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A Systems Approach to High Performance Buildings

R&D Elements Needed to Increase Energy Efficiency in Buildings

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Pushing the Efficiency Envelope: R&D for High Performance Buildings, Industry and Consumers

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Summary

The building sector consumes about 40 percent of the energy used in the United States and is responsible for nearly 40 percent of greenhouse gas (GHG) emissions.

In addressing GHG reductions in the building sector the Department of Energy (DOE), in collaboration with the private sector, should continue to develop and deploy energy efficient building components (lighting, heating, ventilation, air conditioning and other elements.) At the same time, there is an important push for research and development in science and technology to understand and optimize a whole building via a "systems" approach that ensures that efficiency gains are properly designed and also sustained during building operation.

UTC is one of the largest capital suppliers to the building industry worldwide. As such, the development of both sustainable and energy efficient products is of critical importance to UTC, its suppliers and the markets and customers that it serves. UTC takes an active industry role in addressing building energy usage. Key findings of the three year World Business Council for Sustainable Development (WBCSD) project on Energy Efficiency in Buildings (EEB), for which UTC is a co-chair, are that transformation of the building industry is essential to achieving the 77% reduction of carbon emissions called for by the Intergovernmental Panel on Climate Change (IPCC). The transformation of the building sector to reach the carbon emissions goal can occur only through a combination of public policies, technological innovation and informed customer choices. These reductions require:

- Mandated federal building codes that recast regulation for increased transparency on energy use; and
- Ensuring buildings operate as designed by developing and using smart technology to enable and assure continued energy saving behaviors.

Among the key recommendations are:

- Creation and enforcement of building energy efficiency codes and labeling standards
- Incentivizing energy-efficient investments
- Encouraging integrated design approaches and innovations
- Funding energy savings technology development programs
- Developing workforce capacity for energy saving
- Mobilizing for an energy-aware culture

The current design, construction, commissioning and operation phases of the delivery process for buildings allows for efficiency decay that often fails to deliver optimal energy savings. Achieving approximately 80% energy reduction in buildings requires new research and development (R&D) investments in a systems approach to design and operations.

Two types of R&D investments are needed to attack the sources of energy efficiency decay: (1) investments in computational capabilities with specific attention to modeling, analysis, simulation and control of buildings and (2) targeted programs to combine fundamental science &

technology with market impact to address specific market verticals in a Defense Advanced Research Projects Agency (DARPA) style model of projects.

The R&D initiatives to enhance building efficiency and functionality are only one element of a comprehensive national strategy to achieve net zero energy buildings. Other elements should include: the use of Energy Savings Performance Contracts (ESPC); mandated and regular energy audits; implementation of a national performance-based retrofit program; the establishment of a national energy efficiency standard; support for demonstrations and deployment of emerging technologies and products; education and workforce training; development of a building technology roadmap; and financial incentives.

Introduction

As the House Science and Technology Committee considers R&D needs for high performance buildings, United Technologies Corporation (UTC) offers recommendations on cost effective, innovative and environmentally friendly ways to address energy efficiency using a whole building or a "systems" approach.

UTC ranks #37 on the latest Fortune 500 listing and is one of 30 members of the Dow Jones Industrials. Our 2008 revenues were $58.7 billion. UTC products include: Carrier heating, air conditioning and refrigeration; Otis elevators and escalators; Pratt & Whitney aircraft engines; Sikorsky helicopter; Hamilton Sundstrand aerospace systems and industrial products; UTC Fire & Security systems; and UTC Power fuel cells. We are a company of innovators and pioneers. Elisha Otis invented the safety elevator that made multi-story buildings usable; Willis Carrier invented modern air conditioning – just to mention two examples. So, as one of the largest suppliers to the global building industry and a leader in energy reduction, both in our own operations and through energy efficient innovations in our products and services, UTC brings a credible voice to the policy debate.

UTC takes an active industry role in addressing building energy usage. As a co-chair of the three-year long World Business Council for Sustainable Development (WBCSD) project on Energy Efficiency in Buildings (EEB), along with thirteen other major multinational corporations representing various aspects of building design, construction, delivery and operations, UTC is working to identify the barriers, levers, and necessary actions to achieve market transformation and a much needed pathway to net zero energy buildings (NZEB) – those buildings that, over a period of a year, consume no energy. Among other important findings is the fact that professionals in the building industry have widely *underestimated* the impact of buildings on carbon emissions (by a factor of two) while significantly *overestimating* the cost of sustainable construction (by a factor of three). This knowledge gap is just one of several barriers to market transformation of the building sector.

