CASE STUDIES ILLUSTRATING THE TWELVE PRINCIPLES OF GREEN ENGINEERING

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INTRODUCTION

Recently, there has been increased attention on ways of using the classical traditions of engineering expertise in ways that further the goals of environmental protection and sustainability. Approaches to green engineering have been noted in recent years (1-3) and have been demonstrated in a variety of ways in particular industry sectors and engineering disciplines (4-6). These approaches, while important advances have not been implemented comprehensively or systematically either across sectors or disciplines. As a tool for establishing a systematic framework for applying engineering to the goals of sustainability, the Twelve Principles of Green Engineering were introduced (7). The Principles are intended as a way for engineering at all scales, molecular, product, process, and systems and all engineering disciplines chemical, mechanical, electrical, environmental, and civil to have a common set of guidelines that can be useful in identifying sustainable design criteria.

The Twelve Principles of Green Engineering takes the same ingenuity and creativity that has marked the traditions of engineering and applies it within a framework of measurable techniques. While statements of professional ethics and broad sustainability goals (can be useful, the Twelve Principles of Green Engineering are meant to be used as performance criteria in engineering design. It is important to note that these principles are additional parameters in a complex system that will always include other technical and economic factors. Just as it would not make sense to strive for the lowest cost process without building in economic criteria, it also would not make sense to strive for a sustainable process without rigorously including Green Engineering criteria. The framework of the Twelve Principles is one tool that can be used in this task.

The Twelve Principles of Green Engineering allow designers to consider fundamental factors at the earliest stages as they are designing a product, process or a system. The principles should be understood as a collection of parameters in a complex system that needs to be optimized, including taking advantage of synergies and recognizing trade-offs. The application and emphasis of individual principles will be largely contextual dependant on the specific conditions and circumstances of the product, process or system being designed.

- PRINCIPLE 1 - Designers need to strive to ensure that all material and energy inputs and outputs are as inherently non-hazardous 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 a component of the design framework.
- PRINCIPLE 4 - System components should be designed to maximize mass, energy and temporal efficiency.
- PRINCIPLE 5 - System components 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 should be considered a design flaw. This includes engineering "one size fits all" solutions.
- PRINCIPLE 9 - Multi-component products should strive for material unification to promote disassembly and value retention. (minimize material diversity)
- PRINCIPLE 10 - Design of processes and systems must include integration of interconnectivity with available energy and materials flows.
- PRINCIPLE 11 - Performance metrics include designing for performance in commercial "after-life".
- PRINCIPLE 12 - Design should be based on renewable and readily available inputs throughout the life-cycle.

To illustrate how the Twelve Principles can be applied both across scales and across engineering disciplines, this paper seeks to provide case studies from a variety of industrial sectors and disciplines highlighting the design of a product, process, and system through the Principles of Green Engineering. Through these case studies, it will become apparent to the audience that while there are differences in terminology and jargon between those who design molecules versus those who design cars, versus those who design agricultural systems, the fundamental approaches and guidelines in moving toward sustainability are common among designers. By clearly illustrating how the framework of principles has worked in the past, it can also provide a blueprint for how these guidelines can be used in future designs of products, processes, and systems.

PRODUCT DESIGN

At the inception of the product design process, the designer has the ability to influence the type of materials and energy that will be used, not just in the manufacture of the product, but throughout the life-cycle (Principle 10). By designing products based on inherently benign (Principle 1), renewable materials and energy (Principle 12) as described by the Principles of Green Engineering, the designer will also play a significant role in the preventing the exposure of toxic or hazardous materials to the end-user as well as those associated in the manufacture, assembly, distribution, maintenance, or repair of the product. Life-cycle considerations are critical to the implementation of the Principles of Green Engineering in designing products to maximize environmental benefit. A life-cycle approach will also provide an opportunity to highlight any potential trade-offs that arise from applying the Principles to the design of a product for the use phase rather than across the entire product cycle.

