2013 EL Program: Sustainable Manufacturing

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Strategic Goal: Sustainable and Energy-Efficient Manufacturing, Materials, and Infrastructure

Summary:

Traditionally, manufacturing industries are concerned with quality, cost, and productivity. The new dimension added to these as a business megatrend[1] is sustainability[2]. Industry needs a trusted system of metrics and the underlying measurement science to compute those metrics[3]. To address these needs, this program is organized into two thrusts: methodology thrust and integration thrust. The first thrust will develop a methodology for analysis and synthesis (allocation) of the energy and material footprint at the factory level for gate-to-gate[4] life cycle assessment (LCA). To enable this factory-level methodology, the program will develop additional methodologies for characterizing unit-manufacturing processes, and product assembly processes. To verify and validate these methodologies, the integration thrust will develop sustainability modeling and optimization techniques and a testbed based on real manufacturing use scenarios. The results of this program will apply to broad industry sectors, and will lead to internationally accepted measures and practices.

Description:

Objective: To develop and deploy advances in measurement science to enable improvements in resource (energy, material) efficiency and waste reduction across manufacturing processes and product assembly by 2016.

What is the problem?

Awareness of the business benefits of sustainability is increasing. The HBR article[5] titled *"The Sustainability Imperative"* declares sustainability as an emerging megatrend. The April 2012, Business Roundtable's 2012 sustainability report[6] features letters from 126 CEOs of leading U.S. companies summarizing their efforts to improve sustainable business practices. According to the recent MIT sustainability survey[7], investors are now looking at a company's sustainability performance as an indicator of its overall business value. As a result, more and more companies are asserting an important strategic relationship between innovation, competitiveness, and sustainability. These companies see sustainability as a critical part of the next stage of their development with the potential to cause

[1] The Sustainability Imperative by David A. Lubin and Daniel C. Esty, Harvard Business Review, May 2010 & Megatrends: Ten New Directions Transforming Our Lives, John Naisbitt, Grand Central Publishing (August 16, 1988)

[2] The notion of sustainability is broad and in this program we mainly focus on resource (energy, material) efficiency, and waste reduction across the lifecycle of a manufactured product.

[3] Corporate Sustainability-A Progress Report, KPMG and Economic Intelligence Unit, The Economist, April 2011.

[4] Gate-to-gate is a partial LCA looking at only one value-added process in the entire production chain.

[5] The Sustainability Imperative by David A. Lubin and Daniel C. Esty, Harvard Business Review, May 2010.

[6] http://businessroundtable.org/uploads/studies-reports/downloads/2012_04_18_BRT_Sustainability_Report_FINAL_1.pdf

[7] Sustainability Nears a Tipping Point, MIT Sloan Management Review, Winter 2012, Vol. 53, no. 2, 69-74

significant structural and disruptive changes. To plan for these changes, they are building business cases for sustainability. In building these cases, however, they constantly come up against two critical measurement science barriers: the need for well-defined metrics, and a measurement science-based methodology to aggregate metrics across global supply chains within manageable uncertainty.

U.S. manufacturing companies need an integrated systems approach to remove these barriers. A systems approach is the only way designers and engineers can compute, track, and compose selected sustainability metrics. Many metrics and associated computational methods have been suggested. The most critical of these metrics are associated with energy efficiency[8] and material efficiency[9]. However, there exists no measurement science-based methodology[10] to enable analysis and synthesis (allocation) of the energy and material footprints[11] at the factory level for gate-to-gate[12] life cycle impacts. Consequently, the ability to achieve this integrated approach is beyond the capability of most U.S. manufacturing companies.

A recent Office of Science and Technology Policy (OSTP) report[13] recognized the importance of giving companies this capability. That report stressed the need for "*accessible and affordable measurement systems and analytical tools for assessing and managing sustainability across the production process."* A NIST industry workshop report[14] expressed this view. It stated that *"industry is unable to measure economic, social, and environmental consequences of their activities and products accurately during the entire life cycle and across their supplier network."* It is clear that the measurement science is lacking to address the technical barriers. The measurement science for the methodology thrust will focus on science-based methodologies for measuring, tracking, and aggregating measurements at the product, process, and production processes across the supply chain levels. To verify, validate and deploy these methodologies and associated measurement science, the integration thrust will develop sustainability modeling and optimization techniques and a testbed based on real manufacturing use scenarios.

