U.S. Department of Energy
Energy Efficiency and Renewable Energy

Assessment Study on Sensors and Automation in the Industries of the Future:

Reports on Industrial Controls, Information Processing, Automation, and Robotics

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Executive Summary

This report presents the results of an expert study to identify research opportunities for Sensors & Automation, a sub-program of the U.S. Department of Energy (DOE) Industrial Technologies Program (ITP). The research opportunities are prioritized by realizable energy savings. The study encompasses the technology areas of industrial controls, information processing, automation, and robotics. These areas have been central areas of focus of many Industries of the Future (IOF) technology roadmaps. This report identifies opportunities for energy savings as a direct result of advances in these areas and also recognizes indirect means of achieving energy savings, such as product quality improvement, productivity improvement, and reduction of recycle.

The IOFs vary significantly in their adoption of advances in the technology areas considered. Although industry players almost always have in mind a goal other than increased energy efficiency when they purchase a new system, energy savings are a common result. Installations, studies, and tools illustrate that adoption of advances in these technology areas to increase overall productivity can also achieve potential energy savings of 2% to 35%.

Individual IOF roadmaps were reviewed to identify, categorize, and generalize needs falling into each of the four technology areas considered: industrial controls, information processing, automation, and robotics. For most technology areas, needs and potential research were prioritized according to improved energy efficiency by combining (a) likely market penetration, (b) industry inclination toward adoption of advanced technology, (c) the percentage of the production process affected, and (d) end user and supplier estimates of current and potential production energy efficiency levels.

The following needs have been identified across all four technical areas and the IOF sectors considered. Projected annual energy savings in trillions of Btus are shown in parenthesis:

Industrial controls:

- Integrated control of plant/mill, including cogeneration plants (318)
- Real-time control of energy usage (280)

Information Processing:

- Data mining and machine learning for predictive modeling and anticipatory product quality assurance (120)
- Sensor network design for energy-efficient operation (100)
- Energy Informatics: a complete information map of process-wide energy utilization (108)

Automation:

- Automated maintenance and diagnosis (188)
- Closing the loop on quality (318)

Robotics:

- Extreme-temperature robotic systems (202)
- Redesign of robots for increased energy efficiency (25)
- Energy efficiency through use of advanced labor robots (55)

The energy savings for these ten needs totals over 1.7 quads. The total possible energy savings identified in all technology areas exceeds 2 Quads.

1. Introduction

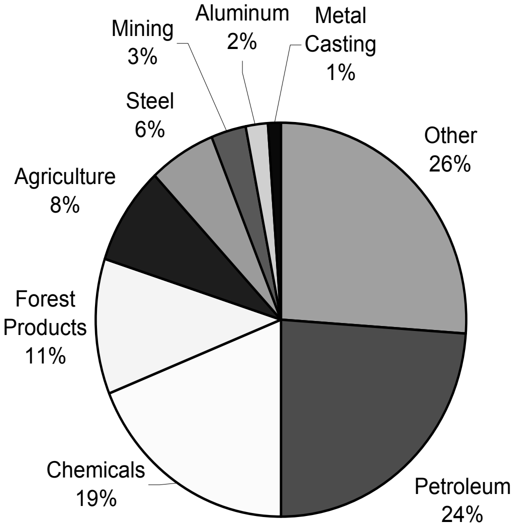
i. Background

The United States is one of the largest consumers of energy in the world. This is due partly to the country's size and climate, and partly to the national standard of living. It is commonly believed that the United States consumes around 35% of the world's energy while representing approximately 5% of the world's population.

Industries of the Future

Over the past decade, the U.S. Department of Energy's Industrial Technologies Program (ITP) has worked in partnership with U.S. Industry to develop and deliver advanced technologies that increase energy performance, improve environmental performance, and boost productivity. In particular, ITP has identified a number of specific, energy-intensive, termed the Industries of the Future (IOFs). Collectively, the IOFs supply 90% of the materials vital to the U.S. economy, produce $1 trillion in annual shipments, directly employ over 3 million people, and indirectly provide an additional 12 million jobs at all skill levels. These industries consist of Aluminum, Chemicals, Forest Products, Glass, Metal Casting, Mining, and Steel. Agriculture, Cement, Food Processing, and Petroleum are potential future additions. To place these sectors in better context, consider the utilization of energy by sector (Figure 1.1).