The following demonstrates the application of the Principles of Green Engineering to the design of an industrial product, a metalworking fluid, used in machining operations (8). Metalworking fluids (MWFs) cool and lubricate during metal forming and cutting processes increasing the productivity and quality of manufacturing operations (9). MWFs represent significant human health and environmental impacts with over two billion gallons sold annually in North America (10). Given that machining and manufacturing will continue to play a vital role in the global economy for the foreseeable future, the human health and environmental impacts associated with MWFs can be eliminated 1) by discontinuing or limiting the use of metalworking fluids or 2) by designing new MWFs products with improved health and environmental characteristics. Currently, replacing MWF function has proven challenging and dry/damp machining may carry with it negative environmental and economic affects of its own (11-14). As such, designing next generation MWFs through the Principles of Green Engineering represents an important opportunity to improve the environmental and health aspects of a widely used and necessary product.

Four types of MWFs have used in practice to accommodate the differences in severity of various machining operations: straight oils, oil-in-water emulsions (soluble oils, semi-synthetics), and true solutions (synthetics). The emulsifiable MWFs are defined by the ratio of water to oil in the formulation, which represents the balance of cooling to lubrication desired for a given machining process. Given that semi-synthetics account for approximately 40% of the market (1) with continuing increases in market share expected (15); recently, a semi-synthetic MWF product was designed using an approach consistent with the Principles of Green Engineering. The most significant contributions of this research include the substitution of MWF components with alternatives that are more inherently benign than traditional MWF ingredients (Principle 1) and the prevention of premature MWF failure leading to excessive environmental impacts due to frequent MWF disposals (Principle 2). The new MWF formulations are based on oil and nonionic surfactants that can be produced from renewable, bio-based resources (Principle 12) that may be less toxic than traditional emulsion systems. This is based on data for the fathead minnow (*Pimephales promelas*), which indicate that the traditional anionic surfactant has an LC_{50} of 0.4 mg/L after 48 hours while anionic in the newly designed MWF has an LC_{50} of 14.1 mg/L after 48 hours (16, 17). By including anionic surfactants in the formulations, the emulsions can be destabilized by the addition of a simple salt, allowing oil separation (Principle 3) as well as oil recovery and reuse (Principles 6 and 10) in the next MWF formulation or for other uses.

In addition, the newly developed MWFs are more hard water stable, a common cause of traditional MWF disposal and subsequent environmental impacts. This stability is achieved by designing the new formulations based on a twin-headed anionic surfactant that has twice as many of moles of anionic head groups to provide electrostatic repulsive, than the traditional surfactant. The improved hardwater stability is achieved even with the removal of two components found in current MWF formulations to improve emulsion stability: ethylenediaminetetraacetic acid (EDTA), a chelating agent, and butyl carbitol, a coupler. By eliminating these two components from the formulation, the overall life cycle environmental impact is likely to be reduced (Principle 9). In addition, there are concerns specific to the disposal of MWFs containing EDTA since EDTA does not readily biodegrade (18) and once introduced into the general environment, EDTA can remobilize heavy metals (19, 20) allowing heavy metals to re-enter and re-circulate in the food chain. Also EDTA can mobilize heavy metals in tool coatings, providing a route for these metals to enter the environment. For these reasons, the removal of EDTA form MWF formulations would serve well toward the design of greener metalworking fluids.

Before a product can be designed in accordance with the Principles of Green Engineering, a fundamental understanding of the desired characteristics and current performance criteria must be developed. Performance is a critical parameter to consider. If the product designed based on the Principles does not meet or exceed the current performance criteria, it is highly unlikely that the product will realize any human health or environmental benefits since it will not be competitive, and therefore adopted, in the marketplace.

As such, the newly developed MWFs, designed with fewer and benign as well as renewable components, were evaluated for several key performance criteria including hardwater stability and machining performance. As shown in Figure 1, when increasing amount of calcium chloride ($CaCl_2$), two commercially available semi-synthetic MWFs (SS1 and SS2) shows a trend of increasing particle size with increasing calcium concentration, behavior indicative of emulsion instability in the presence of hardwater. In fact, when 0.008 M of $CaCl_2$ was introduced to SS2, the MWF emulsion was completely destabilized and split into separate oil and water phases. However, in the case of the MWFs designed in accordance with the Principles of Green Engineering, the particle size at 1000 ppm calcium concentration was measured to be statistically identical to the MWF with no calcium present. In other words, the new formulations are stable at hardwater concentrations above those expected in the field, demonstrating an improvement in both performance and environmental effects. In addition, the machining performance of the MWFs developed in accordance with the Principles was evaluated and compared to that of commercially available MWFs. As shown in Figure 2, all of the newly developed MWFs had a higher machining efficiency than SS1 or SS2.