Why is it hard to solve?

Ensuring sustainable manufacturing requires an integrated systems approach and spans technical, economic, ecological, and societal issues. Interactions within and across these issues are critical to the fundamental understanding of sustainable manufacturing, because focusing on any single issue could result in suboptimal solutions and unintended consequences. Industry recognizes that (1) sustainability challenges in manufacturing can only be addressed through multi-disciplinary methodologies and (2) implementing these methodologies can have significant economic benefits for sustainability in general, and sustainable manufacturing in particular[15]. It is difficult to provide a scientific answer to the question of how to improve the overall efficiency (material and energy) of manufacturing systems, as the fundamental measurement science is still underdeveloped. Also, the necessary standards to represent and report the information used and processed by these methodologies are yet to be developed. Additionally, since these methodologies can be expensive to implement, many companies – particularly small- and medium-sized companies – find it hard to deploy these methodologies. Consequently, most companies have no way to track and compose sustainability-related data of processes, factories, and supplier networks. Developing measurement science for sustainable manufacturing is often very complex and hard because it usually involves various scientific and technical disciplines, and the necessary expertise and competence may not be available in the company to deploy the standards. In order to address this hard

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[8] Energy efficiency may refer to efficient energy use, energy conversion efficiency, and energy conservation.
[9] Material efficiency means providing material services with less material production and processing.
[10] Methodology is defined as a collection of related processes, methods, and tools.
[11] By footprint we mean a generic measure of energy and material resource used and/or consumed.
[12] Gate-to-gate is a partial LCA looking at only one value-added process in the entire production chain. Gate-to-gate modules may also later be linked in their appropriate production chain to form a complete cradle-to-gate evaluation.
[13] http://www.whitehouse.gov/sites/default/files/microsites/ostp/advanced-manuf-papers.pdf
[14] http://www.nist.gov/customcf/get_pdf.cfm?pub_id=905837
[15] SMART 2020 report http://www.smart2020.org/_assets/files/02_Smart2020Report.pdf

problem, the methodology thrust will focus on the development of the measurement science, and the integration thrust will focus on the deployment.

How is it solved today, and by whom?

The problem is not solved, as many of the fundamental and measurement science research issues are underdeveloped. As far the methodology thrust, an increasing number of U.S. manufacturing companies are realizing the importance of implementing sustainability practices in manufacturing operations[16]. There is, however, no systematic, generalized approach to doing the assessment based on measurement science. Furthermore, changes are implemented with limited understanding of their broader sustainability impacts[17]. This typically results in local optimization that can miss opportunities and potentially cause larger, unintended, negative consequences.

With respect to the integration thrust, international research efforts in the European Union (EU), Japan, and South Korea are promoting energy and material efficiency through a list of directives that require the elimination of toxic materials, a reduction in waste going to landfills, and improvements in energy usage. They are also making significant investments for research and technological development[18] in sustainability-related research, innovation, and education. CIRP[19] Working group on Life Cycle Engineering and Assembly (Scientific Technical Committees STC-A) is developing Life Cycle Inventory (LCI) data as required for systematic Life Cycle Assessment (LCA) studies, covering the production stage of individual products[20]. The United Nations Environment Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC) International Life Cycle Initiative[21] is an effort to build guidance on LCI data collection and data processing into databases for widespread use in LCA models. Finally, many EU countries, Japan, and South Korea have also incorporated mandatory performance targets and provide financial incentives to help companies meet those targets.

Why NIST?

This program is aligned with the EL mission to promote U.S. innovation and industrial competitiveness in areas of critical national priority. It is also aligned with the *"Sustainable and Energy-Efficient Manufacturing, Materials, and Infrastructure"* strategic goal. The program researchers have developed extensive measurement science expertise in life cycle assessment, product and process information modeling, interoperability of engineering applications, best practice guidelines, and standards-related research. All are necessary to implement the technical idea and research plan described below. The U.S. Congress, in passing The America COMPETES Reauthorization Act of 2010[22], SEC. 408. Green Manufacturing and Construction, mandated NIST to *"develop accurate sustainability metrics and practices," "to advance the development of standards, including high performance green building standards,"* and *"create an information infrastructure to communicate sustainability information about suppliers."*

What is the new technical idea?