***Figure 1.1** Percentage of primary energy usage in the manufacturing sectors by major industry category (based on 1997 energy use). Other includes: Food Processing, Glass, and Cement (ref: DoE Congressional Briefing, 2001)*



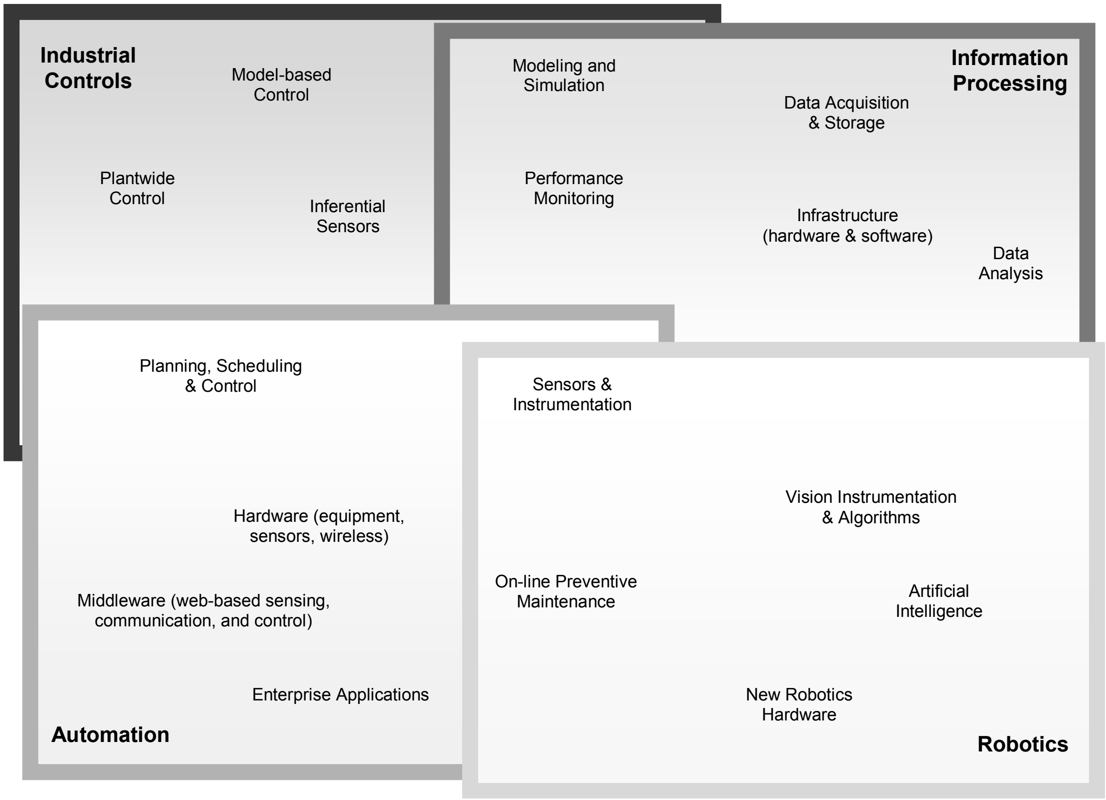
This report presents the results of an expert study of the role that four key technology areas (automation, industrial controls, information processing, and robotics) can play in increasing the energy efficiency of the IOFs. Three of the potential future additions, Agriculture, Cement, and Food Processing, were included as well. Potential research areas were identified and prioritized on the basis of energy gains which could be realized.

ii. Overview and definitions

Definitions for the Four Technical Areas

While four technical areas have been identified for study and analysis, the definition of rigid boundaries between these areas is of limited utility owing to close the interrelationships and interplay illustrated below in Figure 1.2. In this report, the four areas are analyzed separately wherever possible and practical, although in some cases (e.g., industrial controls and information processing); the overlap is so significant as to dictate presentation in a common section.

Figure 1.2 *Illustration of overlap evident in four technical areas*



Industrial Controls constitute a class of algorithms that respond to sensor information with some level of computation, ultimately leading to the generation of a signal that drives an actuating mechanism. At the lowest level, this includes simple programmable logic controllers (PLCs) and feedback controllers such as proportional-integral-derivative (PID) controllers. Extensions to the basic control algorithms may include nonlinear compensation, adaptation, estimation, and gain scheduling. Estimation may include “inferential” strategies, also known as “soft-sensing” in some industries. At the next level of complexity, feedback control algorithms include model-based strategies such as model predictive control (MPC). At the highest level of control algorithm development are multi-unit and plant- or mill-wide strategies for regulating large numbers of processing units simultaneously. At this level, interfaces to real-time optimization (RTO) are required, and higher automation functions such as planning and scheduling can be considered for integration. Supporting the control algorithm development are simulation tools, including operator training simulation.