The research to design new MWFs based on the Principles resulted in a product that is competitive in terms of machining performance with currently available products. These MWF formulations offer the likelihood of extended lifetime under hardwater conditions while utilizing more inherently benign and renewable components. Experience has shown that MWF lifetime extension reduces environmental and economic impacts related to MWF production and disposal. This case study provides an example of environmental and economic “win-win” by designing a replacement product in accordance with the Principles and demonstrating identical or improved performance to currently available products.

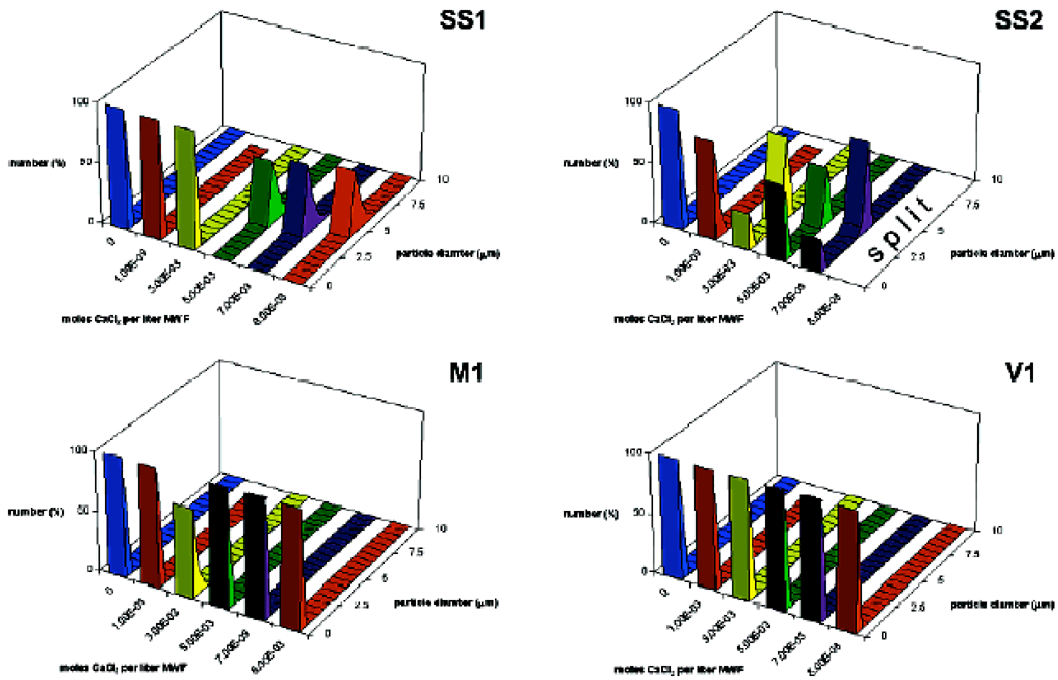

Figure 1: Particle size of SS1, SS2, and representative mineral oil- and vegetable oil-based formulations (M1 and V1) formulated with a twin-headed anionic surfactant as a function of calcium chloride salt molar concentration. For systems where oil-water split occurs, particle size data are not available. (8)

