EcoWorx, Green Engineering Principles in Practice

JEFFERY W. SEGARS,[†]
STEVEN L. BRADFIELD,*,[‡]
JEFFERY J. WRIGHT,[†] AND
MATTHEW J. REALFF[§]

Shaw Industries, P.O. Box 429, Cartersville, Georgia 30120, Shaw Industries, P.O. Drawer 2128, Dalton, Georgia 30722-2128, and School of Chemical & Biomolecular Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332-0100

The 12 Principles of Green Engineering have been proposed as a framework within which to examine existing products and guide their redesign as well as to evaluate new product designs. The EcoWorx system represents a recyclable carpet tile product that is assessed using the 12 Principles of Green Engineering and cradle-to-cradle design principles to evaluate environmental, qualitative, and economic performance as compared to existing Shaw carpet tile products. The product design strategy embodies life cycle considerations of a cradle-to-cradle product that puts technical nutrient recovered materials into repeated use. EcoWorx offers a unique opportunity for Shaw to utilize the 12 Principles to analyze and optimize new products and processes for the additional capacity needed to meet rising demand for sustainable carpet products. The analysis of the EcoWorx system demonstrated the value of the 12 Principles in verifying and formalizing the experience and intuition of product designers. This suggests that the mistrial and error reliance on experience could be enhanced with this formalized approach and hence lead to more widespread success of design practices that result in sustainable products.

Introduction

The objective of this paper is to evaluate the redesign of a major industrial product system, a carpet tile, to assess its environmental, qualitative, and economic performance using two similar conceptions of sustainable design and manufacturing—cradle-to-cradle (C2C) design and the 12 Principles of Green Engineering (see encapsulated description in Table 1) (*1*). Thus, the 12 principles were not used in the design of the product, nor are all of them relevant to the product and the design goals. The purpose of this paper is to illustrate that the outcomes of a business engineering decision-making process guided by experience and intuition ultimately led to results that are congruent with the 12 Principles and C2C design philosophy. This both validates the 12 Principles and bolsters the case for EcoWorx as a environmentally benign product system. Therefore, the framework of the principles could be of significant practical value in guiding future decision-making and may enable further improvements in the EcoWorx product.

Carpet tile is a particular product category that bridges almost all commercial market segments. The product has been in the market for over 30 yr in the United States. It was originally introduced as a functional carpet innovation sold on its ability to replace stained or damaged tiles, to rotate tiles in areas of high wear, and to provide easy access to flat-wire cable installed under the carpet tile. Carpet tile's higher cost, engineered construction using high mass and embodied energy, and rapid market growth made it the most logical place for the carpet industry to begin exploring issues of re-engineering.

Two innovations in the modern office environment fueled the growth of carpet tiles as a flooring system, modular office furniture and raised access flooring. Both require modular floor coverings to utilize their respective advantages. Modular office furniture, or "workstations", can be installed over any type of flooring or carpet. When carpet replacement is necessary, the modular furniture must be disassembled, removed, and reinstalled if typical broadloom carpeting is used. However, carpet tile used as a replacement floor covering can avoid removing the modular furniture at all. The furniture is simply lifted with a proprietary jacking system, and the end-of life (EOL) carpet is cut away and removed. New tiles are then installed under a section of workstations, and the furniture is lowered to its original location.

These "lift systems" are in common use today in open plan office environments. If properly scheduled, little to no disruption of the workplace is experienced. The modular concept was also reinforced by the adoption of raised access floors, which are used in many of today's commercial buildings. Most commercial buildings have concrete floors. Raised access floors allow power, voice, and data cables as well as HVAC ducting to be located under a precision-leveled raised floor panel system 6−18 in. above the concrete floor of the building. The panels are modular and usually 24 in. square. Raised floor panels covered with releasable carpet tiles allow access to the subfloor space with minimal disruption to surrounding operations.

Carpet tile is the fastest growing product category in the commercial carpet market. This growth is expected to continue in the future, displacing some of the broadloom roll carpet historically used in office environments. Development of sustainable carpet tile systems, in keeping with the 12 Principles of Green Engineering, offers a unique opportunity to take advantage of an industry presently adding capacity to meet future needs, but the market has little or no tolerance for an increase in price, loss of performance, or loss of product diversity, even if there are environmental benefits.

A typical carpet tile is comprised of two main elements, the face and the backing. In carpet tile, the backing represents a much more significant investment in materials, engineering, and performance than backings related to typical broadloom carpeting. In the past, U.S. carpet tile has been manufactured primarily with PVC plastisol backing systems. More recently, thermoset polyurethane-cushioned backing systems have made modest inroads. The properties of the yarn, predominantly made of nylon, determine the overall look and feel of the carpet face. The backing provides the tile's mechanical properties and its adhesive compatibility. For example,

* Corresponding author phone: (706)275-3269; e-mail: steve.bradfield@shawinc.com.
[†] Shaw Industries, Cartersville, GA.
[‡] Shaw Industries, Dalton, GA.
[§] Georgia Institute of Technology.

10.1021/es034576a CCC: $25.00

Published on Web 11/07/2003

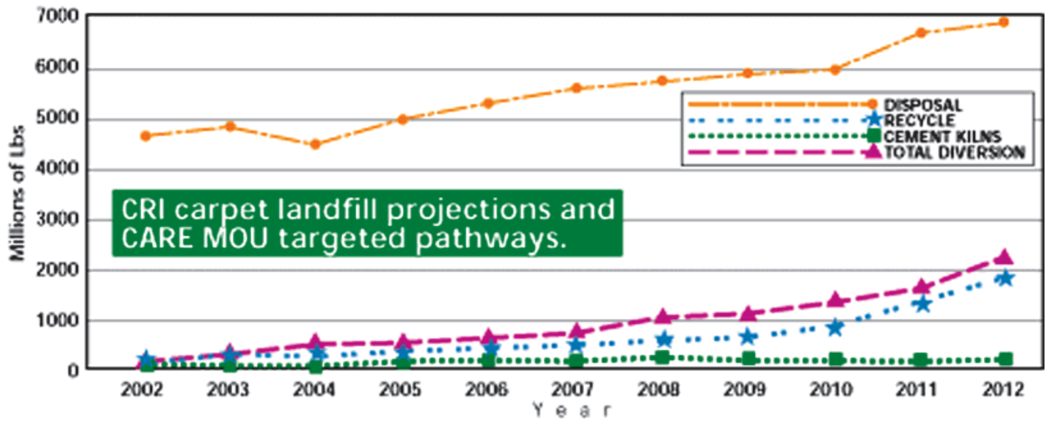

FIGURE 1. CRI carpet landfill projections and CARE MOU targeted pathways.

specific floor preparation and adhesives must be used with PVC plastisol backing due to the potential for plasticizer migration, with resulting product failure.