The EEB report released on April 27, 2009 finds that transformation of the building industry to achieve the IPCC 77% reduction of carbon emissions would require:

- Mandated building energy codes that recast regulation for increased transparency on energy use; and

- Ensuring buildings operate as designed by developing and using smart technology to enable and assure continued energy saving behaviors.

The EEB report recommendations can be summarized as:

- Create and enforce building energy efficiency codes and labeling standards
    - Extend current codes and tighten over time
    - Display energy performance labels
    - Conduct energy inspections and audits on a regular basis (not one time). This supports the continuous commissioning process now gaining favor among advanced energy users.
- Incentivize energy-efficient investments
    - Establish tax incentives, subsidies and creative financial models to lower first-cost and technology adoption hurdles
- Encourage integrated design approaches and innovations
    - Improve contractual terms to promote integrated design teams
    - Incentivize integrated team formation
- Fund energy savings technology development programs
    - Accelerate rates of efficiency improvement for energy technologies
    - Improve building control systems to fully exploit energy saving opportunities
- Develop workforce capacity for energy saving
    - Create and prioritize training and vocational programs
    - Develop "system integrator" profession
- Mobilize for an energy-aware culture
    - Promote behavior change and improve understanding across the sector
    - Businesses and governments lead by acting on their building portfolios

Examples of UTC Energy Efficient Building Technologies

Increasing efficiency in buildings boosts productivity through the reduction of energy costs. Developing better products that improve energy efficiency offers new market opportunities. In 2006, George David, at that time the CEO and Chairman of UTC, spoke at the WBCSD meeting in Beijing:

> *"The lessons I bring from UTC are that we can always reduce costs and increase productivity and performance. The same is true for environmental impacts and potentially to an even greater degree because companies generally haven't worked at these as hard as they have at costs and corporate profitability. Remember that more than 90 percent of the energy coming out of the ground is wasted and doesn't end as useful. This is the measure of what's in front of us and why we should be excited."*

In addition to our collaborative efforts within the WBCSD, UTC is also engaged in developing energy efficient products for buildings including:

- Otis' Gen2 elevators with regenerative drives: Up to 75 percent more energy efficient than comparable equipment a decade ago, the Gen2 sends its excess power back to the building's electrical grid.

- Carrier's Evergreen tri-rotor screw chiller: The world's most efficient water-cooled chiller delivers 40 percent higher efficiency than current ASHRAE 90.1 efficiency standards.

- Carrier and UTC Power's combined heat and power (CHP) products: These products put "waste heat" from prime movers, such as fuel cells and microturbines, to productive use by driving heating, ventilation and air conditioning equipment, boosting efficiency from around 33 percent based on the individual components to nearly 80 percent in the total integrated system. Locating the system at the point of use allows the building to productively use the waste heat and avoid transmission line losses. The onsite attribute is a key component of optimizing the system's performance.

A number of investments have been made at UTC and a number of federal and state programs that can be utilized to move to increased energy efficiency in buildings. The UTC experience in deploying and supporting energy efficient products to the global building sector and providing a range of energy services has convinced us that a systems approach will result in even greater gains.

Understanding Energy Losses in The Delivery Process: Targeting R&D

Achieving energy savings through increasing building efficiency gains represents a tremendous opportunity. The building sector consumes about 40 percent of the energy used in the United States and is responsible for nearly 40 percent of greenhouse gas emissions. For comparison, the entire transport sector represents only 28 percent of energy use. A 50 percent reduction in buildings' energy usage would be equivalent to taking every passenger vehicle and small truck in the United States off the road. A 70 percent reduction in buildings' energy usage is equivalent to eliminating the energy consumption of the entire U.S. transportation sector. These levels of energy reduction in buildings are achievable but the United States today lacks the market drivers as well as the underlying science and technology infrastructure (including scientific and engineering workforce) to broadly realize these levels of efficiency improvements in cost-effective ways. Setting a targeted and aggressive R&D agenda is necessary to position the United States effectively and a well-executed R&D agenda is critical to increasing the competitive position of the United States.

The building sector is made up of multiple stakeholders and decision makers, including state & local government regulators, builders, architects, service and repair companies, owners, realtors, product manufacturers and energy suppliers. The delivery process for buildings can be divided into design, construction, and maintenance phases. It is important to highlight how energy efficiency losses occur in this process[1].