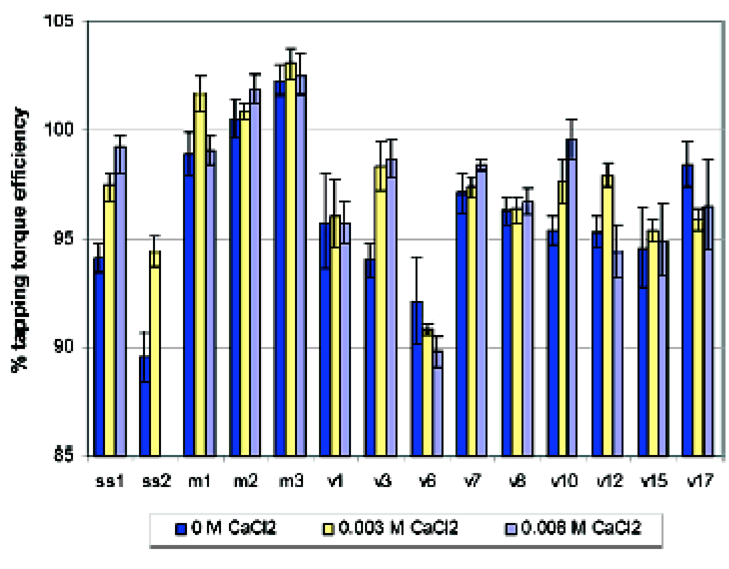

Figure 2: Tapping torque efficiency for SS1, SS2, and representative mineral oil- and vegetable oil-based formulations at 0, 0.003, and 0.008 M calcium chloride. Tapping torque data was not reported for SS2 at 0.008 M calcium chloride due to oil-water emulsion separation. Error bars represent 95% confidence intervals. (8)

PROCESS DESIGN

The design of processes used in the manufacture, repair, maintenance, operation and distribution of materials and energy have a significant impact on the environment and human health. It is imperative to recognize the potential consequences of designing simply for the intended outcome and not considering how that outcome will be achieved. It is also key to recognize the steps necessary to separate the desired outcome from the matrix in which it is generated or the byproducts that are inadvertently formed during production. Separation and purification tasks are often critical process steps in generating the desired product, for deriving pure feed materials, and for recovering ingredients for recycle (21).

The Principles of Green Engineering describe mechanisms to reduce the materials and energy necessary for separation and to minimize the formation of byproducts by explicitly stating this as a design goal from the beginning. The Principles also address the need to maximize mass, energy, space and time efficiency upfront for increased environmental benefit. Principle 5 is another key concept to consider in process design such that the desired outcome can be achieved by pulling, rather pushing through material and energy, the process to completion. Ultimately, the Principles of Green Engineering indicate a need to "intensify" processes to minimize material and energy demands and to prevent emissions of these un- or under-utilized resources. Several scientific and engineering advances have been made towards the goal of process intensification including continuous processing instead of batch operations (22), using high-intensity mixing in reactors or separators, combining chemical transformations with transport in pipelines, or using microreactors (23).

The following demonstrates the application of the Principles of Green Engineering to the design of a process intensification strategy, vapor-liquid separation based on distillation reactive distillation coupled with catalytic distillation, for methyl acetate as described by Malone et al (21). Reactive and catalytic distillation are hybrid combinations of separation and reaction for chemical synthesis that offers improved efficiencies (e.g., reduced energy requirements, lower solvent use, reduced equipment investment, and greater selectivity) (21). Many of these potential advantages are captured in the design recommendations of the Principles of Green Engineering.

Methyl acetate production for acetic acid and methanol, invented and practiced by Eastman Chemical Company, is probably the best-known example of reactive distillation in the literature (24-26). This example of reactive distillation shifted the process from the conventional technology based on 11 major units to a single hybrid unit (Figure 3). In this case, the switch to reactive distillation lowered the investment as well as the energy demand by 80% as compared to the traditional technology (Principle 4). In addition, two solvents were eliminated from the production process for methyl acetate by moving to reactive distillation (Principles 2 and 9). These benefits are obtained not only by overcoming limitations due to chemical reaction equilibrium but also by avoiding or overcoming difficult separation (Principle 3) (21). Although the data are not in public domain, the inventory of materials in reactive distillation is presumably substantially smaller.

Also of interest are the trade-offs between the Principles presented by moving to reactive distillation. As described by Malone et al. (21), reactive distillation systems are a challenge to design and control, and the resulting process equipment may be difficult to reuse for another purpose if and when the original process is no longer viable. This raises the point that the relative effects of a design based on the Principles of Green Engineering must be balanced to achieve the most beneficial outcomes. In the case of reactive distillation, it appears that although there are some trade-offs between Principles, this strategy for process design presents tremendous opportunity providing a greener alternative to traditional chemical synthesis processes. This case study provides an example of environmental and economic "win-win" by designing an alternative process in accordance with the majority of the Principles of Green Engineering while reducing the economic expenditures required for capital investment as operating and maintenance costs.