Carpet face weights have steadily declined over the past decade as improvements in tufting technology and design trends have evolved. Nylon is the single most valuable component in most carpets. Moderate reductions in nylon face weights have not lessened performance and offer greater economy in keeping carpet prices competitive. The current average carpet tile face weight has not reduced the recovery value of the nylon component at the end of the carpet's useful life cycle. Nylon 6 and 6.6 are the only viable nylon fiber types in commercial carpet today. Fibers from bio-based raw materials are being explored and tested now, but flammability and durability issues exist today. These fibers and natural fibers will have difficulty finding a place in the market until development of bio-based backings allow 100% bio-based carpet products.

The backing provides functions that are subject to engineering specifications, such as dimensional stability, compatibility with floor adhesives, and locking the face fibers in place. Currently available alternative coating systems and raw materials have allowed for systematic green re-engineering of the backing system to meet these specifications. Analysis under the 12 Principles aided in its refinement. Thermoplastic polymers show great promise for this role due to their ease of processing and recycling. Most desired is a thermoplastic that is compatible with nylon 6 recycling through chemical recovery of the monomer. Nylon 6 chemical recovery capacities are currently constrained, offering all the more reason to encourage the use of thermoplastic backing materials that will provide incentive to build additional capacity. Thermoset backings systems are problematic because they are not easily recycled and are sometimes used in noncarpet products or, more commonly, landfilled or incinerated.

Several EOL solutions for carpet tile sustainability are already offered in the market and continue to be developed. None of these current product systems significantly reduce the 4.6 billion lb of all carpet types going to U.S. landfills annually. More significantly, unlike the Shaw EcoWorx system described herein, none of these product solutions offers the possibility of adaptation to all types of carpet that consume landfill space. Undoubtedly, new solutions will be offered soon, but by 2013 landfilling of carpet waste will exceed 6 billion lb/yr if left unchecked.

To address landfill consumption and to stimulate market solutions for carpet recycling, a new initiative has been started between the carpet industry and several U.S. states. As shown in Figure 1, unchecked carpet disposal and targets for recovery agreed in the Carpet America Recovery Effort (CARE) memorandum of understanding (MOU) with various Federal and State agencies are reported. Noncarpet uses of carpet waste are being explored by the nonprofit CARE organization (www.carpet-recovery.org). Commitment to the 12 Principles would be a positive step in guiding the development of those noncarpet recycled content products. Individual industry stakeholders such as Shaw find value in the 12 Principles and continue to fund internal research, but those efforts are unlikely to move into the public eye unless commercialized.

EcoWorx Carpet Tile System Overview

The EcoWorx system developed by Shaw Industries offers a way to analyze and refine the cradle-to-cradle (C2C) (*2*) design of a carpet tile system without regard to technology constraints of the past. In this paper, the 12 Principles of Green Engineering and C2C provide a detailed framework in which to evaluate a new technology for engineering a successful carpet tile production, use, and recovery system. Shaw continues to make a PVC plastisol backing known as PermaBac, which had been Shaw's standard since 1990. Since the 1999 introduction of EcoWorx, PermaBac sales have steadily decreased while Shaw's carpet tile production has grown at a double-digit pace. Continued production of two noncushioned carpet tile backings at Shaw that perform the same function is unnecessarily complex and is not in keeping with Principle 8. If current market trends continue, Shaw may exit the PVC plastisol backing process within 24 months. Only capacity constraints imposed by the unanticipated pace of growth in EcoWorx prevent a more rapid transition.

In 1996, Shaw began an research and development effort that resulted in a significant departure from the materials traditionally used for carpet backing. Realizing the potential value that metallocene-catalyzed polyolefins might offer as a replacement for PVC, Shaw re-engineered its carpet backing. The flexibility of the metallocene polyolefin compound enabled the company to replace the PVC plastisol used in Shaw's PermaBac carpet tile. The EcoWorx system makes it possible to recycle both the face and the backing components into the next generation of face and backing components, respectively, for future generations of EcoWorx carpet tile. Compared to conventional PermaBac PVC plastisol-backed carpet tile, the weight of EcoWorx carpet tile has been reduced by 40%, leading to savings in all phases of the product life cycle.

The EcoWorx system also utilizes Shaw's EcoSolution Q nylon 6 premium branded fiber system, which is designed to use recycled nylon 6, and currently embodies 25% post-industrial recycled content in its makeup. The minimum 25% recycled content claim is being validated by a third party, McDonough Braungart Design Chemistry (MBDC). The EcoSolution Q nylon 6 branded fiber system can be recycled as a technical nutrient (*2*) through a reciprocal recovery

TABLE 1. 12 Principles of Green Engineering from ref *1*

Principle 1	designers need to strive to ensure that all material and energy inputs and outputs are as inherently nonhazardous as possible
Principle 2	it is better to prevent waste than to treat or clean up waste after it is formed
Principle 3	separation and purification operations should be designed to minimize energy consumption and materials used
Principle 4	products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency
Principle 5	products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials
Principle 6	embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition
Principle 7	targeted durability, not immortality, should be a design goal
Principle 8	design for unnecessary capacity or capability (e.g., one size fits all) solutions should be considered a design flaw
Principle 9	material diversity in multicomponent products should be minimized to promote disassembly and value retention
Principle 10	design of products, processes, and systems must include integration and interconnectivity with available energy and material flows
Principle 11	products, processes, and systems should be designed for performance in a commercial "afterlife"
Principle 12	material and energy inputs should be renewable rather than depleting

agreement with Honeywell's Arnprior depolymerization facility in Canada without sacrificing performance or quality or increasing cost. This allows Shaw's carpet tile products to make a C2C return to manufacturing, with backing and fiber from EOL tile made into more backing and fiber. This design is unique in the carpet industry and was recently recognized by the US EPA. EcoWorx received the 2003 Presidential Green Chemistry Challenge award in the Designing Safer Chemicals Category.