[1] [1] Throughout each of these stages, the influence of federal, state, and local regulation should be acknowledged. Current design and construction protocols, implemented through myriad building and other codes and regulations, can have an enormous impact on building energy performance.

Owners, architects and architecture & engineering firms set the building design and consider their usage, aesthetics and the energy consumption. The design stage has the highest leverage in the overall delivery process by selecting the architecture and constraining the overall design space. The selection of design elements can significantly enhance – or limit – the ultimate performance depending on how these elements interact. For example, increasing daylighting can influence the amount of lighting that is needed which in turn affects the overall heating and cooling load. These interactions can alter the energy consumption in beneficial or detrimental ways.

The next stage of delivery is construction. Here, components are considered against cost and schedule targets, and typically do not capture the integrated elements of design that are key to efficient energy performance of the whole building.

The last stage, or two stages, relate to the so-called commissioning and post-occupancy, or operations phase of the building. Commissioning should start during design and not just at the tail end of construction. The point to highlight here is that the design intent must be verified and the operations must ensure persistence of design intent.

As a result the current delivery process has energy efficiency losses at four points, outlined below, which represent major barriers to achieving the energy performance transformation required in the broad building stock:

1. **Design:** Inadequate design exploration and the efficacy of the tools that can be deployed for critical trade studies;
2. **Construction:** Inadequate coupling of design intent to value engineering needed to maintain the energy performance intended by design;
3. **Commissioning**: Ensuring that the construction process and installation have been faithful to the design intent with respect to whole building energy performance and not just functional tests at a component level;
4. **Operations**: Ensuring persistence of the design intent as components age and the building changes usage due to movement of tenants and different occupant needs and as operators override the intended operating sequences.

It is critical to understand where energy efficiency is lost to be able to target R&D.

R&D Elements For A Systems Approach

A systems approach can reduce the energy efficiency losses by identifying and controlling the interactions among building subsystems. In this way it is possible to drive down energy consumption dramatically and to ensure that these energy savings persist. It is critical, though, to understand that the substantial science & technology base to reliably and in a cost effective manner realize such savings in the market simply does not exist today.

Two basic flaws in the current design and operation of buildings contribute to poor energy performance. First, the design and construction of commercial buildings do not utilize metrics or tools to identify and quantify critical interactions, or "coupling," between subsystems. Computational tools are not used initially in the design phase nor are these couplings tracked during the changing construction process. Second, the coupling between subsystems are neither monitored nor controlled to avoid the erosion of performance in operation of the building.

The reality of today's methodology and tools is that attempting to couple subsystems – even using higher performance (efficient) components than are routinely used today – does not regularly deliver the levels of efficiency gains needed and, in some cases, produces negative effects from improper integration. Case studies show that even new buildings that are constructed with state-of-the-art "energy efficient" technologies can fail to achieve desired levels of efficiency due to the detrimental coupling of modified subsystems. A study of high performance buildings by the National Renewable Energy Laboratory (NREL) demonstrated that even with a range of advanced component technology (ground source heat pumps, an under floor air distribution system, daylighting, and high performance windows), when the systems were not properly integrated, the building measured a 44 percent reduction ratio versus 80 percent when all components were fully integrated. Unfortunately, the NREL results are not atypical and represent a significant barrier to wide scale adoption of high-performance integrated building systems.

The systems approach considers a building as a complex dynamic system that has considerable uncertainty in both operating parameters and the operating environment. Indeed, the Brown report[2] states:

A complex system is a collection of multiple processes, entities or nested subsystems where the overall system is difficult to understand and analyze because of the following properties:

- *The system components do not necessarily have mathematically similar structures and may involve different scales in time or space;*
- *The number of components may be large, sometimes enormous;*
- *Components can be connected in a variety of different ways, most often nonlinearly and/or via a network. Furthermore, local and system-wide phenomena may depend on each other in complicated ways;*
- *The behavior of the overall system can be difficult to predict from the behavior of individual components. Moreover, the overall system behavior may evolve along qualitatively different pathways that may display great sensitivity to small perturbations at any stage.*

Such systems are often described as "multi-component systems," or when the components are physics based, "multi-physics systems." When the components involve multiple spatial or temporal scales, the adjective ``multi-scale'' can be used as well.

[2] D. L. Brown, J. Bell, D. Estep, W. Gropp, B. Hendrickson, S. Keller-McNulty, D. Keyes, J. T. Oden, L. Petzold, and M. Wright. Applied Mathematics: A Report by an Independent Panel from the Applied Mathematics Research Community. Technical report, Lawrence Livermore National Laboratory, 2008.

