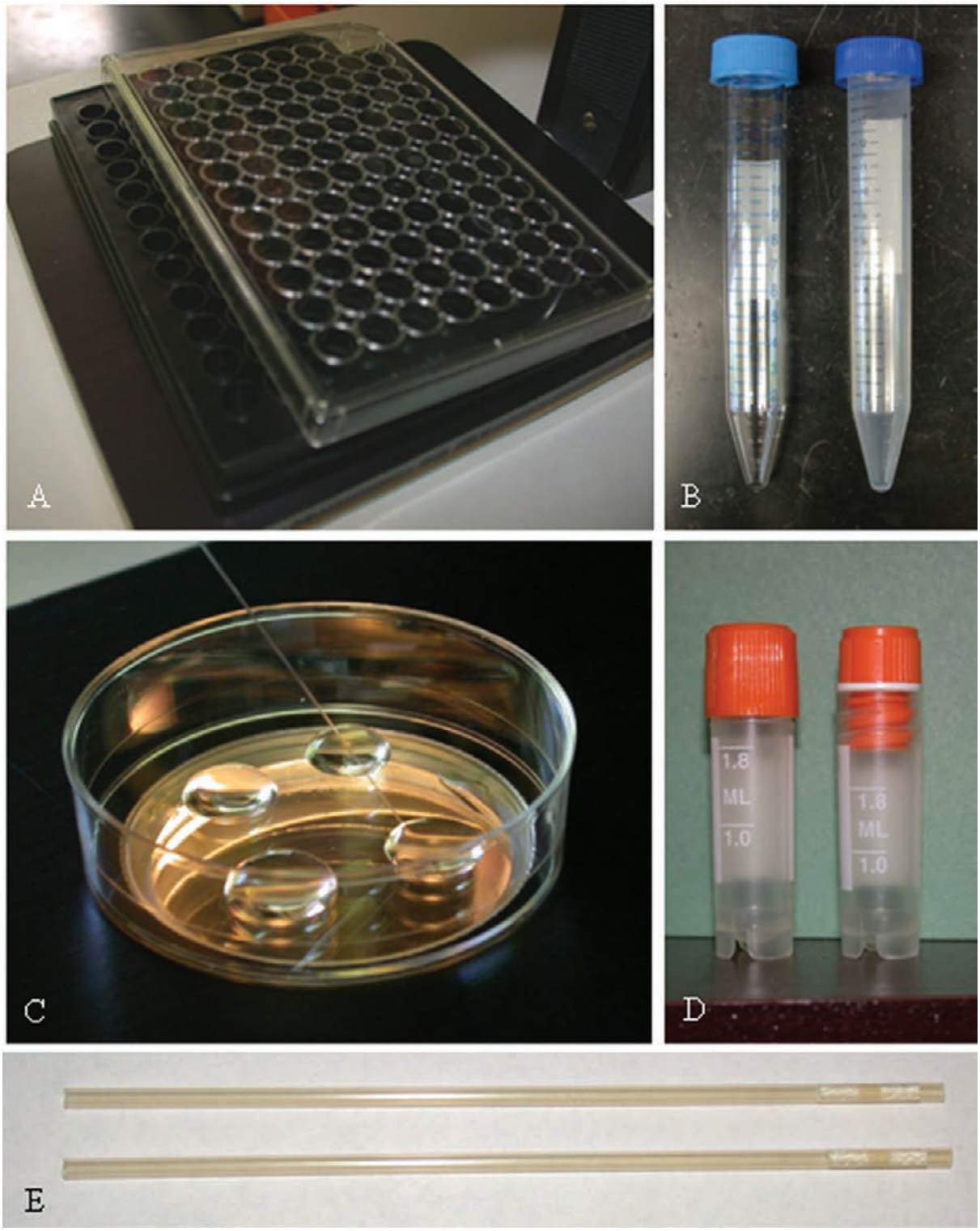

FIGURE 1. Plastic supplies routinely used in biological research related to animal conservation. (a) Polystyrene 96-well dish used for assays. (b) Polystyrene (left) and polypropylene (right) 15-mL tubes for in-culture medium preparation. (c) Polystyrene 3.5-cm dish for in vitro culture. (d) Polypropylene tube for frozen samples. (e) Polyvinyl chloride 0.5-mL straws for frozen samples.

inconvenient (breakable and heavy). However, the long-term effect of freeze-thaw cycles on plastic integrity is a stress condition that has not been explored yet. Besides the use of freezing temperatures to stabilize biomaterials, new preservation techniques including desiccation or biostabilization at room temperatures will soon rely on plastic for long-term storage. The issue here is that plastic containers are designed to be disposable and will be expected to be stable for several decades. Therefore, more studies need to be conducted to understand and mitigate the aging process of plastic polymers.

It is interesting to point out that some plastics that are considered to be good and safe for human usage may be problematic in biological research and vice versa (Table 2). Plastic straws used for semen freezing (Figure 1e) are made of polyvinyl chloride (the most resistant to cryofractures during freeze-thaw cycles), which is also a controversial material because of its potential toxicity from lead and tributyltin (Meeker et al., 2009). Furthermore, there actually are interesting contradictions related to the embryo toxicity of some plastic supplies used for in vitro culture (Table 2). Prolonged usage of polyethylene tubes (Figure 1b) during in vitro culture is known to be embryotoxic, whereas polystyrene tubes and dishes are not.

SEPARATING GOOD PLASTIC FROM BAD PLASTIC IN CONSERVATION BIOLOGY

It is currently difficult to distinguish good plastic from bad plastic aside from the most adverse effects of debris and pollution (e.g., animals dying from plastic ingestion or ecosystems polluted by plastic wastes). In addition, available data on plastic toxicity can be contradictory and not necessarily reflect the actual issues. Most toxicity studies are conducted with doses administered orally or injected. For instance, many reports have clearly demonstrated that plasticizers such as phthalates or bisphenol A have steroid hormone–like effects on living organisms (antitestosterone and estrogen-like, respectively; Thompson et al., 2009). More recent studies also demonstrated that phthalate promotes weight gain in female mice, which in turn produce overweight offspring. The effects occur even at the low concentrations commonly associated with human exposure (Schmidt et al., 2012). However, the main issue is relating the types and quantities of additives present in plastics to natural uptake and accumulation by living organisms. There also is a need for more studies exploring environmentally relevant concentrations and their toxicity on ecosystems.

Furthermore, a vast array of compounds can leach out from plastic polymers during normal degradation over time or after exposure to different physical or chemical conditions. There is a need for more systematic studies and monitoring to identify the significant toxic and disruptive additives from the innocuous ones. It also is time to shed new light on plastic in conservation biology and challenge existing paradigms. As mentioned above, there are obvious bad plastics for the environment as well as good and irreplaceable plastics for animal care and other conservation efforts. Technology now is advanced enough to precisely know the composition of plastics commonly used in laboratories and to clearly identify the types and quantities of additives (Tsang et al., 2009). Thus, it is possible to force out liquid or volatile compounds from the plastic polymers and potentially mimic an aging process. In addition, the impact of the various stress conditions (e.g., extreme temperatures, physical and chemical properties of liquid in contact with plastic, or radiation) has to be assessed. It is important that compounds be thoroughly investigated for their biological effects. For instance, in vitro tools can precisely measure the impact on somatic and germ cell physiology (at the cellular and the molecular levels). Biological testing can also be performed on organs, entire organisms, and populations to explore any species specificity. Besides generating more scholarly knowledge about plastic compounds, results may be used to develop alternate methods to mitigate deterioration and detrimental effects. Data collected in vitro would then be useful to better understand the impact of plastic debris on the environment (water and soil pollution). A parallel approach should be to use biological collections of biomaterial samples (blood serum, hair, feathers, plants, soil) to detect the presence of targeted plastic compounds. Then, it could be possible to take advantage of conservation projects conducted all over the world (such as Global Earth Observatories) to measure and monitor the impact of plastic in the environment. A better understanding and mitigation of the impact of plastic on the various aspects of species survival and ecosystem health perfectly fit with the Smithsonian's goal to find innovative approaches to global problems that stem from biodiversity loss, ecosystem degradation, and human-biosphere interactions.

CONCLUSIONS

Plastics may offer considerable benefits in conservation biology, but our current approaches to production, use, and disposal are not sustainable and present concerns for wildlife as well as for human health. Even though the earliest plastics such as celluloid were invented as a substitute for natural materials like ivory or tortoiseshell (Friedel, 1977), they never really impeded the decline of elephant and tortoise populations in the wild. Conversely, plastic materials dispersed in nature are now blamed for having potential toxic effects. However, many concerns and uncertainties remain about the environmental hazards and information on health effects. Plastic is increasingly present, used, and also plays different roles in each discipline involved in conservation biology. Some successful conservation efforts could even help to consider that plastic can save species. There actually are many examples of species that are not necessarily threatened by plastic in their natural habitat but have been rescued from extinction, have been restored in captivity, and are now being reintroduced in the wild (Wildt et al., 2010) by taking advantage of plastic materials at each critical step (Figure 2).

FIGURE 2. Examples of endangered species benefiting from captive breeding programs integrated with field conservation. None of these species are threatened by plastic in their natural habitat. (a) Eld's deer (*Rucervus eldii thamin*) fawn born after in vitro fertilization and embryo transfer. (b) Black-footed ferret (*Mustela nigripes*) kit born by artificial insemination. (c) Panamanian golden frog (*Atelopus zeteki*) raised in captivity for semen collection. (d) Giant panda (*Ailuropoda melanoleuca*) cub born by artificial insemination.

It is still too early to answer the question about good and bad plastic, but the dichotomy that is recognized in human health and in other areas might not be necessarily valid for conservation biology. The reason is partly due to specific needs covered by plastics that cannot currently be met by other materials. To some extent a stable and durable plastic would be preferred to a biodegradable one. Hopefully, the issues of good usage versus bad usage will also help to solve a lot of problems in the future and help to change the way we think about plastic.

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Plastic and Food Culture

Cory Bernat

ABSTRACT. Like food, the topic of plastic is deceptively simple and an often-overlooked aspect of daily life. Both plastic and food developed new products and new markets for their products as part of the same consumer-oriented culture. As the food and plastic industries simultaneously made their production more efficient and factorylike, plastic wrap helped to present and preserve the finished food products in a slick way. By the end of World War II two industries adapted to and encouraged a postwar economic boom while marketers encouraged new consumer habits to compliment the needs of industry. Recently, plastic has been getting attention for negative reasons, such as its lingering appearance in the environment and in our bodies. The negative attention for the manufacturers of plastic is not unlike that of a much-discussed obesity epidemic for food producers: both industries are affiliated with promoting convenience for consumers *and* with problems of overconsumption. Could mass media reeducate us to become better consumers and disposers? It is hard to imagine that this medium would ever be used to discourage consumption. What shifts in the culture of mass production will compliment consumer awareness already taking place?

INTRODUCTION

For two years, as a member of the Food and Wine History Project at the Smithsonian Institution's National Museum of American History, I helped research and curate a museum exhibition called *Food: Transforming the American Table, 1950–2000*. The exhibition, focused on food in postwar United States, opened in November 2012.

While working on this food-focused project, the topic of *plastic* kept surfacing, and it became hard to ignore. The Age of Plastic research program provided an intellectual home for these observations and surprisingly pressing questions. Both food and plastic appear in many aspects of our daily lives and underline the value of interdisciplinary research. Like food, the topic of plastic is deceptively simple and often overlooked. For Susan Freinkel, author of *Plastic: A Toxic Love Story*, plastic has become "a huge, and yet strangely invisible, part of modern life" that she was startled to realize she knew almost nothing about. "How did my life become so permeated by synthetics without my even trying?" (Freinkel, 2011:3). This question resonated with me, along with similar inquiries into the invisible aspects of our complex food system, and led to the compilation of examples in this chapter. I view this research as a type of unavoidable, yet highly insightful, by-product of other research.

Historian and food scholar Warren Belasco (2008) claims that the field of food studies—my research approach—is now a "respectable" field of study. But he also warns that it is inherently subversive. Food scholars tend to be generalists and tend to ask inconvenient questions. He explains, "We think about matters political, historical, economic, sociocultural, and scientific, *all at once*. We study food as a system" (Belasco, 2008:8). Plastic has become an influential part of that system, often developing alongside modern food industries. As research topics, both food and plastic, perhaps, suffer from the

National Museum of American History, Smithsonian Institution, Washington, D.C., USA. Correspondence: C. A. Bernat, 1goodpotato@gmail.com

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tension that comes as a consequence of depending on a substance while simultaneously questioning its role on our lives.

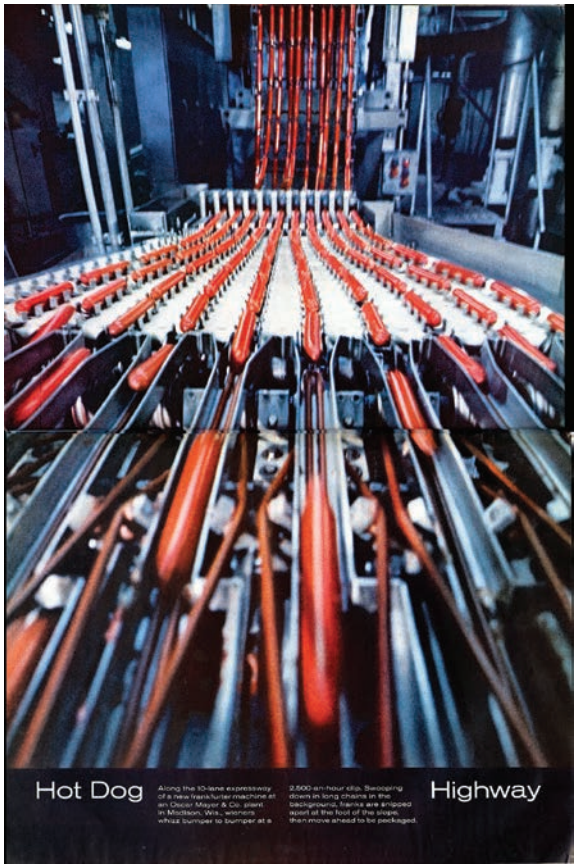
Recently, plastic has been getting attention for negative reasons, such as the planet's overuse of it and our accidental ingestion of chemicals leaching from it. Manufacturers of plastic are feeling the pressure from the negative attention, not unlike how food manufacturers and marketers have to contend with a much-discussed obesity epidemic. Both industries are affiliated with promoting convenience for consumers and with problems of overconsumption. Although this may seem like a pessimistic starting point, this observation led to an appreciation of some of the parallels in the manufacture of plastic and the manufacture of food and to the insights that emerge from this comparison.

PLASTICS AND FOOD: THE PARALLELISM

While researching the postwar food system for the exhibition, it became clear that popular media increasingly embraced the word *abundance* and references to our *land of plenty*, although luxurious living was not the reality for everybody. Nonetheless, the postwar United States saw increased food production and consumption, which publications like *Life* reinforced enthusiastically and even with a sense of pride (*Life*, 1955, 1962). Favorite topics included new capabilities of modern, efficient food producers as well as consumers' reinvigorated purchasing power (Figure 1).

The interior text and photos reflected a great deference for size and speed. An article compared the operations of a large quick-frozen vegetable producer favorably to automobile assembly lines and the military's battlefield strategies (*Life*, 1955:41). The article noted that "in the previous year Seabrook farm grew, gathered, and froze 100 million pounds of 29 vegetables and fruits." Seven years later, a photoessay documented the marvel of food processing (*Life*, 1962a, 1962b), dazzling the reader with a "10-lane expressway of a new frankfurter machine" in which "wieners whizz bumper to bumper at a 2,500-an-hour clip." (Figure 2). These articles are just two examples of a food system extremely skilled at converting nature's bounty into standardized

FIGURE 1. *Life* magazine covers from January 3, 1955, and November 23, 1962. Both issues exalt an impressive and abundant American food system.

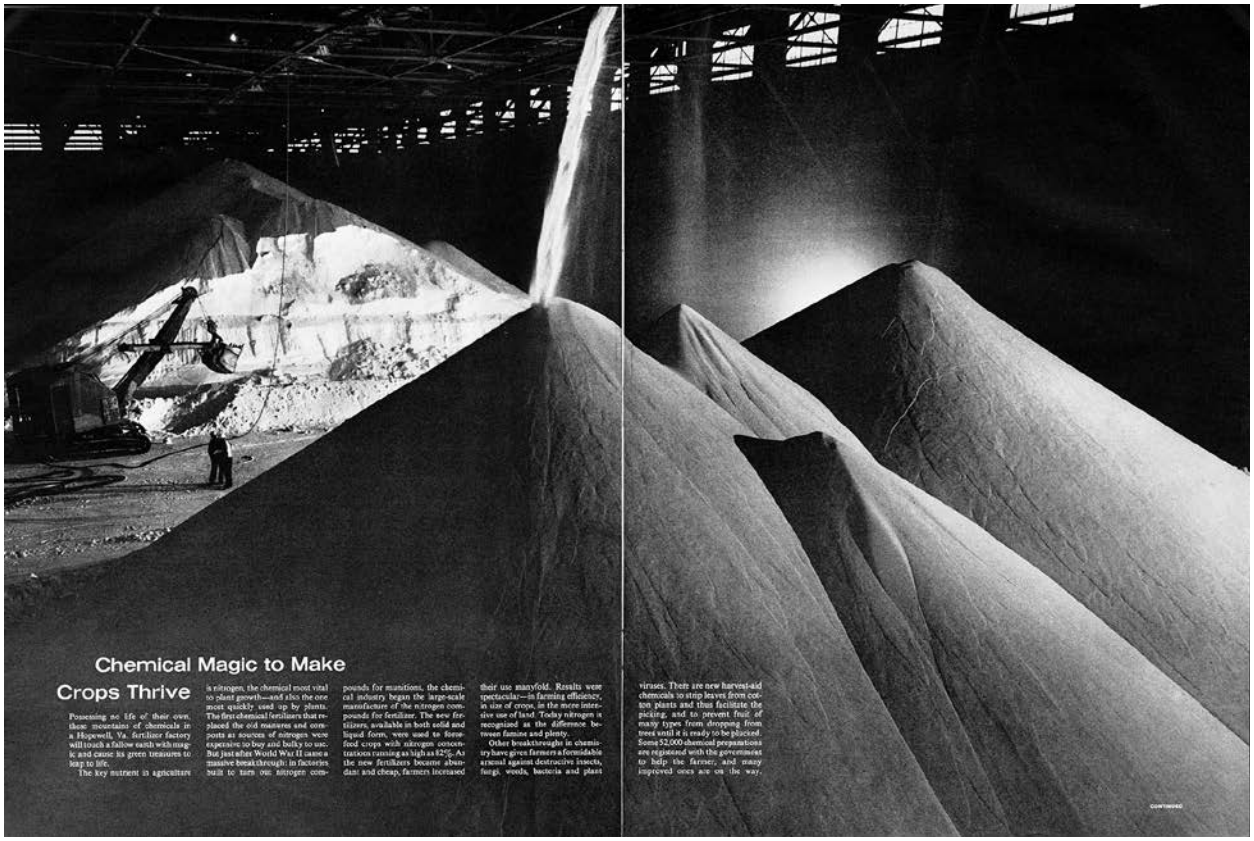


units ideal for a mass market and an increasingly visual media environment poised to document and admire it.

Such impressive food production relied on chemical inputs, such as synthetic fertilizers, to command what many believed was "a mastery over nature." Chemists were praised for conjuring nitrogen out of the air, not unlike how other chemists were praised for conjuring plastic materials where nothing like it had existed before.

In the book *American Plastic*, Jeffrey Meikle (1995) explains how publicists celebrated "the alchemical wizardry of industrial chemistry" and promoted new plastic materials as products of arcane magic rather than rational chemical processes. From Meikle's perspective, "by suggesting that organic wastes from the bowels of the earth could be transformed into wondrous shapes and colors, chemical utopians encouraged ignorance and fostered a feeling that some things are best left unrevealed" (Meikle, 1995:243). It could be argued that *agricultural* utopians encouraged a similar, emotionally charged admiration—an unquestioning admiration—of "chemical breakthroughs" for

FIGURE 2. Spreads from *Life* magazine showing the "Hot Dog Highway" (*Life*, 1962b:136–137) and "Chemical Magic to Make Crops Thrive" (*Life*, 1962a:58–59).



farmers and for the food supply. New methods of farming that increased production were widely accepted as the answer to global famine and the key to prosperity. When plastic and food products are viewed as part of the same consumer-oriented culture, the similarity of each industry's trajectories becomes evident. Both industries developed new products and new markets for their products, and both industries relied on readily available and affordable chemical inputs to expand rapidly at a fast pace. An advertisement by Union Carbide combines them in a concrete way: they can sell you the chemicals that help grow food and the plastics that help preserve it (Figure 3). Fittingly, man's control over nature was a recurring theme of the company's ads in the late 1940s and 1950s.

As another example of food and plastic parallelism, wartime Army rations provided a big boost to both industries. World War II soldiers field-tested processed foods and the plastics in which many rations were wrapped. In a 1943 article *Scientific American* reported, "The packaging revolution perhaps reached its height; the restrictions on tin, steel, and rubber have necessitated sweeping changes. . . . In Army rations, cellophane is being widely employed for sealing in the moisture content of some components, such as the fruit bar and cigarettes, and keeping excess moisture out of others, such as the biscuits, D-bar, powdered bouillon and lemon juice" (Spencer, 1943:217–218). In the same year, Monsanto (1943:2) published *A Wartime Guide to Monsanto Plastics* "to help you answer the question 'Can I do it better, faster, with plastics?'"

The food industry met the demands and the special conditions of war with increased production and with considerable investment in technology. After the war, Laura Shapiro explains that "factories were ready to keep right on canning, freezing, and dehydrating food as if the nation's life depended on it. But peacetime shoppers, unlike soldiers in foxholes, had a choice. . . . What the industry had to do was persuade millions of Americans to develop a lasting taste for meals that were a lot like field rations" (Shapiro, 2004:8). By the end of World War II we have foods with a long shelf life and plastics to help preserve them, reflecting increasingly intertwined industries rapidly adapting to and encouraging a postwar economic boom (Figure 3).

In the book *Twinkie, Deconstructed,* Steve Ettlinger explains in great detail all of the ingredients in a Twinkie and, by default, many of the mysterious processes that enable many familiar, and often beloved, snack foods. Not only do Twinkies "share a subingredient with the most common plastic, made from the most used petrochemical in the world" (Ettlinger 2007:194), but in a reverse pattern, the Twinkie's plastic wrapper can also contain chemicals derived from corn, which also appear in Twinkies. Even if one never read this book-length attempt to understand an ingredients list, the fact that it exists should make anyone wonder how the supposedly powerful consumers are expected to know what goes into a large percentage of our food or how it is made.

FIGURE 3. The carefully packaged Army rations on the left (Army photograph, Division of Work and Industry, National Museum of American History, Smithsonian Institution) provided a model for the consumer products depicted in the Union Carbide advertisement on the right, published in *National Geographic* magazine (July 1948).

In fact, it could be argued that we are not expected or encouraged to know this information at all (Nestle, 2003:20–25). The question arises, How are consumers expected to "know best" when we are encouraged to know so little? Ettlinger explains that at the writing of his book, then Twinkie producer Interstate Bakeries Corporation declined his request for tours and interviews, citing its "preference to help writers who are merely reminiscing about their sweet childhood memories" (Ettlinger, 2007:xiii). Appropriately, after chemical utopians and agricultural utopians appear the snack utopians, who deftly use nostalgia, among other tactics, to promote emotional, unquestioning ties to their products. Wendell Berry (1989:126) wrote about how the ideal eater in modern culture is the *industrial eater*, "who does not know that eating is an agricultural act, who no longer knows or imagines the connections between eating and the land, and who is therefore necessarily passive and uncritical." Typically, most of us do not ask about food ingredients, in part because they have become so complex that even if consumers knew what questions to ask, few of us would understand what the answers mean.

Although some have been critical of our industrial food supply, it has been advantageous for businesses to view agricultural crops, such as corn and soybeans, as raw materials that are components of an array of industrial goods, edible or otherwise. The edifying poster produced by Staley Manufacturing Company from about 1950 proudly displays their factory and their ties to industry and defense (Figure 4). When unfolded, the "Staley Target" lists many corn and soy derivatives and uses as "essential for national defense" and "essential for the civilian economy."

The poster attempts to explain how industrial needs influence and determine the availability of certain consumer products. In the lower right the poster reads "IMPORTANT – in producing any one product from corn or soybeans, other basic products become available which, for economic reasons, must be processed into finished commodities. The complex character and wide range of constituents in the raw material make this unavoidable." For example, the same corn derivative in recipes for gravies and soups is also used in dry cell batteries and fireproofing. In addition, this poster reveals how corn and soy crops—grown for much more than food—have been encouraged to take on the positive properties of plastic, such as its malleability, mass output, and affordability. Warren Belasco (2008:5) recognizes this shift in thinking: "Food is so vague in our culture in part because, thanks to processing, packaging, and marketing, it *is* an abstraction. An almost infinite set of variations based on a theme of corn, which is the basis of so many modern foodstuffs, from Big Macs to Twinkies."

Figure 5 shows a 1963 advertisement for Kodak plastic sheeting, including a wrapped loaf of bread that appears to be out of place with the other industrial uses of plastic. But maybe it isn't out of place at all. In the decades after the war, food was often treated like another industrial product. As the food and plastic industries simultaneously made their production more efficient and factorylike, plastic wrap helped to present and preserve the finished products in a slick way, even if the finished products were not Twinkie-like at all. In addition to breads and other processed foods, the cellophane advertisements depicting produce aisles in Figure 6 point to the wide reach of cellophane and how it influenced, or hoped to influence, the buying and

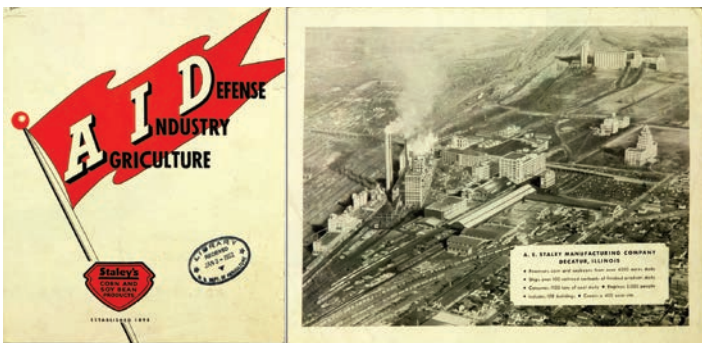


FIGURE 4. Staley Manufacturing Company poster (ca. 1950). Left: The cover reads AID, standing for Agriculture, Industry, and Defense, and the back shows their factory. Right: When unfolded, the Staley Target appears.

FIGURE 5. Kodak advertisement for their plastics (*Fortune*, 1963).

selling practices of seemingly *un*processed foods available to consumers in the supermarket.

WHERE MARKETING TAKES OVER

With a contemporary awareness of the problems with plastic, it is easy to question how something so synthetic could ever be embraced as a go-to material for fresh food. The definition of "freshness," it appears, is as malleable as plastic. Many believed plastic improved fresh produce, and in her book *Fresh: A Perishable History*, Susanne Freidberg (2009:184–188) explains that lettuce and vegetable growers turned to plastic wrap after they noticed a rise in the consumption of canned and frozen foods, especially once canned food makers began claiming that their products were as nutritious as fresh produce. Furthermore, highly influential supermarket chains appreciated wrapped produce, according to Freidberg, because compared with "naked" produce, it was easier to buy, display, and track; it looked neat, sold faster, generally kept longer, and suffered less "customer abuse." In short, plastic helped products from nature to become more standardized, more like manufactured products easily boxed and labeled.

Cellophane transformed meat departments even more dramatically by completely shifting the expectations of customers, butchers, and store managers (Figure 7). The advertisement from

FIGURE 6. Left: DuPont cellophane ad appearing in *Life* in 1955. Right: Avisco cellophane ad appearing in the *Saturday Evening Post,* October 12, 1957.

DuPont in *Life* magazine in Figure 7 has an unusually large amount of text for a 1959 advertisement. Although it explains how cellophane helps keep meat fresh, this ad is really an argument for self-service supermarkets. What DuPont understood was that cellophane-wrapped meat would require shoppers to develop new habits. That is not how they were used to buying it. With promises of freshness and visibility from cellophane, shoppers are reassured that a new store layout is really to their benefit and is a desirable way to shop.

Beyond convincing shoppers of the benefits of cellophane-wrapped food, DuPont carefully explained that self-service was also a desirable way to increase business. Their cellophane division published a few studies with store managers in mind, including a progress report on self-service meats (DuPont, 1945) and a study on impulse buying in which they concluded that "when half of the buying decisions are made at the point of sale (meaning inside the store), then factors such as display and packaging become all-important to stimulate unplanned, IMPULSE buying" (DuPont, 1946).

Historian Roger Horowitz explains what happens to the meat itself in his book *Putting Meat on the American Table* (2006). "By interposing a film between the meat and outside environment, packaging could create artificial conditions that, in essence, performed the work once borne by curing or refrigeration. Cellophane made meat appear more attractive by influencing color, smell, and presentation of a particular cut" (Horowitz, 2006:137). All of this helped sales.

It is also likely that other technological changes, like the increased availability of refrigeration, may have helped DuPont sell cellophane more than anything else. Frigidaire pamphlets used the new concept of self-service meat to promote their refrigerated display cases, which were a necessary investment for any store manager interested in "better looking, busier, and more profitable stores" (Frigidaire, 1952; Figure 8).

Although many frozen foods were not wrapped in cellophane, their colorful cardboard boxes were typically coated in plastic to help handle moist environments and allow for brightly colored printing on the package. Printed packages were

FIGURE 7. DuPont cellophane advertised self-service meat counters in *Life* magazine (*Life*, 1959:44) and encouraged store managers to adopt this way of selling meat with detailed reports about consumer behavior. Courtesy of Hagley Museum and Library.

necessary just to differentiate products because more and more, the contents of the packages were very similar, if not identical. Advertisements showing off the capabilities of meat-packing machines reinforce the concept of interchangeability and malleability among modern foodstuffs in addition to the growing significance of marketing and "eye appeal" (Meat Industry Trends, 1961; Figure 8). In *Paradox of Plenty*, historian Harvey Levenstein describes how in 1954, when General Foods, the largest food conglomerate, selected a new top officer, it chose not a production or financial specialist but a marketing expert. This acknowledged "that the emphasis in the food business has moved more and more from manufacturing to marketing" (Levenstein, 2003:115). By 1967 the American Management Association titled one publication simply *Packaging Is Marketing* (Guss, 1967); plastics made this possible.

Cellophane-wrapped groceries even became symbols of American capitalism. The U.S. Information Agency possessed the image in Figure 9, presumably, to show abroad to impress foreigners with the concept of "abundance without affluence"

FIGURE 8. Refrigerated self-service cases allowed consumers to choose from cellophane-wrapped meat and other products in eye-grabbing packaging, 1951. Image from the National Museum of American History Trade Literature Collection.

FIGURE 9. The backside of this image reads, "A housewife displays a table-full of packaged foods she has purchased from a modern supermarket—farm fresh and easy to prepare." Source: DuPont, National Archives, RG 306 Subject 58-5877.

to bolster arguments about a higher American standard of living available to a greater number of citizens. It shows an average American housewife at her kitchen counter overflowing with packaged groceries after a supposedly routine visit to the grocery store. Lizabeth Cohen (1998:111) writes how "mass consumption not only shaped the economy, but also altered the political realm, becoming a new vehicle for delivering the traditional American promises of democracy and egalitarianism."

At home, consumer-citizens were patriotic citizens. Increased household consumption extended to plastic housewares like Tupperware, which took advantage of the material's malleability. Extensive product lines produced in many different shapes and colors helped create a healthy demand and gave their infamous sales force new products to talk about with their in-home customers (Syracuse University Libraries, 2013). As many historians have noted, the popularity of Tupperware speaks to the embrace of plastic *as plastic* (as opposed to plastic used to mimic more expensive materials) and to new definitions of consumption, convenience, and modern femininity. Its popularity also added to the general comfort level of using plastic containers for food storage (*Life*, 1956:47). Eventually, this comfort level expanded to include microwave ovens and dishwashers once they became commonplace and plastics were formulated for high heat and modern appliances.

According to Susan Freinkel, disposable plastic goods were initially a tough sell; consumers had to be taught to throw plastic away. "The ethos of reuse was so deeply ingrained in the 1950s," she writes, "when vending machines began dispensing coffee in plastic cups, people saved and reused them" (Freinkel, 2011:121); Figure 10 shows a plastic cup advertisement that practically shames people into modern, disposable living (*Life*, 1964:53). To use paper cups would be old-fashioned and miserly according to Scott; plastic cups, like many other plastic goods, were priced to be disposable. In the language of the Cold War, the act of disposing signified liberation—a real distinction at the time between the freedom of capitalism and the bondage of communism.