Using the 12 Principles and C2C Design To Evaluate the EcoWorx Tile System

The 12 Principles of Green Engineering (see Table 1), referenced in the article by Anastas and Zimmerman (*1*), focus on sustainable development through the use of a framework that scientists and engineers can use in designing new materials, products, processes, and systems. The 12 Principles demonstrate a move beyond the traditional paradigms of quality, safety, and performance to consider environmental, economic, and social factors. They are offered as principles, rather than recommendations, because they may be applied universally to the design of organic biological and chemical systems on a molecular level, as well as to the design of large-scale industrial technical systems, such as automobiles and buildings. Shaw found them very useful in the evaluation and optimization of a recently designed carpet tile system. Ideally, they should be integrated into any design project from the start but may also be important in analyzing current products and processes claiming sustainable "green" design. Wide acceptance could help to establish the 12 Principles as a universal standard for evaluating such claims in a balanced and equitable manner.

The 12 Principles are useful in delineating frame conditions and design parameters at the earliest stages of design. They are often interdependent, as optimization of any single attribute may have a profound effect upon another. Fundamental considerations are life cycle data and inherently safe raw materials. The 12 Principles seek to strike a balance between numerous green attributes to provide an optimized system solution within the framework of the original design assumptions. In this sense, the 12 Principles can provide a blueprint for green design based on the conditions and technology that may be brought to bear at a given point in time. This implies a commitment to continuously reassess the underlying design assumptions as technology and other relevant conditions move an optimal design solution in the direction of greater sustainability. With this in mind, it is easy to see how the concepts of C2C design described below provide complimentary tools and methods to the green engineering process embodied in the 12 Principles.

C2C design, in combination with the 12 Principles, demands three outcomes from the design process: human and ecological health and safety, lower embodied energy at source, and a value recovery system to return technical nutrients to the manufacturing stream. C2C design is an integration of how materials are created and how they flow through industrial and natural systems. Just as in the natural world, in which one organism's "waste" cycles through an ecosystem to provide nourishment for other living things, C2C materials circulate in closed-loop cycles, providing nutrients for nature or industry. The C2C model recognizes two metabolisms within which materials flow as healthy nutrients. Nature's nutrient cycles comprise the biological metabolism. Materials designed to flow optimally in the biological metabolism, known in the C2C model as biological nutrients, can be safely returned to the environment after use to nourish living systems. The technical metabolism, designed to mirror the earth's C2C cycles, is a closed-loop system in which valuable, high-tech synthetic and mineral resources—technical nutrients—circulate in a closed cycle of production, recovery, and remanufacture.

The C2C assessment process begins with an inventory of all chemical inputs present in a given material at the 100 ppm level or higher. Once all of the chemical inputs have been identified, each chemical is then screened against 20 human and environmental health criteria to identify any potential hazards. The result of this screening is a color-coded "profile" for each specific chemical. This chemical profile is then evaluated in the context of its use in the specific material under review. It is at this stage that all potential hazards identified in the profiling stage are evaluated for their relevance at the material level. Thus, the material assessment reflects any hazards identified at the chemical level that are deemed to be relevant to that material in its intended use in the finished product.

Physical and Chemical Description of the EcoWorx System

This new product design utilizes a homogeneously branched linear ethylene polymer as the base resin for a carpet backing. This material is compounded with performance additives using a twin-screw extruder. The compound is then sent through a single screw extruder and a 6 ft wide coat hanger sheet die, where the sheet is cast directly on the back of tufted carpet and is pressed by a nip roller against a chilled drum. Extruding a sheet of plastic onto the back of carpet is not challenging, but getting the proper chemistry has been the limiting factor. Dow Chemical has provided the new metallocene-catalyzed polyolefin base polymer for all the required performance characteristics specified by Shaw. Additional compounding is performed at the Shaw manufacturing facility in a proprietary process that completes the material design for carpet tile use.

The compounded backing must have good adhesion properties, where the tenacity of the carpet bond to the backing is referred to as delamination strength. Carpets with adequate delamination strength exhibit good wear resistance and provide long service lives. In addition to adhesion strength, the backing must impart good flexibility to the carpet for ease of installation. The backing must also be dimensionally stable to lay flat against the subfloor and not grow or shrink. To meet this specification the backing usually includes a woven or nonwoven scrim; in the case of the current embodiment of EcoWorx a nonwoven fiberglass mat is used. More details on the chemistry and raw material choices will be described in the individual discussion of the principles that follows. Some processing details have been discussed in general terms due to trade secret protection in Shaw's ongoing manufacturing development program (*3*).

Safety of EcoWorx and EcoSoultion Q materials is being addressed by MBDC's materials protocol assessment, and optimization of all inputs is nearing completion at Shaw. Embodied energy improvements will be assessed by a newly designed embodied energy study but relies today on the theoretical calculations of the design phase that rest primarily on mass reduction through the second life cycle. The recovery system was considered from the outset of the design and currently operates at an appropriate scale for post-industrial and post-consumer technical nutrient recovery. Recovery system components have been designed to expand as the material return rate accelerates, but adequate capacity is now in place for EcoWorx system compliance with FTC rules regarding environmental product claims.

Application of the 12 Principles of Green Engineering to EcoWorx

Principle 1: Designers Need To Strive To Ensure That All Material and Energy Inputs and Outputs Are as Inherently Nonhazardous as Possible. C2Ce design and the 12 Principles share a common goal that all material inputs and outputs of a manufacturing system should be consciously selected to ensure the health and safety of humans and the environment. There are several material changes used in the EcoWorx backing, each one made to satisfy the first principle. The filler in the typical PVC plastisol carpet tile is virgin calcium carbonate. Inorganic filler is used due to its low cost, availability and relative inertness. EcoWorx has been formulated to utilize class C coal fly ash to provide the bulk and loft necessary for the compound to cover the yarn back stitch and provide a smooth embossed backing finish. Material from the specific source of fly ash used has been tested in order to confirm that it is nonhazardous.