The challenges for buildings reflect precisely those stated for complex systems: to predict the overall behavior, which depends critically on the coupling of the subsystems, and the uncertainties in the built environment.

The coupling of components is difficult to achieve and requires the development and use of new science and engineering approaches to avoid the detrimental coupling discussed in the NREL work mentioned above. New science, design methodologies and tools will then be used to capture the complex couplings, enable the deployment of technologies that can take advantage of the natural dynamics of the building (*e.g.*, natural ventilation, free cooling, and thermal storage).

More specifically, what is needed for targeted R&D relative to the picture of energy efficiency losses and the benefits of a systems approach for complex dynamical systems. In our view several specific R&D elements at the science & technology level should be established. We believe these recommendations are necessary in order to meet the challenge laid out by Secretary of Energy, Dr. Steven Chu, in his March 2009 testimony before the U.S. House of Representatives Committee on Science and Technology wherein he states:

We need to do more transformational research at DOE to bring a range of clean energy technologies to the point where the private sector can pick them up, including: Computer design tools for commercial and residential buildings that enable reductions in energy consumption of up to 80 percent with investments that will pay for themselves in less than 10 years; and…

Computational R&D Thrusts

The foundational elements UTC believes will support this vision are computational support for design, optimization and control. Attention to modeling, analysis, simulation and control is also advisable along the following directions:

- **Systems Engineering and Design Methodologies**
  - Rigorous and scalable process and tool environment for building project requirements management & system architecture exploration
  - Integrated mechanical and control design methodology and simulation environment
  - Architectural exploration tools with rigorous capture of performance uncertainties

- **Optimization and Control of Multi-scale Dynamics**
  - Analytical techniques for system decomposition, analysis and uncertainty propagation in heterogeneous, networked, multi-scale building systems
  - Optimization and simulation techniques for multi-scale computations
  - Nonlinear dynamical systems theory tools to exploit natural dynamics

- **Robust Control and Decision Support Algorithms**
  - Control and Commissioning Systems
  - Supervisory and de-centralized control theory and algorithms

- Estimation and machine learning techniques to synthesize actionable information from heterogeneous, asynchronous and uncertain data streams
- Automated fault detection and diagnostic (FDD) capabilities using building automation systems

The focus here is on computational capabilities. Hardware testbeds should be used to validate models and capture the relevant physics for subscale experiments to provide environments where subsystem interactions can be captured in a controlled environment, and help identify gaps in existing components. There should be a range of testbeds which move from subscale to full scale systems. The testbeds are also a critical element to enable teaming between academic, National Laboratories and industry and to facilitate adoption of new technologies by end users.

It is worth emphasizing that these areas of R&D targets are not unfamiliar to other industries[3]. In the aerospace and automotive sectors, performance requirements have driven both investments in underlying science & technology along the lines of computational support for design, optimization and control along the lines listed above.

UTC has partnered with numerous federal and state agencies to further technology and standards development. In particular the United Technologies Research Center led, proposed and executed a National Institute of Standards & Technology (NIST) Advanced Technology Program project, “Integrated Building Energy and Control Systems (IBECS),” that focused on system-level modeling and simulation environments as a means of understanding and reducing building energy consumption. UTC is developing advanced control and information systems to improve energy efficiency in buildings using a systems approach to building modeling and operation in collaboration with Lawrence Berkeley National Laboratory, the University of California at Berkeley, and the University of California at Santa Barbara, and seeks to demonstrate those technologies on the University of California at Merced’s campus. This program, co-sponsored by DOE’s Energy Efficiency & Renewable Energy, the California Energy Commission, and UTC, represents an example of multi-disciplinary teams composed of industry, academia and National Laboratories. The program’s work is also an example of full scale demonstrations that must be carried out to enable risk reduction of new technologies in building energy performance but that utilize foundational science & technology.

In addition to the development of science & technology, a number of UTC business units participate in standards bodies. Work in interoperability with the BAC-net[4] standard has been led by Automated Logic Corporation (ALC) while engagement with the ASHRAE 90.1 standard has been strongly engaged by Architectural Energy Corporation (AEC), both of which are units of Carrier.

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[3] See for example the PITAC report “Computational Science: Ensuring America’s Competitiveness,” June 2005.

[4] BACnet is a data communication protocol for building automation and control networks. BACnet was developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) to create a protocol that would allow building systems from different manufacturers to interoperate.