FIGURE 10. Scott plastic disposable cups (*Life*, 1964:53).

In *Waste and Want: A Social History of Trash*, historian Susan Strasser echoes Wendell Berry and notes how new materials, especially plastics, became the basis for a relationship to the material world that required consumers to buy things rather than make them and to throw things out rather than fix them: "Nobody made plastic at home, hardly anybody understood how it was made, and it usually could not be repaired" (Strasser, 1999:267). Just as most of us have become further removed from the production of our food and more dependent on industrial agriculture, we have also become removed from the production of any goods that are made with plastic. Although unnerving to some, a little ignorance has also been interpreted as a sign of progress: "Civilization advances in proportion to the number of operations its people can do without thinking about them" is an observation attributed to philosopher A. N. Whitehead (1911) and an awareness that the convenience of new technologies in our lives requires trust in a series of unknowns (Talbott, 1995).

Some of the most interesting convenience packaging is never marketed to the end consumer at all. A newsletter from the Hotel & Restaurant Division of Heinz announced that ketchup is now set to enter into the "single-service field" (H. J. Heinz Company, 1958). Although this packaging did not become widely used until the late 1960s, little helpers such as these fed into the habit and the expectation of convenience that Americans have become addicted to. It is a highly sophisticated little thing indeed:

> The package which meets Heinz standards is lined on the inside with a type of polyethylene that is compatible with food. The middle layer of this three-layer pouch is made of aluminum foil. Outside the foil is a layer of glassine high transparency paper that is printed in four colors. This triple-laminated package will stand the intense heat of filling while, at the same time, the glassine outer layer protects the printing from refrigeration "sweating" as well as from the damage of handling. (H. J. Heinz Company, 1958)

This description is reminiscent of the complex layering that goes into the newest bagged lettuce packaging, which works invisibly to preserve fresh greens in ways consumers are typically unaware (Bilger, 2004).

The coffee cup lid collection of Louise Harpman and Scott Specht, who have recently donated a selection of lids to the National Museum of American History, calls attention to another common instance of single-use plastic packaging that is tied directly to consumer habits and a widespread addiction to coffee. Lids from their collection are currently on display in the food exhibition *Food: Transforming the American Table, 1950–2000* (Smith, 2012), in a section about changing eating habits, in particular, eating on the go (Figure 11). Or in this case, drinking hot liquids on the go, which Harpman and Specht (2005) described as a "uniquely American phenomenon, responding to a particularly American set of expectations." The patents for the lids reveal the engineering and considerable thought these objects have received. Harpman and Specht explain how each new patent designation identifies an "improvement" so as to differentiate it from other models. Some of the current innovations include "mouth comfort, splash reduction, friction fit, mating engagement, and one-handed activation," any of which, the collectors joke, "could easily describe other, more intimate, bodily pleasures" (Harpman and Specht, 2005).

As interesting as the lids are as designed objects, I have also taken note of how people dispose of the single-use plastic lids and their corresponding disposable cups. Figure 12 gives some examples of photographs taken during a major public event in downtown Washington, D.C., when it was cold out and people clearly wanted their coffee. Such an ordered arrangement of our single-use trash can be seen as evidence that people feel guilty about this decadent habit, even if only briefly.

Fear and guilt are certainly motivating factors on an individual level, but plenty of vested interests have researched and surveyed consumers to find ways to lessen any guilt and prevent us from changing any so-called bad habits. The website "Plastic Food Service Facts" (American Chemistry Council, 2010–2012) was created to relieve consumers of any guilt; it maintains that takeout food containers are a civilized and sanitary convenience

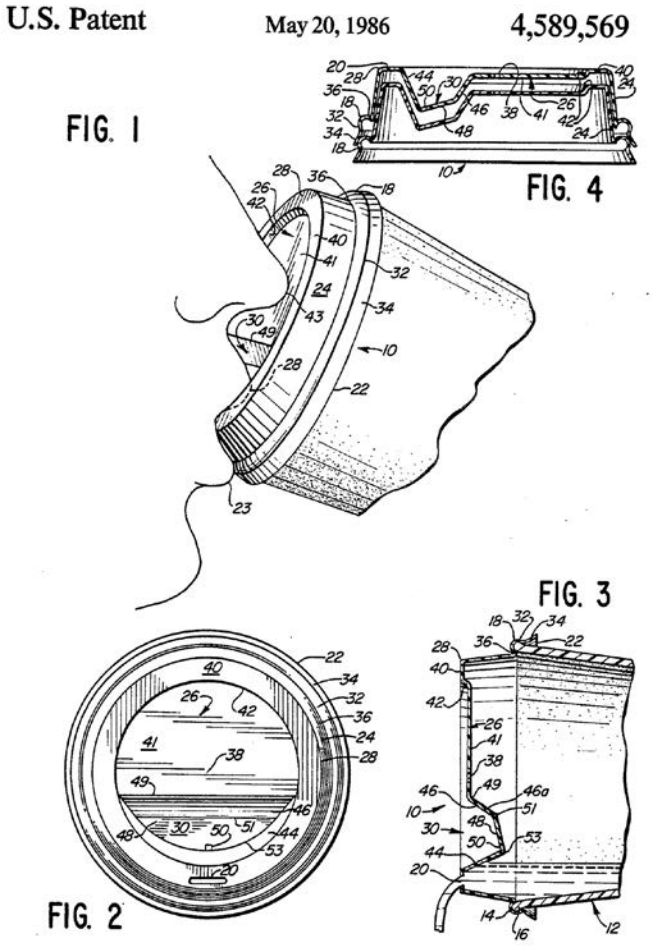


FIGURE 11. Top: Coffee cup lids collected by Louis Harpman and Scott Specht, on display in the National Museum of American History in 2012. Left: Patent drawing from U.S. Patent 4,589,569.

that should be celebrated for making our lives better and not demonized or even questioned.

Still, large companies have been convinced to stop serving certain types of packaging products deemed particularly harmful. McDonald's famously stopped using Styrofoam clamshell boxes for sandwiches in 1990 after environmental groups publically complained about the packaging and the amount of trash the fast-food restaurants produced (Figure 13). The Associated Press (1990:3) quoted the company president at the time: "Although some scientific studies indicate that foam packaging is environmentally sound, our customers just don't feel good about it. So we're changing." Chemicals in the lined papers that currently wrap hamburgers are reportedly more detrimental to consumers' health (Walsh, 2010), but the clamshell container is an example of how public concerns, scientifically founded or otherwise, can influence behavior and affect major business decisions.

CONCLUDING REMARKS

The examples I included relate to plastic and food, but they are also about behavior and some of our favorite, addictive

FIGURE 12. Coffee cup disposal during a major winter event in downtown Washington, D.C. Photographs courtesy of Robert Wechsler, 2009.

FIGURE 13. McDonald's Styrofoam packaging in the collection of the National Museum of American History, Smithsonian Institution.

habits. Habits are notoriously difficult to change, although mass production and advertising actively encouraged Americans to become overconsumers and quick disposers. Could mass media reeducate us to become more conscientious consumers and disposers? Perhaps, but it is hard to imagine that this medium would ever be used to discourage consumption. Recent attempts to develop "bioplastics" and even more recycling at the end of the consumption process do not do much to alter consumer behavior. However, investment in these efforts implies that consumers are paying attention, asking questions, and applying pressure. What shifts in the culture of mass production and overconsumption will compliment consumer awareness already taking place?

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Ford's Driving Role in the Bio-Based Materials Age

Debbie Mielewski, Ellen Lee, Angela Harris, and Cynthia Flanigan*

ABSTRACT. The world has seen multiple waves of innovation since the Industrial Revolution, from the so-called Steam Age to the Steel Age, Oil Age, Information Technology Age, and so on. The authors propose that we are entering a new wave of economic development in cleantech and sustainability, aimed at returning us to a low-carbon world. Ford Motor Company has been a leader throughout these innovation waves and continues to drive the path forward to the bioeconomy, albeit the company's motivations for pursuing bio-based materials have evolved. This chapter details several key innovations and ongoing research at Ford in the development of bio-based materials, including polyurethane foam derived from soybeans, wheat straw–reinforced polypropylene, and experiments with polylactic acid.

INTRODUCTION

The world has seen multiple waves of innovation since the Industrial Revolution, such as the Steam Age, Steel Age, Oil Age, and Information Technology Age (Freeman and Louca, 2002). In 2001, Ford Motor Company added a biomaterials team to their research program, and that team has since developed new bio-based plastics that perform well, are economically competitive, and are being used in Ford production automobiles. With these successes and from their vantage point working with so-called green materials, there is a strong feeling that the world is moving into a new wave of cleantech and sustainability through which bio-based materials will help return us to a low-carbon world.

Great ideas endure the test of time. Henry Ford, founder of the Ford Motor Company and the automotive assembly line, was an avid inventor with more than 160 U.S. patents. He dreamed of cars that were reasonably priced, reliable, and efficient, not far from our ambitions today. Part of this philosophy included activities like the use of agricultural products and reuse of materials that today would be considered through a lens of sustainability, but the cultural context at that time was very different. For example, at one point, Ford commissioned his supplier to change the dimensions of shipping crates with the sole purpose of reusing the crate as part of the floor boards in vehicles (McDonough and Braungart, 2002). This made business sense because it reduced the car's cost. Today, repurposing materials that would otherwise be discarded is also considered environmentally responsible.[1]

Ford also sought, in the 1930s and 1940s, to utilize biological plants for both the car's materials and its fuel. This desire was such a passion that Ford conducted much of

Ford Motor Company, MD3182/ RIC Building, P.O. Box 2053, Dearborn, Michigan 48121, USA.
* Correspondence: D. Mielewski, dmielews@ford.com
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the materials science research in his own laboratory, which still stands within Greenfield Village at The Henry Ford museum in Dearborn Michigan.

To put this work in perspective, in 1937 Ford was producing 300,000 gallons of soy oil a year for use in car enamels (Shurtleff and Aoyagi, 2016*Soybean Digest*, 1947), and by 1939 the Ford Motor Company was harvesting about 100,000 bushels of its own soybeans. Ford Motor Company formulated soybean resin and natural fiber–reinforced body panels (recipes were said to include soybeans, wheat, hemp, flax, and ramie), and Mr. Ford demonstrated their resiliency by taking an axe to them (The Henry Ford, 2016). Most of the time, they survived. The panels were said to be able to withstand a blow 10 times as great as steel without denting (Collective Evolution, 2013). The windows were also said to be made of plastic, a light-weighting ambition that still exists as active research at Ford today.

Soy was not the only feedstock with which Ford worked. Fordite material, used in the steering wheels of the Model T, contained wheat straw as a reinforcing fiber.[2] Much of the straw used to produce Fordite came from Henry Ford's Dearborn area farm (Ford Motor Company, 2009). Ford was also the first auto manufacturer to grow his own timber. In 1919, Ford purchased a northern Michigan tract of land to be used for a source of hard and soft wood. Ford even owned several rubber and tung tree plantations, and although these endeavors were unsuccessful, they demonstrate his persistence in using plant materials for automobiles. Recently, we were made aware of laboratory notebooks at Ford's Palm Beach vacation home that suggest using goldenrod as a homegrown natural rubber source, rather than the one imported from the Pará rubber tree (*Hevea brasiliensis*), which was difficult to ship during World War II.

After 12 years of research, Ford unveiled the experimental "Soybean Car" (Figure 1) at the Dearborn Days festival on August 13, 1941 (McCann-Erickson, Inc., 1941). The car had a tubular steel frame with 14 plastic panels attached to it. The car weighed around 2,000 pounds, a third lighter than a typical steel car. Even though the exact composition of the body panels remains unknown, they are purported to have contained soybeans, wheat, hemp, flax, and ramie (The Henry Ford, 2016).

Why was the soybean car built, and what motivated this emphasis on agriculture in general? The context in which Mr. Ford lived was different from today. The bounty of nature was certainly appreciated by industrialists, but as "a seemingly endless supply of natural 'capital'" (McDonough and Braungart, 2002). Development of wild landscapes into crop land was a harnessing of nature that yielded renewable resources, unlike nonrenewable

FIGURE 1. Henry Ford's experimental Soybean Car.

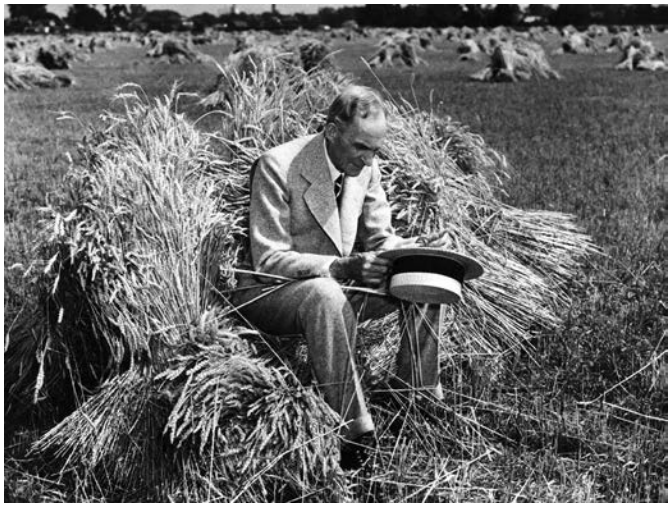

FIGURE 2. Henry Ford sporting a suit made from soy fibers.

activities like mining. However, it is not clear what Mr. Ford felt about our social responsibility toward the environment. He did believe in a strong partnership between industry and agriculture, so that each could utilize the products of the other. This interest in synergistic collaboration extended even to his personal wardrobe. In Figure 2, he is shown wearing a suit he had developed out of soybean fibers. A Chicago Tribune article, dated October 4, 1936 quotes Mr. Ford as saying, "If we want the farmer to be our customer, we must find a way to become his customer."[3]

This period was characterized by the growth of oil, automobiles, and mass production (Freeman and Louca, 2002). During the same time that Henry Ford was innovating in personal transportation, plastics were also developing quickly. New inventions and unique new materials were being produced from petrochemicals, which stemmed in part from a key discovery in 1907. In that year, chemist Leo Hendrik Baekeland produced Bakelite, the first commercially successful plastic made of a polymer that was synthesized from nonpolymeric materials (Cohoe, 1945). Although Ford and many others before him had investigated ways to manipulate plant-based substances to form plastics, this new synthetic route to creating polymers was a key moment in the so-called Age of Plastic.[4] Plastics proliferated not only in consumer goods and packaging but also in durable applications like transportation. Many technologies were made possible by advances in plastics during these years such that our lives have been improved in innumerable ways. Today, we can see that plastics are a mainstay and convenience of everyday life. Less known may be the fact that around 10% of a modern automobile's weight is in plastic materials, and that number will surely grow as we make automobiles more lightweight to improve fuel economy.

Expansion of the plastics industry in the ensuing decades was also fueled by a growing coal, petroleum, and, eventually, natural gas infrastructure. The price of petroleum stayed relatively flat from 1907 when Bakelite was discovered until the 1970s, and supply was increasing. Plastic technology based on fossil fuels outpaced developments in natural and renewably sourced plastic materials in that period.

Starting in the 1970s, large fluctuations in petroleum prices and a growing dependence on foreign sources of oil were beginning to have a significant effect on the petrochemical and plastics industries (Figure 3). Although petroleum prices plunged to an all-time low in 1999, significant price volatility and a general upward trend have again spurred interest in the development of plastics from feedstocks with more stable price and availability (Williams, 1996–2011). Furthermore, the energy needed to produce oil, and hence its cost, has grown significantly from 1% of its energy content at the beginning of the oil age to 5% today (Kricher, 2012), further closing the gap for agricultural feedstocks. As oil begins to grow scarce, alternatives to petrochemicals and petroleum-based materials will be sought. Even within the past 15 years, research has advanced bioplastics significantly, and now renewably sourced plastics are able to perform at a level equivalent to that of those derived from fossil fuels. This progress is one of many reasons why the idea of using things we can grow to manufacture automobiles is coming back to life at Ford.

When Bill Ford took over as chairman and CEO of Ford in 2001, he made it clear that part of Ford's revitalization plan included making the company more environmentally responsible. The great-grandson of Henry Ford is an avid environmentalist in an industry that seemingly turned its head to such a notion then. For instance, Ford spearheaded the rebuilding of his Dearborn River Rouge plant into a test lab for sustainable manufacturing practices, including natural sunlight for workers, conservation areas, and, at that time, the world's largest green roof (Bonini and Kaas, 2010). He commissioned the RAT (Recycling Action Team, also known as the RAT patrol within the company), a group of employees whose mission was to improve the environmental sustainability of Ford products. Led by Andy Acho, then worldwide director of environmental outreach, they championed the development and implementation of aggressive environmental stewardship actions that would protect the environment and save the company millions of dollars annually. The RAT's successes included transforming more than 50 million two-liter soda bottles, 1 billion bottle caps, and 27 million square feet of old carpeting into reliable vehicle components. They also initiated the recycling of more than 10 million tires into rubber products used for playground mulch, athletic and riding arenas, and roads. In 2003, following in his great-grandfather's footsteps, Bill Ford introduced the "Model U" concept vehicle (Figure 4). Succeeding the Model T and the soybean car, the Model U displayed the younger Ford's vision that transportation could be environmentally friendly and embrace agricultural plastics. In addition to a hydrogen internal combustion engine that ran much cleaner than our gasoline engines, the Model U sported sustainably produced polyester textiles, soy-based seating foams, and soy-based paint.

Within the past several years, the automotive industry has finally caught up with the forward thinking of the Fords. Interest in sustainability and environmentally friendly technologies has grown, and concepts like local sourcing are new again. For

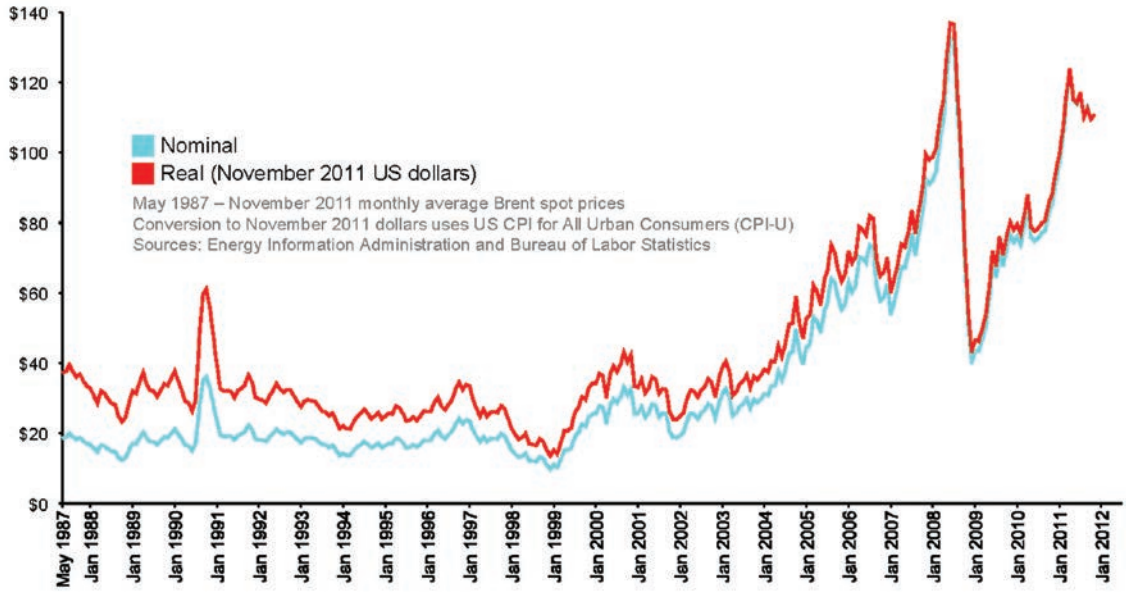

FIGURE 3. World oil prices from May 1987 to January 2012. Created by TomtheHand, Wikimedia Commons, 2012. No changes were made to the image. Creative Commons Attribution-Share Alike 3.0 Unported, https://creativecommons.org/licenses/by-nc-sa/3.0/.

FIGURE 4. Left: Exterior view of the Model U concept vehicle. Right: Interior view.

the transportation industry, especially the automotive sector, sustainable technologies apply to manufacturing, the use phase (driving), and the product itself. Alternative powertrains and fuel economy–improving technologies can significantly reduce the carbon footprint of a vehicle, and so too can the development of more sustainable agricultural materials for the vehicle itself. Because plants take up carbon dioxide during photosynthesis, plant-based feedstocks create durable goods with a reduced carbon footprint from sequestration. Furthermore, some of the renewably sourced materials can be produced at a fraction of the energy required for petroleum-based alternatives.

In many cases, renewably sourced material may have a performance advantage, such as the density reduction of natural fiber reinforcements over fiberglass reinforcement. The reduced weight of these vehicles can improve driving dynamics and fuel economy. Over a vehicle's lifetime these improvements can significantly reduce fuel consumption and carbon dioxide emissions.

SUSTAINABLE MATERIALS STRATEGY

Ford Motor Company's commitment to sustainability has been expanded to include a formal statement on the strategy for sustainable materials. The overarching vision is that Ford Motor Company will ensure that our products are engineered to enable sustainable materials leadership without compromise to product quality, durability, performance, or economics. To this end, recycled and renewably sourced materials must be selected whenever technically and economically feasible, and technologies and tools that help us validate, select, and track the use of these materials in our products will be further enhanced. This corporate stance toward sustainable materials is an important motivator, but technical, economic, and logistical challenges remain. The large number of materials in the average vehicle, coupled with the significant variations between models and geographic regions, means that tracking materials can quickly become intractable. On average, over 300 pounds of plastic and nearly 100 different grades of plastic are used in every vehicle. Selection of these materials is an extremely complex process, with numerous material and performance requirements to consider for each application. This analysis must be combined with a comparison of each material's sustainability. Thus, it is clear that considering the sustainability of materials used in our cars also requires development of new analytical tools to facilitate the material selection process. Doing so should allow the proportion of recycled and renewably sourced materials to increase year after year and model by model.

Case Studies on Ford's Successful Implementation of Biomaterials

Soy-Based Polyurethane Foam

Ford Motor Company's most significant success to date with biomaterials has been the implementation of functionalized soybean oil in the manufacture of flexible, polyurethane foam for automotive seating. This technology substitutes a portion of the petroleum-derived polyol with a soy-derived polyol within the formulation of a two-part polyurethane foam. Figure 5 shows two competing reactions that give rise to a polyurethane foam: the gel reaction, which forms the polyurethane linkages, and the blow reaction, which forms the cells, or voids, in the foam. The Ford biomaterials team invented and developed novel foam formulations that maximize the performance and processing of soy-based foams to meet all of the stringent requirements of automotive seating. After completing numerous processing trials on headrest, armrest, and seating applications, Ford launched soy-based foam on seat backs and seat cushions in the 2008 Ford Mustang (Figure 6). Since that initial launch, soy foam has been successfully migrated to all vehicle programs in North America for seat backs, seat cushions, and headrests. With this soy-based foam, Ford reduces its petroleum usage annually by over 5 million pounds. Life cycle assessment shows a net decrease of 5.5 pounds of carbon dioxide per pound of soy polyol used, which

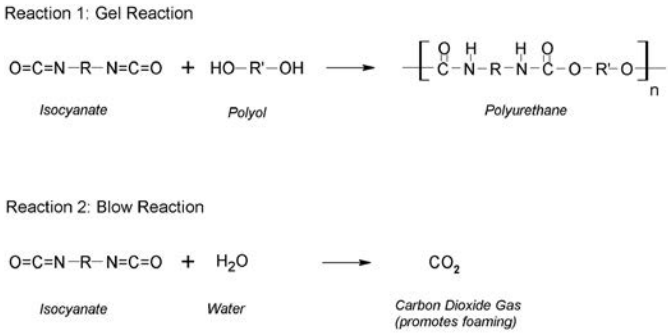

FIGURE 5. Competing reactions in the formation of polyurethane foam.

FIGURE 6. Soy-based polyurethane foam introduced in the 2008 model year Ford Mustang seat.

results in a net decrease of 20 million pounds of carbon dioxide annually (Pollack, 2006).

This soy foam was an industry-leading innovation. In 2002, many chemical companies considered incorporating soy oil into urethanes but claimed that it could not be done, even in small concentrations. However, Ford Research was committed to the concept and wanted to pursue work in this area. A soy foam research program was initiated at Ford in 2001, and in 2004, Ford Research was awarded a three-year grant by the United Soybean Board's New Uses Committee to help advance and accelerate commercialization of the foam as a way to utilize excess soybeans. The goal was to use crops that would otherwise be wasted rather than to plant new soy fields that would compete with other crops.

From proof of concept to implementation of the new foam in our vehicles, there was a long road of technical challenges to overcome and many other hurdles before the material could be adopted. Key technical challenges inherent to soy materials included lower chemical reactivity than the petroleum equivalents, separation of the blended materials, odor, and fogging. Initial foams created at Ford Research had poor mechanical properties and very noticeable, unpleasant odors. Foam cell structures were coarse or collapsed, and foams had weak structural integrity. There also were challenges for production. Soy-based foams are inherently less reactive than petroleum-based materials because of the secondary nature of the hydroxyl functionality versus a primary hydroxyl on petro-based materials. As a result, the time needed to create the foam is too long for the production environment. All these issues had to be addressed and overcome.

In a typical polyurethane formulation, more than 10 chemicals are blended together, including surfactants, a blowing agent, catalysts, polyols, and isocyanates. Through innovative chemical studies and multiple experimental designs, we ultimately created foams with biocontent that could pass several of the key requirements for automotive seating (Mielewski et al., 2005). Cell structure was improved by adding specific combinations of surfactants and catalysts (Perry et al., 2016). The team developed two formulations for interior automotive applications: methylene diphenyl diisocyanate (MDI) based and toluene diisocyanate (TDI) based chemistries that use soy polyols in combination with the other chemical constituents.

One key technical challenge of substituting soy polyols for petroleum polyols is that of fogging (release of volatile compounds that condense on the windshield and create a haze), which became a major hurdle in our development work. Surfactant and catalyst packages were reformulated to overcome this issue and were ultimately successful. Another challenge that had to be addressed by the team was the smell. The natural odor of soy-based materials is like rancid oil. Our strategy to reduce the smell included an odor stripping method called thin-film evaporation that removed the smelly, low-molecular-weight species. A panel of human sniffers judged that this method reduced the perceivable odor from a rating scale of 4, unacceptable, to 2, acceptable (see Table 1 for ratings). This low-odor soy polyol went into production for soy-based foam. These formulations used up to a staggering 40% soy in the polyol blend (Flanigan et al., 2007).

TABLE 1. Odor ratings. A maximum rating of 2 is required to pass the odor panel test. From Flanigan (2009).

Rating	Description
1	No noticeable odor
2	Slight but noticeable odor
3	Definite odor but not strong enough to be offensive
4	Strong offensive odor
5	Very strong offensive odor

Once methods were discovered to overcome the odor and fogging, our group concentrated on optimizing the soy foam formulations and processing methods to meet automotive requirements and current production cycle times for molding automotive seats. The United Soybean Board and Michigan Soybean Association funded an investigation of properties of soy foam during processing and in finished parts. The first factory-produced parts exhibited issues with surface skinning, low tear strength, and low density. In addition, issues were encountered with separation between the bio-based and petroleum constituents of the polyol blend. We resolved the latter by compatibilizing the two materials. In total, more than 15 trials were completed to improve reaction rates of the soy foam formulation to suit manufacturing conditions and to verify that the soy foam parts performed well. By experimenting with processing designs and additives to the polyol blend, the team was able to produce production-quality parts. Ultimately, Ford's soy foam formulations met requirements for odor, fogging, vinyl staining, indentation load deflection, density, tear resistance, and compression set (Flanigan et al., 2008).

Ford has since expanded this soy-based foam to other consumer product markets, including office furniture, home furniture, bedding, agricultural equipment, and marine applications. We are proud to have been recognized as a leader in developing and using sustainable materials. Ford has received numerous awards, including the 2008 award for "plastic materials from renewable sources and applications" from Global Plastics Environmental Conference, the 2009 R&D 100 Award for "soy based automotive seating foam," and the 2008 Environmental Excellence in Transportation (E2T) Award by SAE International. In addition, the United Soybean Board awarded Ford its Excellence in New Uses Award for creating a commercial product from soybeans. More than 200 media articles have covered news of Ford's innovative use of soy oil in polyurethane foams, including coverage in major media outlets CNN, CBS, PBS, and Fast Company, among others (Toebben, 2007; *Car and Driver*, 2007; Lear Corporation, 2007). Ford Marketing has also included "soy foam seats" as an advertised feature for many vehicles (Ford Motor Company, 2010, 2013).

By introducing bio-derived content into polyurethane foams, Ford proved that this material could be used in one of the

most challenging foam applications of all, seating. Given more than 30 pounds of flexible foam are used in a single automobile, there are many more potential applications for this foam, including headliners, instrument panels, and armrests. For example, we have incorporated soy foam into the headliners of the Ford Escape. Currently, Ford researchers are actively working with suppliers to investigate the use of soy foam for additional components, global programs, new applications, and formulations with increased biocontent.

Injection-Molded Wheat Straw Polypropylene

A second example of successful implementation of a biomaterial at Ford was the world's first wheat straw–reinforced plastic in an injection-molded application. This technology replaces glass fiber or mineral reinforcement (i.e., talc) in a thermoplastic polymer matrix with wheat straw fiber, a by-product of the wheat grain harvest. In addition to the carbon sequestered by incorporating a renewable fiber into the plastic, the technology also reduces weight and process cycle times. The following study describes Ford's research, development, and eventual implementation of wheat straw–reinforced polypropylene (WSPP) in the 2010 Ford Flex for an injection-molded storage bin. By launching this material in the Ford Flex, Ford reduced petroleum use by 20,000 pounds/yr and CO_2 emissions by 30,000 pounds/yr.

Natural fiber composites have been used for many years in automotive and nonautomotive applications. Previous applications of injection molding– and extrusion-grade materials for durable goods used the renewable additives as a filler that displaced a portion of the petroleum-based resin—meaning the plastic could be produced with less resin—but did not improve the performance of the material. Examples include sawdust-filled composites commonly called "woodstock" and composite decking. Today, compressed and consolidated hardboards are available with 50% natural fibers mixed with 50% polypropylene or polyethylene terephthalate fibers in a nonwoven mat construction. Current and developing technologies include injection molding–grade composites and engineering resins that contain natural fibers as a reinforcing agent, rather than just a filler, and replace traditional fiberglass and mineral reinforcement. Fibers including, but not limited to, hemp, kenaf, sisal, coconut coir, purified cellulose, and wheat straw have been investigated at Ford for injection molding–grade materials, primarily in polyolefin resins.

Wheat straw, a by-product of wheat grain crops, contains a bast fiber that has very little use outside of animal bedding. In 2007, Ford joined the Ontario BioCar Initiative, a government-funded research program aimed at introducing agricultural products into automotive parts, and formed a development team of partners and stakeholders from throughout the supply chain. The team comprised a research institution, raw material suppliers (e.g., farms), a natural fiber processor, a compounder/material supplier, a molder/Tier 1 supplier, and an end user/automotive original equipment manufacturer. The team's goal was to develop a production-grade polypropylene plastic reinforced with wheat straw. The case study was completed in only 20 months, much faster than a typical case for the automotive industry, because all key stakeholders were included from the outset. Funding from the Ontario BioCar Initiative also helped us accelerate our research and development plan.

Wheat straw fiber was obtained from six Ontario farms and delivered to the processor to be cleaned and milled to a uniform length and aspect ratio (the relationship between length and width) prior to melt compounding with polypropylene (PP). Although the fiber itself was not treated, compatibilizers and other additives were added to the straw-PP mixture during compounding to enhance the interface between the fiber and plastic matrix, improve flow and processability, and inhibit oxidation and degradation of the wheat straw. Ford researchers decided that the final product should meet the same mechanical performance standards as talc-reinforced polypropylene homopolymer, a common polymer composite used in similar applications. Together with university researchers and the compounder, initial formulations were produced that resulted in good preliminary properties and a significant decrease in the density, and hence weight, of the composite material because wheat straw is less dense than talc. In terms of mechanical properties, a slight decrease in tensile strength and flexural modulus was observed, but notched Izod impact and heat distortion temperature were improved over talc-reinforced PP. This initial screening of properties allowed us to assess the feasibility of the material and select an automotive material specification. Once the basic formula had been optimized to meet our initial material properties targets, the team worked with the molder to customize that formula and the injection molding process to make specific automobile components.

In 2009, WSPP was introduced in the 2010 model year Ford Flex in an interior storage bin (Figure 7). Ford was selected as a

FIGURE 7. Wheat straw–reinforced polypropylene introduced in the 2010 Ford Flex third-row storage bin.