The second change is the replacement of the PVC and phthalate plasticizer by a mixture of materials, the primary component of which is a low-density homogeneously branched polyethylene (LDPE) using a metallocene catalyst. The base polyolefin resin has a short-chain branching index of less than 50%; density of 0.86−0.90 g/cm^3; melt index (at 190 °C) of 1−175 g/10 min, preferable around 30; and a molecular weight distribution defined by $M_w/M_n < I_{10}/I_2 - 4.63$. The polymer is a copolymer of ethylene and at least one C_3-C_{20} α-olefin, such as 1-octene. The base polyolefin resin used in EcoWorx complies with U.S. FDA 21 CFR 177.1520(c) 3.2c as a food contact plastic. In this aspect alone, material safety of the EcoWorx polymer is built upon a well-established foundation.

An example that points to the intersection between functional and material safety requirements is the use of flame retardants. The flame retardant used in a Shaw's PVC carpet tile is antimony trioxide (Sb_2O_3). This receives much more scrutiny in Europe than in the United States. The compound has been evaluated by the EU and has been assigned the risk phrases R52 (harmful to aquatic organisms) and R53 (may cause long-term harm to aquatic organisms) (*4*). This flame retardant works by using the heat of the fire to convert the antimony trioxide to antimony tri- or pentachloride, which is a gas that is heavier than air. The principle mechanism of fire retardation for this product is by excluding oxygen from the flame.

TABLE 2. Peto 26 Performance Data

	PermaBac	EcoWorx	spec	test method
delamination (lbf/in width)	5.335	16.51	>2.5	ASTM D3936
dimensional stability	pass	pass	<± 0.2%	ISO 2551 (Aachen)
critical radiant flux (W/cm^2)	0.51	0.95	>0.45	ASTM E648-94a
smoke density	393	184	<450	ASTM E662-93
indoor air quality (mg/(m^2 h))	na	pass	<0.5	CRI Green Label

An alternative mechanism is the oxidation of aluminum trihydrate, which yields aluminum oxide through an endothermic reaction; hence, removing energy from the fire. The use of both of these flame retardants is common within the industry, but patent protection prevents Shaw from using aluminum trihydrate within its PVC-backed carpets. The development of a flame retardant tile without toxicity was a major design requirement in the development of EcoWorx and illustrates the first principle of green engineering. Table 2 documents that the new composition is more effective in achieving the desired functionality of reducing the fire hazard of the tile as indicated by the increase in critical radiant flux (CRF). A description of the standard CRF test may be found in Radiant Panel and Smoke Generation Testing Protocols (*5*).

Principle 2: It Is Far Better To Prevent Waste Than To Treat or Clean Up Waste after It Is Formed. A common goal of the 12 Principles and C2C design in relation to EcoWorx optimization is one that inherently minimizes and/or eliminates waste at the end of the product life. As a result, the in-process scrap is designed to be recovered immediately through the same process. The product is designed using technical nutrients (*2*), employing the philosophy that waste equals food in creating a repeated cycle of recovered components that virtually eliminates the concept of carpet tile waste. EcoWorx technology has been developed and implemented to achieve this goal. With the current raw materials and technologies integrated into the EcoWorx carpet tile system, the waste generated is vastly reduced when compared to Shaw's PermaBac carpet tile. Shaw's goal is to reduce this waste to zero.

In designing the EcoWorx system as a first-generation polymer with little feedstock of second-generation EcoWorx scheduled to return to us until roughly 2007, we find ourselves penalized in government sales for introducing a new sustainable material as defined by the 12 Principles. Today carpet tiles with plentiful feedstocks of recycled PVC plastisol content are seen by government purchasing agencies as preferable to the EcoWorx system. This is because of the reliance on recycled content as the primary metric for determining an "environmentally preferable product (*6*)". The Comprehensive Procurement Guidelines (CPG) under RCRA 6002 have proposed nylon carpet for regulatory designation. Adoption of this designation could have the effect of preventing the purchase of first-generation sustainable materials strictly on the basis of their lack of post-consumer recycled content today.

Moreover, this PVC recycled content is a small fraction of the overall total carpet tile material annually removed, so the vast majority of PVC carpet tiles still make their way to

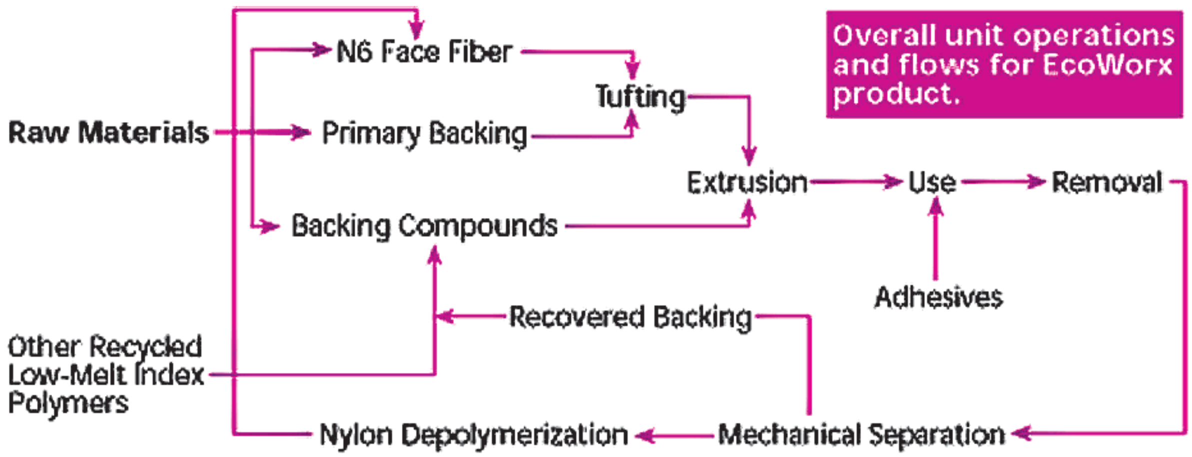

FIGURE 2. Overall unit operations and flows for EcoWorx product.

U.S. landfills. By contrast, every EcoWorx tile produced can be recovered and returned to the EcoWorx system, reducing the need for virgin materials and preventing landfill pollution. Only the outcome of this EPA designation decision will tell if this initial-stage bias reduces Shaw's ability to sell EcoWorx carpet tile to a broader cross-section of purchasers that receive Federal funds.