To address the needs of industry, the program will develop a footprint[23] methodology for analysis and synthesis (allocation) of the energy and material footprint at the factory level for gate-to-gate life cycle impacts. Cradle-to-gate is an assessment of a partial product life cycle from resource extraction (*cradle*)

[16] http://www.nist.gov/customcf/get_pdf.cfm?pub_id=905837
[17] Sustainability: Embracing Change, Manufacturing Trends, August 22, 2011, Vol. 19, No. 26, www.nacfam.org
[18] The European Union's Seventh Framework Program - http://cordis.europa.eu/fp7/home_en.html
[19] The International Academy for Production Engineering takes its abbreviated name from the French acronym of College International pour la Recherche en Productique (CIRP)
[20] http://www.mech.kuleuven.be/co2pe!/index.php
[21] http://www.estis.net/sites/lcinit/
[22] http://www.govtrack.us/congress/bill.xpd?bill=h111-5116
[23] by footprint we mean a generic measure of energy and material resource used and/or consumed

to the factory gate. Gate-to-gate is a partial LCA looking at only one value-added process in the entire production chain. The end-of-life disposal step for the product is a recycling process. In this phase of the program we will focus on design to manufacturing of a product for the gate-to-gate life cycle analysis and synthesis. In the latter phases of the program we will include cradle-to-gate and gate to end-of-life cycle studies. Such a methodology will enable the computation of energy efficiency and material efficiency across different product life cycles. The analysis aspect of the methodology will enable the composition of energy and material footprint from the unit processes level, product assembly processes level to the factory level for a particular product under consideration. This analysis can then be applied to different factories and factory-to-factory to compute the footprint at the production network level. The synthesis aspect of the methodology will enable allocating the total energy and material footprint from the factory level to product assembly process level to unit processes level and down to the product design specification level. This synthesis can then be repeated at different factories that are part of the production network. The analysis and synthesis will also enable *"what-if"* evaluations at the product design stage to provide manufacturers with early insight into the life cycle impacts of a product stemming from the design stage and help to mitigate the sustainability impact of products while also opening up opportunities for cost savings and product efficiencies. The analysis aspect of the methodology will be the major focus in Fiscal Year (FY) 2013 and the synthesis aspect will be the major focus in FY 2014.

The program has two measurement science thrusts: (1) methodologies for characterizing sustainable processes and resources, and (2) integration framework for sustainable manufacturing. Apart from the overall footprint methodology, there will be sub-modules of this methodology for characterizing unit-manufacturing processes, and product assembly processes with respect to energy and materials. These characterizations will be used to predict energy and material assessments for those processes. This will provide information composition and decomposition for computing the energy and material footprint for manufacturing at factory level for a particular product. This methodology can then be repeatedly applied to different factories to compute the footprint at the production network level. These assessments can finally be used as criteria for evaluating design, material, and process decisions by industry. In the integration infrastructure thrust, we will develop a testbed to support verification and validation of the energy and material footprint at the factory level for gate-to-gate life cycle impacts and standards based on real manufacturing scenarios. We will also develop an integration architecture that will allow industry to utilize the testbed to evaluate analytical computations based on traceable measurements.

Why can we succeed now?

There is a heightened awareness of the economic and competitive importance of sustainable manufacturing technologies by U.S. manufacturing industry. Concurrently, there is an emerging body of research results that will support incorporating sustainability considerations (including an increasing number of indicators, and their associated weighting and uncertainty factors) in manufacturing processes. Recent studies conducted by Harvard Business School[24] and the MIT Sloan School of Management[25,26] concluded that sustainable product and process development across all industry sectors *"is essential to remaining competitive."* Further, industrial organizations that predict and plan for a sustainable future are more likely to survive into the next generation[27]. There has also been an increased effort by the manufacturing sector to collect sustainable manufacturing information using energy management systems, data collection systems, material declaration systems, and best practices. To succeed now, many manufacturing companies are leveraging the efforts and results from lean manufacturing initiatives. A company familiar with lean principles will easily grasp sustainability. Lean principles can be leveraged to better understand environmental impacts and there is a window of opportunity for environmental