R&D Thrusts to Fuse Foundational Science & Technology with Market Transformation

The building industry in the area of energy consumption lags behind other industries in the use of computation, theory and information technology. Also, while the automotive and aerospace industries serve as a starting point in what is needed for the science & technology base, much work needs to be done to understand the relevant physics, capture the physics into appropriate modeling tools, and develop computational and analysis algorithms. Furthermore, additional work is necessary to tailor research to the needs of buildings and to enable a work force that can effectively use the new methodology and tool set. These efforts transcend any one company and are therefore appropriate for DOE investments.

Computational infrastructure is critical to remove points where energy efficiency is potentially lost and to enabling cost effective scaling of new design processes such as the Integrated Project Delivery approach for concurrent engineering advocated by the industry.[5] This R&D thrust by itself, though, is not enough to achieve transformational change. We believe that DARPA style investments, such as those that could be accomplished within the Office of Science in the newly created ARPA-E organization, are also necessary. We believe that large, multi-institutional, focused teams with specific milestones and aggressive metrics are necessary to advance energy performance enhancement solutions. One area that could utilize such investments is the design and operation of retrofits. In this area investments are needed that develop and utilize science & technology but also include prototyping and technology demonstration at scale.

In the area of retrofitting, R&D targets should include similar elements to those recommended above for the computational development but should target specific technologies and increase the performance of targeted market verticals. Elements of such an R&D program should include the following

- Building performance assessment
  - Need: Process and tools for rapid failure mode assessment, sensing, model calibration, and analysis of the lack of building performance.
  - Response: Mathematical tools, measurement systems, scalable algorithms and application (for example focusing on DoD, GSA, and university campuses).
- Design of systems for effective and robust retrofits
  - Need: Process and tools for trade studies and optimization of multi-scale dynamic systems (focusing especially on emerging technologies: active facades, natural ventilation, passive heating and cooling technologies).
  - Response: Tools (integrated within BIM) and application.
- Robust and persistent implementation
  - Need: Modular platforms (equipment *and* controls) and decision support (for rapid implementation and performance persistence).
  - Response: Scalable, simple-to-use toolset, DoD/GSA/campus implementation.

[5] Integrated Project Delivery: A Guide, The American Institute of Architects, 2007.

In summary there should be two types of R&D investments to attack the sources of energy efficiency loss. One is investments in computational infrastructure. The other is large, targeted programs to attack specific issues and market verticals and to couple the science & technology with demonstrations.

We believe that a heavier focus on fundamentals in the R&D portfolio than has occurred in the recent DOE history is required to move the needle on energy consumption in buildings. We believe that the two specific thrusts above are needed in addition to tighter coordination between elements of DOE, specifically, the computational resources within the Office of Science and the building domain expertise and demonstrations currently within the Energy Efficiency and Renewable Energy office.

Policy Recommendations: Comprehensive National Strategy

The House Science and Technology Committee must address the potential future contributions that can be made from supporting and overseeing basic and applied scientific research, development, demonstration, commercial application of advanced energy technologies, and energy efficiency. But this is just one piece of the jigsaw puzzle.

In the short term, Congress should take immediate steps to encourage and enhance building efficiency. Specifically, Congress should enact legislation that promotes investment in energy efficiency in the buildings sector, for example *The American Recovery and Reinvestment Act of 2009* provided tax incentives to spur investment in energy efficiency, funding for energy efficiency and green buildings and support for various science and technology programs.

Congress should continue to focus on energy efficiency in buildings as it considers comprehensive energy and climate change policy through a number of relatively short term measures including:

- Use of Energy Savings Performance Contracts (ESPC) that will multiply the job creation potential of recovery funds used for energy efficiency projects, and will ensure those funds are used in a transparent and verifiable manner.

- Establishment of a national performance based standard for building retrofits that measures success in energy efficiency based on actual measured savings after a retrofit is complete.

- Energy audits for existing buildings should be required to ensure that existing property is operating at the highest level of efficiency. All commercial buildings should commit to ongoing (i.e., at least every three years) energy surveys to measure and monitor energy use, and to identify opportunities for improvement.

- Those who invest in reducing energy consumption and demonstrate validated results should be eligible for accelerated deprecation schedules or other financial incentives.

- Establishment of a national energy efficiency standard either as a stand alone requirement or included as a compliance mechanism as part of a national renewable electricity standard to encourage low emission, high efficiency base load energy resources.

- A systems approach to tying these technologies together in commercial buildings and removing regulatory barriers to implementing near- and long-term cost-effective net zero energy building approaches.