Principle 3: Separation and Purification Operations Should Be Designed To Minimize Energy Consumption and Material Use. The EOL separation of EcoWorx uses mechanical size reduction and elutriation of the nylon fiber and backing material (see Figure 2 for the system cycle). This process has relatively low-energy inputs and supports preserving the embedded complexity invested in the tile by closing recycling loops at the material level rather than just at the product level. Nylon 6 may be returned to nylon carpet fiber use and the backing returned to backing. The cross contamination of backing into the nylon stream represents a small yield loss for the recycling process but has no other negative impact on the depolymerization process. The presence of, even small levels, of PVC plastisol are incompatible with current methods of depolymerization of nylon 6. Nylon contamination in the backing stream represents a minimal loss of valuable face fiber as filler but, again, will have no negative performance issues with EcoWorx backing at low contamination levels. The purity of the separation yield is determined by the number of elutriation stages that the product passes through. Purity will increase as volume and capital investment increase.

A thorough analysis of this closed-loop system has not yet been completed. However, it is possible to examine the major substitution, the LDPE for the PVC, and compute the changes in mass efficiency of the cyclical system. For this evaluation, the PermaBac system includes plasticizer as a major backing component and nylon 6.6 as a common face component as well as other processing energy resulting from the use of these two materials. The embodied energy impact of these factors in relation to the EcoWorx system is unknown at this time due to the proprietary nature of the nylon 6 depolymerization process owned by Honeywell. However, we will examine the life cycle efficiency from a materials perspective. The life cycle impacts will be comparatively analyzed rather than absolutely.

The approach is essentially that of a computing a life cycle inventory (*7*), and as prescribed by the ISO 14041 standard (*8*), it is necessary to define a functional unit and a system boundary for comparison. A square meter of floor is chosen as the basic unit, and the function is to cover it with carpet for a "significant" period of time, where significant means at least two generations of floor covering in order to include the first- and second-generation component recycling. The system boundary includes all the material flows that are required to manufacture the two generations of product. The functional performance of the PermaBac and EcoWorx tiles are assumed to be equivalent during the use phase. It is also assumed that the environmental impacts associated with the EcoWorx product are reduced due to improved efficiency in the manufacture, packaging, and transportation phases as described under Principle 4.

The focus of the inventory analysis is to capture the different material efficiencies—grams of virgin material/ square meter—in PVC and nylon versus LDPE and nylon. The flows are predicated on the assumption of the current 25% recycled content of the EcoSolution Q face fiber and that PVC tile, when recycled, can only be placed in the lowest backing layer, called the cap coat, of the next generation tile. It should be assumed that any material not included in the next generation tile may go into to other tiles (presuming an expanding market for PVC tile) or other applications. The mass flows for the two products are shown in Figures 3 and 4.

Principle 4: Products, Processes, and Systems Should Be Designed To Maximize Mass, Energy, Space, and Time Efficiency. The second life cycle phase after the selection of raw materials is manufacturing and installation. The manufacturing of PVC plastisol tile requires a radiant gas heating step to fuse the backing to the tile. This step is energy intensive and releases the plasticizer from the PVC as volatile organic compounds (VOC). The overall energy consumption for Shaw's PermaBac PVC plastisol carpet tile is 0.85 kW-h/ sq yard, with the majority of this energy being in the form of combustion of natural gas and the remainder as electricity. This drove the development of a different method for applying the backing that would improve energy and material efficiency.

The key problems are that ordinary low crystallinity elastomeric polyolefin's generally have relatively high viscosities and recrystalization temperatures. High recrystalization temperatures result in short molten times during processing making them difficult to process. This is usually overcome by formulating low molecular weight polyolefin's with waxes, tackifiers, and other elastomeric materials such as ethylene–vinyl acetate copolymers (EVA) to form a typical hot melt adhesive. The melt strengths of these hot melts are usually too low to allow for extrusion coating and thus typically use a roller or knife application.

Conventional LDPE resins can be extruded but have poor flexibility, which results in excessive stiffness of the carpet and difficulty of installation. The wide polydispersity (M_w/ M_N) of the LDPE makes extrusion a viable alternative. The