[24] Why sustainability is now the key driver of innovation, Harvard Business Review, Sept. 2009, pp. 56-64
[25] MIT Sloan Management Review Special Report, http://www.mitsmr-ezine.com/busofsustainability/2009#pg1
[26] MIT Sloan Management Review, 2011, http://sloanreview.mit.edu/feature/sustainability-advantage-executive-summary/
[27] Towards a sustainable industrial system, http://www.ifm.eng.cam.ac.uk/sis/industrial_sustainability_report.pdf

considerations when companies are embarking on lean initiatives and investments. The research issues and challenges from transitioning from lean to sustainable manufacturing provide an excellent opportunity to address the measurement science needs for sustainable manufacturing[28]. This, coupled with advances in multi-scale physical modeling, engineering information systems, information modeling, integration technologies, and decision support methodologies, provides the critical foundation for success in characterizing manufacturing processes and aid performance assessment and decision making at all levels. Also, EL staff has the necessary mission, expertise, and relationships with key industry stakeholders and standards development organizations necessary to further the advances and trends.

What is the research plan?

The research plan is organized into two main thrusts and five research projects. In this program, a sustainability metric is a value that measures some aspect of sustainability, especially energy and material efficiency and waste reduction. Characterization is the process of using a computational method to compute that value.

The **Methodologies for Characterizing Sustainable Processes and Resources Thrust** focuses on (1) defining, computing, and composing sustainability metrics of unit and assembly processes and (2) using those metrics in life-cycle predictions and decisions. In this phase of the program, we will focus on the early stages of the life cycle – design through production. The thrust has three major projects:

1. **Sustainability Metrics for Design and Manufacturing**: This project will focus on three crucial aspects of the sustainability problem as it relates to manufacturability: (1) a generic product structure to support smart process decisions, (2) methods for integrating material properties into downstream life-cycle processes, and (3) an approach for developing a standard reference vocabulary to support sustainable manufacturing.
2. **Sustainability Characterization for Unit Manufacturing Processes**: This project will develop a science-based assessment methodology for characterizing unit manufacturing processes (UMP) with respect to energy and materials. The methodology will provide the manufacturing industries a well-defined procedure to characterize any specific manufacturing process so that they can build a repository of UMPs. The project will further facilitate the development of a structured information base by enabling a standard reference model for UMPs.
3. **Sustainability Characterization for Product Assembly Processes:** This project will develop a science-based assessment methodology for characterizing assembly processes with respect to energy and materials. The methodology will provide the manufacturing industries a well-defined procedure to characterize key assembly process. If the components that go into the assembly come from other suppliers in the production network, this project will compute and include any material or energy impacts associated with the logistics necessary to transport those components.

The **Integration Infrastructure for Sustainable Manufacturing Thrust** focuses on sustainability modeling and optimization techniques and testbed based on real manufacturing scenarios. To enable that integration, the thrust will develop an information framework that includes commercial software tools. That framework is needed to (1) define, declare, track, and exchange sustainability metrics and (2) analyze, and optimize the processes that generate those metrics. The thrust has two projects:

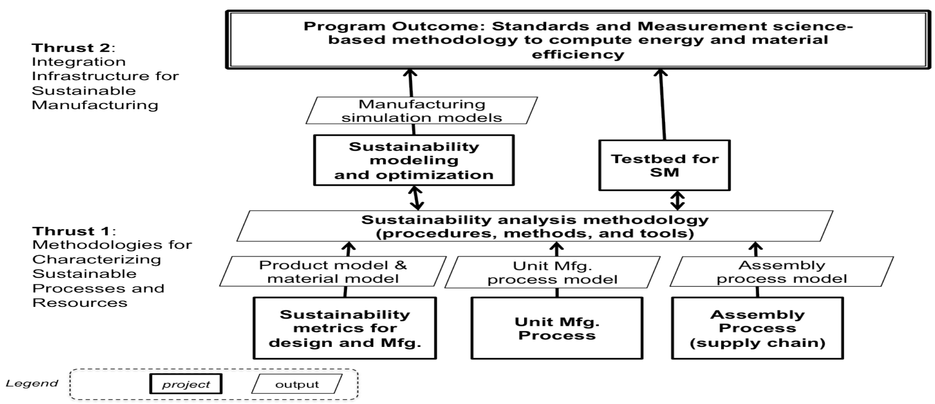
4. **Sustainability Modeling and Optimization:** This project will develop a formal representation of manufacturing use scenarios and framework that integrates multiple standalone methodologies and associated applications for assessing and reporting sustainability information. The framework will meet both the internal integration needs of sustainable manufacturing projects and external needs for industry to integrate engineering tools involved in sustainability assessments.
5. **Testbed for Sustainable Manufacturing:** This project will develop real manufacturing use scenarios at the factory level. The scenarios, developed through industry collaboration, will demonstrate the use of program deliverables, deploy the metrics and measurement science, and assess sustainability