Blue Ribbon Finalist for the 2009 Society of Plastics Engineers, Automotive Innovation Award in the Environmental Category based on the successful launch of this new wheat straw material. The success of the wheat straw project was also instrumental in Ford winning, on the basis of their biomaterials research portfolio, the Society of Manufacturing Engineers' 2010 award for Innovations That Could Change the Way You Manufacture. Ford Research is continuing to expand WSPP and other natural fiber composite materials into other applications and Ford vehicles globally.

CURRENT CHALLENGES ASSOCIATED WITH THE IMPLEMENTATION OF BIO-BASED MATERIALS

For a new material to be successfully launched on a Ford product, the material must meet all of Ford's existing material and performance specifications and then some. In automotive applications, plastic materials have a unique set of performance requirements that are very different from other consumer product applications. Plastic parts are expected to be extremely durable, for at least 10 years in service, under the hood and as exterior and interior components. The materials are expected to perform well in all climates, including the extremes, from hot, humid southern Florida to the Arctic cold temperatures of northern Canada.

A typical injection-molded plastic interior trim component must pass many *material* performance tests that measure things like flexibility, tensile strength, impact strength in cold temperatures, how well the material deflects heat, aging in warm conditions, resilience to weather, odor, and fogging. In addition, there are other overall performance requirements for each specific application of the material. For example, the requirements for interior plastic storage bins differ significantly from those for automotive seating fabrics, even though they may be made of similar thermoplastics. Although both are located in the vehicle's interior cabin, each has a set of unique requirements that are designed to demonstrate how the component might fail in the field. A molded interior component is tested for the requirements described above, whereas seating fabrics are tested for wear, seam strength, tear strength, rubbing resistance, soiling and cleanability, resistance to staining, and shrinkage, among others. Since the *design* of a component can also play a role in its failure, both material and component testing are critical.

Natural Fiber Composite Technical Challenges

These stringent automotive requirements can be difficult to meet even with traditional petroleum-based plastics. When bio-based materials are considered, the material has to meet existing requirements, and new failure modes must be considered that are specific to the class of biomaterial. For example, natural fiber composites will have different potential failure modes than glass fiber composites. The following are a few of the unique performance challenges for these types of biomaterials.

Reinforced thermoplastic composites are typically manufactured by melt extrusion followed by injection molding or other melt processes, in which the thermoplastic is heated to a molten state. The melt temperatures of the thermoplastics are often high enough to cause some thermal degradation of the natural fiber reinforcements and fillers. Thermal damage can include discoloration or odor that may or may not affect mechanical performance, depending on the degree of degradation. Novel processing techniques or, as in the case of WSPP, formulation changes can improve the thermal stability of the fibers in the hot, melted state. For other natural fiber–reinforced composites that rely on dispersion at the much finer fibril level or for thermoplastics with very high melt temperatures, reducing thermal degradation and odor is an active area of research.

Because of the lignocellulosic make up of natural fibers, their surface chemistry gives rise to behaviors that are quite different from fiberglass and mineral reinforcements in a polymer matrix. Cellulose is itself a water-insoluble polymer, but because of its anhydroglucose repeat units, it has a rigid hydrogen bonding network and can swell significantly in moist conditions (Kontturi, 2005). There is a fundamental incompatibility between water-loving (e.g., hydrophilic) cellulose and a nonpolar, water-repelling (e.g., hydrophobic) polyolefin matrix. To avoid this incompatibility, our composites could have been made with polyamide or polylactide polymer matrices, which can themselves absorb moisture and are therefore more compatible with cellulose reinforcement, but moisture absorption of the finished plastic can be a critical problem. Instead, we opted to enhance the interfacial adhesion between PP and the straw, either by adding a compatibilizing agent during compounding or by surface modification of the fibers themselves. Also, because of their water-absorbing (e.g., hygroscopic) nature, natural fibers require drying to drive off moisture prior to any melt processing. Once compounding and manufacturing processes were optimized, still more tests were required to ensure the storage bin worked well.

Polylactide and Its Technical Challenges

The soy-based polyurethane and WSPP are derived from combinations of renewable and fossil fuel raw materials. Polylactide or poly(lactic acid), also known as PLA, is a thermoplastic polyester derived completely from a renewable feedstock and has several end-of-life options, including chemical and mechanical recycling and composting. It can be processed into many forms from fibers to films to molded components. Polylactide plastics are popular with the sustainability movement and have found moderate success in recent years in consumable applications that take advantage of PLA's relatively fast degradation in industrial composting environments. Use of PLA for automotive applications requires the assessment of long-term performance. Whereas a fast degradation rate is desirable for disposable things, long-term stability (i.e., slow degradation rate) is necessary for

durable goods. For automotive components, not only does the material need to meet the mechanical performance specifications for a newly molded part, but it must maintain its performance throughout the lifetime of the vehicle (>10 years). Because PLA is formed by condensation polymerization, its primary mode of degradation is by hydrolysis, which is accelerated with exposure to high heat and humidity.

Ford researchers have extensively studied the processability, performance, and durability of commercial injection molding grades of PLA (Harris and Lee, 2007, 2010). Sufficiently durable for consumer products such as electronics, these commercial grades showed a dramatic decrease in molecular weight (i.e., breaking down of the polymer chain) and mechanical performance over time when subjected to conditions that mimic the environment inside a car in the southeastern United States. The evaluation involved conditioning samples of crystalline and amorphous PLA together in a humidity chamber that was maintained at 50°C and 90% relative humidity. On the basis of previous correlations (Bauer et al., 2006) for petroleum-based polymers, one week of exposure at these conditions was considered to be approximately equivalent to an automobile interior exposed for two months in Florida. Therefore, a material suitable for an interior automotive application would need to maintain mechanical performance for at least 60 weeks at these exposure conditions in order to meet 10-year durability requirements. During this test, the flexural strength of the PLA samples decreased, and the samples became more brittle. After only 8 weeks of conditioning, both the amorphous and crystalline samples had lost significant strength and by 12 weeks no longer had mechanical integrity (Harris and Lee, 2010). Thus, these types of PLA were unsuitable for the interior of an automobile.

Improving the durability of PLA to meet automotive requirements is the subject of current ongoing research. Blending or alloying PLA with certain petroleum-based resins could reduce hydrolysis to an acceptable level. An alternate approach might be to eliminate the potential for the hydrolysis reaction by which PLA breaks down. The addition of moisture scavengers or sacrificial compounds and capping functional groups at the ends of the polymer strands are strategies that can address the root cause of PLA's instability without reducing the amount of renewable content.[5] Significant improvements in durability are required prior to more widespread durable use in automotive applications.

Economic Challenges

These technical challenges are significant, but there is no doubt that they can be addressed. At the same time, for these bio-based materials to be a more sustainable solution for automotive applications, they must be economically and socially sustainable as well. The move from a petrochemical economy to a future bioeconomy will need concurrent development of technology and infrastructure that enable stakeholders to participate along the entire supply chain. Many of the economic hurdles for the first implementer in the bio-based materials space can be overcome by establishing tools and infrastructure for the collection and delivery of agri-based feedstocks, construction of biorefineries, co-location or hubs to connect the new value chains, and increasing volumes to take advantage of economies of scale.[6] All of these things need to take place in a coordinated manner, so cooperative research and open innovation are essential.

FUTURE OUTLOOK FOR BIO-BASED MATERIALS AT FORD MOTOR COMPANY

We are encouraged by the sustainable material successes we have implemented over the past 15 years at the Ford Motor Company. From our perspective, the biomaterials industry and the number of people now working in this space has exploded. With more university research and small companies innovating, we expect to accelerate our progress. The proportion of bio-based materials continues to increase in packaging and consumer goods and also in durable applications like transportation. Continued innovation and growth will be propelled by drivers such as consumer awareness, desire for sustainability, and petroleum availability. We believe that as current innovation waves like information technology mature, the next innovation wave will center on sustainability and cleantech.

Ford Motor Company's biomaterials research team has been on the leading edge of bio-based materials research and development, and we plan to continually demonstrate our leadership in this area for years to come. It is our goal to further expand bio-based material technologies we have already developed to new product applications and vehicle programs. This expansion will require partnerships with our supply base, the farming community, and academia as well as leveraging resources from government institutions and other third parties. We will also strive to strengthen our research portfolio and fill the technology pipeline to ensure that Ford has novel, renewably sourced material formulations that meet or exceed our stringent specifications for years to come. It is our hope to implement many Ford-first biomaterials in future products and continue the legacy of Henry Ford.

NOTES

1. Henry Ford's thrifty attitude that waste materials could be repurposed in other products is also discussed by Brooks (this volume).
2. This is not to be confused with today's Fordite, an ecojewelry material made of layers of hardened automotive paint that is collected from automobile assembly plants and cut and polished to create gems that resemble agate.
3. Henry Ford's experimentation with soy fiber and the problems with soy fibers in general are discussed by Brooks (this volume).
4. Examples of creating plastics from agricultural feedstocks are discussed by Madden (this volume), Brooks (this volume), Friedel (this volume), and McGath and Madden (this volume).
5. Note that here the authors' goal is to create plastics from renewable sources, but they do not want to, and cannot, work with plastics that break down easily. This illustrates that there are multiple issues to consider in debates about plastic and the environment.

6. This need for better infrastructure to streamline biofeedstock processing is similar to Mike Biddle's call in this volume for infrastructure to aggregate discarded plastics so they can be recycled efficiently. Technological solutions often require that regulatory and industrial structures be modified as well.

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Conservation of Plastics at the Smithsonian American Art Museum

Lucian H. Shockey Jr.

ABSTRACT. The collection at the Smithsonian American Art Museum includes more than 200 works that list "plastic" as all or part of the work's composition. The museum's highly active loan and exhibition program requires that many of these plastic works receive conservation treatment before they are exhibited as aesthetic objects. Examples of deterioration in the collection are presented, followed by treatments of three specific artworks that show varying degrees of conservation intervention and exemplify the methodology and type of treatments that have been carried out on sculpture composed, wholly or in part, of modern polymers as case studies.

INTRODUCTION

For nearly 20 years visitors to the Smithsonian American Art Museum (SAAM) have been greeted by a colorful bucking stallion ridden by a pistol-wielding cowboy. The sculpture *Vaquero* by the American sculptor Luis Jimenez (1940–2006) stands more than 16 feet tall and is the artist's proof of a series of five casts from 1981 (Figure 1). Its colorful surface is a pigmented acrylic-urethane copolymer coating on a fiberglass form that is supported by an internal steel armature. This monumental sculpture is one of more than 200 works of art in the SAAM collection that list "plastic" as their medium in the database of collection holdings. That number would be higher if the museum's collection were closely considered to include minor constituents of the artworks. Because SAAM is an art museum dedicated to the aesthetic experience, objects and sculptures are expected to appear at their best when on view. This requirement is a challenge for a sculpture conservator who must address plastics that vary widely in composition, may become chemically unstable as they age, are damaged unintentionally or by vandalism, or are exhibited under inclement conditions like *Vaquero*, which has spent nearly two decades outside. These problems are illustrated here with some examples from the SAAM collection and some solutions I have developed for their care.

Smithsonian American Art Museum, Lunder Conservation Center, MRC 970, P.O. Box 37012, Washington, D.C. 20013-7012, USA. Current address: St. Louis Art Museum, Conservation Department, Forest Park, 1 Fine Arts Dr., St. Louis, MO 63110, USA.
Correspondence: L. H. Shockey, hugh.shockey@slam.org
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PLASTIC IS A CATEGORY OF MATERIALS

We tend to recognize plastic when we see it, but most of us do not know much about what it is or how it is made. Just as there are many different metals, there are many kinds of plastic, each with a peculiar name and particular material properties. A plastic may be named for its polymer component like polyester or cellulose acetate butyrate (CAB), for a popular brand name like Lucite, or by a common name like vinyl, which usually refers to polyvinyl chloride (PVC). Most plastics also contain additional substances that modify the plastic's color, opacity, or flexibility, for example. Myriad possibilities of composition,

FIGURE 1. *Vaquero* by Luis Jimenez graces the north entrance to the Smithsonian American Art Museum. Modeled 1980/cast 1990; urethane, fiberglass, steel armature, 199 × 114 × 67 in. (505.5 × 289.6 × 170.2 cm.). Gift of Judith and Wilbur L. Ross Jr., Anne and Ronald Abramson, and Thelma and Melvin Lenkin, 1990.44. Photograph by author.

some of which hold up well in a museum and others that do not, are the result. The composition of a plastic also affects how conservators treat it. For example, composition influences what can be used to clean it, what substances can adhere to it, and what kinds of repair materials will visually match the original. For these reasons it is important to distinguish which kind of plastic one is dealing with, but that is not necessarily possible by looking alone. For example, three entirely plastic works on exhibit at SAAM are very similar in color, texture, and scale but differ in composition. Frederick Eversley's *Untitled* is a solid piece of cast polyester resin (Figure 2). John McCracken's *Untitled* also is made of polyester, but the resin is filled with reinforcing glass

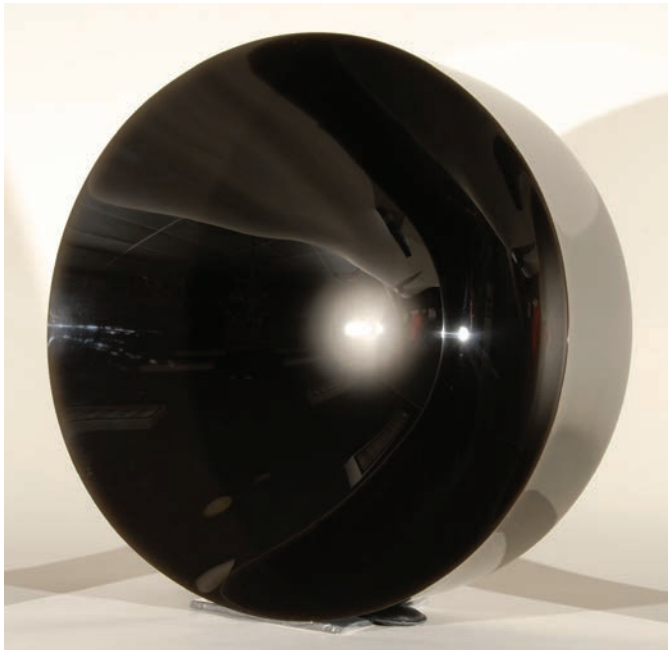


FIGURE 2. Frederick Eversley, *Untitled*, 1974. polyester resin/cast, approximately 19.5 in. diameter and 6.5 in. deep (50 × 17 cm). 1983.82, Smithsonian American Art Museum. Photograph by author.

FIGURE 3. John McCracken, *Untitled*, 1981. Resin and fiberglass, 98 × 20¼ × 2½ in. (248.8 × 51.5 × 6.2 × 6 cm). Bequest of Edith S. and Arthur J. Levin, 2005.5.45, Smithsonian American Art Museum.

FIGURE 4. John Safer, *Chandelle*, 1969, revised 2013. Lucite, approximately 77 × 27 × 13 in. (196 × 69 × 33 cm). Gift of the artist, 2007.23, Smithsonian American Art Museum.

fibers (Figure 3). John Safer's *Chandelle* is crafted from a sheet of black glossy plastic that is described in the museum records as Lucite, which is a brand name of polymethyl methacrylate (Figure 4). These three glossy, dark plastic sculptures are chemically and structurally quite different.

PLASTIC CONSERVATION CHALLENGES

Some works in the collection cannot be shown because they have condition problems that have yet to be solved. In other cases, we do find ways to treat artworks so that they can be exhibited. Interaction between the artwork and packing materials during long-term storage is one common problem. Robly Glover's *Fish Bait Necklace* (2002) is an elastomeric work, shown in Figure 5. The "fish baits," or lures, have begun to exude a liquid into the Tyvek dust cover that protects the sculpture in storage. This liquid may be an oily plasticizer or other additive in the plastic fish baits that is attracted to the nonpolar nature of Tyvek, a nonwoven polyethylene fabric produced by DuPont. Glen Kaufman's *The Knights* (1976) is a much larger, flexible sculpture made of vinyl tubing (Figure 6a,b). The green smudges visible in Figure 6b appear to be a reaction between the tubing and its packaging.

Substances migrating out of plastic is a common problem that we sometimes choose to treat and other times do not. *Fish Bait Necklace* and *The Knights* are not exhibited now because of their disfigurement. On the other hand, Robert Morris's *Model*

FIGURE 5. Robly Glover, *Fish Bait Necklace*, 2002. Silicone, 15 3/8 × 12 1/4 × 1/2 in. (39.1 × 31.1 × 1.4 cm). Gift of Kenneth R. Trapp in memory of F. Harry Bottoms, 2002.85.1, Smithsonian American Art Museum.

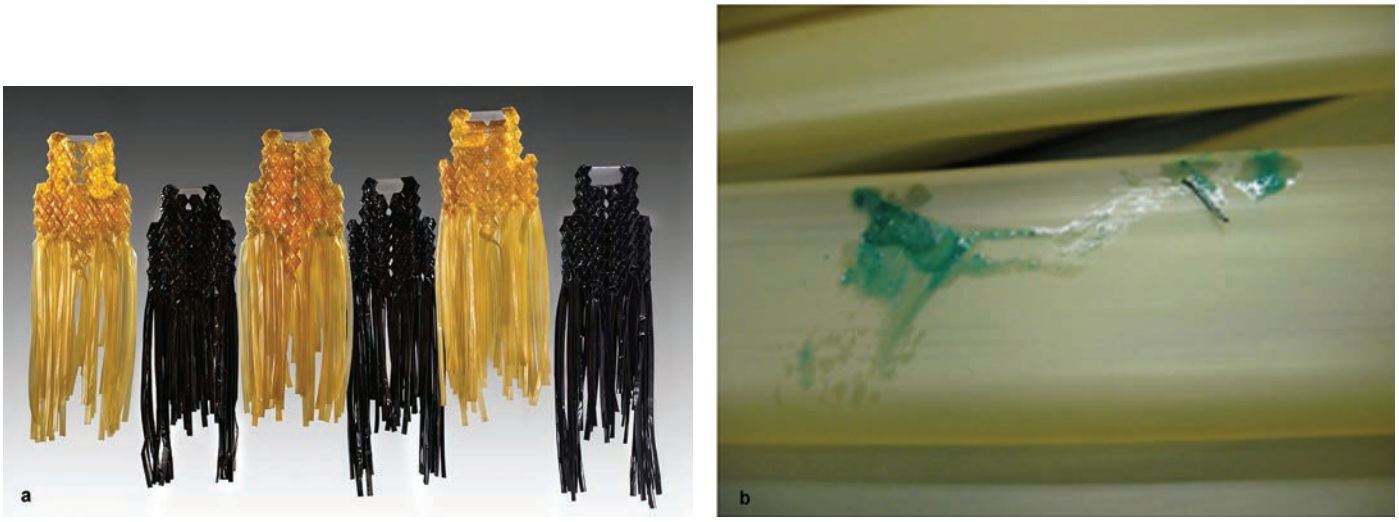


FIGURE 6. (a) Glen Kaufman, *The Knights*, 1976. Vinyl tubing, each unit 48 in. tall (19 cm). Gift of the artist, 1992.61, Smithsonian American Art Museum. (b) Detail of *The Knights* that shows a reaction between the vinyl tubing with the packing material. Photograph courtesy of Helen Ingalls, Smithsonian American Art Museum.

(1967) is a vacuum-molded sheet of bright green CAB that was treated before being loaned to another museum (Figure 7).

Scratches, scuffs, chips, and other mechanical damage are common in plastic artworks. Most plastics are soft and easily marred by routine handling, resting the object on a harder rough surface, contact with packaging materials, and even routine dusting.

Finally, presenting artworks in our galleries also carries some risk. Occasionally, pieces have been damaged by our visitors. These damages must be remedied if the artwork is to remain on exhibit.

FIGURE 7. Robert Morris, *Model*, 1967. Cellulose acetate butyrate, 23 1/8 × 19 3/8 × 1 1/4 in. (58.7 × 49.1 × 3.1 cm). 1971.84.86, Smithsonian American Art Museum. Photograph by author.

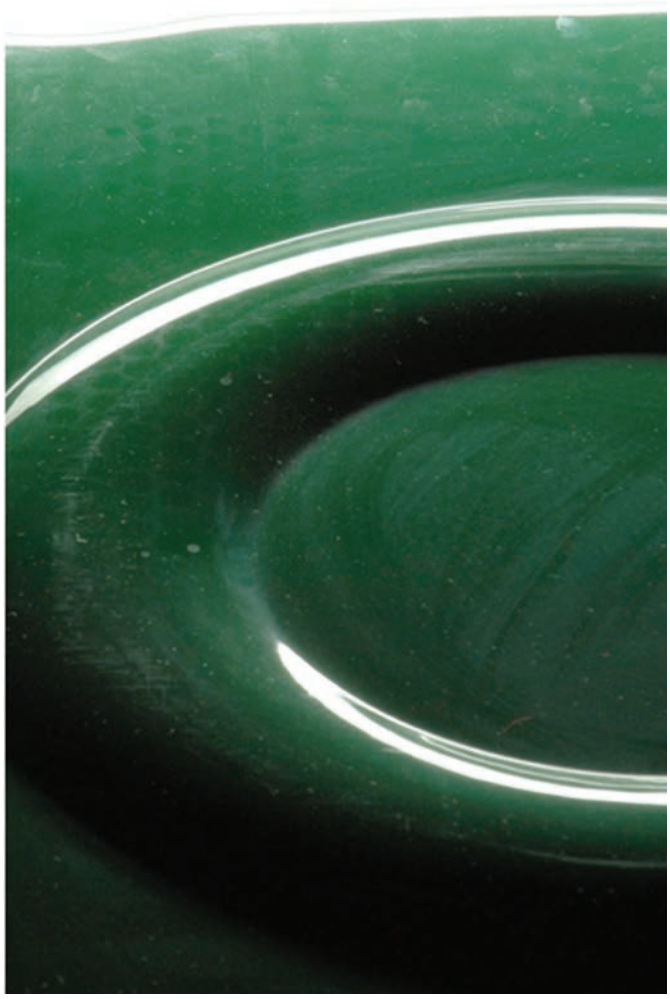


FIGURE 8. White haze on the surface of *Model*. Photograph by author.

CASE STUDIES: THREE APPLIED TREATMENTS

Conservators strive to prevent these damages from happening in the first place with preventive preservation methods. However, when treatment is required, the methodology is carefully considered (American Institute for Conservation, 1994; International Council for Monuments and Sites, 1964). The least invasive methods are always preferred, but sometimes a more interventive approach must be taken to correct the problem. Three case studies of treatments performed on our collection are presented here in order of invasiveness.

Model: Minimum Intervention

As described above, *Model* is a vacuum-molded CAB sheet work. During a routine examination in preparation for its shipment, a white haze was observed along with scuffs and scratches (Figure 8). The haze was visually distracting and drew attention away from the sculpture's color and shape. With closer observation we saw a white substance on the surface, but we did not know if it had emanated from within the plastic or had been deposited onto it from some external source. A pattern of spots resembled the bubble wrap in which the sculpture had been wrapped at one time. Whether the white substance came from the sculpture, the bubble wrap, or a reaction of the two remains unanswered. The most common way to remove a surface haze is to wipe it off with a cloth and maybe some water or other solvent. However, CAB has an intrinsically soft surface that can be scratched by even gentle wiping, and it can swell in some solvents, which softens it further. It is particularly sensitive to water (Y. Shashoua, National Museum of Denmark, personal communication). I chose instead to try ablating the white surface haze with carbon dioxide (CO_2) snow (Hill, 1994; Sherman et al., 1999; Cano, 2001; Sherman, 2007). In this technique a

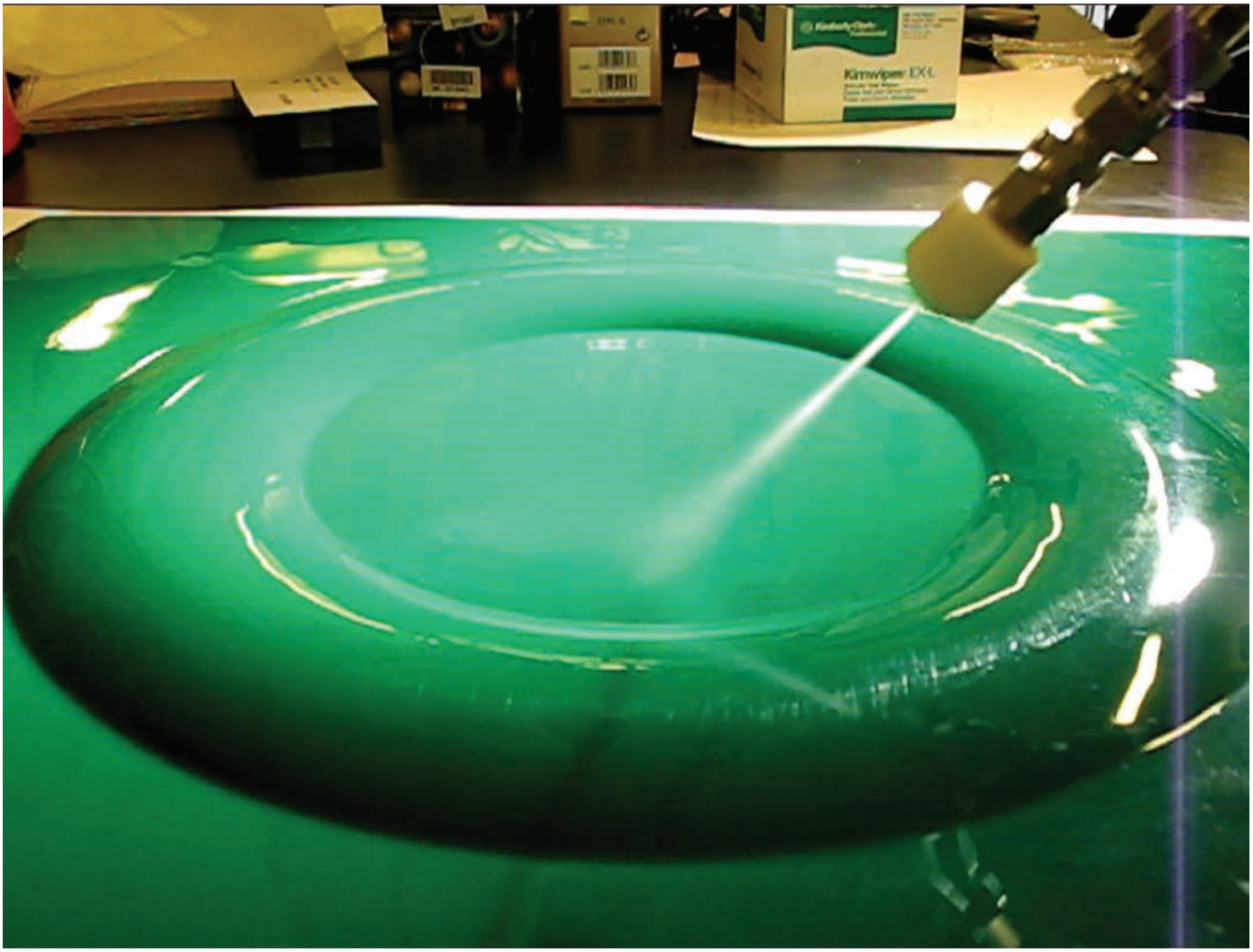


FIGURE 9. The CO_2 snow ablation process in action. Photograph Susan Edwards.

high-velocity stream of dry ice microcrystals is blown onto the sculpture and lifts away small loose particles (Figure 9).The dry ice crystals sublimate into CO_2 gas on contact with the sculpture and leave no residue behind. This method worked well in initial tests, so the decision was made to move forward with treating *Model* (Figure 9). The carbon dioxide snow ablation was carried out at atmospheric pressure in a climate-controlled room at 22°C (72°F) and 45% relative humidity.

The surface before and after cleaning was compared under a microscope (Figure 10). It is important to keep in mind that the goal of the treatment was to remove only the hazy white material without introducing—or removing—other surface deformations. The red oval in each panel highlights a scuff that was not affected by this treatment.

Nearly all traces of the haze were removed, and those that remain are visible only in a few areas under extreme lighting conditions (Figure 11). However, the haze no longer distracts visually, and the sculpture's overall form and color have regained precedence (Figure 12).

Preamble: Moderate Intervention

Preamble is an assemblage of 51 polymer-coated automobile license plates mounted on a wood support that is covered with vinyl-coated fabric and edged with aluminum (Figure 13). The license plates are arranged alphabetically by state (plus the District of Columbia), and the plate codes phonetically spell out the Preamble to the United States Constitution. In an unfortunate incident this work was vandalized with what appeared to be a blue felt-tipped marker.

The blue, solvent-based ink absorbed into and stained the polymer coating of the Georgia plate (Figure 14). My goal was to

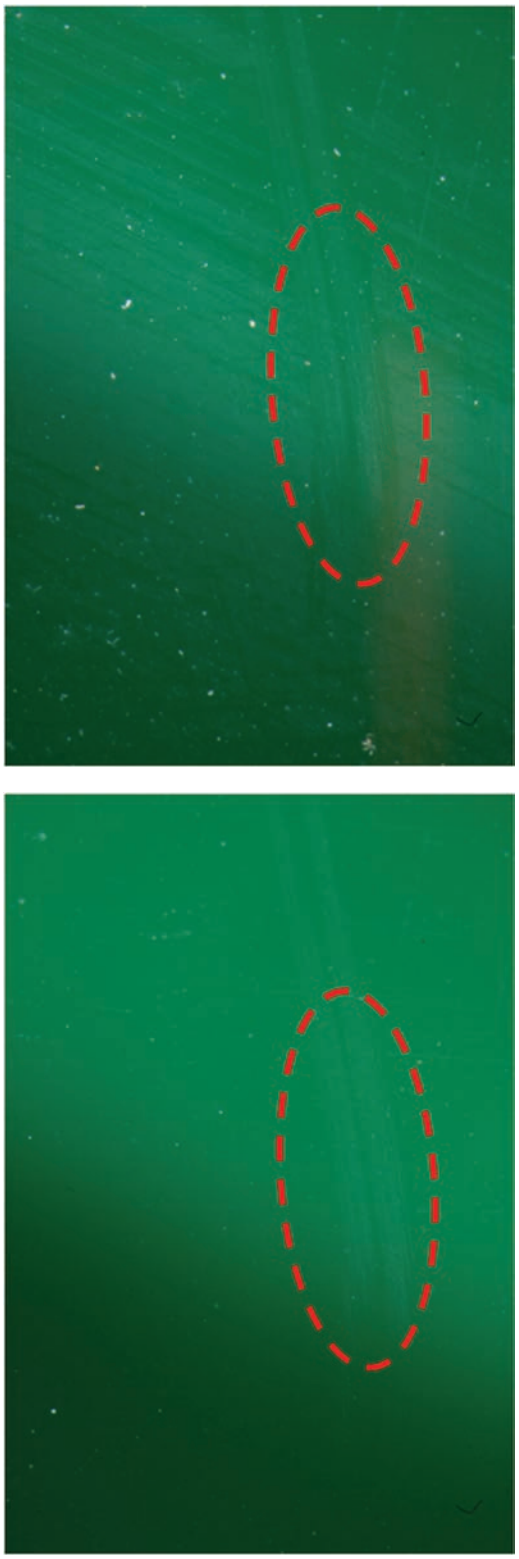


FIGURE 10. Surface before treatment (top) and after treatment (bottom) as seen under a microscope. Scuffs on the surface, circled in red, were not removed. Photographs by author.

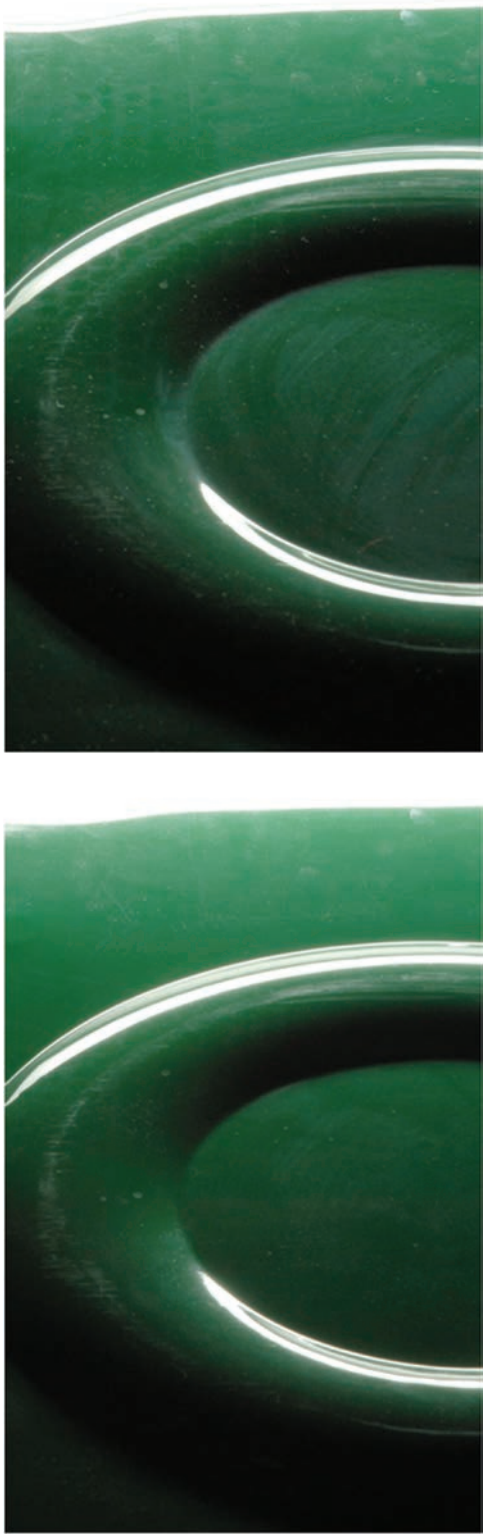


FIGURE 11. Surface before treatment with white haze (top) and after treatment with the haze nearly entirely removed (bottom). Photographs by author.