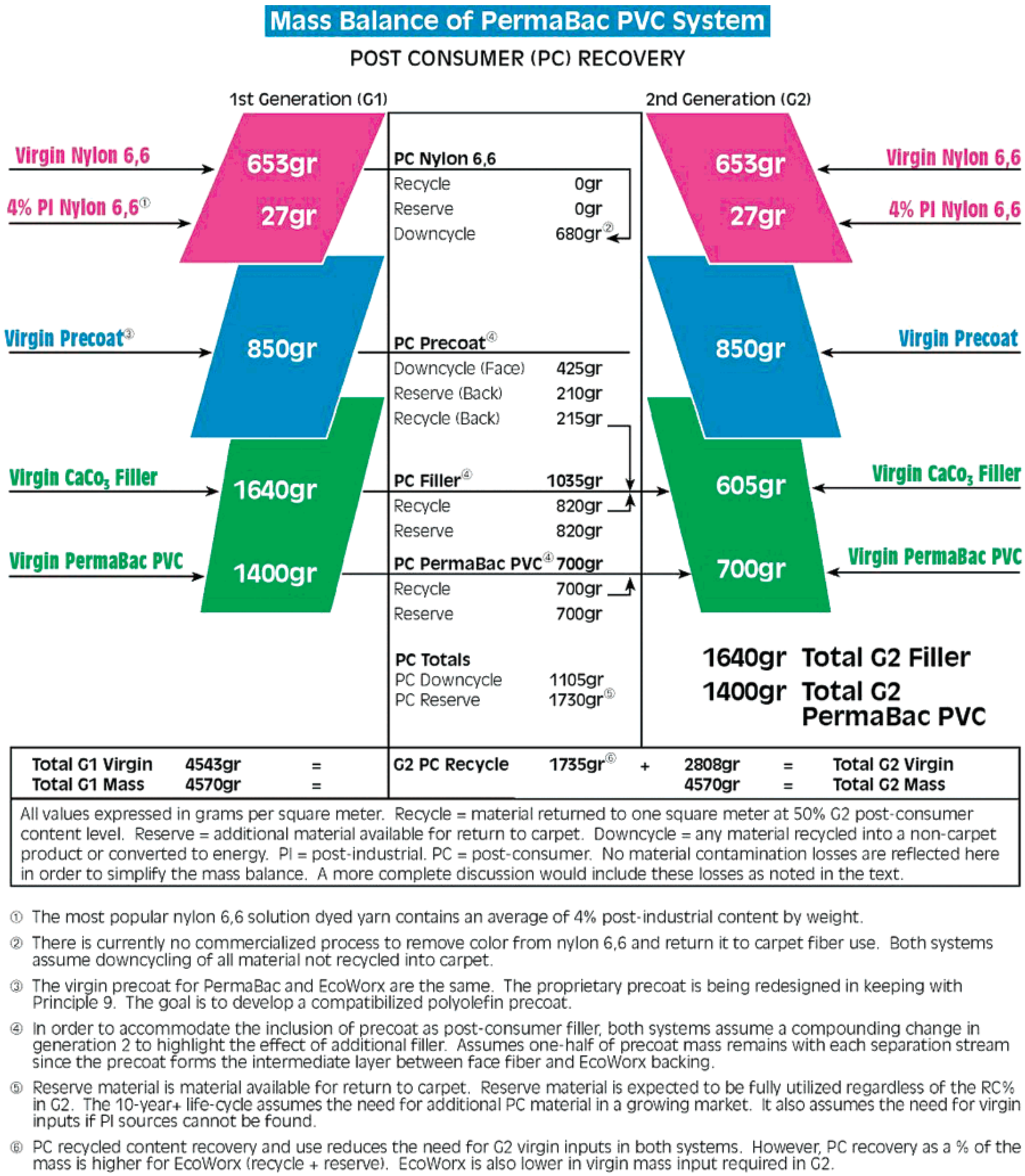

FIGURE 3. Material consumption for PermaBac tiles on a square meter basis over two generations of embodiment. Mass in grams.

energy consumption for Shaw's EcoWorx extrusion coating process is 0.4 kW-h/square yard. A key property of the base LDPE is that it does not display memory of its processing history; it is a non-Newtonian shear thinning fluid with viscoplastic properties. When stored in roll form prior to cutting into carpet tiles, it does not then display curl when packaged or during installation.

Beyond the efficiencies introduced into the manufacture of raw materials and their efficiency gains imparted to the thermoplastic extrusion of EcoWorx in the carpet production process, packaging and distribution also impact the efficiencies of the product system. Cardboard use has been minimized by using telescoping two-part boxes that leave no air voids in the tile box. This allows the stacked tiles to be self-supporting without crushing the tile face or damaging the tiles in any way. However, the box tops and bottoms require additional labor to breakdown at the installation site for recycling. A new packaging process designed to use 25% less cardboard held in place by LDPE shrink wrap to protect the tile edges in transport is under development to cut packaging waste at the installation site and require less labor in separation, compaction, and transport of the packaging materials.

Distribution of carpet tiles has generally been accomplished by over-the-road transport in 53-ft trailers pulled by diesel tractors. Sometimes the piggy-back rail system can be used to reduce the costs of longer trips. Traditional PVC plastisol tiles (i.e., PermaBac) weigh roughly 10 lb/square yard. When pallet weights are added, the legal load limit of 45 000 lb allows only about 4400 square yards of PVC tiles to be shipped on a trailer outbound for installation or inbound for recycling. EcoWorx tiles are 40% lighter in weight, or roughly 6 lb/square yard. This allows the load to increase to 7400 square yards, taking almost full advantage of the cubic space available to palletized carpet tiles in these trailers. PVC tile shipments exceed legal weight limits before the cubic