[28] http://www.epa.gov/lean/environment/pdf/leanreport.pdf

performance. Initially the testbed will be used to validate, and integrate results from the other projects within this program. Eventually, the testbed will be used to test and evaluate use of the metrics and methods by manufacturing industry.

How will teamwork be ensured?

The program staff is drawn from Systems Integration Division (SID) and Applied Economics Office (AEO). The individual project plans provide details of the coordination of research activities and external collaborations through CRADAS, cooperative research agreements, contracts, and SBIRs. These plans also include details for collaborations within EL and also across NIST OUs such as ITL, and MEP. This program will closely work with (1) the Smart Manufacturing Processes and Equipment program for work related to methods to evaluate energy efficiency of machining equipment, (2) the Next-Generation Robotics and Automation program for work related to measuring energy efficiency of a robotic assembly, and (3) the Systems Integration for Manufacturing and Construction Applications for work related to production networks. The program will host Sustainable Manufacturing Seminar series to get external inputs from outside experts and thought leaders. The program staff is actively involved in the NIST Caucus on Sustainable Manufacturing. The overall objective of the program will be delivered through the outputs, outcomes and impacts from the projects under these two thrusts as shown in the figure below.



What is the impact if successful?

U. S. industry consumes approximately 30 quadrillion BTU of energy per year– almost one third of all energy used in the United States. U.S. uses a hundred million billion BTUs of energy each year for all sectors and 57% of that is wasted[29]. There is a huge potential for energy savings, but to do better we need strong measurement science. It is essential that U.S. manufacturing industry achieve significant increases in energy and material efficiency, while also creating value and enhancing competitiveness. This program will provide analysis capabilities that identify opportunities to improve resource efficiency. Further, advancing manufacturing measurement science will act as a catalyst for the growth and development of new industries in the U.S., as reported in the recent Business Round Table report[30].
Impacts anticipated:

Methodology Thrust:

- Improved manufacturing industry energy and material efficiency at the supplier, plant, equipment, and product levels using the measurement science-based methodology.
- Improved supply chain competitiveness achieved through the deployment of the measurement science-based methodology, standards, metrics and optimization techniques focusing on energy, material, and waste within these chains and overall costs.
- Improved manufacturing information systems achieved through standards, seamless software tools integration and knowledge capture.

[29] *http://www.eia.gov/totalenergy/data/monthly/pdf/sec2_3.pdf*
[30] http://businessroundtable.org/uploads/studies-reports/downloads/2012_04_18_BRT_Sustainability_Report_FINAL_1.pdf

Integration Thrust

- Improved U.S. manufacturing industry sustainability performance through the use of testbed to verify their modeling and optimization techniques.
- Continuous improvement through enhanced analysis and optimization capabilities. The economic return – for any company willing to embrace the values of sustainability – in operational efficiencies and the achievement of cost savings for re-investment into new technologies.[31]
- Improved engineering information exchange utility to **B**uilding for **E**nvironmental and **E**conomic **S**ustainability (BEES) and other analysis applications for incorporating specific industry manufacturing data derived from plant floor and supplier operations with other databases.

What is the standards strategy?

Our current strategy is to pursue the development of sustainability-related standards through the ASTM E60[32] Committee, which is currently focused on infrastructure/buildings standards. We have proposed a new subcommittee on manufacturing and a number of working groups and it is approved. The proposed work items under ASTM E60 are already getting wide support from industry[33]. We will serve in a leadership/convener role in the working groups. All of the projects in this program will be performing the underlying research necessary to support the standard activities within those groups. This program identified the following new standards development needs for methodology and integration thrusts and the fiscal years by which they will be developed.