FIGURE 12. View of the *Model* after treatment. Photograph by author.

remove the ink with a solvent that would not affect the polymer coating or otherwise change the plate's appearance.

I happened to have an old license plate with a similar surface that allowed me to test various solvent and application methods to determine which combination might work to remove the ink and avoid damaging the license plate (Figure 15).

The first approach was to apply a solvent poultice of kaolin clay wetted with a solution of diacetone alcohol (4-hydroxy-2-keto-4-methylpentane) and deionized water (1:1 by volume) that would dissolve the ink and on drying draw it out of the polymer film. This worked well on the test plate (Figure 15). However, it was too aggressive for the artwork's Georgia plate. The solvent mixture swelled the polymer coating (Figure 16). This swelling was recorded with a Hirox KH-7700 digital microscope, which can help visualize subtle changes in transparent materials. It may be that the polymer coating on my old license plate had cross-linked chemically and had become more resistant to solvents after many years of exposure to sunlight and air. The Georgia plate of *Preamble* was never installed on a car and exposed to the elements, so the polymer coating might be more sensitive. This observation alone is worthy of note as it suggests the properties of a polymeric film that has become tougher yet appears to retain transparency with age.

Ultimately, the method that proved most successful was a solvent mixture of 1:1 by volume of diacetone alcohol and petroleum benzine (a blend of mixed-chain-length aliphatic hydrocarbons that evaporates quickly) that I dabbed on the inked lines with the sharp edge of a cut polyurethane cosmetic sponge. This removed much of the blue color but also slightly altered the gloss of the treated area. To unify the sheen, the entire plate was treated with two coats of water-soluble methylcellulose: the first by brush and the second sprayed to adjust the final surface. This coating can be easily removed with water, if necessary. Figure 17 shows the license plate after ink removal and coating.

Untitled: Major Intervention

Frederick Eversley's *Untitled* is a solid piece of cast pigmented polyester resin (Figure 18). Mr. Eversley is associated with the West Coast Light and Space movement, and this sculpture is a black parabolic mirror with a transparent center. The way the sculpture interacts with light is critical, and in the artist's own words the surface should be "pristine" (F. Eversley, personal communication). Figure 19 shows two photographic exposures of the front of the sculpture before treatment. The photograph on the left was taken at the proper exposure, and the surface appears acceptable and without major blemishes. In fact, the surface is covered in scratches and is far from pristine, and these damages are visible in person and in the overexposed photograph on the right. The back of the sculpture was also deeply scratched. The thin front edge of the mirror was also marred by conchoidal chips (Figure 20). Grime had accumulated in these chips and made them more unsightly.

Given the distraction of the damaged surface and the artist's desire for it to be pristine, it was decided that the edge chips would be filled with a pigmented resin and the entire sculpture surface would be repolished. The first step was to clean the surface of dirt and grime, particularly in the chipped area, before filling it with resin. Cleaning was done with a 0.25% (volume to volume) solution of Triton XL-80N detergent in deionized water on nonwoven cotton linter pads. Detergent residue was removed with deionized water.

The edge chips were filled in next. I contacted Mr. Eversley to learn more about the process he had used in the past, whether this had changed over time, and how he would suggest restoring his pieces (F. Eversley, pers. comm.). The artist provided enough information to devise a plan, and he even specified a specific polyester resin to use. Nonetheless, many mockups and tests were required before I felt I could reliably craft a fill that matched well in color and transparency and that had a repeatable cure time. A series of mockups with varying proportions of polyester resin, catalyst, and pigment were created. Ultimately, the fill was made with Silmar SIL95A-40 (batch 11250040F) polyester resin, tinted with North American Composites A-802 "Black Pigment" (batch 150), and catalyzed with methyl ethyl ketone peroxide. The resin and catalyst are toxic and flammable until cured, so the work needed to be carried out under good ventilation.

FIGURE 13. Mike Wilkins, *Preamble*, 1987. Painted metal on vinyl and wood, 96 × 96 in. (244 × 244 cm). Gift of Nissan Motor Corporation, U.S.A., 1988.39, Smithsonian American Art Museum.

The last step was also the most invasive. To reestablish a finish that resembled the artist's original "pristine" surface, the sculpture was repolished with abrasive methods following a combination of the artist's original and current polishing processes. The artist's original process for this sculpture back in 1974 was to wet sand through to 600 grit followed by machine buffing with custom buffing compounds and applying a final coating of automotive wax. However, by the time I treated this sculpture his polishing methods for cast polyester resin sculptures had evolved to wet sanding sequentially through 12,000 MicroMesh grit followed by machine

FIGURE 14. *Preamble* vandalized plate with blue ink graffiti. Photograph by author.

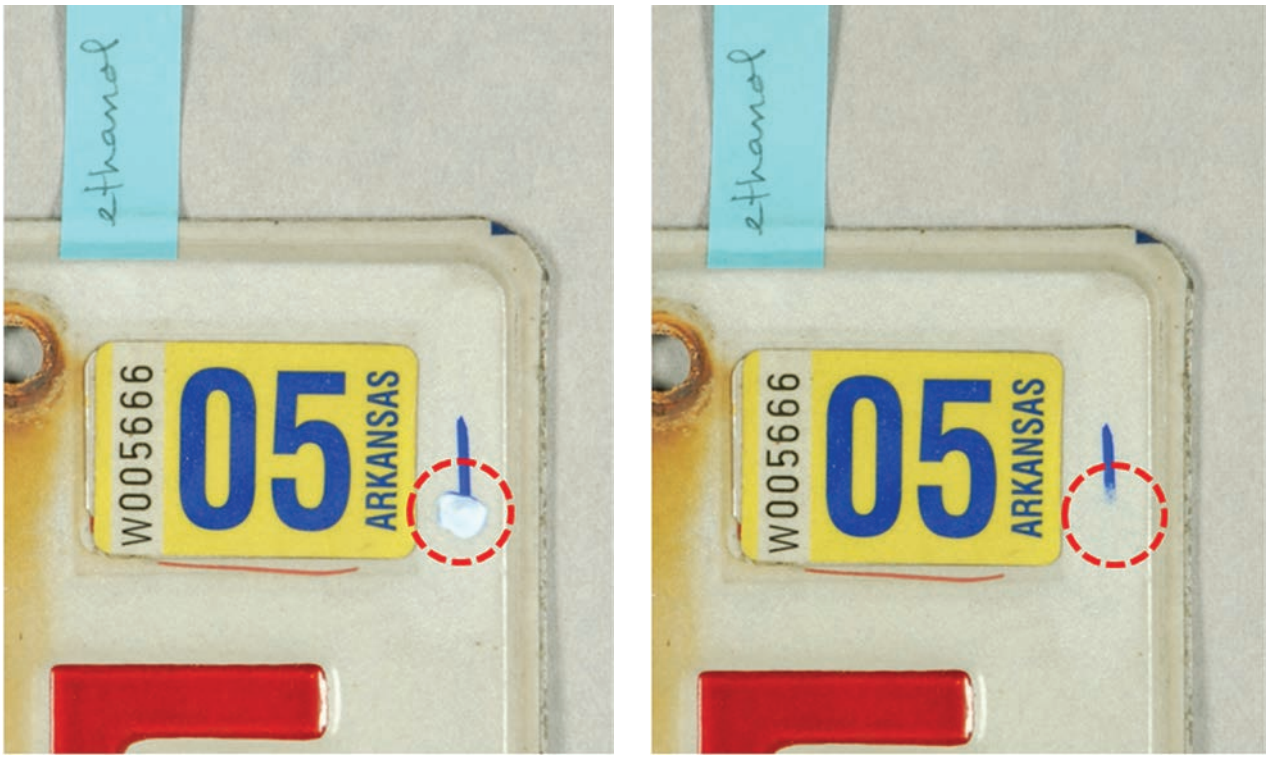


FIGURE 15. Kaolin poultice on test license plate (left) and the plate after removal of the poultice (right). The ink stain is reduced, and the change to the plate surface is barely visible. Photographs by author.

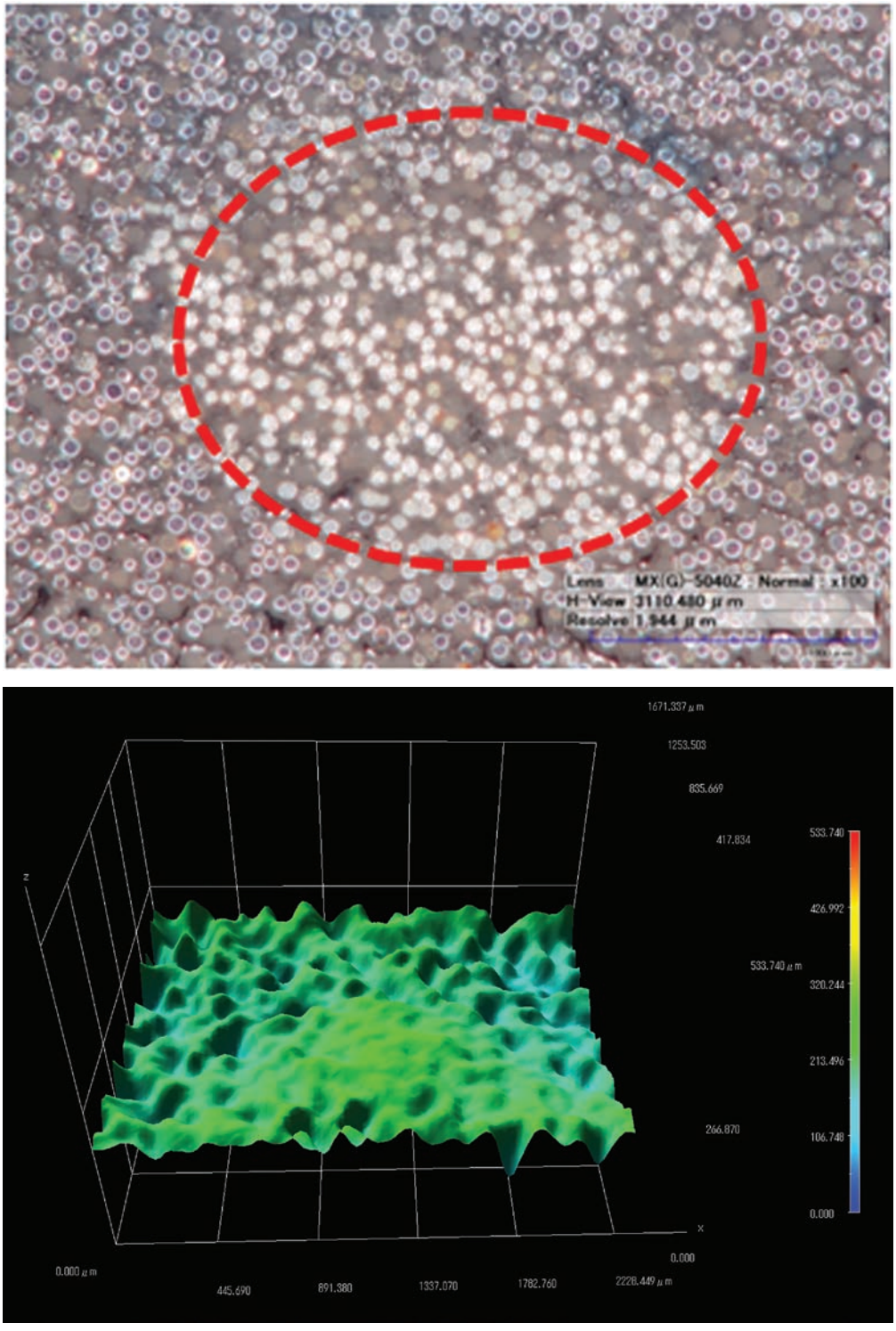


FIGURE 16. Top: Photomicrograph of the *Preamble* Georgia plate in which bright dots circled in red are the polymer coating swelled by the applied solvent (140×). Bottom: Three-dimensional, digital, topographic rendering of the red circled area on the left. Here the slight increase in height of the swelled polymer is shown in lighter green. Three-dimensional digital technology can be very useful to help interpret subtle surface changes in transparent materials. Photographs by author.

FIGURE 17. The license plate after treatment. Photograph by author.

FIGURE 18. Frederick Eversley, *Untitled,* 1974, as exhibited. The optical effects of mirror and transparency dominate rather than the surface texture. Photograph by author.

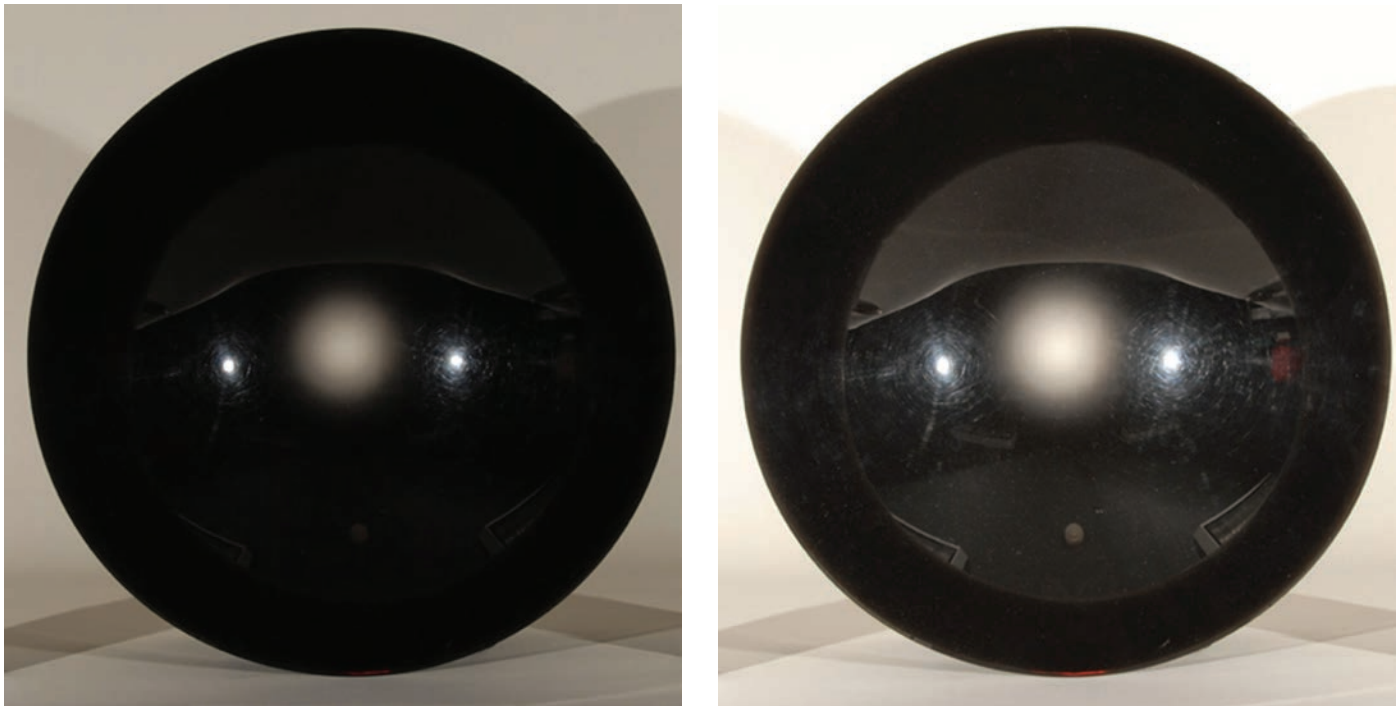
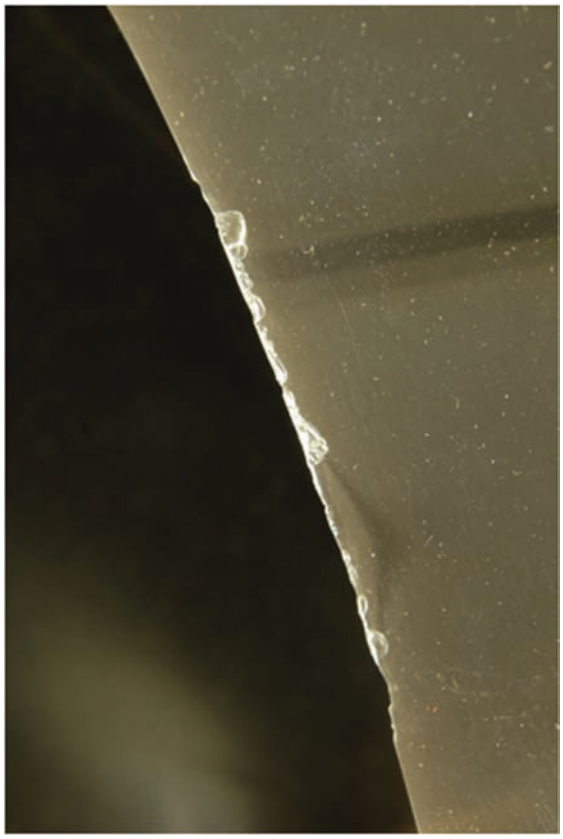


FIGURE 19. *Untitled* as seen under normal lighting for exhibition (left) and an overexposed image in which scratches and other damages are evident (right). Photographs by author.



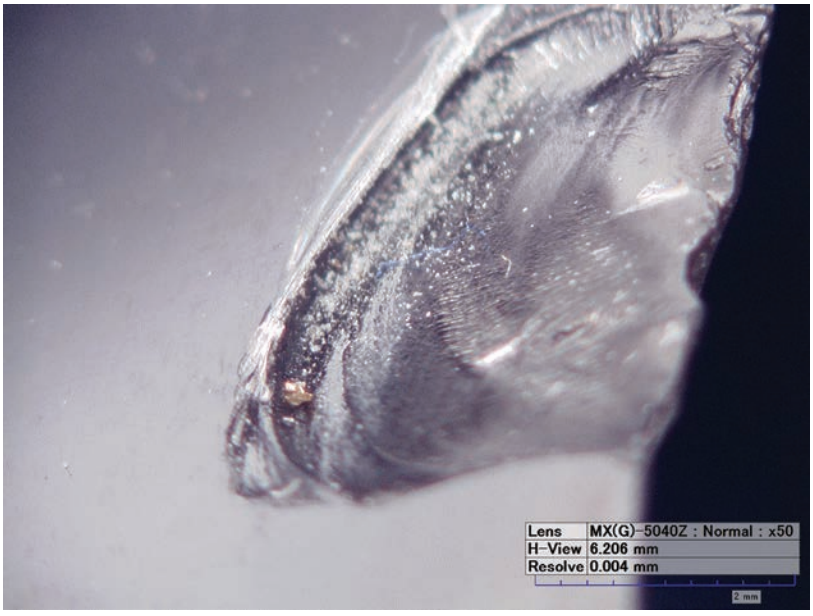


FIGURE 20. Left: Detail of the chipped outer edge of the parabola. Right: The chipped edge as seen under the microscope at 50× magnification. Photographs by author.

polishing up to 1 µm with MicroMesh fluid polish, and a final machine buff with 3M Perfect-It Machine Polish, a proprietary wax, microabrasive, and silicone solvent mixture for final surface finishing. These differences are important because no surface is without texture, and what looks smooth to the eye is relative. One could expect a 1974 Eversley surface would look ever so slightly different from a sculpture he would create today. I also was faced with a different surface from what Mr. Eversley started with, so my polishing sequence would necessarily be different. To honor his methods and restore the damaged sculpture sitting in front of me, I tried to combine elements of his processes with my own.

My first step was to measure the depth of damages I wanted to remove. For example, a gouge on the back surface is detailed in Figure 21. Viewed at 100× magnification, one can see that

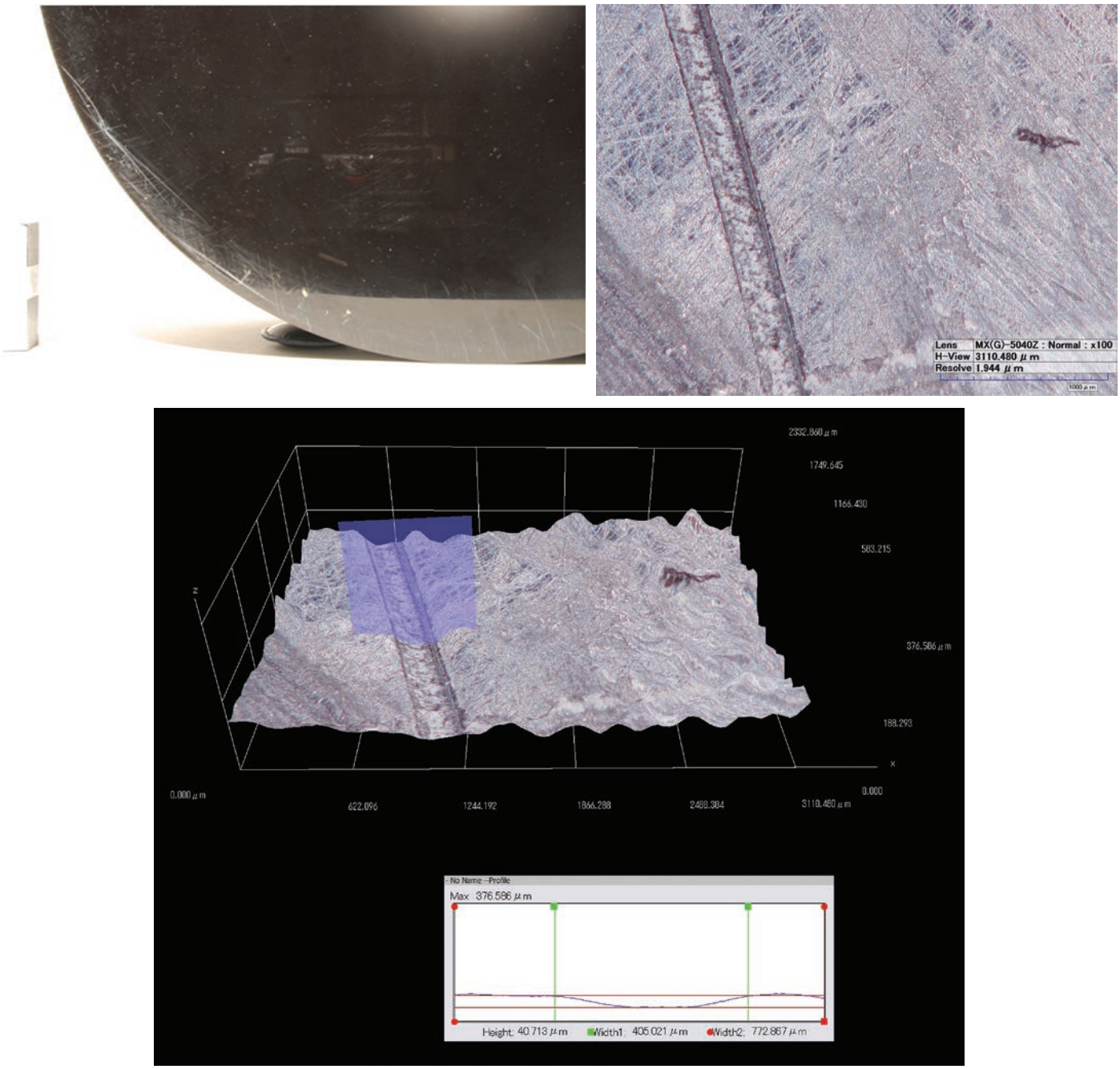


FIGURE 21. Top left: Detail of scratches on the back of the sculpture. Top right: At 100× magnification, a deep scratch is visible crossing the network of finer polishing marks. Bottom: Three-dimensional rendered image of the same area from which the gouge was measured to be 40 µm. Photographs by author.

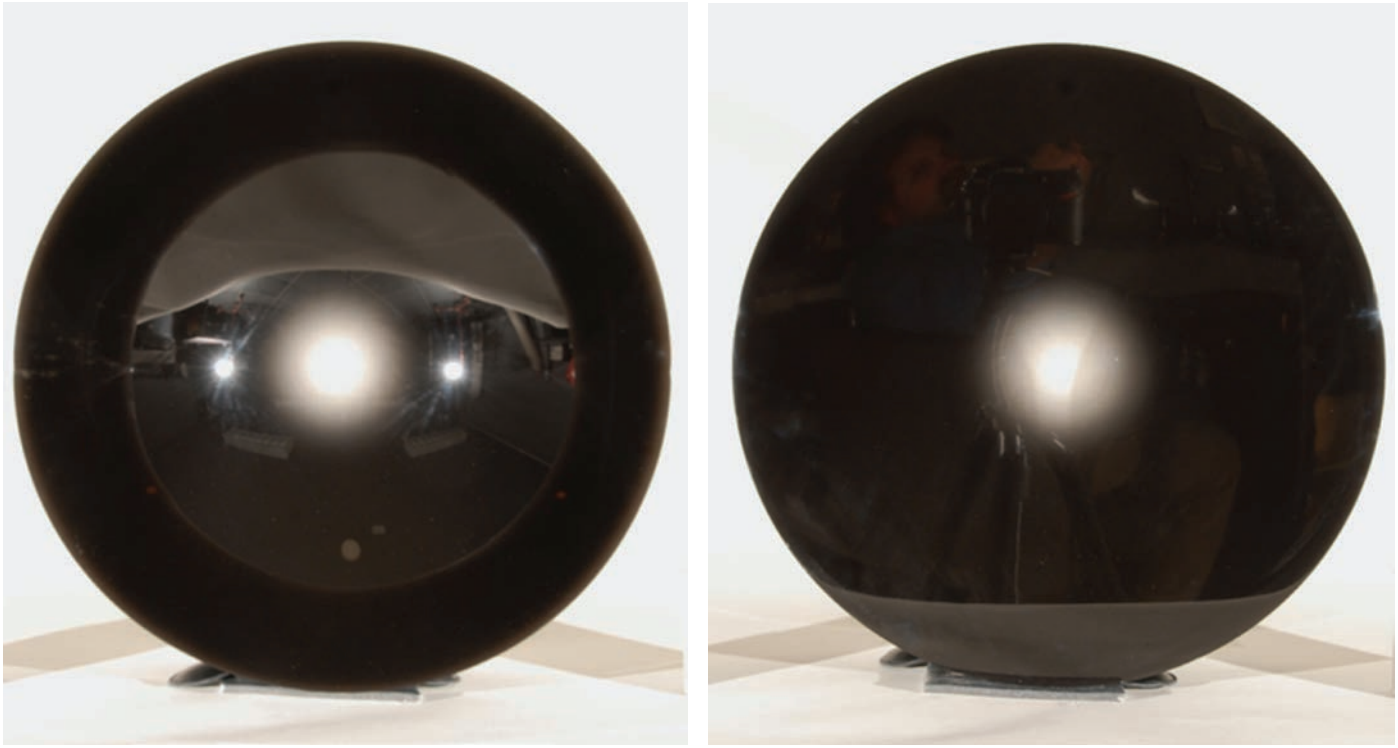


FIGURE 22. *Untitled* front (left) and back (right) views after completion of the treatment. Photographs by author.

the deep scratch was surrounded by a finer network of scratches that were left by the artist's polishing and finishing process, and these fine scratches constituted the sculpture's original pristine finish. The depth of the gouge was measured by creating a three-dimensional computed image with our Hirox digital microscope. Knowing the depth of the scratch was 40 µm helped me to select the most appropriate grit sandpaper to remove these scratches. Grit is a standard measure of the size of abrasive particles on a piece of sandpaper. Matching the particle size to the scratch depth was important to remove just enough material to make the scratch less evident but not cut too aggressively. Armed with an idea of how much surface I needed to remove to erase the most serious gouges, I decided on a polishing regime of wet sanding up to 2800 grit and then 3800, 4000, 6000, and 8000 MicroMesh grits, followed by a machine polish with 5 µm and then 1 µm MicroMesh fluid compound. Figure 22 shows the sculpture, both front and back views after completion of the treatment.

CONCLUSION

It is my hope that this chapter offers others charged with the stewardship of culture's plastic property a reference for considering the scope of restorative intervention. The use of polymers for the creation of art is certain, but their composition and durability are less so, which ensures an ongoing need for their care and periodic rejuvenation. The case studies presented here demonstrate how the current fundamentals of conservation decision making, treatment strategies used for traditional fine art materials, and new technological tools can be applied to the conservation of nontraditional artist materials. Wide variability in plastics demands that artworks be considered on a case by case basis, and professionals will often be confronted with no viable solution other than waiting to see if knowledge and technology eventually catch up with an answer. Our current understanding of the problems, processes, and products of preservation treatments is limited, partly because we have only just begun to wade into a growing tide of culturally significant plastic objects that demand something be done about their condition. Many current conservation practitioners are cautious about sharing techniques because of the specificity of the objects treated and the possibility of misappropriated protocol. I believe the climate for collaboration and information exchange will become more supportive as our experience with treatments for plastics grows and its terminology and technology become more broadly familiar. New conservation professionals will join the field with ever-better curriculum-based understanding of plastic materials. It is my opinion that we should move collectively toward fostering a more rapid buildup of knowledge that includes both successes and failures in the conservation of cultural materials made of plastics.

Acknowledgments

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Preserving Plastic: Challenges in the Conservation of Modern Art Objects

Thea van Oosten

ABSTRACT. Museum collections contain increasing numbers of plastic objects. Since the first production of plastics at the beginning of the twentieth century, a wide variety of plastics has been brought onto the market. Currently, there are hundreds of different types of plastics, each with specific properties to suit their purpose. Because of the unfamiliarity and complexity of modern plastics, recognition of modern plastics by their visual appearance is not very easy, and chemical analysis is often required.

Scientific research plays a crucial role in the study, documentation, and conservation of modern and contemporary art, specifically by drawing in expertise from other disciplines. The problem is to strike the correct balance between technical studies and research into conservation treatments. At the Cultural Heritage Agency of the Netherlands (RCE) significant research has been carried out during the past 22 years into the conservation of plastics used for and applied in modern and contemporary art and design objects. However, before research into conservation of plastics can be beneficial, thorough research into the material plastic itself, its history, its manufacturing, and its degradation has to be performed. Only with thorough knowledge of the material and its properties and an understanding of how to solve problems that are encountered will conservation research be of value. Therefore, an introduction to plastics, identification, setting up reference collections, degradation, and the conservation of plastics will be included in a case study included in this chapter.

INTRODUCTION TO PLASTICS

Plastics are so intertwined in our daily life that a world without this material is hard to imagine. The majority of our present-day activities would not even be feasible without plastics. Think of the use of computers, telecommunications, packaging, domestic appliances, and modern design. Everyday plastic items from the past are now highly collectible.

Plastics are materials that can be molded into required shapes by the application of heat and/or pressure. Most plastics are derived from organic starting materials such as oil, cotton, sugar cane, coal, and corn. Plastics have been classified in many ways. One scheme revolves around the origin of the raw material. *Natural* refers to a biologically synthesized material that can be molded in its natural form; examples include amber, horn, rubber, and tortoiseshell. *Semisynthetic* describes a chemically altered natural material, for example, casein, and cellulosic plastics. *Synthetic* plastics are created in

Zuiderzeepark 49, 1024 ME Amsterdam, Netherlands.
Correspondence: T. van Oosten, vanoostenthea@gmail.com
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laboratories from starting materials that are not polymers; examples include phenol formaldehyde, polymethyl methacrylate, and other polyplastics.