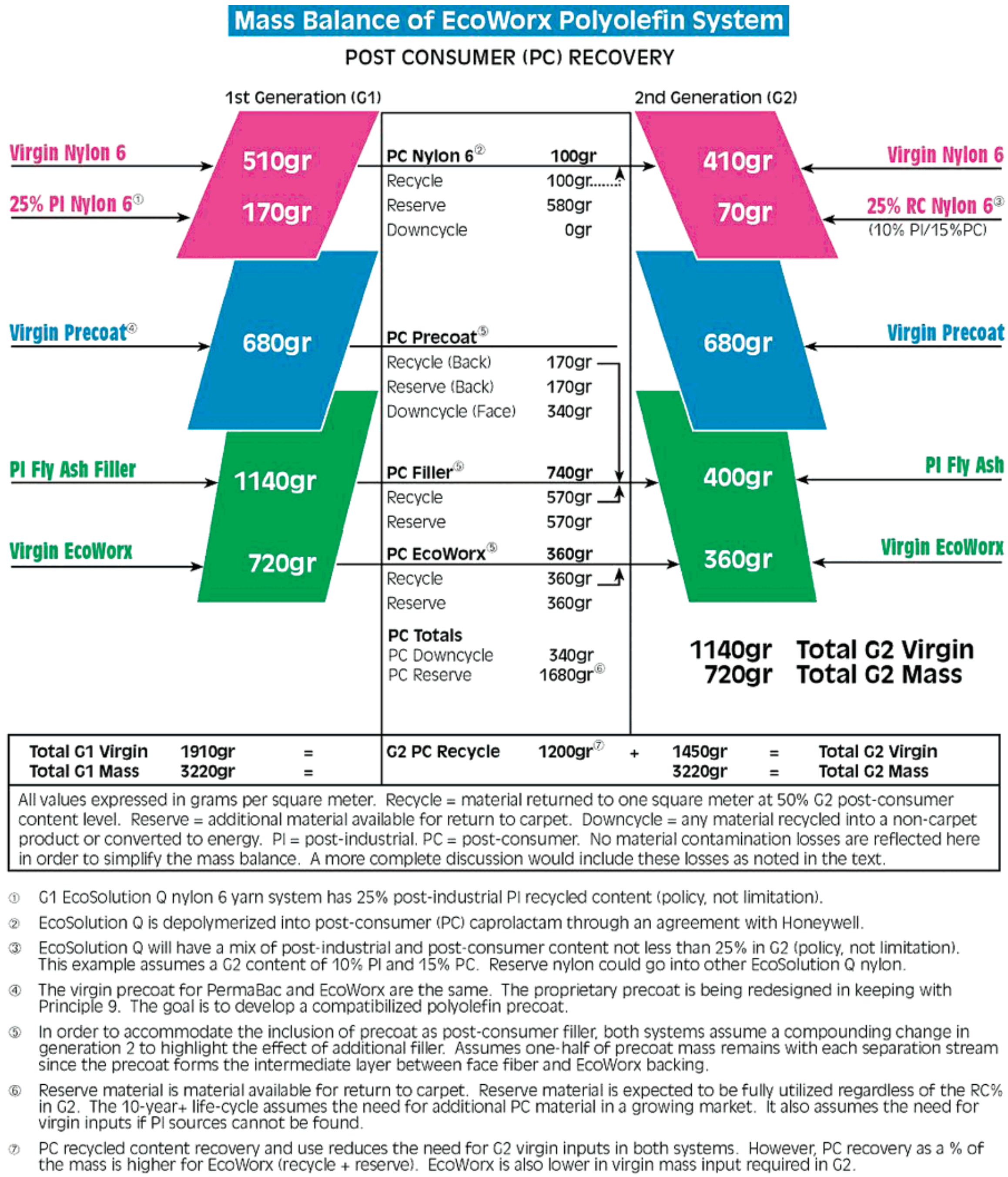

FIGURE 4. Material consumption for EcoWorx tiles on a square meter basis over two generations of embodiment. Mass in grams.

space is similarly utilized. The lower weight and simple packaging of EcoWorx tiles will accrue more "per square yard" unit benefits in transport and physical handling by installers and demolition workers at the installation site. These benefits are being quantified for inclusion in the complete energy study of the EcoWorx system.

Principle 5: Products, Processes, and Systems Should Be "Output Pulled" Rather Than "Input Pushed" through the Use of Energy and Materials. In closed-loop manufacturing systems, it is not clear that this principle applies since outputs become inputs to the next generation of the product. For example, finished inventory and other supply chain measures have not been affected by the switch to EcoWorx. The major change in the system caused by EcoWorx is the creation of an economic value in the EOL materials that previously may have gone to disposal or down cycling. The EcoWorx materials were designed to stay in the technical nutrient loop of manufacturing indefinitely. Preliminary life cycle analysis indicates that this can be done at a lower cost than using 100% virgin materials. A comparative BEES or other life cycle analysis is not available at this time.

Principle 6: Embedded Entropy and Complexity Must Be Viewed as an Investment When Making Design Choices on Recycle, Reuse, or Beneficial Disposition. Design choice of the polyolefin backing system allows for the recycling of both the nylon as well as the polyolefin. This allows both of the materials to be used as technical nutrients. In recycling PVC carpet tiles, no commercial process exists to recycle nylon into uncolored nylon 6 or nylon 6.6 due to contamination issues previously discussed. Economical separation technologies available today cannot ensure complete separation of any backing from recovered carpet nylon. Nylon recyclers are generally reluctant to take PVC-contaminated nylon for noncarpet applications where equipment could be damaged by the potentially corrosive effects of any HCL generated by processing PVC. The chemical recycling of nylon 6 is also unforgiving of PVC contamination due to contamination of the caprolactam monomer yield from breakdown of the PVC plastisol. The EcoWorx system meets all of the PermaBac PVC product performance criteria while allowing the product to be fully recycled.

Shaw chose not to design a product for reuse due to limited market applications and inevitable losses. Likewise, we did not choose to develop a product for a beneficial final disposition because the C2C concept of continuous reuse of components was considered an achievable goal. Total C2C sustainability (no new materials required) may never be realistic due to continued market growth and current material complexity, but every step forward is beneficial.

The final life cycle phase is the disposal or recovery of the product. Figure 2 sketches the overall material pathways that will operate as the tile is recycled. The dotted lines indicate that transportation steps are involved as the material moves from one process to the next. Viewed in the light of these pathways several of the earlier material selections become significantly clearer, indicating a systems approach involving the commercial "afterlife" is an important driving force.

Principle 7: Targeted Durability, Not Immortality, Should Be a Design Goal. In the case of carpet tile, this principle has limited applicability as a design principle. The EcoWorx product was designed to match the existing durability of current carpet tile products in the market. This was a design constraint and was factored in to the design and material choices from the outset. Given that the recycling of the tile is economically desirable, Shaw has established a take-back program. Each tile is imprinted with a toll free telephone number that encourages customers to recycle the tile. Shaw provides transportation and reprocessing at no cost to the customer because this is less expensive than acquiring virgin materials and encourages recycling.

Principle 8: Design for Unnecessary Capacity or Capability (e.g., "One Size Fits All") Solution Should Be Considered a Design Flaw. In our analysis of the EcoWorx tile, we have not revealed any unnecessary capacity or capability; its function is at the levels demanded by the market. However, it is not clear if our stated goal of pushing this backing system into broadloom applications would adhere to this principle. The broadloom backing performance requirements are significantly less severe than those for tile so all aspects of dimensional stability, adhesive compatibility, and other high-performance aspects need to be reevaluated. This is a situation where the principles may help guide us in the future. However, it may prove that reducing material diversity by expanding the EcoWorx polymer into performance broadloom could cause unnecessary "overbuilt" capabilities to be incorporated in a one size fits all sense. However, this will need to be weighed against the environmental benefits.

Principle 9: Material Diversity in Multicomponent Products Should Be Minimized To Promote Disassembly and Value Retention. Carpet tiles are a complex matrix of materials designed to meet performance requirements and the need for cost minimization. Material diversity minimization to one or two raw materials is not currently feasible. From a green engineering perspective, ideally a carpet tile should be made from a single nonhazardous material that can be easily recycled or be made from naturally derived polymers that decompose only at the end of the tile's life. The use of metallocene polyolefin as a backbone for the diverse range of tile and 6-ft backings at Shaw is an example of Principle 9.

EcoWorx utilizes a variety of materials to achieve all of the economic and performance requirements of the market. However, the diversity of the raw materials should not be viewed as a negative because they do not lose their value. As previously discussed in Principle 3, EcoWorx is able to be separated into nylon and backing. Therefore, it is feasible to consider the multicomponent backing system as one material that theoretically will be continuously reused.