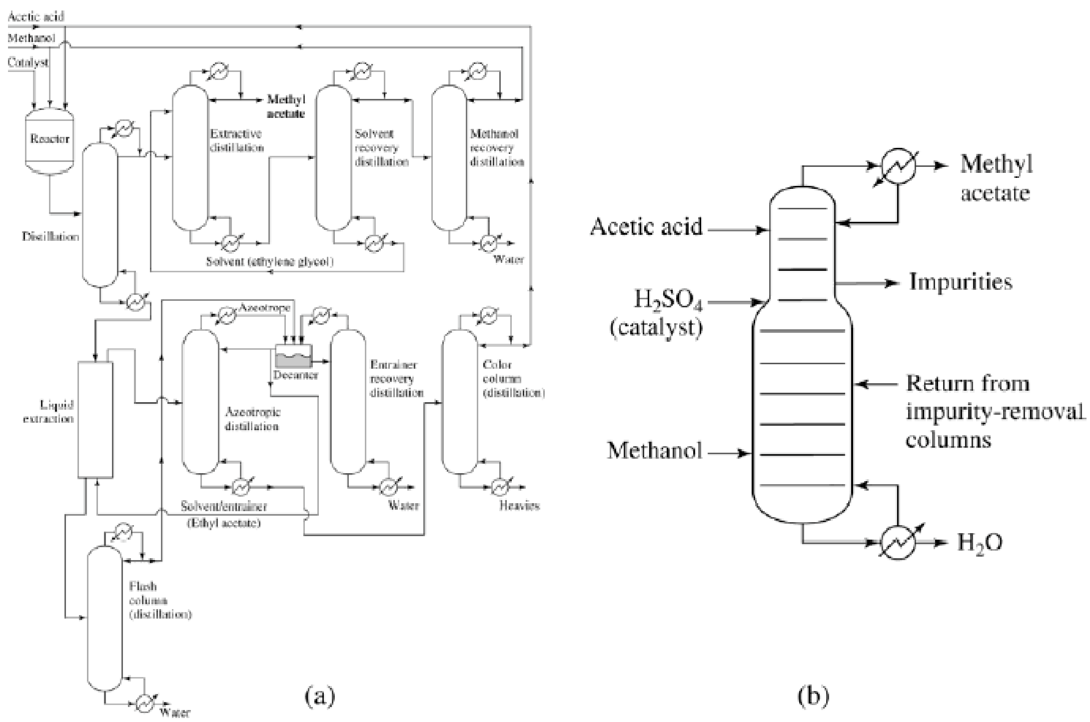

Figure 3: Schematic of (a) conventional and (b) reactive distillation technologies for the production of high-purity methyl acetate (26).

SYSTEM DESIGN

By addressing the integration of products and processes at the beginning, a system can be designed that considers all stages of the life cycle simultaneously from acquisition to use to recovery. By focusing on the entire system, the design will have a broad perspective that considers material and energy flows from one product to another and one process to another (Principles 2, 10, and 11) to maximize mass, energy, space, and time efficiency (Principle 4). Systems thinking, in contrast to traditional analysis, focuses on how the design being considered interacts with the other constituents of the system, a set of elements that interact, of which the individual product or process is a part. This means that instead of isolating smaller and smaller parts of the system being studied, systems thinking works by expanding its view to take into account larger and larger numbers of interactions as an issue. This can result in strikingly different conclusions than those generated by traditional design focus on an individual product or process, especially when what is being designed is dynamically complex or has a great deal of feedback from other sources, internal or external. (27) The case study presented to highlight systems design in accordance with the Principles of Green Engineering is the EcoWorx carpet tile system developed by Shaw Industries (28). The EcoWorx system design considers carpet tile production, use, and recovery as a single system designed to optimize the environmental and economic benefits.

At the foundation of this carpet tile system design is the ability to recycle both the carpet face and backing components in the next generation face and backing components, respectively, for future generations of EcoWorx tiles (Principles 2, 6, 7, 8 and 10) (Figure 4). The EcoWorx system has many features to highlight the goals of these Principles. For example, the in-process scrap is designed to be recovered immediately through the same process (27). In fact, it is Shaw's goal to have EcoWorx returned for recycling as this is the primary and most cost-effective feedstock for next generation carpet tile manufacture. 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 end-of-life materials based on projected return rates (27). This design strategy truly captures the notion that viewing embedded entropy and complexity as an investment has environmental and economic benefit.