Plastics can also be described by their material properties, such as the terms thermoplastic, thermoset, and elastomer. *Thermoplastics* such as the cellulosic esters, polyamide, polycarbonate, polyethylene terephthalate, polypropylene, polystyrene, polyethylene, and polyvinyl chloride (PVC) are plastics that can be remelted again and again after molding and thus can be recycled by melting and reforming. *Elastomers* such as rubber (natural and synthetic), polyurethane rubbers, PVC rubber, and silicon rubber are elastic materials with specific (elastic) properties. *Thermosets* such as casein formaldehyde, glass-reinforced polyester, hard rubber, melamine formaldehyde, phenol formaldehyde, polyurethane foam, and urea formaldehyde are plastics that, on being heated and molded, set permanently and thus cannot be remelted and reformed (Plastics Historical Society, 2011). A more detailed discussion of what plastic is and how it degrades is offered in Appendix A.

Plastics have been recognized and appreciated by artists. One of the first to use them was Naum Gabo, who created his *Head of a Woman*, a three-dimensional construction of cellulose nitrate sheets, in the 1920s. Modern plastics like polyethylene, unsaturated polyester resins, polystyrene, polymethyl methacrylate, polyvinyl chloride, and polyurethane had already been developed before World War II but were at the time used only for military applications.

In the 1950s and 1960s plastics were once again available for civilian use, and artists started working with them again. The development of new additives and compositions in the 1980s and 1990s improved the texture of plastics and presented new possibilities, which caused a boom in their application (Plastics Historical Society, 2011). Unfortunately, we are discovering that many of these plastics are chemically unstable in the long term, and many artworks are degrading more rapidly than other more traditional artists' materials. Here we present two case studies in the preservation of polyurethane (PUR) foam.

INTRODUCTION TO CASE STUDIES

In the 1960s, Piero Gilardi was a young Italian artist nourished by American pop art, Italian Arte Povera, and European New Realism. These art movements were inspired by industrial production methods and growing consumption of industrial goods in daily life. Artists belonging to these movements, such as Giovanni Anselmo, Yannis Kounellis, Mario Merz, Pino Pascali, and Giuseppe Penone, used quick and easy techniques, and their materials were picked up from shelves of supermarket or from manufactured objects that they recycled. The work of art placed these objects in a new perspective and in some cases gave them a playful dimension.

Piero Gilardi maintained an exceptional position within his movement. His use of synthetic and bright colors diverged from those of natural materials and minimum coloring in the work of the others (de Jonge, 1999). In 1965, Piero Gilardi began to make his *Tappeti-natura* (*Nature Carpets*) from polyurethane foam, playing with the concept of "artificial nature." The polyurethane foam material enabled him to give shape to his visions very rapidly. The fruit and leaves arranged on Gilardi's carpets were made in series, and he cut them from uncolored blocks or plates. The leaves were cut using templates, and the clump of grass was made of rolled strips of foam.

In their finished state, the carpets are pieces of idealized nature and extremely colorful. The texture of the polyurethane foam that remains visible suggests an unreal lightness and softness. The sides of the carpet contrast with the upper part; they are straight and even surfaces coated with a thick black skin, suggesting that the carpet was a "cut" from nature (Lorne, 1999).

In the 1950s and 1960s, many artists and designers assumed that the works of art made with these new materials would always remain smooth, shiny, and flexible. It is now evident that they were wrong. In fact, these materials became matt and stiff, their elasticity disappeared, and splits and tears became apparent. Polyurethane foam eventually degrades, even when used in modern and contemporary art works and design objects, thus confronting curators, conservators, and conservation scientists with the consequences of the limited durability of this material: brittleness, crumbling, disintegration, deformation, cracking, delaminating, and discoloration. From 1990 onward, conservators have carried out consolidation of flexible PUR foam using various consolidating agents as a curative method on degraded objects in the hopes of retarding or inhibiting their degradation (van Oosten, 2011).

Open (flexible) foams have a limited life span, and therefore, a research program was carried out at RCE to find a consolidation method to inhibit photooxidation and to prolong the life span of the works of art. In order to predict the longevity of polyurethane foam, the current condition and rate of decay of the object need to be ascertained. Better insight into the condition of polyurethane foam makes it easier to decide whether to consolidate or postpone consolidation treatment. As long as polyurethane foam has not lost its structural integrity, objects can in some cases be restored using traditional techniques whose suitability and reversibility have been proven. Objects that have degraded to such an extent that they will soon lose their significance require invasive treatments. For these objects there is simply no time to wait for a better treatment because the condition of the foam is so bad that the object will soon cease to exist altogether. Reversibility is not an issue when the chosen method is essentially a last resort. The research program into the application of a mixture of a consolidant and light stabilizer system (sunblock) onto degraded PUR foam included the following steps:

- research into the artist's techniques, materials, and intent
- identification of the materials of the works of art and testing samples using Fourier transform infrared spectroscopy (FTIR)

- artificial light aging to observe degradation
- research into the best consolidant and the best application method to restore PUR foam works of art
- microscopic examination, measurement of cell strut thickness of the foam, and visualization of the consolidant
- monitoring consolidant behavior by examining the flexibility of the foam after consolidation
- condition assessment of the PUR foam by hydroxyl index measurements using FTIR and measuring cell strut thickness
- testing the consolidation method on (painted) polyurethane foam of works of art
- applying consolidant plus stabilizer (sunblock) mixture on real works of art
- dissemination of results and method

A key issue for conservation and restoration is the artist interview to get insight into the materials and techniques used by the artist and the artist's intent. In an interview with Gilardi in 1998, the artist demonstrated the techniques he used and donated materials to serve as test objects for experiments (Figure 1).

DEGRADATION OF POLYURETHANE FOAMS

Polyurethane foams undergo two types of degradation: (photo)oxidation and hydrolysis. Polyurethane ether (PUR-ether) foam is more prone to photooxidation, and polyurethane ester (PUR-ester) foam is more prone to hydrolysis. When it is unclear whether the polyurethane foam is of the ether or ester type, identification methods are required: FTIR analysis, requiring only a very small sample (about 0.6 mm^2), or a simple dissolving test of polyurethane foam in a 10% weight/volume KOH solution, requiring a sample of at least 1 mm^2. The PUR-ester foam dissolves in this solution, whereas PUR-ether does not; both methods are invasive. Noninvasive identification techniques that may be used are near-infrared spectroscopy, fiber-optic FTIR, and Raman analysis, none of which require taking a sample.

FIGURE 1. Gilardi at work in his studio in Turin (1998). Photo by author.

STUDIES ON NEW POLYURETHANE ETHER FOAMS

As most PUR works of art are made of PUR-ether foam, research at RCE focused on this type of foam. Test samples of new PUR-ether foam were artificially light aged using a Xenotest Alpha High Energy (Atlas) chamber in which they were exposed to the radiation of a filtered xenon arc lamp (105 klx, 50°C, 40% relative humidity) to induce photooxidation. A 4-hour Xenotest is equivalent to one year's exposure to museum conditions at 200 lx.

Polyurethane ether foam is very sensitive to light aging, and because of the presence of aromatic structures in the polyurethane foam formulation, the artificially aged samples yellowed very fast. After 72 hours of artificial light aging (equivalent to 18 years of museum lighting at 200 lx), the surface of the foam began to lose its original characteristic surface. Moreover, after 96 hours of light exposure, wrinkles or cracks began to appear in the superficial layer of the foam. After 216 hours, wrinkles had developed all over the surface, and the foam had turned brittle and powdery. Underneath this damaged layer, the original color and structure properties of the foam remained unchanged (Figure 2).

Treatments Applied

The outcome of the first part of the polyurethane research project confirmed that PUR-ether foams are especially sensitive to oxidation, and therefore, further tests using consolidants to inhibit photooxidation were carried out. Various conservation and restoration methods for conserving flexible polyurethane foams have already been carried out and described elsewhere (van Oosten, 2011).

Impranil DLV (Bayer Material Science, currently Covestro), an anionic polyester/polyether-urethane dispersion of aliphatic isocyanate in a 40% emulsion, was selected as the consolidant because it was easy to apply and had good aging behavior characteristics. Also selected for testing was Tinuvin B 75 (Ciba-Geigy, currently Novartis), a light stabilizing system. New PUR-ether foam test samples were consolidated with a mixture of stabilizer plus consolidant using a nebulizer with the help of an air compressor that turned the liquid into a thin mist (for concentrations and solution preparation details, see Appendix B). This process provided a deep and homogenous penetration of the consolidating agent (as was visualized when the mixture was tinted with methylene blue). When the mixture was nebulized for 5 minutes, a 20-mm-thick consolidation layer could be observed, whereas when it was nebulized for only 1–2 minutes, a consolidation depth of about 10 mm was reached and a very thin film of consolidant (10–15 µm) was deposited from the mist on the foam cell struts (Figure 3).

Artificial Light Aging

Three test sample sets were prepared from new PUR-ether foam: untreated (i.e., control), treated with the stabilizer

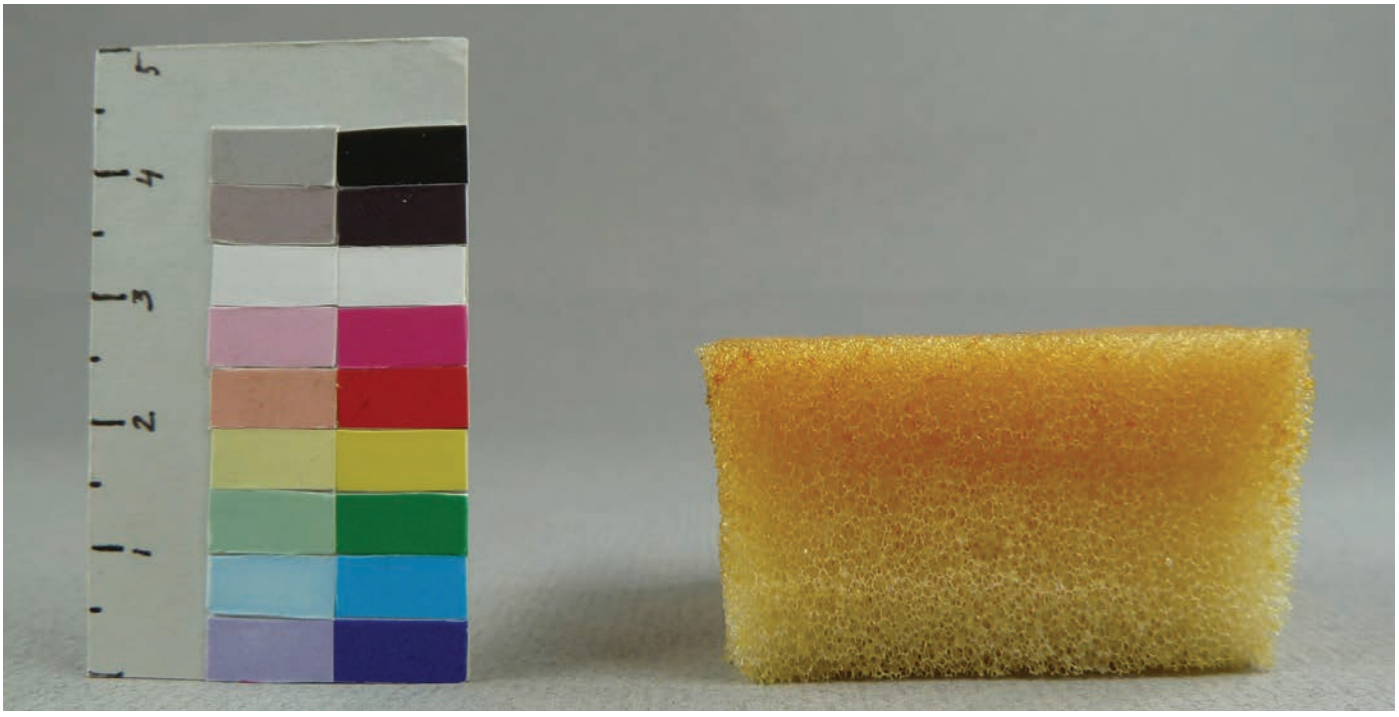

FIGURE 2. Yellowing and crumbling of the superficial layer of new polyurethane ether foam after 216 hours of artificial light aging. Photo by Olivier Beringuer, RCE, 2015.

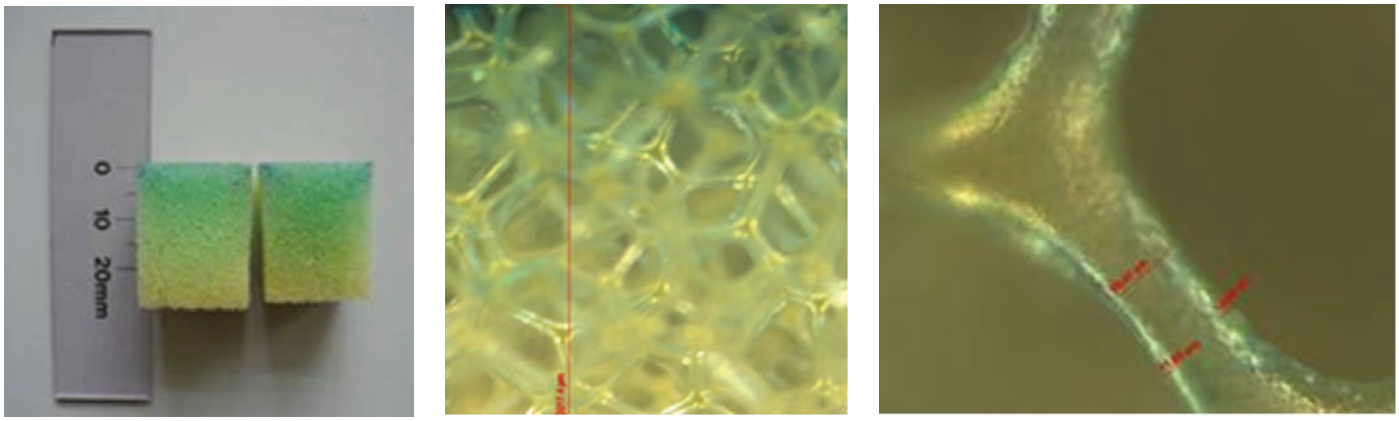

FIGURE 3. Consolidant mixture tinted with methylene blue to visualize the consolidant layer. Left: The new foam test sample after 5 minutes of nebulization. Middle: Detail of the cell foam structure at the edge of the consolidated layer. Right: Detail of the thickness of the consolidated layer on the cell structure wall after 2 minutes of nebulization. Photos by Olivier Beringuer, RCE, 2015.

Tinuvin B 75 (i.e., stabilized), and consolidated with the mixture of Tinuvin B 75 plus Impranil DLV (i.e., consolidated). These samples were subjected to artificial light aging tests. For this purpose the Xenotest Alpha High Energy (Atlas) chamber at RCE was used, and the samples were exposed to the radiation of a filtered xenon arc lamp (105 klx for 24 hours at 50°C and 40% relative humidity) for up to 1,100 hours to induce photooxidation. Aged test samples were examined after 48, 96, 144, 192, 300, 400, 570, 594, 618, 666, 764, and 1,100 hours.

For both the control and the consolidated PUR-ether foam test samples, discoloration started after 96 hours of artificial light aging. The stabilized test samples showed significant protection against discoloration and retained their original flexibility after 500 hours of xenon exposure. Even after 1,100 hours of artificial light aging, no crumbling of the upper layer of the consolidated PUR-ether foams was observed. The concentration of the stabilizer solution affects the time required to apply a given amount of product as well as the life span of the treatment: the higher the concentration of the solution, the shorter the nebulization time. The higher the amount of stabilizer spread into the foam, the longer the effectiveness of the treatment.

Microscopic Examination

The cell strut thickness of the polyurethane ether foam test samples before and after artificial aging was measured using a Zeiss Axioplan 2 imaging research microscope equipped with a digital camera (Zeiss Axiocam MRc with AxioVision software; Figure 4). Measurements of the width of the cell struts were made using the measurement tool after calibration scaling of the AxioVision software.

An average cell strut size of 95 µm was measured for the control samples, whereas after artificial light aging (192 hours), the strut size decreased to about 50 µm, a decrease of about

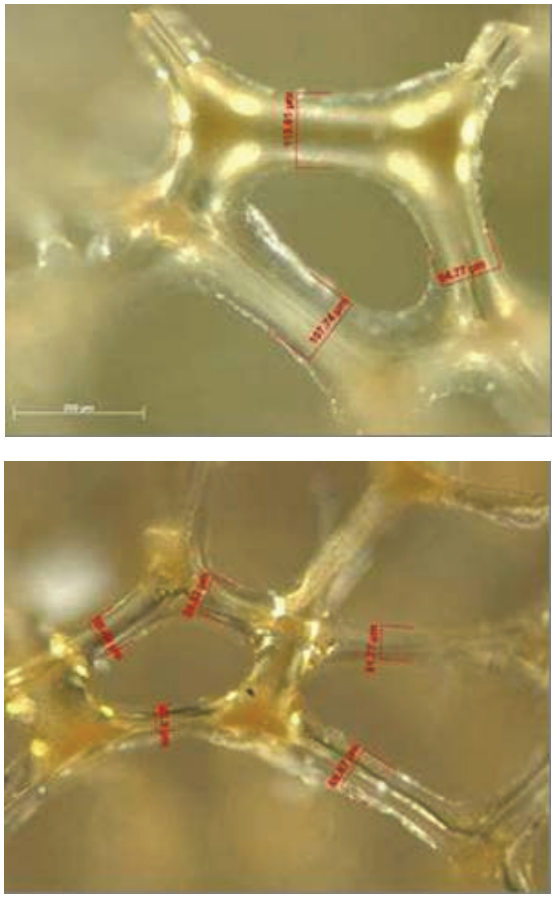

FIGURE 4. Microscopic appearance of the control PUR-ether foam. Top: New, unaged foam. Bottom: Foam artificially light aged for 192 hours. Note the decrease in the width of the cell struts after aging. Photo by Olivier Beringuer, RCE, 2015.

40% in thickness. From this point onward, breaks in cell struts were visible under the microscope, and the foam was brittle and crumbly when touched. The decrease in cell strut size due to photooxidation is a result of chain scission and cross-linking of the polymer, resulting in a decrease in molar mass. Its "critical" molar mass means that at a certain point, the stress already imparted during the manufacture of the foam is higher than the strength of the polymer itself, resulting in breaking of the struts at their weakest point, which is generally located in the middle.

After consolidation with the mixture solution, the cell strut widths increased from 90 to 105 µm, whereas the stabilized samples showed no changes on the foam skeleton widths. After artificial light aging, there was a significant decrease in the width of the cell struts due to photooxidation for all samples.

After 192 hours of artificial light aging, the widths of the cell struts of the control PUR-ether foams reached a minimum value of about 55 µm, which represents a 42% decrease from the original width of 95 µm. In contrast, stabilized samples showed a decrease in cell strut width only after 1,100 hours of light aging; the decrease was from 95 to 75 µm, about 21%, and no brittleness or breaks were detected in the cell struts. The best result was achieved with the consolidated samples (with the mixture solution), for which the thickness decrease was 12.5%, with no breaking or crumbling after 1,100 hours of light aging (Figure 5).

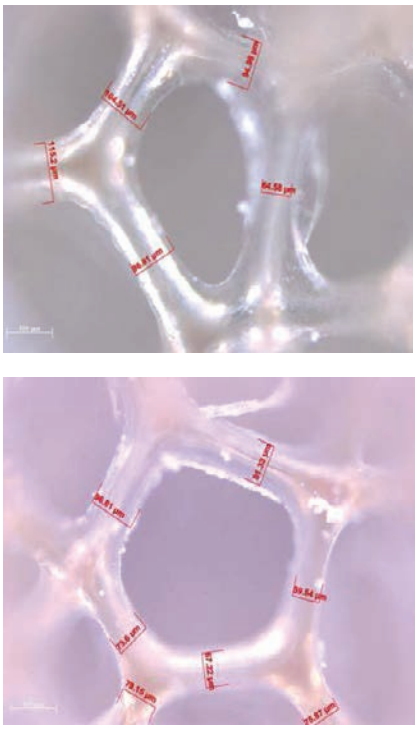

FIGURE 5. Artificial light aging behavior of PUR-ether foam. Top: Consolidated sample prior to artificial aging. Bottom: Consolidated sample after 1,100 hours of light aging. The average decrease in strut width is 12.5%. Photos by Olivier Beringuer, RCE, 2015.

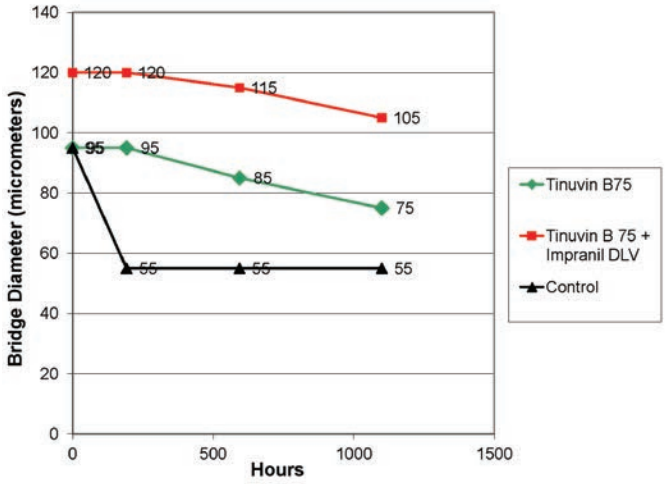

FIGURE 6. Cell strut size in micrometers versus hours of light aging for control samples and samples treated with only the stabilizer (Tinuvin B 75) or the stabilizer plus consolidant mixture. The measured cell strut decreases for the samples at the end of the experiment were 42% (control), 21% (stabilized), and 12.5% (consolidated).

The foam cell strut thicknesses of all PUR-ether foam test samples before and after artificial aging are plotted in Figure 6. The unaged control samples had an average strut width of 95 µm. This width did not change with the application of the stabilizer and increased to 120 µm after consolidating with the mixture solution. After artificial light aging, all test samples, control, treated, or consolidated, showed a decrease in the initial cell strut size due to photooxidation. These decreases were 42% for the control, 21% for the stabilized sample, and 12.5% for the consolidated sample. The samples stabilized with Tinuvin B 75 showed a decrease in cell strut size from 95 to 75 µm (21%) after 1,100 hours of light aging. No breaks were visible in the cell struts, and there was no brittleness. The consolidated samples (with the mixture solution) showed the smallest decrease in cell strut size, from 120 to 105 µm (only 12.5%) after 1,100 hours of artificial light aging (see Figure 5).

Fourier Transform Infrared Spectroscopy

To verify the composition and study the molecular changes caused by artificial aging, the FTIR spectra of the test samples were recorded before and after consolidation as well as after artificial light aging. A PerkinElmer Spectrum 1000 FTIR spectrometer combined with a Golden Gate Single Reflection Diamond ATR unit (sample size 0.6 mm^2) was used to record the spectra from 4000 to 600 cm^{-1}.

Polyurethanes can be identified by the presence of three characteristic absorption bands corresponding to the amide II band (NH deformation) at approximately 1,538 cm^{-1}, the amide

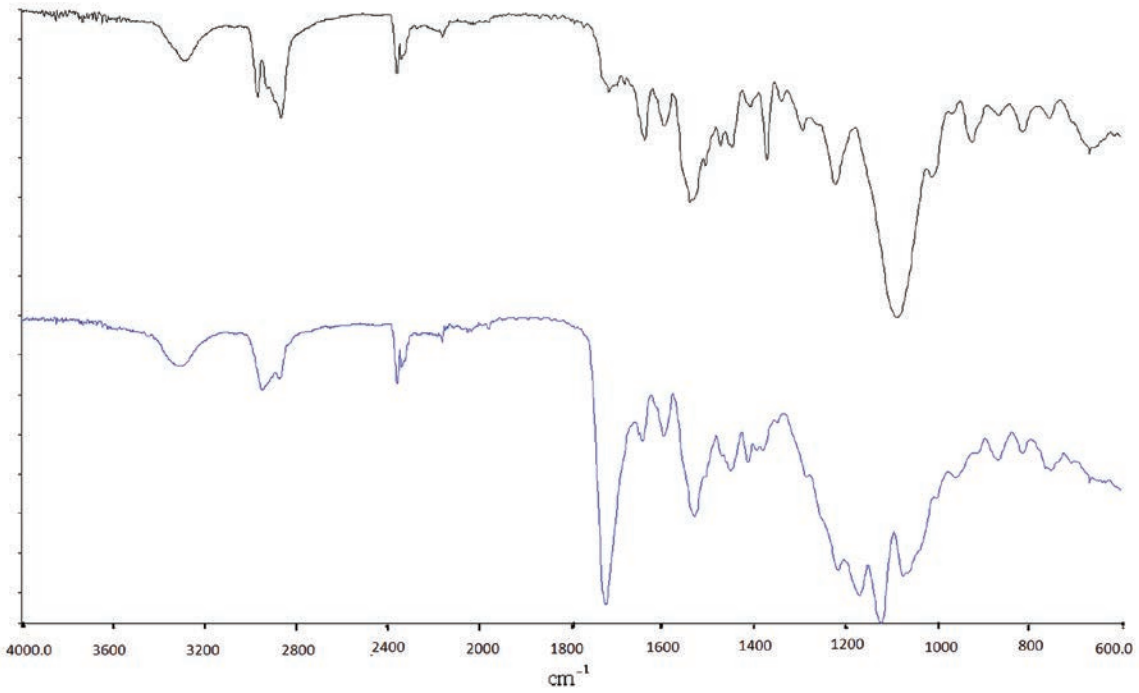

FIGURE 7. The FTIR spectra of polyurethane ether (black spectrum) and polyurethane ester foam (blue spectrum), adapted from van Oosten (2011).

I band (C=O stretch) at 1,724 cm^{-1}, and the NH stretch around 3,300 cm^{-1}. The presence of polyether or polyester linkages in the polymer chain can be established by examining the relative intensity of the rather large bands around 1,100 cm^{-1} due to C–O–C (ether linkage) and O=C–O–C (ester linkage). In the case of PUR-ester foam, the ester linkage at 1,124 cm^{-1} is more intense, whereas the ether linkage at 1,088 cm^{-1} is more dominant for PUR-ether foams. Specific ester absorptions of PUR-ester are the carbonyl at 1,725 cm^{-1} and the O=C–C–O–C absorption at 1,218, 1,170, 1,124, and 1,078 cm^{-1} (Figure 7).

Chemical changes in polyurethane foams due to degradation can be seen in the FTIR spectra by the increase in hydroxyl and carbonyl absorption bands. However, the increase in carbonyl absorption could not be used because of the obscuring effect of the infrared absorptions by the consolidating agent (Impranil DLV) and the light stabilizer (Tinuvin B 75). Therefore, only the hydroxyl absorption was measured. By measuring the height of the hydroxyl absorption peak at 3,450 cm^{-1} (A3450) and that of the peak at 1,850 cm^{-1} (A1850), where no organic infrared absorption occurs, the ratio of the relative absorbance (A3450/A1850) can be calculated, that is, the hydroxyl index (HI), which can be used to evaluate photooxidation. The higher the HI is, the more oxidized the polymer is, and the more brittle and breakable an object is. The degradation due to photooxidation of both untreated and treated PUR-ether foams was expressed as the HI and plotted against artificial light aging in hours (Figure 8).

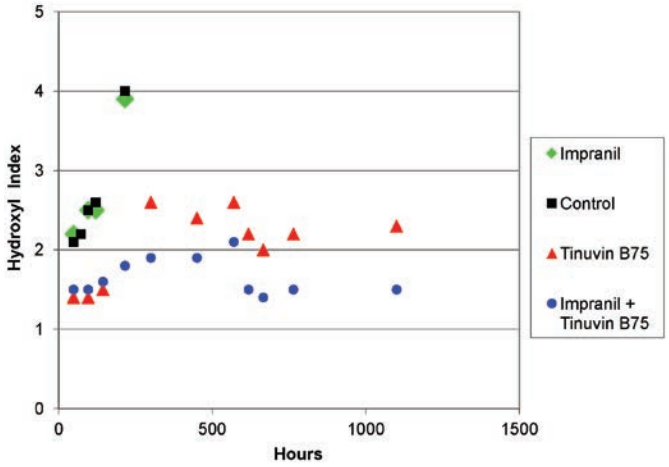

FIGURE 8. Changes in the hydroxyl index (A3450/A1850) for PUR-ether foam control samples and those treated with the stabilizer (Tinuvin B 75), the consolidant (Impranil DLV), or their mixture during artificial light aging.

New PUR-ether foams, as they leave the factory, have an HI of around 1, whereas the 5-year naturally aged foam had an HI of close to 2. The foam used for the experiments had already aged 5 years in the laboratory and therefore had an HI of around 2,

reaching a maximum of 4 after 216 hours of artificial light aging. At this point the foam crumbled completely, with a total loss of flexibility. In keeping with previous research, it was observed that PUR-ether foam starts crumbling when an HI of 3 is attained.

The PUR-ether foam treated with the stabilizer solution or consolidated with the stabilizer plus consolidant mixture (Tinuvin B 75 + Impranil DLV) showed no significant increase in the HI, even after more than 1,100 hours of artificial light aging. The exposure to 1,100 hours of artificial lighting (114,444 klx hr) is approximately equal to 275 years of exposure to museum light conditions at 200 lx.

CONSOLIDATION OF DEGRADED AND/OR PAINTED POLYURETHANE ETHER FOAM

The applicability of the stabilizer plus consolidant mixture using a nebulizer was also tested on three different levels of degraded PUR-ether foam samples: discolored; discolored and stiff; and discolored, stiff, and brittle. Moreover, final testing on painted degraded PUR-ether foams was performed on some test pieces from the works of art by Piero Gilardi, who kindly donated them at the time he was interviewed by the author in his Turin studio in 1998 (Figure 9).

Test pieces of PUR-ether foam with yellow and green paint were nebulized with the stabilizer alone or with the stabilizer plus consolidant mixture solution. The latter showed the best results after artificial light aging for 320 hours. The PUR-ether foam showed no serious discoloration and no crumbling. Furthermore, the paint had not faded, and the flexibility of the foam had not changed. The nebulizing system of the mixture also worked well for the painted PUR-ether foam, not filling the cells, but only applying a layer of about 10–15 μm of consolidant on the surface of the painted foam cell struts.

CONDITION ASSESSMENT OF PUR-ETHER FOAM IN WORKS OF ART

The condition of naturally aged PUR-ether artworks was assessed by comparing data acquired from naturally aged works of art (between 8 and 40 years) with the degradation indices of the artificially light aged test samples from research carried out at the RCE. For this purpose, the hydroxyl index values of naturally aged PUR-ether foams in works of art and artificially light aged test foam samples were compared. For example, nondegraded foam has an HI between 1 and 2, whereas artificially light aged foam with an index of 4 is totally crumbled. Foam that had been

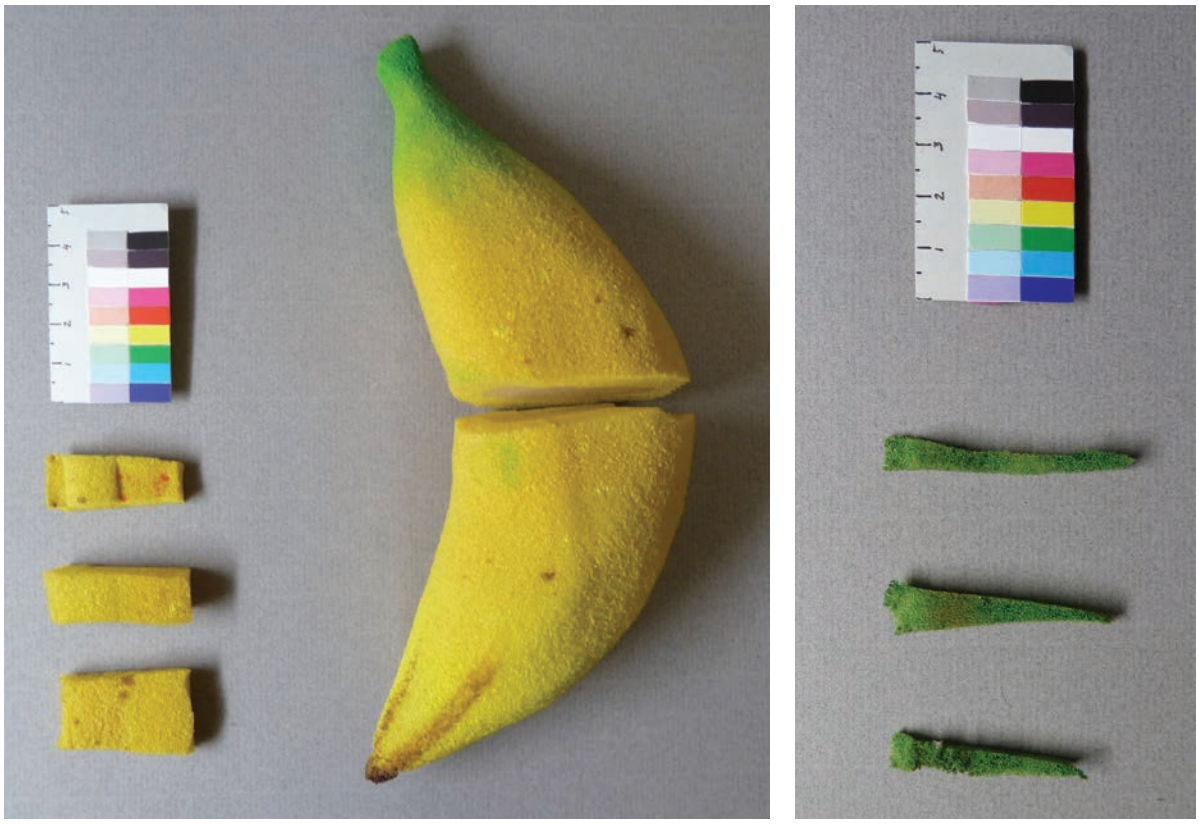

FIGURE 9. The PUR-ether test foam samples consolidated and artificially aged. Photos by author.