A lightweight fiberglass mat is a hallmark of all properly stabilized carpet tile.. The weight of the glass mat as a percentage of total weight is small, and the encapsulated glass has no hazardous qualities. The redesign of carpet tile to eliminate a fiberglass stabilizer would be ideal under Principle 9, but not if stability is adversely affected. Today the shattered glass, resulting from EOL elutriation, becomes filler for future generations of EcoWorx with little adverse effect beyond the contamination it represents. The industry has long looked for the means to make a carpet from 100% nylon; however, such a carpet is mechanically and economically unrealistic. EcoWorx has come as close to a single polymer carpet tile as any yet conceived. EcoWorx is produced for limited applications with a polypropylene face yarn tufted into a polypropylene primary backing, raising the polyolefin content to almost 50%. The balance is inert filler, precoat, flame retardant, and glass. Unfortunately polypropylene yarns are not durable enough for most high-traffic commercial uses.

Principle 10: Design of Products, Processes, and Systems Must Include Integration and Interconnectivity with Available Energy and Material Flows. The extrusion process requires only electricity and cooling water. The cooling water is provided by a closed-loop, integrated plant-wide system. This system provides chilled water to not only the extrusion process but also various other plant processes including HVAC, which increases the overall efficiency of the system. Extrusion coating is important because it allows for the addition of recycled content in the form of granules, pellets, powders, etc. of other recycled polymer streams that may come available. The C5 aliphatic hydrocarbon tacifying resin ensures compatibility with other low-melt resins due to the design requirement for recycling. It is desirable not only to recycle EcoWorx backing back into EcoWorx but to also be able to substitute the main resin with other suitable polymers. Anticipatory design of a robust system tolerant of low-melt polymers is a major component of the long-term viability of the EcoWorx backing.

Metallocene-catalyzed polyolefin is limited in its geographic availability due to its specialized processing requirements and has to be shipped in bulk to the manufacturing facility; coal fly ash is purchased from a coal-fired power generating plant located in nearby Macon, GA. This is the closest supply of class C ash to the manufacturing facility. The coal fly ash qualifies under RCRA 6002 as a recovered material and eliminates the mining of calcium carbonate for this use. Opportunities to utilize Shaw's internal polyolefin wastes from polypropylene yarn extrusion continue to be explored. In addition, there are other streams of recyclable LDPE and HDPEs which, due to the low-melt requirements of the material in the backing, may be included in the formulations, upgrading their material value.

Principle 11: Products, Processes, and Systems Should Be Designed for Performance in a Commercial Afterlife. The concept of C2C design of EcoWorx with EcoSolution Q fiber provides superior environmental and performance attributes through reuse of technical nutrients in the product. It is Shaw's goal to have EcoWorx returned for recycling. To help facilitate this, each EcoWorx tile is back printed with a toll free number to contact for disposition of the material for recycling. A value recovery system is in place to handle the flows of EOL material based on projected return rates. EcoWorx EOL product components are projected to be less costly to process than virgin components. This afterlife value eliminates EOL EcoWorx tiles from the category of waste, placing EcoWorx instead in a category of raw materials.

Principle 12: Material and Energy Inputs Should Be Renewable rather Than Depleting. Shaw's parent company, Berkshire Hathaway, is investing in a 310-mW wind farm in Iowa through their MidAmerican Energy subsidiary. Consequently, Shaw is not investing in short-term demonstration technology for renewable energy. Shaw is committed to long-term adoption of renewable energy as economics dictate. The materials in the Ecoworx product are renewed through the appropriate design of recovery and recycling systems. This is in contrast to adopting materials that can be renewed by biological cycles. Both approaches are valid strategies for improving the environmental performance of carpet products.

The 12 Principles and C2C provide a framework for development of EcoWorx that incorporates anticipatory design, resource conservation, and material safety. Shaw remains committed to the continuous reduction of all processes and practices that are resource depleting. Shaw will continue to work on the mechanical and chemical properties of safe materials and their recovery, which are less energy-intensive. Experience and intuition were largely sufficient to guide decision making in the case of the EcoWorx carpet tile system. However, they were insufficient to analyze and optimize that system. A more formal framework represented by the 12 Principles of Green Engineering and C2C has been invaluable in this step. Moreover they have provided mechanisms to explain the benefits of the EcoWorx system and educate the marketplace on the desirability of sustainable products as qualitatively, economically, and environmentally superior replacements for a product system that has been in place for 30 yr. The future modification of EcoWorx as the backbone of versatile backing solutions for many other carpet systems is a challenging prospect.

Literature Cited

(1) Anastas, P. T.; Zimmerman, J. B. 12 Principles of Green Engineering. *Environ. Sci. Technol.* **2003**, *37* (3), 94A−101A.

(2) McDonough, W.; Braungart, M. *Cradle-to-Cradle*: *Remaking the Way We Make Things*; North Point Press: New York, 2002.

(3) U.S. Patent Pending 20020134486. September 26, 2002.

(4) Commission Directive 2001/59/EC. Official Journal of the European Communities: 2001.

(5) Radiant Panel and Smoke Generation Testing Protocols, 4 CRI. http://www.carpet-rug.com/drill_down_2.cfm?page=13&sub=18 (accessed May 22, 2003).

(6) (a) Presidential Order 13101, Greening the Government Through Waste Pollution, Recycling, and Federal Acquisition. *Fed. Regist.* **1998**, *63* (179). (b) Resource Conservation and Recovery Act (RCRA). Public Law 94-950, 90 Stat. 2795, as amended (42 USC 6901−6907) Section 301 of Title 3, United States Code.

(7) Consoli, F.; Allen, D.; Boustead, I.; Fava, J.;Franklin, W.; Jensen, A. A.; De Oude, N.; Parrish, R.; Perriman, R.; Postlethwaite, D.; Quay, B.; Seguin, J.; Vignon, B. *Guidelines for Life Cycle Assessment*: *A Code of Practice*; Society of Environmental Toxicology and Chemistry: Pensacola, FL, 1993.

(8) ISO 14000 Standard. http://www.iso.ch/iso/en/prods-services/otherpubs/iso14000/index.html (accessed on May 26, 2003).

Received for review June 9, 2003. Revised manuscript received September 12, 2003. Accepted September 22, 2003.

ES034576A