In the longer term, UTC believes that in order for investments to fully realize the benefits of whole building design and operation, the DOE and other agencies must address a number of science and technology issues including:

- **Recommendation I: Measurement and Transparency.**
  The federal government, especially the Department of Energy and the National Institute of Standards and Technology, should consider establishing measurement science for building energy performance and devising common measurement standards and metrics to ensure that building energy performance can be effectively evaluated by the marketplace. Such evaluation should include the measurement of energy efficiency at the whole building level both in the design stage, using computational methodologies, as well as in the commissioning and operations stages.

- **Recommendation II: Technology and Organization.**
  The federal government should create specific research programs implemented through private-public partnerships to maximize the effectiveness of technology development and transition. Research and technology investments must be made in *systems*: the creation of system engineering practices and associated design processes and tools. The newly established Advanced Research Projects Agency – Energy (ARPA-E) is supported by UTC and the recommendation is to create an office within ARPA-E whose investments would solely focus on systems methodologies, tools and technologies for building energy efficiency. Projects in the ARPA-E portfolio should be conducted on a multi-year basis with joint university-National Laboratory-industry teams.

- **Recommendations III: Computational Methodology and Tools**.
  The federal government should initiate programs that build foundational infrastructure in modeling, simulation, analysis and controls focused on building systems. The portfolio should include elements that address (a)capturing fundamental physics, (b)developing simulation algorithms and computational infrastructure tailored to building physics and (c) developing analysis tailored to the specific dynamics of the built environment. Automated fault detection and diagnostics would be included in this set of tools.

- **Recommendation IV: Facilities.**
  The federal government should encourage public-private partnerships with incentives to promote facilities that help users validate and test the performance of hardware and software in a real, integrated building environment to reduce risk and enable wide-scale commercialization, particularly for "systems" technologies and solutions. Demonstration

projects to engage key stakeholders in the buildings industry will reduce risk for deployment to the entire building stock. The DOE Energy Efficiency and Renewable Energy program portfolio should be augmented with systems technology and methods should be matured through relevant demonstration programs that are planned and executed with joint multi-disciplinary university-National Laboratory-industry teams.

- **Recommendation V: Talent.**
  The federal government should invest in education and training carried out to define the new knowledge and skills required by the methods, systems, and tools for deploying and maintaining systems. University and government buildings and facilities should be used as case studies and demonstration sites for advanced monitoring, control, simulation models, prototypes, component, and systems research. There must be engagement with all components of post secondary education including professional and vocational training with community colleges and other organizations for building design, construction, commissioning, energy analysis, energy accounting, and operations to ensure a talent base that can design, install and maintain building systems.

Thank you for the opportunity to submit this testimony to the Committee. I would be delighted to respond to any follow up questions regarding this testimony or the recommendations contained within.

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McQuade has held senior positions with technology development and business oversight at 3M, Imation and Eastman Kodak. Prior to joining UTC in 2006 he served as Vice President of 3M's Medical Division. Previously, he was President of Eastman Kodak's Health Imaging Business. Earlier, McQuade held technology and business leadership positions at Imation Corporation after its spin-off from 3M in 1996. His early career at 3M was focused on research and development of high-end acquisition, processing and display systems for health care, industrial imaging and remote sensing. He has broad experience managing basic technologies and the conversion of early stage research into business growth.

McQuade holds doctorate, Master of Science and Bachelor of Science degrees in physics from Carnegie Mellon University. He obtained his Ph.D. in experimental high-energy physics for research on hadronic charm quark production performed at the Fermi National Accelerator Laboratory.

McQuade is a member of the American Physical Society and is a member of the Boards of Directors of the Connecticut Science Center, the Connecticut Technology Council and the advisory boards of the Schools of Engineering at Yale University, the University of California at Berkeley, the University of Connecticut and the Institute for Energy Efficiency at the University of California at Santa Barbara. He is also a member of the Board of Trustees for the Center for Excellence in Education and Board of Directors of Project HOPE.

United Technologies Corp., based in Hartford, Conn., is a diversified company providing high technology products and services to the aerospace and building industries worldwide. Its businesses include Pratt & Whitney aircraft engines, Sikorsky helicopters, Hamilton Sundstrand commercial and military airplane and space-based systems, Carrier heating, air conditioning and refrigeration equipment, Otis elevators and escalators, Chubb and Kidde security and fire detection and prevention systems, and the world leading fuel cell products from UTC Power.