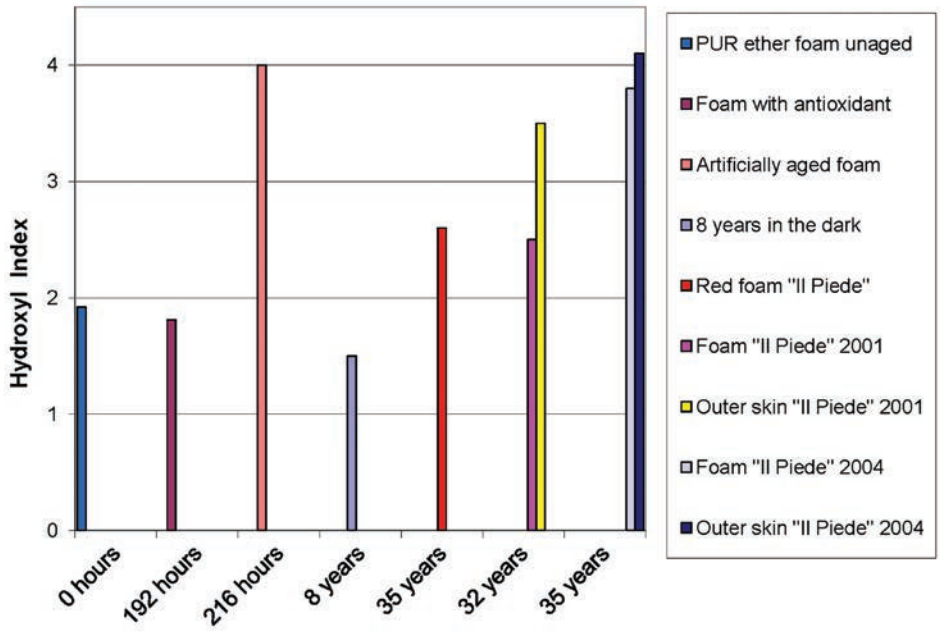

FIGURE 10. Hydroxyl index (A3450/A1850) of PUR-ether foam as a function of years in aging.

kept for 8 years in the dark had an HI of 1.7, whereas for foam from the chair Il Piede (from the collection of the Vitra Design Museum in Weil am Rhein, Germany) the HI was 3.4 after 32 years of natural aging. When the HI of the foam from the chair from the Vitra Design Museum was remeasured three years later, it had increased to 4.2, and the foam was more degraded. In contrast, foam from a red Il Piede chair from the collection of the Kunstgewerbemuseum in Berlin showed an HI of 2.6 because the foam was protected by the red paint layer (Figure 10).

A difference between the condition of the outer surface and that of the inner foam exists. The outer layer has a higher HI, being more degraded than the foam directly under the surface because light penetrates only about 300 µm into an open-structured surface, leaving the layer underneath unaffected.

Examinations using strut size measurement with a Zeiss Axioplan 2 imaging research microscope and/or measuring the HI by FTIR could provide sufficient information to determine the condition of an artwork made of polyurethane ether foam. A three-category condition table of PUR-ether foam was set up using the data from the HI, the cell strut measurements, and the color change (Table 1). Condition 3 prescribes immediate consolidation, condition 2 recommends consolidation in due course, and condition 1 does not require consolidation but needs regular inspection.

The stabilizer plus consolidant mixture solution gave the best results overall. Its success can be attributed to the properties of the mixture that has both a curative effect, repairing broken cells, and a preventive one, inhibiting oxidation, thus prolonging the service life of both new and degraded PUR-ether foam. Applying the consolidating agent by nebulizer results in the formation of a 10- to 15-µm-thick homogeneous layer on the cell struts of the foam without filling the cells of the foam, thus keeping the

TABLE 1. Condition assessment of PUR-ether foam objects.

Condition of PUR-ether foam	Category	Color change	(C–OH) hydroxyl index	Cell strut size (µm)	Recommendation
Good	1	Slight discoloration	<2	96	Only general preservation required
Poor	2	Discoloration	2–3	75	Consolidation treatment recommended
Bad	3	Strong discoloration	>3	55	Highly urgent consolidation treatment required

intrinsic flexibility of the foam. Application improves the mechanical properties such as flexibility and resilience of already aged and hence brittle foams and conserves new polyurethane ether foams (van Oosten, 2003, 2011).

In general, new and painted PUR-ether foams should be nebulized directly with a mixture solution of 5% Tinuvin B 75 + Impranil DLV to prevent oxidation (van Oosten, 2003, 2011). Crumbly, that is, degraded, PUR-ether requires a preliminary nebulization with 3% Tinuvin B 75 in isopropanol and, subsequently, a second nebulization with the 5% mixture solution of Tinuvin B 75 + Impranil DLV.

Case Study 1: Gilardi's *Zuccaia*

The treatment of *Zuccaia*, part of the *Tappeti-natura* series, in which the artist created almost perfect copies of natural subjects utilizing an entirely synthetic material (PUR-ether foam), finally became possible in 2007 and was carried out by conservators Aleth Lorne and Ron Kievits at RCE. For several years, the carpet had been carefully stored in the dark. The condition of the polyurethane foam had remained reasonably stable (Figure 11).

The PUR Research Project had studied the degradation mechanisms of PUR-ether foam, and excellent consolidation results had been achieved with the consolidant plus stabilizer mixture solution discussed previously. Applied at an early stage of the oxidation process, the consolidant would prolong the foam's life span by a considerable amount. The success of the method resulted from a combination of both the properties of the mixture itself and the nebulization application method.

The consolidation of this large polyurethane foam object required a methodical approach. Good knowledge of the materials and manufacturing techniques of the artwork proved essential for the interpretation of the condition. The condition assessment of the polyurethane foam was a useful aid in designing a specific consolidation plan for the carpet. The mixture solution of consolidant plus stabilizer is a tool that can be combined in different ways, depending on the problems posed by the polyurethane foam object. The success in conserving polyurethane foam is related to its degree of oxidation. The turning point for the oxidation process is attained when the struts at the surface of the foam object begin to break. This breakdown may occur at variable moments during the lifetime of a polyurethane foam

FIGURE 11. *Zuccaia* by Piero Gilardi as it appeared in 1993. Photo courtesy Aleth Lorne.

object, depending on the properties of the polyurethane, the artist's technique, and the conditions to which the object was exposed. Consolidation of polyurethane foam can be carried out at the moment when the cell struts at the surface of the foam begin to break or even before this. However, very limited treatment possibilities exist for crumbled polyether urethane; for example, the removal of dust is no longer possible. Further, the consolidation process may alter the appearance of the object; for example, the surface may be flattened, and discoloration may occur.

Therefore, the care of PUR-ether foam objects in collections involves three essential preventive measures of conservation:

- minimal exposure to light, both in time and intensity, no UV light, and total darkness during storage
- good protection from dust
- consolidation of the PUR-ether foam with the consolidant plus stabilizer mixture before surface damage occurs

Hopefully, the life span of *Zuccaia* can now be prolonged to a hundred years or more, provided it is kept under the proper conditions (e.g., low light levels of 200 lx and minimum dust exposure).

Case Study 2: Gilardi's *Sassi*

The artwork *Sassi* by Piero Gilardi forms part of a decorative interior and was completed in 1972. It also belongs to the *Tappeti-natura* series (Figure 12). In 2010 it was restored by Barbara Ferriani (Ferriani conservation studio, Milan, Italy). She had attended the "Working with Plastics" workshop at RCE in 2001 and worked in close collaboration with RCE for this project.

FIGURE 12. *Sassi* by Piero Gilardi as it appeared in 1972. Photo courtesy Barbara Ferriani.

Some "sassi" (stones) had become detached from the base, and these were fixed and stabilized with an acrylic adhesive (Lascaux 360 HV, Lascaux, Switzerland) in relation to the base of the piece and its support, taking care not to force the object back to its exact original position so as not to further compromise the elasticity of the material. Since the consolidating solution contained a UV blocker and had been applied only to those areas of polyurethane visible to the eye, it was decided to apply the stabilizer to the entire surface. In this way an attempt was made to protect even the microcracking present in the paint by covering the entire surface to prevent further photooxidization and any resultant chromatic alteration. For this purpose it was important to find a solvent in which to dissolve the Tinuvin B 75, and as the microcracking in the paint surface would channel the solution into the underlying polyurethane layer, this solvent had to be safe for the polyurethane. The solubility of the stabilizer in various solvents was tested, including isopropyl alcohol (which had been used in the stabilizer plus consolidant mixture) and ethyl acetate. The former has the disadvantage of containing a high percentage of water, which can have a negative effect on the PUR-ether foam as it is retained longer. In order to avoid this problem, a more volatile solvent was needed, and ethyl acetate was found to significantly reduce the retention time in the foam. Once the solubility of Tinuvin in both solvents, isopropanol and ethyl acetate, had been verified, solutions at 2% and 3% concentration in both solvents were prepared. These solutions were applied to four samples and several original fragments by nebulization for different amounts of time. The cells of the samples did not display significant changes in any of the cases. Given the higher volatility of ethyl acetate in comparison to that of alcohol, it was decided that the Tinuvin should be dissolved in ethyl acetate at the 3% concentration. Upon conclusion of the project, no chromatic or tonal variations were noted in the paint layers, nor was there evidence of the polyurethane surfacing through the microfissures.

On completion of the restoration process, the original aesthetic value and correct visual rendering of the work had been almost completely restored, whereas the small signs testifying to its history were toned down but left in place. Obviously, the work could no longer exist fully as a carpet with people walking or playing on it, and the few remaining stains testifying to its former life can at least remind us of its past use. Although it may have been prudent to protect the work from the adverse effects of UV radiation, the accumulation of atmospheric particles, and variations in humidity by placing it in a transparent case with UV protection, both the artist and the owner preferred not to do so.

CONCLUSIONS AND RECOMMENDATIONS

The treatment developed for the PUR-ether foams at RCE was preceded by an extensive research phase of the PUR project led by the former Netherlands Institute for Cultural Heritage.

This research allowed students to trace and follow the deterioration processes and to identify appropriate treatment materials while also creating an opportunity to establish a comprehensive research methodology that provides procedure guidelines and control checks that are easy to apply throughout the process.

It was found that simple methods, such as strut width measurement or instrumental analysis, for example, measuring the hydroxyl index (A3450/A1850), provide sufficient information to determine the condition of an artwork made of PUR-ether foam. Furthermore, it was established that consolidation with Impranil DLV in combination with the light-stabilizing system Tinuvin B 75 prolongs the service life of both new and degraded PUR-ether foam by repairing broken cells and by reducing the oxidation rate. The higher the amount of stabilizer distributed inside the foam is, the longer the effectiveness of the treatment is. The concentration of the mixture solution affects the time needed to impregnate the material with a given amount of product: the higher the concentration of the mixture solution is, the shorter the nebulization time needed is. However, although impregnated, discoloration of PUR-ether foam still occurs on aging, albeit at a slower rate. Eventually, both treated and untreated PUR foam test samples show the same extent of discoloration after 1,100 hours of light aging (equivalent to about 275 years in a museum environment at 200 lx).

The final recommendation that can be made is that it is critical to study and document the object to understand its deterioration process. Only when that process is understood can a proper treatment be developed for it. Although the approach described here has worked well in the presented examples, it is fundamental that it be adjusted to the particular object to be treated. Art objects are unique, and therefore, they require unique conservation interventions.

Acknowledgments

The author thanks conservators Aleth Lorn, Ron Kievits, and Barbara Ferriani for their valuable help during the research project on the consolidation of PUR foams and Aleth Lorne and Barbara Ferriani for the conservation of works of art made from this material using the developed consolidant.

APPENDIX A. BACKGROUND INFORMATION ON PLASTICS

Manufacturing

The raw materials used for the manufacture of synthetic polymers are derived from petroleum and coal, whereas for semisynthetics, wood pulp and milk form the building blocks of the polymer. All plastics are polymers, but not all polymers are plastic. Polymers are rarely useful as such and are most often modified or compounded with additives (including colors) to form useful materials. At the processing point, plastics consist of granules, preformed tablets, powders, syrups, or pastes. The performance, appearance, and stability of a specific plastic can be modified by a mix of additives in its recipe. Additives are used for a wide range of reasons, for example, to provide additional strength or dimensional stability, to act as plasticizers or lubricants, to supply decoration or pigmentation, to improve chemical resistance, to act as fire retardants, to protect against ultraviolet degradation, and to act as fillers to reduce cost. Commonly found additives include calcium carbonate as filler, camphor and phthalates as plasticizers, pigments as coloring agents, gas and air as foam expanders, glass and other fibers as reinforcement, antioxidants as stabilizers, and talc and wood flour as strengtheners. It would be impossible to process most polymers into useful objects without additives. Additives can be added in different quantities and can affect the long-term stability of the plastic

Manufacturing techniques for plastics such as injection and blow molding and vacuum forming are commonly used, and plastic objects can be identified by the marks of those techniques. However, nowadays, developments of plastics include the application of new technologies such as 3-D rapid prototyping under fused deposition modeling, a manufacturing technology commonly used for modeling, prototyping, and production applications. This technology was developed by S. Scott in the late 1980s and was commercialized in 1990 (*Wikipedia*, 2013). Furthermore, selective laser sintering is a manufacturing technique that uses a high-power laser to fuse small particles into a mass that has a desired 3-D shape (Deckard, 1989). Another innovative technique is PolyJet 3-D printing technology developed since 2000. This technique works by jetting a photopolymer in ultrathin layers (16 µm) onto a build tray until the part is completed. Each photopolymer layer is cured by UV light immediately after it is jetted, producing fully cured objects. Because of these new technologies and techniques to fabricate plastic objects, many more new innovative fabricated plastic objects will turn up in museum collections, and it will become even more difficult to identify an object by the look and feel or touch and probing.

Identifying Plastics in Modern Art Objects

Plastics in art objects need to be correctly identified to ensure any applied conservation treatment is safe and that collection records are accurate (Hummelen and Sillé, 1999). Identifying the composition of a plastic, that is, the polymer plus additives, such as plasticizers, is not so easy. Analysis can be unsuccessful if, for example, the level of a particular component is low or the available technique is limited in sensitivity. Therefore, additional information that will help the researcher to interpret the results is needed, including the following:

- when the object was acquired or when was it made
- trade names or trademarks on the object

- whether the object has been conserved or restored or any parts have been replaced
- the recent and past storage and/or display conditions
- the time degradation was first noticed, the signs of degradation, and whether similar objects are behaving the same way

Having some level of documentation on the type of plastic used in a work of art, either from the collection from which it came or the artist, is also not uncommon. Other useful information that can help with the (nonanalytical) identification process includes knowledge of the history of plastics, an understanding of a particular artist's methods and materials, and knowledge of the plastic identification codes (SPI) on some objects (Coxon, 1993). Sometimes the nature of the degradation itself can help to characterize an aged plastic. However, all these sources of information can be absent or incomplete and/or unreliable. It is also known that various plastics can show similar characteristics to each other, so that simple tests may give false answers (van Oosten, 2001; Shashoua, 2008; Waentig, 2009).

Fortunately, many scientific methods exist for identifying plastics more reliably. The most useful are those that reveal the chemical composition of a material from microscopic sample sizes or even via noninvasive, in situ techniques (van Oosten, 1999). For this discussion, it is helpful to make a distinction between *identification* (i.e., the polymer class) and *characterization* (additional information about a polymer's makeup and behavior, including more quantitative analysis of all the components in a product, molecular weight distribution, polymer size, and physical properties) of plastics.

Spectroscopic and chromatographic techniques such as Fourier transform infrared spectroscopy (FTIR) and pyrolysis–gas chromatography–mass spectrometry (Py-GCMS) are extremely useful for the identification of plastics. Since the 1990s, spectroscopic techniques have improved significantly in terms of the size of sample required, the speed of analysis, the user interface, and portable and/or mobile instrumentation. The use of these spectroscopic methods has become widespread in conservation and is likely to increase further with the recent development of handheld instruments (FTIR, Raman spectroscopy, and near infrared spectroscopy [NIR]) for rapid, noninvasive, in situ analysis. Although Raman spectroscopy has improved regarding many of the problems it had initially with fluorescence coming from additives in the plastics and both NIR and ultraviolet-visible spectroscopy have become more sensitive and more useful, the most widely used technique for identifying plastics is still FTIR. The technique is highly versatile and also permits the analysis of surface-deposited degradation products, polymer bond changes, depth profiling, and the monitoring of polymer loss. For the identification of complex mixtures of plastics and additives, however, Py-GCMS offers many advantages over FTIR. The main disadvantages to this technique seem to be the lack of low-cost models and the additional resources needed for maintenance.

Reference Collections of Plastics

In order to evaluate suitable analytical tools for the identification of plastics and to support these analyses, a reference collection of plastics has to be used. For this purpose, at the Cultural Heritage Agency of The Netherlands (RCE) over 600 plastic objects have been collected, described, and analyzed. All data have been put in FileMaker Pro (S. Conover, RCE, *The VOC Collection Database*, unpublished, 2011). This database is great help for the interpretation of the analyses of unknown plastic objects.

Another database with references called SamCo has been set up for Preservation of Plastic Artefacts (POPART), a European project for the conservation of plastic artifacts in museums (Lavédrine et al., 2012). SamCo is a box containing a collection of well-characterized reference materials representing new and degraded plastics found in museum collections. SamCo consists of almost 100 plastic reference samples, corresponding to standard materials and documented and identified objects. Each standard represents the reference material of a "pure" plastic, whereas each object represents the reference of the same plastic as in the standards but compounded with pigments, dyestuffs, fillers, antioxidants, plasticizers, etc.

Plastics Degradation and Durability

The most frequently asked question about a contemporary work of art containing plastics besides what is it made of is, How long will it last? Lifetime expectancy is often many years; however, service conditions may be complex, and definitive data on durability are scarce. The situation is complicated by the fact that there are a vast number of degradation agents, service conditions, important properties, and different plastics to consider before durability can be defined or understood (McGlinchey, 1993; Feller, 1994; Rabek, 1995; Brydson, 1999).

Polymer degradation is a change in the properties such as tensile strength, color, shape, etc., of a polymer or polymer-based product under the influence of one or more environmental factors such as heat, light, or chemicals such as acids, alkalis, and some salts. These changes are usually undesirable, such as cracking and chemical disintegration of products, but can be, more rarely, desirable, such as biodegradation or deliberately lowering the molecular weight of a polymer for recycling. Polymeric molecules are very large (on a molecular scale), and their unique and useful properties are mainly the result of their size. Any loss in chain length lowers tensile strength and is a primary cause of premature cracking. The changes in properties are often termed aging or deterioration.

Most assessments of the lifetime of plastics are made by considering some measure of performance, such as impact strength, and specifying some lower limit for the property, which is taken as the end point. These measurements require rather large test samples, which is not an option when dealing with works of art. The quality of plastics with regard to durability is not what museums would wish for. Plastic degrades, despite the fact that some

believe that plastics are unbreakable and durable. Plastics in modern and contemporary works of art degrade, and curators and conservators are confronted with the phenomena of limited durability of these materials: brittleness, crumbling, disintegration, deformation, cracking, delaminating, discoloration, and chalking. When plastic ages, it often has an "induction time," during which it shows hardly any sign of deterioration. The induction time is followed by a phase during which the object ages rapidly.

Problematic plastics that suffer from degradation due to intrinsic properties are cellulosic esters such as cellulose nitrate, cellulose acetate, cellulose butyrate, plasticized PVC, polyurethane foams, and elastomers. Some plastics, for example, unsaturated polyesters, polyethylene, and polypropylene, suffer from degradation due to external circumstances such as outdoor exposure. To predict the longevity of plastics, the current condition and rate of decay of an object should be known.

Photochemical Degradation

Plastics are highly sensitive to spectral radiation, especially high-energy UV radiation, and can absorb wavelengths above 285 nm because of impurities, in particular oxygen-containing species and trace levels of metals and other species present, arising from production processes (Lemaire and Lacost, 1988). Moreover, degradation is initiated in the extrusion of plastics when carbon-carbon bonds in the polymer chains break because of high temperatures, and unstable radicals are formed.

Photons react with the polymer surface to form radicals. These radicals react rapidly with atmospheric oxygen, and hydroperoxide is formed. The photooxidative degradation process of polymers is a free radical chain process characterized by three steps: initiation, propagation, and termination. Free radicals, which are formed during the initiation and propagation steps, may undergo further reactions such as chain scission and chain branching with atmospheric oxygen, which will lead to changes in the physical characteristics of the bulk polymer (Dolezel, 1978; Vink, 1979; Lemaire and Lacost, 1988). The decomposition of the hydroperoxide groups produces oxygen functional groups on the surface, including C–OH, C=O, and COOH. The amount of oxidized materials created on the polymer surface increases with exposure to light.

Hydrolysis

Ester-type polymers, such as unsaturated polyesters, polyamides, and polycarbonates, can be degraded by hydrolysis to give lower-molecular-weight molecules. The hydrolysis takes place in the presence of water containing an acid or a base as catalyst, and it is the reverse reaction of the synthesis of the polymer.

Plastic Damage Atlas

A plastic damage atlas is currently under construction at RCE. This database will be part of the International Network for the Conservation of Contemporary Art database to facilitate the search for plastics, degradation phenomena, and contemporary art, artists, and artist interviews. Another plastic damage atlas has been constructed for the POPART project (Lavédrine et al., 2012).

APPENDIX B. PREPARATION OF SOLUTIONS

3% Stabilizer solution in isopropanol

The solution is prepared by dissolving 3 ml of Tinuvin B 75 in 97 mL of isopropanol.

5% Stabilizer plus consolidant mixture

For 200 mL of solution, the following mixing order should be followed to obtain a homogeneous solution:

1. Mix 10 mL of Tinuvin B 75 with 12.5 mL of isopropanol until the Tinuvin B 75 is dissolved.
2. Mix 50 mL of Impranil DLV with 12.5 mL of isopropanol.
3. Mix the two solutions and dilute carefully with 115 mL of demineralized water while stirring with a magnetic stirrer for several minutes.

10% Stabilizer plus consolidant mixture

For 200 mL of solution, the following mixing order should be followed to obtain a homogeneous solution:

1. Mix 20 mL of Tinuvin B 75 with 12.5 mL of isopropanol until the Tinuvin B 75 is dissolved.
2. Mix 50 mL of Impranil DLV with 12.5 mL of isopropanol.
3. Mix the two solutions and dilute carefully with 105 mL of demineralized water while stirring with a magnetic stirrer for several minutes.

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Engineered Self-Disassembly: A Plastic That Turns into Gravel

Molly McGath and Odile Madden*

ABSTRACT. Spontaneous fracturing of museum artifacts is undesirable. Historic injection-molded cellulose acetate artifacts have begun to disintegrate into small pieces after 60 years in museum collections. A compound mechanism of volatile component loss and recrystallization is suspected to contribute to the deterioration and is proposed as a potential pathway for volume reduction in plastic waste. These underlying mechanisms of deterioration that occur over decadal timescales may have applications for other industries, such as recycling and waste management. The critical components of the plastic are described, and methods for inducing self-disassembly over shorter timescales are proposed as seeds of inspiration for new plastic materials that can break down for disposal in either waste or recycling streams.

INTRODUCTION

In 2014, plastic solid waste (PSW) made up 12.9% of the total municipal solid waste stream, which measured 258 million tons, in the United States (U.S. Environmental Protection Agency, 2016).[1] Made predominately of carbon and other light elements, plastics have relatively low density, can be formed into a wide range of shapes and sizes, and lend themselves to objects with a high volume for their weight. Increasing stress on landfills and the desire to reduce fossil fuel use and increase recycling are motivators for improved methods to break plastic objects into smaller pieces (Hopewell et al, 2009).[2] Volume reduction allows for efficient transport and storage, both for landfill waste and for feedstock. Small, generally uniform shapes also facilitate effective combustion for energy recovery, as well as washing, recompounding, and extrusion steps in recycling.

Currently, volume reduction of plastic waste is accomplished by thermal and mechanical processes. Thermoplastic polymers can be softened with heat into more compact masses (United Nations Environment Programme, 2009). Granulators, shredders, guillotines, and grinders cut and mill plastic waste into pieces or finer powder (Biddle et al., 1999; Rapra Technology Ltd., 2002; Goodship, 2007). Some chemical alteration to the plastic is inevitable in this processing. Thermal effects, either by intentional heating of plastic to its softening temperature or by friction with mechanical cutting and grinding surfaces, can cause oxidation, volatilization, and rearrangement of molecules that can bring about branching, cross-linking, and an increase in molecular weight (Rapra Technology Ltd., 2002). Introduction of cutting fluids to cool mechanical cutting equipment would introduce the need for an extra decontamination step that may not clean the plastics completely of these fluids. Mechanical breakage of plastics tends to cleave polymer chains, which reduces molecular weight and changes the softening temperature and strength of the processed plastic (Rapra Technology Ltd., 2002). It also seems likely that friction with metal cutting and grinding surfaces introduces some metallic contamination

Museum Conservation Institute, Smithsonian Institution, 4210 Silver Hill Road, Suitland, Maryland 20746, USA.

* Correspondence: M. McGath, molybdenumart@gmail.com

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into the plastic scrap and that cutting surfaces become dull and require periodic sharpening, which incurs expense and temporarily halts work (Biddle et al., 1999).

It has been observed that some injection-molded cellulose acetate objects in museum collections spontaneously disintegrate into gravelly particles over decadal timescales (Tsang et al., 2009). The authors are studying the underlying mechanisms with the ultimate goal of avoiding this fate for other cultural heritage artifacts. We also recognize that what is catastrophic and irreparable damage in the museum could have value in contexts where a self-disassembling plastic is a desirable outcome.

Mechanisms that we believe contribute to the disintegration of a collection of World War II era injection-molded cellulose acetate artifacts could suggest new methods of volume reduction in waste plastics made of cellulose acetate or other polymers that might reduce heat-induced alteration and contamination from cutting processes and obviate certain equipment maintenance procedures such as sharpening. Here we offer a thought experiment of how this might be accomplished.

CELLULOSE ACETATE PLASTICS

Cellulose acetate is a polymer that was developed in the early twentieth century, reached the height of its popularity at midcentury, and now is a common material in museum collections. Often called a semisynthetic substance, cellulose acetate is manufactured by modifying natural cellulose polymer obtained from vegetal sources with acetic anhydride and sulfuric acid (Schilling et al., 2010), which creates a material that can be reformed with organic solvents and heat. Because the polymer's softening temperature range approaches and can overlap with the temperature at which it decomposes (Sata et al., 2004), external plasticizers often are added to create molding powders with lower, more reliable processing temperatures. The plasticizers also modify properties of the final product, for example, by improving impact resistance. Low-molecular-weight phthalates, including diethyl and dimethyl, have been popular, and many objects incorporate some proportion of triphenyl phosphate (TPP; Stannett, 1950; Sully, 1962).

By 1944, 309 million pounds of cellulose ester flake were produced, which was more than any other moldable polymer except phenolic resin. According to a bulletin from Arthur D. Little Inc., 66 million pounds of this flake were destined for molding powders, which represented 30% of the total molding powder produced (Sollenberger, 1945).[3] In the ensuing decades other polymers, such as acrylonitrile-butadiene-styrene (ABS), became more common for injection molding, although cellulose acetate, propionate, and butyrate esters have remained polymers of choice for certain items like eyeglass frames, screwdriver handles, and playing dice (Rustemeyer, 2004). Nearly 1.8 billion pounds of cellulose acetate were produced globally in 2008 and were destined for filter tow, textile threads, films, and molded plastic objects (Puls et al., 2010). Today, the polymer has the potential to increase its popularity as a renewable, plant-derived plastic that can be biodegraded under the right conditions (Puls et al., 2010; Laird, 2013; Solvay, 2013).

Cellulose acetate plastics are known to be unstable in the short and long term and degrade by multiple mechanisms (Wilson and Forshee, 1959; Edge et al., 1989). In the short term, cellulose acetate (CA) is vulnerable to damage by ultraviolet light and biodeterioration, and one can expect CA to break down quite quickly in the environment relative to many other synthetic polymers (Buchanan et al., 1993; Puls et al., 2010). For CA that is not discarded outdoors but rather is protected in an indoor environment, acetate side groups grafted onto the cellulose during production of the polymer slowly are released as acetic acid, which drops the pH of the material, cleaves the cellulose polymer chain, and gives off the notorious "vinegar" odor of the deteriorating material. Loss of volatile plasticizers further contributes to weight loss, shrinkage, and warping. More dramatic deterioration has been observed in a subclass of injection-molded CA plastics that contain diethyl phthalate (DEP) and TPP (Tsang et al., 2009). The authors have observed that this composition has a tendency to shrink more drastically and fracture spontaneously into many smaller pieces, whereas objects of the same shape without TPP do not (Tsang et al., 2009). This subset of deterioration sparked an idea for plastics that disassemble themselves and reduce their volume for waste and recycling.

Triphenyl phosphate is a white crystalline solid at room temperature and is soluble in a wide range of organic solvents. The compound has a long history as a plastic additive and first was patented as a plasticizer for cellulose nitrate in 1901 (Sachs and Byron, 1921). It later was incorporated into cellulose acetate plastics but was unpopular in some quarters because it had been found to crystallize in cellulose acetate lacquer and make the film more brittle (Hofmann and Reid, 1929). By 1950 it was recognized that the solubility of TPP in CA was enhanced with the addition of a coplasticizer such as dimethyl phthalate (Stannett, 1950). Triphenyl phosphate also can stabilize volatile plasticizers like dimethyl and diethyl phthalates, which are known to leave the plastic over time (Sully, 1962).

THE MECHANISM: OBSERVATIONS OF CULTURAL HERITAGE

Since 2007, the authors have examined more than 210 examples of three-dimensional injection-molded cellulose acetate artifacts in Smithsonian collections and conducted laboratory experiments on prepared facsimiles. A study of 49 coupons of Lumarith brand cellulose acetate plastic that make up a 1940s era salesman's sample kit was published in 2009 (Tsang, 2009). Forty-six coupons were in fine condition, but three exhibited extreme cracking and weighed 30% less despite having the same molded dimensions. All contained cellulose acetate and diethyl phthalate, but only the three deteriorated coupons also contained TPP. A collection of 160 World War II era aircraft recognition

models in the National Air and Space Museum collection is deteriorating similarly (Figure 1).

Although it is assumed that all of the models have a similar composition of cellulose acetate, TPP, and DEP (plus black pigment and some other compounds), around 20% currently exhibit visible deterioration. Degradation of the model planes appears to progress as shrinkage that brings about distortion, particularly of the airplane wings, and formation of cracks that progresses until the planes disintegrate into gravel, sometimes with sufficient force that fragments are launched across a distance of a few feet. The broken plastic is very brittle and riddled with jagged, angular, and conchoidal fractures.

FIGURE 1. Intact (top) and deteriorated (bottom) aircraft recognition models in the National Air and Space Museum collection, Smithsonian Institution. Photos by E. Keats Webb, National Air and Space Museum, top, and Odile Madden, Museum Conservation Institute, bottom.

We believe the mechanisms that distinguish this kind of deterioration are a combination of volatile component loss and recrystallization. Over many years, acetyl side groups hydrolyze from the polymer as acetic acid, cleave the cellulose chain, and diffuse out of the plastic along with volatile, low-molecular-weight phthalates. This weakens the plastic, causes it to shrink, and introduces internal stresses. The loss of phthalate plasticizer reduces the impact resistance of the plastic, which becomes more brittle. The resulting environment is less hospitable to TPP, which has lost much of its coplasticizer and is less soluble in the plastic. Ultimately, the TPP recrystallizes, and the force may shatter the embrittled, tensioned plastic. We also have evidence that solid particles within the plastic can act as nucleation sites from which the recrystallized TPP radiates.