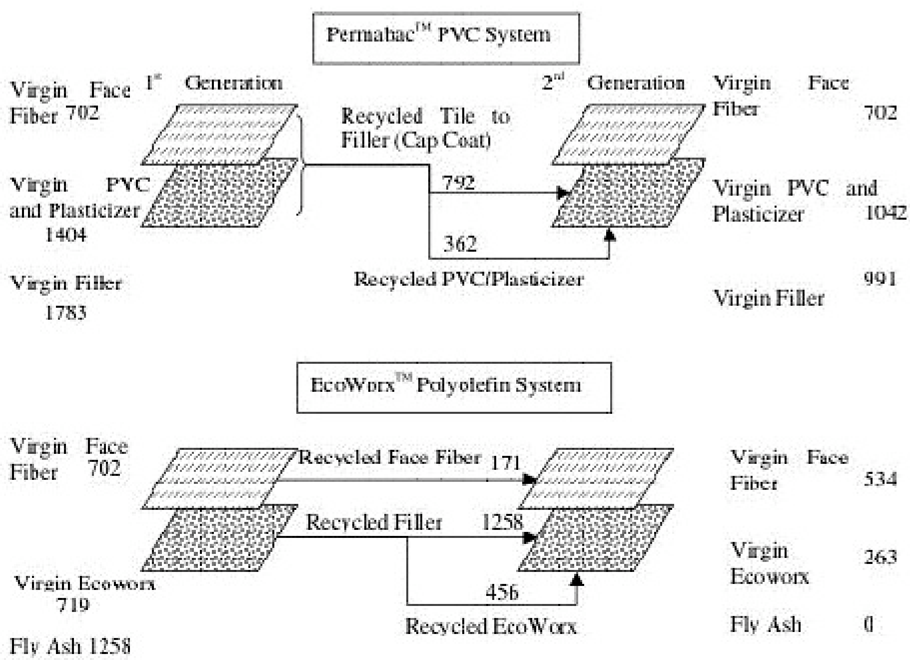

Figure 4: Material consumption for Permabac and EcoWorx tiles on a square meter basis over two generations of embodiment. (Masses are given in grams) (27)

Another key component of this system design as highlighted by the Principles of Green Engineering is need to base the design on the most inherently benign materials and energy possible (Principle 1). Shaw began to research and develop metallocene-catalyzed polyolefins as an alternative to the traditional polyvinyl chloride (PVC) backing due to environmental and human health concerns. Another example of inherently benign design in the EcoWorx system is in the use of flame retardants. The flame retardant used in Shaw's traditional PVC-backed carpet tile is antimony trioxide (Sb_2O_3), a compound that receives much scrutiny in Europe for potential environmental and human health effects. An alternative flame retardant mechanism to reacting Sb_2O_3 is the oxidation of aluminum trihydrate. This compound designed into the EcoWorx system is more effective in achieving the desired functionality of reducing the fire hazard of tile while representing a lower toxicity capturing the foundation of Principle 1 and the strategy of Green Engineering.

The Principles of Green Engineering provide a framework for the development of systems, in this case EcoWorx carpet tile system, which incorporates anticipatory design, resource conservation, and inherent safety. The Principles can provide a mechanism to optimize the holistic environmental benefits of the integration of products and process across the life cycle. Developing new systems requires the design of interconnections and relationships in addition to the individual components and the framework provided by the Principles of Green Engineering can be engaged throughout the design of system components as well as the interactions of these components.

CONCLUSION

The examples presented in this paper represent the application of the Twelve Principles of Green Engineering at various scales, product, process and system. While it is recognized that each of these examples have as yet only been able to achieve the significant sustainability advantages of a subset of the principles, future technologies will continue to build on these advances in an iterative fashion constantly improving and increasingly incorporating the principles and systematizing them into design. The improvements necessary for the designs of tomorrow are among some of the most technologically challenging that our engineers face, however, the traditions of brilliance and creativity that have brought about advances in the past will continue to meet the challenges of sustainability in the future.

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