Methodology Thrust:

- Key terminologies, and concepts, to categorize and prioritize sustainability metrics (FY13).
- Standard methods and supporting tools that will enable manufacturers to characterize their manufacturing unit processes and assembly processes and contribute these models to an open library of standard manufacturing unit processes (FY14). Extend these models from part level to the product assembly level with defined measurement uncertainty quantification (FY15).
- Standard for material and energy information and associated product manufacturing information to enable the computation and comparison of energy and material efficiency metrics within a manufacturer and across the supply chain (FY15).

Integration Thrust:

- Integration architecture and data integration procedure to enable simulation and optimization of energy and material efficiency and waste elimination (FY 15).
- Sustainable manufacturing testbed made accessible to manufacturing industry partners to evaluate analytical computations and simulations to verify and validate real manufacturing use scenarios to deploy metrics, and standards at the factory level (FY 16).
- Measurement science for product declaration based on Product Category Rules (PCRs)[34] and third party verification and validation to reduce the trust gap between claims and performance. (FY 16)

We are aware of parallel standards development efforts in ISO. The ISO 50000, ISO 14020, 14040 and 14060 series cover various aspects of sustainability. The ISO 50000 series focuses on energy management; ISO 14020, 14040 and 14060 series focus on life cycle analysis. Our current strategy is to follow closely what is happening in these standards and to establish liaisons between the new ASTM-E60 subcommittee and the corresponding ISO subcommittees. As standards are developed in ASTM, we will consider using the ISO process to make them available in the international standards arena.

These standards will impact the way industry (1) measures energy and material efficiencies at the supplier-, plant-, equipment-, and product-levels, (2) evaluates the energy efficiency of their existing, and potentially new, manufacturing processes, and (3) assesses the sustainability of their products and

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[31] Sustainability: Embracing Change, Manufacturing Trends, August 22, 2011, Vol. 19, No. 26, www.nacfam.org

[32] http://www.astm.org/COMMITTEE/E60.htm

[33] The Toronto Specifier, Series 39, Edition 7, March 2012. http://toronto.csc-dcc.ca/img/content/march_2012_specifier_-_new.pdf

[34] These are the detailed instructions on how to perform the LCA for product declarations - A Roadmap to Environmental Product Declarations in the United States, *www.lcacenter.org/pdf/Roadmap-to-EPDs-in-the-USA.pdf*

determines the complete listing of materials required to produce a product. Finally, our efforts will be a catalyst for the collection of traceable data for energy and material standards, and third party verification and validation to reduce the trust gap between claims and performance.

How will knowledge transfer be achieved?
Knowledge transfer will be accomplished through (1) technical publications, workshops and conferences, scientific and technical societies, technical efforts in standards development organizations and standards, development of best practices, and (2) collaborations (formal and informal) with MEP, academia, industry, consortium, other national labs, and international partners. Industries partners and collaborators include Stanley Black and Decker, Boeing, GM, GE, Ingersoll-Rand, Caterpillar, Ford, 3M, Dow, Procter and Gamble, Xerox, PTC, Siemens PLM, Dassault System. Academic collaborators include George Washington University, George Mason University, Stanford University, Syracuse University, University of California Berkeley, Pennsylvania State University, and University of Maryland – College Park.

Major Accomplishments:
- Sustainability Standards Portal.
- A materials data model for the IPC[35] 1752 Material Declaration Standard[36], one of the earliest sustainable manufacturing standards, has been widely used by the U.S. manufacturers.
- A new sub-committee on manufacturing under ASTM E60 is approved.

Recognition of EL:
Sudarsan Rachuri is elected as ASME fellow.
NIST Sustainability Standards Portal: Department of Commerce International Trade Administration recognized NIST EL's work by creating a link to the NIST Sustainability Standards Portal. This work was highlighted in NIST Techbeat[37] and ASME[38].
IPC 1752 Material Declaration Standard: The most downloaded standard from the IPC web site in 2010, and the NIST researchers involved in this standard were recognized with a Rosa award and a Bronze medal.

[35] In 1999, IPC changed its name from Institute for Interconnecting and Packaging Electronic Circuits to IPC.
[36] http://www.ipc.org/ContentPage.aspx?pageid=Materials-Declaration
[37] http://www.nist.gov/public_affairs/tech-beat/tb20110426.cfm
[38] ASME Mechanical Engineering Magazine, August 2011