Fragments of these shattered objects retain the original polymer, solid plasticizer (now in crystalline form), a reduced concentration of phthalate plasticizer, and the other additives. It is expected that the polymer has a lower degree of acetylation because of the loss of acetic acid evidenced by the vinegar odor and that fracturing has shortened the polymer chains such that there is a wider range of molecular weights. It also is possible that deacetylation brings about cross-linking and increased molecular weight or crystallinity.

Crystallization-induced degradation of porous materials is well known in architectural heritage and archaeological materials that contain soluble salts (Plenderleith, 1956; Paterakis, 1987; Cronyn, 1990; Scherer, 1999, Steiger et al., 2014). In porous materials (e.g., concrete, masonry, stone, ceramics, bones, teeth, and wood) that salts dissolved in water have penetrated, eventual evaporation of the moisture results in recrystallization of the salt, and the formation of this new phase exerts mechanical stresses on pore walls that can disrupt the material. This situation may be analogous to the authors' observations of cellulose acetate plastics. The volatile plasticizer and cellulose acetate hold TPP in solution, but the diffusion of volatile plasticizer and acetic acid out of the material weakens, stresses, and embrittles the plastic and ultimately brings about recrystallization of TPP, which helps break apart the plastic.

HARNESSING THE MECHANISM FOR RECYCLING AND WASTE MANAGEMENT

We envision that deteriorated cellulose acetate artifacts could be inspiration for an intentionally engineered self-disassembling plastic that is composed of one or more polymers, a volatile plasticizer, and a crystalline solid that is soluble in the polymer plus volatile plasticizer system but less soluble in the polymer alone. Incorporation of particles that can act as nucleation sites

for recrystallization also may be desirable. This discussion has focused on a specific polymer-plasticizer system, but the mechanisms conceivably could work with other polymers that require a volatile plasticizer for processing and impact resistance in the finished product. Plasticizers other than phthalates could be chosen that take into account properties like toxicity and environmental fate. Similarly, TPP has a relatively long history within the short timeline of plastics history but is only a potential first case for using recrystallization for size reduction in recycling and waste management.

Transferring this knowledge into a useful technology would have several challenges, the biggest of which is turning a process that has occurred naturally over a 60- to 70-year period into an industrially feasible activity. Unlike fine cheeses, wines, and scotch, for which aging increases the value of the product, plastic is famously inexpensive largely because of quick production cycles. Recycled material must be less expensive to compete with virgin feedstocks. Chasing off the volatile plasticizer more quickly with heat, rapid air exchange, and possibly solvation by plasma or high pressure potentially would speed this process. Because we believe formation of internal stresses is an important factor in disassembly, the process by which the volatile plasticizer is removed should not anneal the plastic and relieve its internal tension.

A controlled process could be engineered to favor loss of volatile plasticizer but inhibit deacetylation of the polymer. The volatile plasticizer could be collected, and if the goal is to create a recycled feedstock, it could be reincorporated into the disassembled plastic gravel prior to extrusion. A shock event might be included to initiate crystallization, and once recrystallization has occurred, the brittle fragments could be broken further by crushing.

CONCLUSIONS

The materials science of cultural heritage offers some unique perspectives that might not be obvious in the research and development phase of manufacturing. Aging behavior has long been a feature of R & D for new materials, but the time horizon is limited to the intended service life of the finished product, which is tied to the first failures of the material. However, once an object is accessioned into a museum collection, its service life is redefined as indefinite. Ideally, the object will be stored in an environment that favors preservation, with controlled light, temperature, humidity, air quality, and air exchange and where handling of the object is limited. This careful storage extends the life of plastics to timescales in which we witness types of deterioration never seen before. For some years we have mused that disintegrating cellulose acetate artifacts are a disaster in the museum context, but a plastic that eventually turns to gravel surely would intrigue people involved in recycling. We offer this paper as potential inspiration for incorporating solid plasticizers and other particles into materials that can undergo controlled deterioration and contribute to an economy of sustainable and recyclable plastics.

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NOTES

1. Municipal solid waste consists of the everyday items that are found in trash or garbage and excludes industrially produced wastes or wastes that come from construction, demolition, and municipal wastewater treatment sludge (U.S. Environmental Protection Agency, 2013).
2. For another perspective on recycling plastic, see Biddle (this volume).—Ed.
3. Although Sollenberger (1945) does not specify, the authors assume these values refer to plastic production in the United States.

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Midway: A Message from the North Pacific Gyre

Jan Vozenilek

ABSTRACT. The author's interest in photography and ecology serve as a brief introduction to a project he worked on from 2009 to 2012 in collaboration with artist Chris Jordan: a feature-length documentary film about the plight of the Laysan albatross on Midway Island. The film, along with a host of photographs, videos, and blogs produced during the project, was intended to raise awareness about the problem of the seabird's ingestion of plastic garbage. Indeed, awareness raising is necessary since the negative effects plastic pollution in the oceans has on marine life have been known for more than half a century, yet little has been done to mitigate the problem.

MY INVOLVEMENT IN ECOLOGY

I have always been an environmentalist. From an early age my parents instilled in me an appreciation and love for nature. From countless camping trips and hikes into the forests of former Czechoslovakia, where I grew up, to the coastal mountains of lush British Columbia, where we moved when I was 12, I loved going to such places to find serenity from the hustle and bustle of city life. To this day, when I lay under a tree listening to the birds and the trees swaying in the wind, this is where I am most at peace. This is what I love.

My father also had a lot to do with my second love: photography and filmmaking. During our childhood adventures in the woods, I would borrow his Praktika camera and snap shots of our holidays. Once, when I was nine, we stumbled across a film set for a local sci-fi TV show. But did I care about the famous actors? No. All I could do was ogle that film camera and its operator. I knew that would be me one day.

MIDWAY NATIONAL WILDLIFE REFUGE AND THE GREAT PACIFIC GARBAGE PATCH

Six years ago, I met Chris Jordan, a world-renowned photographer and cultural activist, at a conference. Five months later, we were on a 1962 Gulfstream 1 prop plane, taking a harrowing five-hour flight from Honolulu, headed west to the almost geographic center of the world's biggest ocean—a tiny atoll called Midway, a national wildlife refuge since 1988 (Figure 1). Our purpose for going was to document one of the world's most devastating and symbolic environmental tragedies: the deaths of tens of thousands of baby Laysan albatross (*Phoebastria immutabilis*) from the accidental ingestion of disposable plastic trash. It was the Great Pacific Garbage Patch that had drawn our attention to this phenomenon a few months earlier. We wanted to create a body of visual evidence to raise global awareness about this silent issue.

4273 Turner Road, Kelowna, British Columbia V1W 2N5, Canada.
Correspondence: J. Vozenilek, jan@coppersky productions.com
Manuscript received 19 August 2016; accepted 13 February 2017.

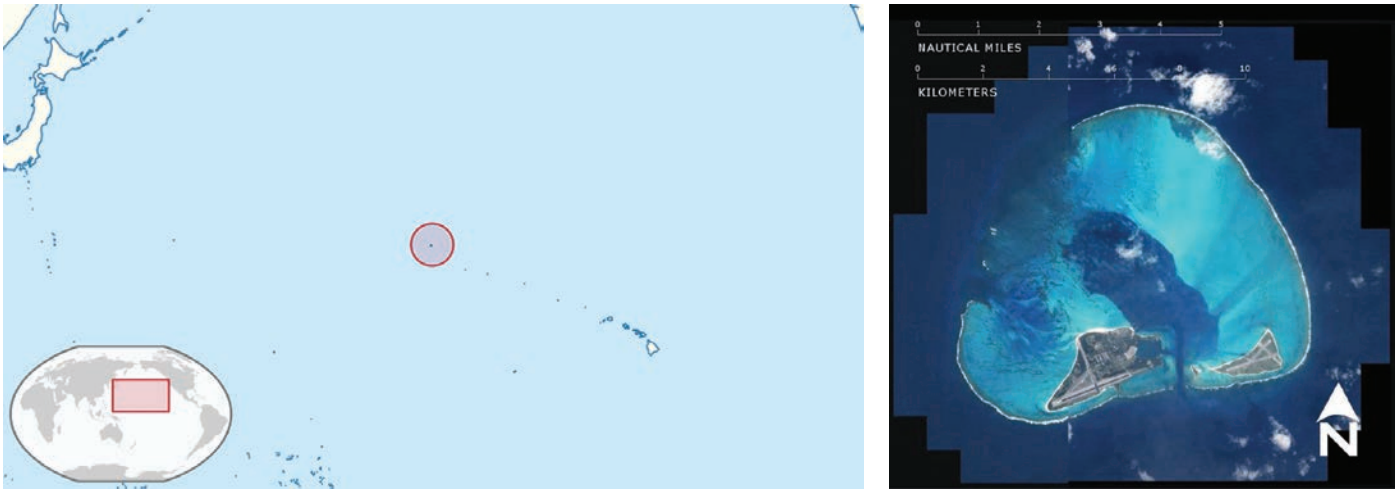

FIGURE 1. Left: Location of the Midway atoll, in the central north Pacific, northwest from Hawaii. Photo from Wikipedia Commons, http://wikitravel.org/en/File:Midway_Atoll_in_its_region.svg. Right: Satellite view of the atoll, comprising three main islands, generally referred to as Midway Island(s), a larger island that subsided, leaving only the higher areas above water level. Photo from the National Centers for Coastal Ocean Science, https://products.coastalscience.noaa.gov/collections/benthic/e98nwhi/midway.aspx.

We had learned that our oceans are filling up with so much plastic pollution that in some places, scientists find more plastic particles than plankton (Kayser, 2012), which is the basic building block of the ocean's food chain (see Wallace and Parker, this volume). We also learned that photographing and filming this kind of garbage patch was impossible because this marine pollution is diluted throughout the entire ocean and because a lot of the plastic is the size of fingernails or smaller (Aguilera, 2012). Yes, there are a few areas where smaller ocean gyres (Scripps Oceanography, 2010; Scripps Institution of Oceanography, 2014) and currents concentrate this material, but if one were to go there on a boat, at first glance, it would just look like the crystal-clear Pacific Ocean.

Only a few steps from where the plane landed on Midway, close to the breeding ground of the albatross (Figure 2), we saw the first albatross. It lay motionless, its bony remains and a few feathers still blowing in the wind, and directly in its center where its little stomach used to be were about two handfuls of bottle caps, cigarette lighters, and brightly colored plastic shards (Figure 3). We stood still in shock and in awe—we could not believe the amount of plastic inside that little body. It was truly hard to believe. What was even tougher was finding another one when we walked a few feet further, and a few steps away yet another. The island was covered with thousands of dead baby birds (Figure 4).

Witnessing this was life-changing for everyone on our team. Our cameras rolled and shutters snapped continuously for the full two weeks we were on the island. We wanted to document as much as we could so that people would get to know how the types of products we choose to use—from thousands of miles across the great ocean—can affect even the remotest of places. A place like Midway.

THE PROBLEM

Sea birds, including the albatross, do not differentiate between a piece of plastic, such as a bottle cap, or an equal-sized fish or squid. Thus, this mistaken identity leads to the tragedy (Laist, 1987). Whatever they find floating on the surface of the ocean, they assume might be food. Thus, they fill their bellies with both fish and plastic, one assumes proportionately to their presence near the surface of the sea, and fly back to Midway to feed their chicks. There they regurgitate this to their babies, who have been patiently waiting on their nests for their next meal (Figures 5 and 6). Whatever the parent feeds them, they trust is food. Unfortunately, a large percentage of what they are fed is plastic, most of it being the single-use items that we use every day. Thus, the babies slowly fill up with this material, and because they are too young to regurgitate it, their bellies eventually clog up, leading over time to their slow death, mostly by starvation, dehydration, choking, or the sharp shards of plastic puncturing their stomachs (J. Klavitter, U.S. Fish and Wildlife Service, personal communication).

I was struck hard by the juxtaposition of this tragic horror against the incredible abundant beauty of Midway. Only a few feet from one of these dead albatrosses, on a little tree branch, was a tiny white tern (*Gygis alba*) chick, sitting there quietly,

FIGURE 2. The nesting ground of the albatross on Midway Atoll. Photo by the author.

FIGURE 3. Body of a baby albatross showing the plastic objects collected in its stomach. Photo by the author.

FIGURE 4. Masses of dead young albatross covered the island. Photo by the author.

FIGURE 5. Albatross chick and its returning parent. Photo by the author.

FIGURE 6. Albatross feeding its chick. Photo by the author.

waiting for its parents to come back with the next meal (Figures 7 and 8).

These small birds are not as affected by the plastic presence because they eat smaller fish, and smaller plastic pieces do not seem to harm them the way larger ones do the albatross. Nonetheless, these smaller pieces, generally less than 1 cm in size, have the potential to transfer toxic chemicals, so-called persistent organic pollutants (POP) that certain plastics adsorb in the ocean (Andrady, 2011). Although these terns may not have the dramatic end of the albatross, they risk being slowly poisoned (Cole et al., 2011). However, we did witness the tiny pieces of plastic that wash up on Midway's beaches being eaten by small crabs (Midway Journey, 2009a) and the pieces floating on the surface of the ocean being skimmed off by a school of fish (Midway

FIGURE 7. A White tern chick waiting for its parents to come and feed it. Photo by the author.

FIGURE 8. White tern feeding its chick. Photo by the author.

Journey, 2009b). So this material and the POP it carries are being ingested by many forms of marine life. The Laysan albatross is just the most obvious and dramatic example.

RAISING AWARENESS

Although the Laysan albatross has been studied in particular (Auman et al., 1997; Safina, 2002), its plight on Midway Atoll was only slowly brought to public attention even though the changes on this island have been followed for years (Pala, 2012). Using social media tools like Facebook (Midway Film, 2012a), YouTube (Midway Journey, 2009a; Midway Journey 2009b), Twitter (Midway Film, 2012b) and Vimeo (Midway, 2011), we posted many short films of our findings right from the island. It was amazing to see the interest of viewers quickly grow.

The circle of life and death on this island goes round and round, as it does everywhere on our planet. But the thought that my personal habits contributed to these albatrosses dying, that those were, in fact, my bottle caps in their stomachs, and that symbolically, it was me who lay there was really overwhelming. We are slowly poisoning our oceans, the very foundation of life, where the world's biggest food supply comes from. Where do we go from here? What does it mean for the future of our planet that one of the remotest places on earth is suffering this way?

It was the late Raylene Ha'alelea Kawaiae'a, a Hawaiian elder, who gave me another perspective. We had the honor of spending time with her prior to our trip to Midway, and she suggested that we not consider the albatrosses as victims, but rather view them as paradigmatic heroes. A paradigm for all the other sea life endangered by plastics, ranging from planktivorous organisms (Boerger et al., 2010) through gastropods (Aloy et al. 2011) to sea turtles (Lazar and Gračan, 2011), dolphins (Denuncio et al., 2011), seabirds, including penguins (Brandão et al., 2011), and marine mammals that are more prone to plastic net entanglement (Laist, 1987). The albatross are trying to convey a message to us that we need to heed.

Over three years, Chris Jordan and I, along with our respective teams, visited Midway Atoll eight times and created a feature-length documentary film about this symbolic phenomenon. The film trailer (Jordan, 2012a) has had more than 17 million views on the website, and awareness campaigns spread around the world. More than 60 short films were created and made available on social media (Jordan, 2012b; Vozenilek, 2012).

CONCLUSION

Plastic pollution in seas and oceans is now ubiquitous and affects all of us, as clearly described by Freinkel (this volume). For the paradigmatic Laysan albatross, ingestion of plastic is *visible*, and images of their plight alert the world to this global problem. Perhaps these noble messengers also will raise awareness that the problem begins thousands of miles away when we allow huge numbers of plastic objects that we decided are disposable to end up in the ocean, as if there are no consequences. I use my camera to spread their message because awareness is crucial to finding a solution.

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Debris in the Marine Environment

Nancy Wallace and Dianna Parker*

ABSTRACT. Marine debris is a global problem, and it is an everyday problem. There is no part of the world that is untouched by debris and its impacts. It is pervasive, it is an eyesore, and it harms our natural resources. Marine debris is a threat to our environment, navigation safety, the economy, and human health. Most of all, marine debris is preventable. The National Oceanic and Atmospheric Administration (NOAA) Marine Debris Program leads national and international efforts to research, prevent, and reduce the impacts of marine debris. The program also spearheads national research efforts and works to change behavior in the public through outreach and education initiatives. Removing debris from the marine environment does not fully address the problem. More research is needed into debris and its impacts, including how plastics and the chemicals in them behave in the ocean. Prevention is also the key—individual responsibility must become a priority, and scientists, policy makers, and teachers must take action for the long-term health of our oceans.

INTRODUCTION

Ask anyone on the street to define "marine debris," and they will probably say that it means garbage in the ocean—the kind that swirls in great "garbage patches" such as that found in the Pacific Ocean. That is partly right, but the marine debris issue is much more complex.

Legally, marine debris is defined as "any persistent solid material that is manufactured or processed and directly or indirectly, intentionally or unintentionally, disposed of or abandoned into the marine environment or the Great Lakes" (Federal Register, 2009). That definition covers quite a bit: plastics, textiles, rubber, paper, glass, metals, and processed wood—the list goes on. Marine debris is anything from cigarette butts, plastic bottles, or other litter that makes its way from land into the marine environment to derelict fishing gear and abandoned vessels.

This debris is everywhere. It is on coastlines and in the water column; it is resting on reefs and seabeds and in the stomachs of wildlife. Marine debris is found near urban centers all over the globe and in remote, fragile places, such as the northwestern Hawaiian Islands. The National Oceanic and Atmospheric Administration (NOAA) removes about 52 metric tons of fishing nets from these islands each year, which is a massive amount of debris for an ecological paradise.

THE PROBLEM

Marine debris is an international, ongoing problem that impacts marine life, the economy, navigation safety, and human health. Fortunately, there is a growing movement across the globe to address it, from the highest levels of government down to concerned individuals who depend on the ocean for recreation and sustenance.

NOAA Marine Debris Program, 1305 East-West Highway, Room 10201, Silver Spring, Maryland 20910, USA.

* Correspondence: N. Wallace, nancy.wallace@noaa.gov

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In 2005 NOAA formed a Marine Debris Program to deal with this problem, when its Office of Response and Restoration received funds in its budget to address "Marine Debris." The next year, the late Sen. Daniel Inouye of Hawaii and Rep. Sam Farr of California introduced and helped pass the Marine Debris Research, Prevention, and Reduction Act, which officially established the program. The act sealed into law NOAA's responsibility to address marine debris and gave it a mandate "to reduce and prevent the occurrence and adverse impacts of marine debris on the marine environment and navigation safety" (Marine Debris Research and Reduction Act, 2006). Reducing and preventing the occurrence and impacts of debris has been no small task, given the scope of the problem, debris' pervasive nature, and the complexities of determining sources.

Debris experts typically lump marine debris sources into two categories, land based and ocean based, but the line is blurry. There is no way to tell whether a plastic fork in the Caribbean Sea came from a storm drain in Miami or whether it was tossed overboard from a fishing vessel near Brazil. Marine debris moves with currents and can travel long distances, making it virtually impossible to trace.

Plastics, besides being a blot on the marine environment, can break down into smaller pieces called "microplastics" when they are exposed to the elements over long periods of time. Birds, fish, and marine mammals can mistake these plastic bits for plankton or other prey. They eat them, but they can't digest them.

Crab pots and lost fishing nets can scour, break, smother, or otherwise damage important coral reefs, sea grass, and other sensitive areas as they drift with currents. Many of these habitats serve as the basis of marine ecosystems, and they are critical to the survival of many species. Nets and pots indiscriminately tangle and kill countless marine mammals, seabirds, fish, and invertebrates.

It is also an economic problem. Coastal communities often assume the burden of cleaning up debris that washes up on their shorelines every year, even with tight budgets. Fishing gear can "ghost fish" for years after it is lost or abandoned, depleting fisheries, reducing abundance or reproductive capacity of the stock, and causing untold economic losses for fishermen. Between 2008 and 2012, the Virginia Institute of Marine Sciences pulled nearly 40,000 derelict pots from the Chesapeake Bay, which contained more than 30,000 animals, including commercially viable blue crabs (Center for Coastal Resources Management, 2013),

FINDING A SOLUTION

Because of these compelling impacts, the NOAA Marine Debris Program is moving on a comprehensive path forward for addressing debris that includes removal, research, reduction, and prevention activities. Each year, the program supports some efforts to remove debris from U.S. coastal waters and shorelines through local projects in order to mitigate immediate impacts. However, removal is not the ultimate solution. It is a temporary fix for a persistent problem that will continue unless we tackle it from all angles. That is why the program also places great emphasis on science and finding ways to head off debris at its source: us.

Prevention is the key. The NOAA Marine Debris Program's outreach and education initiatives focus on raising awareness in different communities about their choices. The three R's—reduce, reuse, and recycle—are a timeless and important message, as is "don't litter." Our outreach also extends to the fishing industry and working with fishermen on finding responsible ways to dispose of gear at the end of its life.

Marine debris is a relatively new field of research, and there are many opportunities to advance our understanding of debris' impact. The National Oceanic and Atmospheric Administration is pursuing studies that will help us understand how fast debris degrades and whether or not plastics leach chemicals while in the marine environment. Are these chemicals affecting birds and fish that eat the plastic, and does that affect us in turn? We are also exploring the economic impact. Exactly how much does it cost coastal communities to clean up litter every year? Are there overlooked, indirect costs, such as hits to tourism?

Having answers to these questions and sound data about debris, its source, and impacts will help us prioritize removal and prevention activities. What's more, it will help us tell the whole story to the public—and help us measure the success of our efforts. The full extent of the damage marine debris is doing to our oceans needs to be part of the conversation, so that we can encourage behavior and policies that prevent debris in the first place.

The marine debris problem did not happen overnight, and it will take time to solve this very public, global issue. We need everyone, including scientists, policy makers, and teachers, to make marine debris a priority and take action for the long-term health of our oceans.

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Closing the Loop with Plastics

Mike Biddle

ABSTRACT. Plastics have become ubiquitous because they are such a versatile material. They are easily formed into about any shape, and there are many types and grades of plastics with very different properties, which can be easily tailored to meet a wide variety of specific end use requirements. Furthermore, unlike steel or wood, plastics usually do not have to be painted or coated to change their color or protect them from the elements. Their low density offers important light-weighting benefits in a wide variety of products. Most plastics are derived from petrochemicals and natural gas. Ever more remote locations and drilling ever deeper wells are needed to extract these limited resources. These practices have significant economic and environmental implications that are already evident today. The recycling of plastics can save as much as 90% of the energy of making plastics using traditional chemical synthesis and polymerization routes and can save between 1 and 4 tons of CO_2 per ton of virgin plastics replaced. But recycling plastics is more complicated and difficult compared to recycling metals, posing both technical and economic challenges. After decades of research and mostly small-scale commercial undertakings, solutions to these difficult challenges have begun to emerge in several locations around the world and demonstrate how societies can finally realize the consequent environmental and economic benefits of recovering this valuable resource and keeping it from polluting our environment.

MORE PLASTIC THAN STEEL

Most of us come into contact with plastics in the majority of the products we touch every day without realizing it. Plastics have become so ubiquitous because they are such a versatile material. They are easily formed into about any shape, and there are many types and grades of plastics with very different properties. And even these properties are easily tailored to meet a wide variety of specific end use requirements. Furthermore, unlike steel or wood, for example, plastics usually do not have to be painted or coated to change their color or protect them from the elements. Plastics also have a low density and thus offer important light-weighting benefits in a wide variety of products.

By virtue of some of the properties noted above and other factors, plastics also provide economic and environmental benefits not provided by other materials. For example, many other materials consume considerable energy and generate commensurate CO_2 emissions in their extraction, refinement, and manufacturing into shapes. Plastics Europe (2011) points out that "plastics are the true resource champions by saving more resources than they use, i.e., 'more means less'. For example, substituting plastics with alternative materials would result in a 46% increase in energy consumption, a 46% increase in CO_2 emissions and generate 100 million tons more of waste every year across the EU."

Because of these benefits, worldwide production of plastics has averaged an impressive 6% annual growth rate since 1970 (European Plastic Converters, 2009). In comparison, the average growth rate of steel since 1970 has been about 2%. Although the weight of steel consumed worldwide is greater than that of plastics, if one divides each by its approximate specific gravity of about 8 for steel and 1 for plastics, the volume of plastics produced and consumed every year worldwide is actually greater than that of

MBA Polymers, Inc., 610 Castle Rock Road, Walnut Creek, California 94598, USA.
Correspondence: M. Biddle, mike@evokinnovations.com
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steel, or about 260 billion liters of plastics in 2007 compared to about 168 billion liters for steel (Plastics Europe Market Research Group, 2007).

"In NAFTA and Europe, the annual per capita consumption of plastics is about 100 kg and is expected to reach as high as 140 kg/person by 2015. In the rapidly developing Asia region (excluding Japan), the per capita consumption is approximately 20 kg and this is expected to grow dramatically, which suggests that the worldwide consumption of plastics will likewise grow rapidly given the large population in this region" (Hieronymi et al., 2012:92). Even assuming a lower 4% average annual growth rate, the amount of plastics consumed in the world will grow dramatically in the next few decades.

PLASTIC'S LOW RECYCLE RATES COMPARED TO THAT OF OTHER MATERIALS

Decades ago, it became clear that extracting metals from ever wider, deeper, and more remote mines around the world was not sustainable and that reusing metals via recycling made a lot of sense. As such, the recycle rates for most metals are well over 50%. For example, about 60% of the steel used in the United States is made from electric arc furnaces that predominantly use recycled sources of material. U.S. recyclers processed over 74 million metric tons of iron and steel in 2010 (Institute of Scrap Recycling Industries, 2011).

Most plastics are derived from petrochemicals and natural gas. The world goes to ever more remote locations and drills ever deeper wells to extract these limited resources. These practices have significant economic and environmental implications that we are already seeing today.

The recycling of plastics can save as much as 90% of the energy used in making by traditional chemical synthesis and polymerization routes (Hutchison, 2008; Hopewell et al., 2009). Looking at it another way, the International Association of Plastics Distribution (IAPD) reports that recycling a single one-gallon plastic milk jug saves enough energy to power a 100-W lightbulb for over 11 hours (IAPD, 2017).

Mechanical recycling can also use less water and generate considerably fewer greenhouse gases than making plastics from chemical routes. For example, between 1 and 4 metric tons of CO_2 per metric ton of plastic can be saved by using recycled plastics in place of traditional virgin plastics (Hieronymi et al., 2012; Wäger and Hischier, 2015).

However, we recycle only a very small fraction of the plastics compared to that produced each year. Europe probably has the best record of any region for plastics recycling. In 2012, Europe recycled about 6.6 million metric tons of plastics. This amount represents about 26% of the plastics that were estimated to be collected, or less than 15% of the plastic consumed in Europe (see slide 10 in Plastics Europe Market Research Group, 2007). In the United States, the recycle rates are generally lower. The U.S. Environmental Protection Agency (2015:8) estimated that about 9% of the plastics waste generated was recycled in the United States in 2013.

Much of what is collected in both Europe and the United States and counted as recycling is simply baled and shipped to overseas traders, who often move it on to "informal recyclers" who lack the knowledge or the resources to recycle the materials in ways that protect the workers and local ecosystems. These recyclers are able to recycle only the plastics that can be easily sorted by humans or simple sink-float approaches, so much of the plastic is not recovered, and the actual recycling rates can therefore be considerably lower than reported.

Many believe that the recycle rate for plastics is low because they are a "throw-away material" with very little value. Actually, plastics are several times more valuable than steel on a price per weight basis.

WHY DOES SUCH A VALUABLE MATERIAL HAVE SUCH A LOW RECYCLING RATE?

Metals can be separated from other materials and from one another with straightforward available technology. Metals and most other materials have very different densities from one another (Figure 1). They have different electrical and magnetic properties, and they even have different colors. Therefore, humans and machines can exploit a variety of different properties and techniques to separate metals from one another and from other materials.

Plastics, in contrast, have overlapping densities over a very narrow range. They have very similar electrical and magnetic properties, and any plastic can be any color. So the traditional ways of separating materials simply do not work for plastics.

Because plastics are so plentiful and valuable, a growing number of people are trying to recycle this material, particularly in developing countries where virgin plastics are relatively expensive. Figure 2 shows just one example of a photo taken in one of the largest slums in the world in Mumbai, India.

These recyclers store waste plastics on the roofs (Figure 3) and eventually bring them into small workshops where people try to separate the plastics by color, shape, feel, or any other property they believe will differentiate the many different types and grades of plastics (Figure 4). Sometimes they resort to what is known as the "burn and sniff" technique in which they burn the plastic and smell the fumes and pull at molten plastic fragments to try to determine the type of plastic, as shown in Figures 5–8. While many of the recycling practices taking place in developing countries put the health of workers and local ecosystems as risk, most of these recyclers care about the environment and certainly their health.

Recently, trade magazines and national news agencies have also discovered that recycling of plastics done improperly can result in risks to human health and local ecosystems (Minter, 2009; Peng, 2011). Furthermore, these techniques seldom result

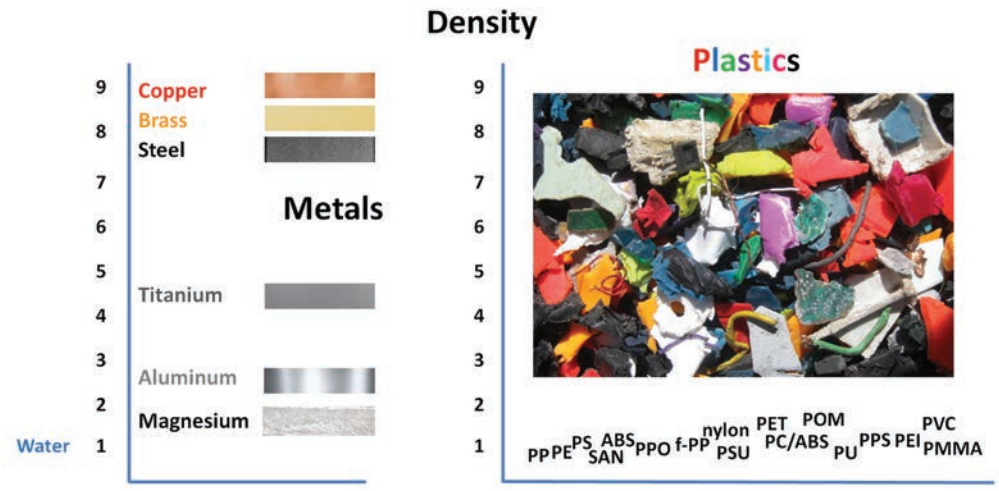


FIGURE 1. Density and color differences between metals and plastics.

FIGURE 2. Plastic waste stored on rooftops of slums before being processed by hand, Dharavi, Mumbai, India, 2007. Photo by the author.

FIGURE 3. Plastics stored on roofs awaiting to be sorted out, Dharavi, Mumbai, India, 2007. Photo by the author.

in any significant amount of recycling because of the lack of scale and the typical low and inconsistent quality of the products. Although sending waste to developing countries might be the low-cost solution, it is certainly not the low environmental or human health and safety cost solution. This practice should be called environmental arbitrage. It's not fair, it's not safe, and it's not sustainable.

Figures 2–8 and the abovementioned reports show what can happen to the plastics that are not recycled or incinerated. Some end up littering the countryside or in streams that eventually feed into our oceans, which can lead to dire consequences for sea life. A number of organizations have started to make people aware of how discarded plastics, much of which floats in water, find their way into local streams that eventually lead out to sea. The Ocean Recovery Alliance (2011), for example, has even created a program called the Global Alert that enables people to "See, Share and Solve their floating trash problems."

Sometimes the plastics that humans are unable to sort is intentionally dumped into streams and rivers because they are continuously "self-cleaning." These informal recyclers often do

FIGURE 4. Top: Workshop in an Indian slum where plastics are hand sorted by shape, color, feel—a far from perfect separation but sometimes good enough to sort low-quality materials. Bottom: Detail of the sorted plastic, Dharavi, Mumbai, India, 2007. Photos by the author.

FIGURE 5. Burn (top) and sniff (bottom) technique by a plastics recycler and broker in Ningbo, China, 2002. Photos by the author.

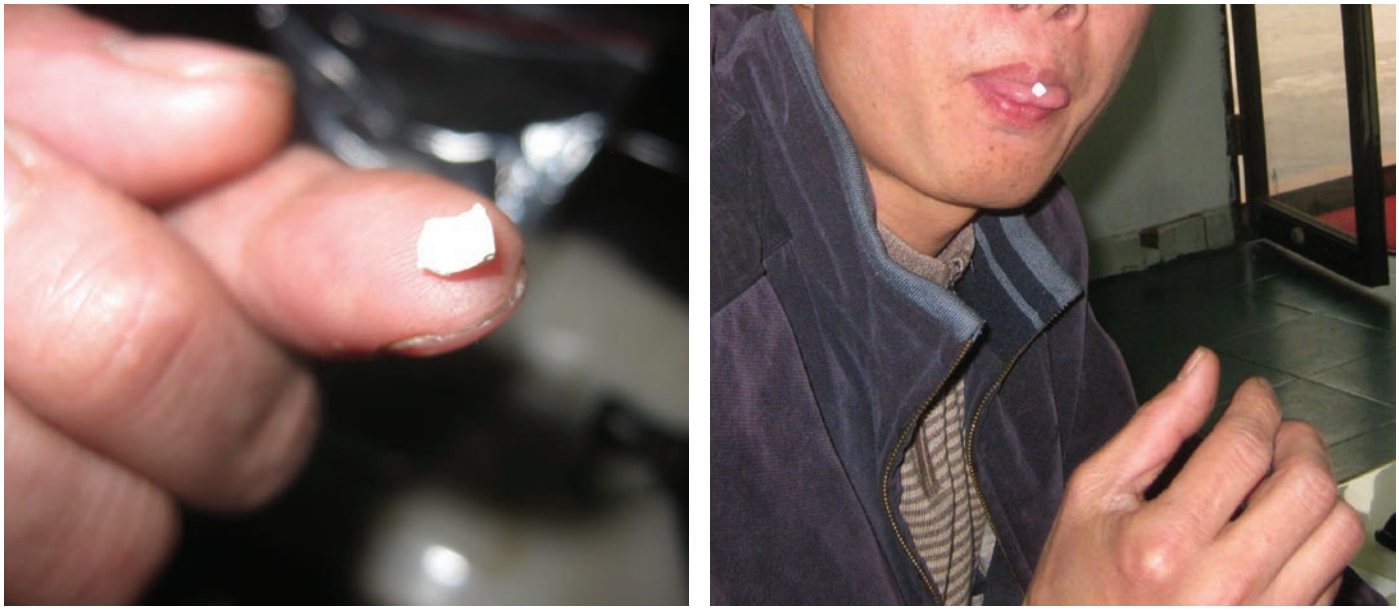
not have access to disposal alternatives and are also trying to save costs of disposing of the plastics responsibly so they can compete with the hundreds of other informal recyclers. The dramatic impact of these practices was documented by filmmaker Wang Juliang, who directed a film called *Plastic China* (Asia Society, 20164).

In summary, beyond the significant economic and local ecosystem benefits, recovering plastics responsibly is important to the health of people, our global ecosystem, and our seas.

WHAT CAN BE DONE TO RECYCLE MORE PLASTICS IN RESPONSIBLE WAYS?

Until recently, one of the primary reasons that plastics were not being recycled at scales similar to metals was a lack of

FIGURE 6. Left: Pulling a strand of the molten plastic to determine its "quality." Right: If it pulls before breaking, it is considered "good quality." Shunde, China, 2012. Photos by author.



IGURE 7. A piece of a bitten off plastic (left) and a Chinese recycler tasting the plastic pellets to determine type and quality (right), Shunde, China, 2012. Photos by the author.

available, economic, and robust automatic separation and purification technologies. Fortunately, this situation changed rather quickly, and plastics can now be recovered from a growing number of waste streams (La Mantia, 2002; Goodship, 2007; Hieronymi et al., 2012). One step in the recycling process is to break the plastic to be recycled into smaller pieces, and a new way to accomplish this is discussed by McGath and Madden (this volume).

I personally took on this problem in my garage in 1992 and founded a company now called MBA Polymers. MBA Polymers sorts and recycle plastics from diverse waste streams and produces a recycled plastic feedstock that other companies purchase and make into new electronics, appliances, consumer goods, and even automotive products (Biddle et al., 1999). An overview of our process was presented in a TED Talk in 2011 (Biddle, 2011)

FIGURE 8. Burn and sniff technique practiced by a recycler/broker in Dharavi, Mumbai, India, 2007. Photo by the author.

and in two documentaries, one carried as part of the Big SHFT project, which highlights 10 innovators changing the world, and another by CNN (CNN, 2014).

Achieving plastics recycling on a large scale and in a commercially attractive manner requires the application and integration of many different types of technologies sometimes adapted from other industries and sometimes developed for this specific purpose. The wide-ranging technologies that are being used to tackle the many challenges of recovering value from complex mixed waste streams is discussed in a dedicated chapter on closing the loop with plastics in the book *E-Waste Management: From Waste to Resource* (Hieronymi et al., 2012). In short, the classes of steps usually follow these categories, with multiple technologies being used in each category and categories/technologies repeated as necessary to achieve the high purities required to be able to reuse these materials in demanding applications.

Plastics recyclers are also taking business model lessons from other more recycled materials such as steel (Biddle, 2015). It took steel recycling a number of decades to achieve the big three commercial requirements—purity, consistency, and volumes—necessary to move from low-value reinforcing bar (rebar) into more demanding applications like automobiles, construction, etc. As noted above, the majority of the U.S. steel demand is provided by recycled steel today.

So if technology and business practices to recover plastics from waste streams are becoming more well known and demonstrated, then why aren't more plastics being recycled? The primary reason has to do with the "first mile problem." An analogy might be useful here. That most people don't have access to extremely high speed Internet in their homes is often referred to the "last mile problem." Getting technology to population centers is not so difficult, but delivering it to every single household becomes extremely expensive. For recycling, it is just the opposite. The most expensive part of any recycling system is getting the "waste" (or raw materials) from each and every household in ways that makes it accessible for recycling.

The first evolution of plastics recycling technology focused on the items that were easy for machines and humans to recognize and sort, which was predominantly polyethylene terephthalate (PET) and high-density polyethylene (HDPE) bottles. The waste and recycling collection schemes relied on consumers to deliver their "recyclables" to a recycling center or, if part of a curbside collection program, to provide some level of sorting of their garbage.

In recent years, with the advances in automated sorting technologies augmented by hand sorting, more communities have moved to either single-bin collection or "single-stream" mixed recyclables collection processed at materials recovery facilities because it is less expensive (and more environmentally friendly) to pick up one or two different bins from each household than to make several trips to pick up different bins or use compartmentalized trucks in which one compartment always fills first, leaving the truck capacity underutilized for each trip.

But because the embedded sorting systems at most recycling centers in the developed world still focus on bottles and mostly PET and HDPE, the rest of the collected plastics are mostly incinerated, landfilled, or traded to recyclers in the developing world, often with the consequences discussed above. Two things need to happen for the recycling rate of plastics to take the next leap forward and for it to be treated in safe and efficient manners: (1) investments need to be made in automated separation technologies, and (2) developed countries need to stop exporting their "recyclables" to the developing world unless they can be sure that these materials will be handled in a responsible manner.

The second step not only protects people and the local ecosystems, it provides a level playing field that will allow recyclers to make the needed large investments in plant and equipment to recycle the materials safely. Therefore, the second step not only enables the first but also encourages it.

Consumers have increased their awareness and concerns for how their products are made. Why do we not have similar concerns for how the materials from our end-of-life products are recovered, especially when material processing can be riskier than product manufacturing if not done in a responsible manner? The answer is most people still largely view their end-of-life stuff as "garbage" rather than as valuable resources.

Manufacturers will be consuming ever more resources to meet the demand from the expected 3 billion new middle class consumers around the world, and many leading business strategy consultants point to the need for a revolution in the way we think about consuming, conserving, and recycling resources (Dobbs et al., 2012). Communities have responded by increasing the amount of materials they collect for recycling, helping to solve the first mile problem.

In summary, commercial-scale processing of mixed plastics streams has now been demonstrated. It is now up to communities

to demand responsible management of their waste streams because it is now clear that shipping mixed waste to processors ill equipped to process it has significant negative consequences.

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Falling in and out of Love: Our Troubled Affair with Plastic

Susan Freinkel

ABSTRACT. Plastic is the defining medium of modern life, touching all aspects of the way we live from clothes to cars, homes to hospitals, toys to technology. Yet its ascendance is recent, dating only to the late nineteenth century. This chapter traces the rise of plastics, from the early commercially produced plastics such as celluloid and Bakelite to modern commodity plastics such as polyethylene, polystyrene, and polyvinyl chloride. The early plastics held appeal as materials that promised to preserve scarce resources, democratize consumer goods, and improve standards of living. World War II transformed the industry, sparking a rise in production that continues to the present day. But proliferation, particularly of single-use disposable products, which are now half of all plastics production, has tainted the materials' reputation. Today, significant problems are associated with dependence on plastic, including pollution, exposure to hazardous chemicals such as phthalates and bisphenol A, and lack of recycling. The metaphor of a love affair gone wrong is a useful one for describing the arc of our relationship with plastics—from infatuation to disenchantment to unhealthy dependence.

INTRODUCTION

When a French-American salvage expedition discovered the wreck of the *Titanic*, they found a treasure trove of early twentieth-century life. There were jeweled necklaces and rings, silver pocket watches, gold pince-nez spectacles, and leather goods. But what most impressed one member of the expedition was that in all those everyday items, there was not a single thing made of plastic. "That, if nothing else, shows how much times have changed," he said at a press conference (Fenichell, 1996:4).

Of course, any modern ship that went down today would not only be filled with plastic objects; chances are the vessel itself would be mostly plastic. Just as the *Titanic* has become one of our defining metaphors, so has plastic. More than that, plastic is the defining medium of life today—touching every aspect of our lives: our homes, our workplaces, the ways we dress, eat, play, and transport ourselves.

The extent to which plastic pervades modern life became clear to me when I tried to go an entire day without touching anything plastic. The futility of this experiment became apparent about 10 seconds into the appointed morning when I shuffled bleary-eyed into the bathroom. The toilet seat was plastic, as was the sink, my toothbrush, the toothpaste tube. I quickly revised my plan. I would spend the day writing down everything I touched that was plastic. By the end of the day I had an enormous list comprising things that looked and felt very different and that seemingly touched every aspect of my life. Here's a brief sample:

> Pencil case; trash bag; glasses frame; glasses case; cell phone; patio chair; rayon; ball point pen; bubble wrap; underwear, bra; yogurt tub; steering wheel; brush; backpack; stove knobs; flip-flops; bike helmet; balloon; twist tie; lunch case;

1291 29th Avenue, San Francisco, California 94122, USA.
Correspondence: S. Freinkel, susanfreinkel@gmail.com
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> Tupperware; tail light; hair band; barrette; dental floss; chewing gum; candy wrapper; thermos; travel mug; car seat; golf ball; bike lock; garden hose; compact disc; contact lens; carpet; DVDs; audio tape; scotch tape; keyboard; printer; telephone; radio; doll; Legos; chair; binder; computer mouse; mouse pad; lotion bottle; lipstick tube; underwear; bra; spandex; acrylic nails; comb; bungee cord; Velcro; recycling bin; seat belt; Tencel; pantyhose; six-pack ring; take-out clamshell; syringe; detergent bottle; extension cords. (Freinkel, 2011:2)

What happened between the sinking of the *Titanic* and my failed day without plastic? How did plastic become so utterly ubiquitous in fewer than 100 years? How has that change transformed both the planet and us?

One way to think about our history with plastic is as a long love affair gone wrong. At first, we were enthralled and rushed headlong to embrace synthetics. Over time, we became disenchanted and yet continued to deepen our involvement. Today, we are completely reliant on plastic even as we recognize that aspects of that dependence are not healthy for the environment or us. Such unhealthy dependence is the classic definition of a dysfunctional relationship. But it's not an irreparable relationship. In fact, it has to be fixed because plastics are going to be more, not less, important to the future.

HISTORIC OVERVIEW

Humans have been using natural plastics such as rubber, amber, and horn for millennia. But the creation and commercialization of man-made plastics dates only to the mid-nineteenth century. Victorians were growing restless with the existing palette of materials (Friedel, 1983), frustrated by the physical limitations of traditional materials such as metal, glass, and wood and also increasingly aware that many natural materials were starting to be in short supply. One of the biggest sources of worry was ivory. Ivory was then being widely used for an array of everyday conveniences—buttonhooks, cane heads, handles, trays, combs, piano keys, and especially billiard balls. At least 1 million pounds of ivory were being consumed each year, prompting fears of an impending shortage (*New York Times*, 1867:2). In 1863, so the story goes, a New York billiards supplier ran a newspaper ad offering $10,000 to anyone who could come up with a suitable alternative (Fenichell, 1996:39). That ad caught the eye of an amateur inventor in Albany, New York, named John Wesley Hyatt.

He spent several years tinkering with the natural polymer, cellulose. Eventually, he found a way to combine it with alcohol and camphor to create a malleable substance with the consistency of shoe leather; he called it celluloid. This invention was the start of the romance because here was a wholly new material with life-changing possibilities.

Celluloid had amazing properties. It was waterproof and oilproof. It was malleable but could harden into a fixed shape. One of its most winning features was its capacity for imitation: it could be made to look like any number of natural materials, including luxurious substances such as ivory and tortoiseshell. Celluloid made possible "counterfeits" so exact that they deceived "even the eye of the expert," Hyatt's company proclaimed in one pamphlet (Meikle, 1997:15). It "has given the elephant, the tortoise, and the coral insect a respite in their native haunts; and it will no longer be necessary to ransack the earth in pursuit of substances which are constantly growing scarcer," another brochure touted (Meikle, 1997:12). Today, plastic is often portrayed as a threat and menace to nature, but Hyatt's creation was seen as a valuable savior of the natural world. Unfortunately, it wouldn't replace ivory billiard balls, in part because it was highly volatile. The first balls Hyatt made produced a loud report, like the crack of a shotgun, when they knocked into each other. One Colorado saloonkeeper wrote Hyatt that "he didn't mind, but every time the balls collided, every man in the room pulled a gun" (Fenichell, 1996:41).

Celluloid was also important because it could be mass manufactured, albeit in a much slower, more labor intensive process than later plastics. Now things that had once been luxury items were affordable for common folks. As Hyatt's company boasted, a "few dollars invested in Celluloid" equaled "hundreds expended in the purchase of genuine products of nature" (Meikle, 1997:15). Combs, a common celluloid product, exemplified the effect. With celluloid, anyone could afford a comb and brush set that looked as if it were carved from finest ivory; any shop girl or secretary could pin up her hair with exquisite decorative combs that looked like tortoiseshell. As historian Jeffrey Meikle notes, "By replacing materials that were hard to find or expensive to process, celluloid democratized a host of goods for an expanding consumption-oriented middle class" (Meikle, 1997:14). Like other plastics that followed, celluloid leveled the playing field for consumption.

One of the next significant breakthroughs came in 1907 when Belgian émigré Leo Baekeland created the first fully synthetic molecule—a substance that he dubbed Bakelite. Like Hyatt, Baekeland was seeking a substitute for a scarce natural material: shellac, which is made from the sticky secretions of the lac beetle (*Laccifer lacca*). Demand for shellac had begun to skyrocket because the country was in the midst of electrifying, and shellac, it turned out, was a fabulous electrical insulator. Trouble was, it takes 15,000 beetles six months to make enough of the resin needed for a pound of shellac (Fenichell, 1996:87). To keep up with the rapid expansion of the electrical industry, clearly something new was needed (Fenichell, 1996:87). The answer Baekeland cooked up in his homemade lab was a material so unlike any other that the company advertised it as representative of the new "fourth kingdom," (as in animal, mineral, and vegetable).

Although Baekeland's goal was a new electrical insulator, Bakelite was soon deployed for many more uses, from industrial gears and bushings to jewelry, telephones, ashtrays, radios, and even billiard balls. Its market impact was even stronger than

that of celluloid. Bakelite served as "a mechanical multiplier" capable of making the comforts of the rich available to everyone, one contemporary admirer wrote. It exemplified how synthetic chemistry would deliver "democratic luxury" to middle-class life (Meikle, 1997:70).

Whereas celluloid allowed us to emulate nature, Bakelite became the medium for an entirely new aesthetic, one that celebrated the modern, man-made world. This tough, durable, dark plastic spoke "in the vernacular of the twentieth century . . . the language of invention, of synthesis," wrote furniture designer Paul Frankl (Meikle, 1997:108). Bakelite also introduced designers to how freeing synthetic materials could be. Plastics, *New York Times* art critic Hilton Kramer later wrote, were "the answer to an artist's dream"—an "entire family of materials that can be made to assume virtually any size, shape, form, or color the mind of man may conceive" (Kramer, 1968:D39).

Hyatt and Baekeland were lone entrepreneurs, trying to solve a specific problem. But by the 1910s, major petroleum and chemical companies had begun to get into the plastics business. Companies such as Dow, DuPont, Industrial Chemical Industries, and I.G. Farben recognized that there might be a use for the vast amounts of waste and by-products, such as ethylene, generated in the processes of oil refining or manufacturing chemicals. And they had whole departments of industrial chemists working with these by-products or doing basic research to create new molecules for which new markets and products would have to be found. The result was a burst of polymer innovation; indeed, many of the major commodity plastics we know today—polyethylene, polystyrene, polyvinyl chloride, nylon, acrylic—were developed in the 1920s and 1930s.

Some were accidental discoveries. Polyethylene, for instance, was the product of a lab accident; a reactor vessel leaked, and the chemists found a white waxy substance at the bottom that was "so unlike the polymers known at the time . . . no one could envisage a use for it," one of the researchers recalled (Meikle, 1997:189). It was the same story with Teflon—at first no one knew what to do with this super slippery new material that seemed impervious to acids, solvents, or other damaging agents (Fenichell, 1996:221).

DuPont, on the other hand, knew exactly what it was after when it developed nylon. The world had been searching for an alternative to silk for a long time, so headlines crowed the news when DuPont announced it had achieved that breakthrough. The company worked that excitement masterfully. It unveiled the first nylons at the 1939 World's Fair, but then waited a year before releasing them for sale and then only in limited supplies at a select group of stores. On the first day, nylon stockings went on sale, May 15, 1940, women thronged the hosiery counters, and in some cities there were actual nylon riots (Fenichell, 1996:145–149).

Nylon was not the only polymer to inspire such admiration. Cellophane was another: Cole Porter sang its praises, and people told pollsters they considered *cellophane* the third most beautiful word in the English language, behind *mother* and *memory* (Nunberg, 2004:4–5). The love affair with plastics was heating up. In his book *American Plastic,* historian Jeffrey Meikle describes the utopian promise some saw in plastics. Nowhere was this clearer than in the vision laid out by two British chemists writing just before the outbreak of World War II:

> Let us try to imagine a dweller in the "Plastic Age." This "Plastic Man" will come into a world of colour and bright shining surfaces, where childish hands find nothing to break, no sharp edges or corners to cut or graze, no crevices to harbor dirt or germs. . . . It is a world free from moth and rust and full of color . . . a world in which man, like a magician, makes what he wants for almost every need. (Yarsley and Couzens, 1941:154–158)

Much of this excitement was anticipatory, because in actuality there was still relatively little plastic in most people's daily lives. And with the outbreak of World War II, that would remain the case. The military monopolized many of the newly developed plastics, pressing the still nascent industry to supply substitutes for strategic materials such as rubber, brass, steel, and silk. Plastics were used for parachutes, aircraft components, antenna housing, bazooka barrels, enclosures for gun turrets, helmet liners, bugles, whistles, and countless other applications. The industry's first million-dollar order was for a mortar fuse (DuBois, 1972:198). Polyethylene found a place during the war when it was discovered the polymer had the capacity to shield high frequencies and high voltages. The British took advantage of that property to build the first airborne radar systems, which gave them a critical advantage over German fighter planes since the Germans did not have polyethylene (Fenichell, 1996:201–202). Teflon was also pressed into wartime service when scientists realized its power to withstand the most corrosive substances because that power could be useful for handling the volatile gasses used to develop the atomic bomb (Emsley, 1998:133).

As so often happens in wartime, the romance deepened. Newspapers and magazines described plastic's heroic performance on the battlefield, and those feats became selling points after the war. The war not only showed what plastics could do; it helped build the industry. Production nearly quadrupled from 213 million pounds in 1939 to 818 million pounds in 1945 (Meikle, 1997:125). This huge production capacity coupled with nearly two decades of pent-up consumer demand meant that once the war ended, plastics exploded into consumer markets. Production skyrocketed on the order of 400% to 500% in the decade after the war and continued to steadily rise for the next 60 years, with just one minor bump in 2008, when the global markets crashed. As one plastics executive recalled, in 1946, "virtually nothing was made of plastic and anything could be" (Meikle, 1997:180).

Just months after the war's end, the industry held its first national tradeshow. Some 87,000 people lined up for blocks in midtown Manhattan to see the new kinds of products made possible by the plastics that had proven themselves in the war. For

a public weary of two decades of scarcity, the show offered an exciting and glittering preview of the promise of polymers. There were window screens in every color of the rainbow that would never need to be painted; suitcases light enough to lift with a finger, but strong enough to carry a man; clothing that could be wiped clean with a damp cloth; fishing line as strong as steel; clear packaging materials that would allow a shopper to see if the food inside was fresh; flowers that looked like they had been carved from glass (*New York Times*, 1946:31). Here was the era of plenty that the hopeful British chemists had envisioned.

At first, the main markets for plastics were in durable goods: appliances, electronics, household furnishings, textiles, and cars. Toys were a major market thanks to the baby boom and the sheer low-cost availability of some of the new plastics. In the early 1950s, for instance, eight different chemical companies quickly built factories to start producing polyethylene, widely viewed as the most promising of the new plastics. Prices plunged to less than a dime a pound. The low cost stimulated scores of new applications; these absorbed supplies of the plastic and in turn stimulated more production. Suddenly, toy stores filled with a host of new cheap toys, like dime-store cowboy and Indian sets or snap-together Pop beads (which at one point were absorbing 40,000 pounds of polyethylene a month; Freinkel, 2011:57).

THE TURNING POINT

At a certain point it became clear that there were only so many cars and refrigerators and stereos people would buy, and the industry began casting about for other markets to expand. One obvious answer was disposables. As an industry executive told attendees at a 1957 conference, "Your future is in the garbage wagon" (*Modern Plastics*, 1957:93).

Soon all those durable long-lasting materials developed for the hardships of war were being turned to ephemeral conveniences of peace. The vinyl-based compound Saran, which had proved so useful in protecting military cargo, was redeployed to the short-term protection of leftovers, and polyethylene's extraordinary capacity to insulate high frequencies was sidelined for a new career bagging up sandwiches and dry cleaning. Styrofoam, once used for lifeboats, now was deployed for cups and coolers (Freinkel, 2011:121).

Initially, such products were a tough sell. The ethos of reuse was so deeply ingrained that when vending machines began dispensing coffee in plastic cups in the mid-1950s, people at first tended to save and reuse them (*Modern Plastics*, 1957:96). They would have to learn—and be taught—to throw away.

The lesson was quickly absorbed, driven home by an ever-expanding array of new disposable products from lobster bibs to diapers (which some pundits suggested were responsible for the rise in postwar birth rates), pens, razors, and lighters. *Life* magazine celebrated what it dubbed "Throwaway Living" with a photo that showed a young couple and child with their arms raised in exultation amidst a downpour of disposable items: plates, cutlery, bags, ashtrays, dog dishes, pails, barbecue grills, and more. Cleaning them once would have taken 40 hours, *Life* calculated, but now "no housewife need bother." No wonder the young mom looked so happy (*Life*, 1955; Freinkel, 2011:121)!

Plastics did not create the throwaway lifestyle. There were a lot of cultural and economic forces behind it: the rise of suburbia, the development of self-serve grocery stores and fast food restaurants, and women's entry into the workforce. The building of the interstate highway system was a major factor in the death of refillable beverage containers because bottlers no longer were limited to regional distribution networks (Ackerman, 1997:124–135).

Plastic may not have been responsible for the shift to throwaways, but because they are lightweight, versatile, malleable, and cheap, they helped facilitate it, especially as we got better and better at making polymers do exactly what we need them to do. For instance, disposable bottles arrived when in 1973 Nathaniel Wyeth, brother of artist Andrew Wyeth and a chemical engineer, found a way to harness explosively carbonated beverages in a polyethylene terephthalate (PET) bottle. Soon PET bottles were being made by the billions, and more than 200 billion were sold in 2010 (Container Recycling Institute, 2013).

THE PROBLEM

As we have grown increasingly addicted to the convenience of disposables, the amount of plastics dedicated to one-time uses has steadily risen. Today, half of all plastic produced goes into single-use applications (Hopewell et al., 2009), and about a third of that is for packaging (American Chemistry Council Plastics Industry Producers' Statistics Group, 2012).

This is where the romance began to go seriously astray. Plastic's role in throwaway living is arguably partly why the word *plastic* started to take on pejorative meanings in the 1960s. Its widespread use for throwaways and low-value goods encourages people to look at plastics as worthless junk when they are actually valuable concoctions of hydrocarbons that were hundreds of millions of years in the making and excavated from the earth at great effort and cost.

Plastic's reputation is not helped by taking molecules engineered for long life and durability and putting them into products destined for the briefest of uses, such as coffee cups and plastic bags. Often as not, these become prefab litter because we have made few provisions for recapturing those single-use items at the end of their useful lives. Nearly all plastic *can* be recycled, but less than 10% actually is recycled—a lower rate than glass, paper, or metals (U.S. Environmental Protection Agency, 2011). The rest is either landfilled—an incredible waste of precious hydrocarbons—or it ends up in the environment, where it can persist for decades or longer.

All too often plastic litter winds up in the ocean, the downhill of everywhere and the terminus of all inland waterways (Andrady, 2003; Thompson et al., 2004). Plastic debris is now found on beaches around the world in even the most remote places. British biologist David Barnes described his crew going ashore on a tiny outcropping deep in the Antarctic Ocean, aptly called Inaccessible Island, and finding fishing buoys, plastic bottles, and disposable lighters (David Barnes, British Antarctic Survey, personal communication). Each of the five major oceans is now host to a "garbage patch," an area where plastic debris collects, trapped by the currents. The largest and best known, deep in the north Pacific, collects plastic trash from both North America and Asia. According to a recent study the debris there has grown 100-fold since the early 1970s, and the proliferation of all that plastic may be altering the pelagic ecology by expanding the available habitat of sea insects that lay their eggs on flotsam (Goldstein et al., 2012).

There is no question: plastic pollution in the ocean poses a risk to marine wildlife. Consider the case of the Laysan albatross, a bird that nests on Midway Atoll and forages for food in stretches of open ocean including the area of the north Pacific garbage patch. The birds mistake floating debris for food and over the last several decades have increasingly been returning to Midway with bottle caps, lighters, toothbrushes, broken pieces of plastic, and other trash that they feed to their young (Auman et al., 1997; Vozelinek, this volume; Wallace and Parker, this volume). Wildlife biologists on Midway now estimate that almost all of the 1.2 million albatrosses on the atoll have some quantity of plastic in their guts (John Klavitter, U.S. Fish and Wildlife Service, personal communication). And the albatrosses are not alone: more than 260 species of animals have been documented to have been killed or injured by plastic debris, including nearly all sea turtles and almost half of sea birds and marine mammals (Derraik, 2002).

But there is another danger to marine debris as well. Plastic does not biodegrade in the ocean—it photodegrades, typically into tiny fragments. Researchers have found those fragments absorb toxins already present in seawater, such as polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane (DDT), and other persistent organic pollutants (Ogata et al., 2009). Fish at the bottom of the marine food chain, such as the deep-sea lantern fishes (Myctophidae) and others that live on plankton, can ingest these tiny poisonous bits. In one recent study, some 9% of these mesopelagic fish sampled had plastic in their stomachs (Davison and Asch, 2011). Researchers are now investigating whether the toxins contained in those plastics are sorbing into the fish's tissue; in other words, whether the toxins can enter the food chain and wind up on our dinner plates.

The billions of pounds of plastic in the oceans cannot be easily cleaned up. Although it is possible to collect large pieces of debris, such as ghost nets, and recycle them into diesel fuel, there is no feasible way to gather the blizzard of plastic confetti suffusing the water column in the North Pacific garbage patch (Laist, 1997). The only solution is preventing litter at the source, which means resolving the end-of-life issues for plastic: creating better infrastructures for collecting, reusing, and recycling used plastics.

The other problem that is becoming clear about our dependence on plastics is the fact that many are made with or contain hazardous chemicals. As biomonitoring studies are finding, chemicals contained in plastic products or packaging are winding up in us (Koch and Calafat, 2009; Muncke, 2011). Most Americans now harbor traces of plasticizers, bisphenol A, flame retardants, Teflon, and other industrial chemicals.

What are the risks? It is difficult to know for sure because we cannot do controlled experiments with people. But animal studies and epidemiological studies suggest that there is cause to be concerned about some of our chemical exposures. Bisphenol A (BPA), which is used to harden polycarbonate plastic and for the epoxy that lines food and beverage cans, was invented as a synthetic estrogen and seems to mimic estrogen in the body. Researchers have found associations between low-level exposures to BPA and heart disease, diabetes, breast and prostate cancer, behavioral issues, and other disorders (Vom Saal and Hughes, 2005; Vandenberg et al., 2012; Vogel, 2012). Phthalates, a widely used family of chemicals, are another source of concern, especially di(2-ethyl-hexyl) phthalate (DEHP), which is used as a plasticizer to make vinyl flexible and soft and found in such common products as blood bags, flips flops, garden hoses, flooring, shower curtains, and toys. Studies suggest it can interfere with testosterone and have found associations between DEHP exposure and changes in the male reproductive system, impaired sperm quality, thyroid dysfunction, and behavioral issues (Swan, 2008; Meeker, 2009; Freinkel, 2011).

These chemicals do not work like classic toxins where the poison is in the dose. They act more like hormones, interfering with the endocrine system, the network of glands that govern growth and development. There is increasing evidence that they may therefore have significant impacts at very low doses, depending on when someone was exposed. During certain critical windows of development, very tiny amounts of a compound like BPA may have very big impacts that do not show up for years (Vandenberg et al., 2012).

We have reached a crossroads in our long marriage to plastics. We have produced nearly as much in the first decade of this century as in the entire twentieth century (Thompson et al., 2009), and all signs suggest production will only continue to grow. The boom in shale oil gas is triggering new investments in the American plastics industry; experts predict a 25% increase in production of polyethylene, the most commonly used plastic (Howard Rappaport, HIS Chemical, personal communication). Experts also envision rising plastics consumption in China, India, Africa, and other parts of the developing world, which to date have lagged far behind the United States and Europe (Freinkel, 2011:69), yet at the same time, we are seeing more clearly than ever that there are serious downsides and dangers to our dependence on these materials.

OUR FUTURE

Divorce is not an option. Even if it were possible, it would not be desirable. We need synthetic materials to feed, clothe, house, heal, and sustain a population of 7 billion people and growing. Medicine would grind to a halt without plastic, as would our efforts to develop more fuel-efficient cars and planes. Plastics are critical in harnessing solar power and other renewable forms of energy. These lightweight materials are essential for protecting, preserving, and transporting food in a global supply chain, especially in an era when carbon calculations are a primary consideration.

The issue is not the material. It is what we do with it, the ways we produce, use, and discard plastics. And that has to change. We need to wean ourselves from the casual single-use habit and deploy green chemistry techniques to make polymers we know will be safe for our health and the environment. We need to build end-of-life considerations into the design of polymers and plastic products. We need to develop a recycling and composting infrastructure to deal with plastics at the end of their useful lives. And over the long term we will have to shift from fossil fuels as a basis for plastics. Currently, about 4% of global oil and gas supplies are used as feedstocks for plastics, and another 4% are used in energy to actually produce them (Andrady and Neal, 2009).

Already, there is a vigorous movement to create plastics from various renewable sources, including food crops such as corn and sugar cane, nonfood crops such as switchgrass and algae, bacteria, and waste from both agriculture and human activity. Although bioplastics currently make up only about 1% of all plastic production, the field is expected to grow at double-digit rates in coming years (Ramani Narayan, Michigan State University, personal communication; Freinkel, 2011:208).

Yet bioplastics will be no panacea for our plastic woes unless they are developed with a more holistic, cradle-to-cradle approach. A biodegradable trash bag made from corn plastic is no great bonus without a composting facility where it can be taken to biodegrade. Otherwise, it goes to a landfill where it can be more of a problem than conventional petrobased plastic: a recent study suggested biodegradable plastics breaking down in landfill could generate methane, an even more potent greenhouse gas than carbon dioxide (Levis and Barlaz, 2011). Bioplastics are certainly the future of our ongoing love affair with plastic, but unless we approach them with greater awareness and foresight than in the past, it will be as problematic a relationship as the one we currently have.

So far, I have been using the metaphor of a love affair to describe our relationship with plastic. But there is another way to think about it: Plastic is us; we are plastic. We have created these materials. They comprise our material reality, and they have, in turn, shaped us. Plastics reflect and tap into both our best and worst impulses. Depending on how we go forward into the age of plastic, it could be an era that reflects carelessness, greed, and shortsighted thinking. Or it could reflect our ingenuity, wisdom, and willingness to safeguard the planet for future generations.

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