Industrial controls, in connection with information processing, can be viewed as a means to respond (i.e., to manipulate process variables in response) to a changing state of process knowledge. This knowledge is generated from information gathered from process data using the approaches described in the information processing technical area.

Information Processing in industrial concerns encompasses an entire spectrum of activities: data acquisition; the transformation of raw data to useful information; and the use of this information for quality assurance, process control, improved process design, process operation and energy minimization. In this view, “data” is *not* synonymous with “information.” Raw data sets must be “operated upon” and appropriately transformed to extract the information contained.

Automation as used here refers to systems that assist or replace human efforts in the “sense-infer-act” loop common from low-level control problems to long-range planning for an entire enterprise. With specific regard to automation for large-scale, energy-intensive manufacturing operations such as the IOFs, this includes:

1. Hardware: technical advances in plant equipment, new sensor technologies, and wireless solutions and standards
2. Middleware: web-based sensing, communication, and control, client-server and peer-to-peer application middleware
3. Online and enterprise applications: integration of process and business information systems, knowledge management, and autonomous systems (e.g., software agents)

In large-scale manufacturing, “automation” has traditionally referred primarily to the physical pieces of plant equipment that perform various functions such as heating, cooling, transport, cutting, extruding, assembling, crushing, and rolling. The broader definition used here includes intellectual and business components of production and software (middleware and online applications), which can also result in substantial improvements in energy usage.

Robotics denotes reprogrammable, multifunctional manipulators designed to move materials, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks. Robotics can be considered to be a subfield of automation. As a field, robotics is multi-disciplinary with far-reaching applications in manufacturing, medicial surgery, planetary exploration, and the handling of hazardous materials, to name a few.

"Industrial robotics” is defined as any use of robots or other similar hardware and complementary technologies in an automated setting to make the production, conversion, transmission, or utilization of energy more efficient. It is clear that this definition is rather general, and goes beyond simply replacing a human being in an industrial setting.

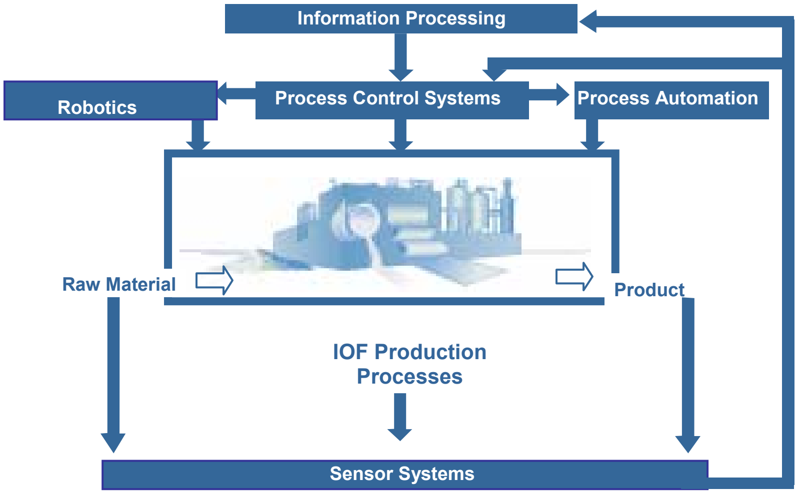
Distinction between automation and robotics

Before delving further into this field, it is important to clearly delineate the respective concepts of “automation” versus “robotics.” As defined above, “automation” refers to systems that assist or replace human efforts in the sense-infer-act loop that is common from low-level control problems all the way up to long-range planning for an entire enterprise “Robotics” is a subfield of automation involving automated machinery that can be programmed to perform a wide variety of tasks. As a general rule, robots are flexible and taskable, while generic automation is not.

There is an obvious, and inescapable, gray area implied by this distinction. For example, Japan is widely thought to make far wider use of robotics within its production plants. Closer inspection, however, reveals that Japanese engineers use the term "robot" more broadly than do their US counterparts. Consequently, automated, non-programmable machinery, which would be called "automation" by US standards, is often classified as "robotic" in Japan, thereby overstating the number of operational robots on Japanese shop floors.

Another way to view the four technical areas considered here is in terms of their functional relationship within the manufacturing process, as is shown in Figure 1.3. Sensors obtain measurable characteristics of the raw material, of the process itself and of the product. This information is fed to a process control system, controlling the process either directly or through automation or a robotic system. Sensor data may be analyzed through information processing, and the resulting signal used to control the production process, as noted above.

Figure 1.3 *Sensors & Automation R&D Focus Areas and Goals*



iii. Analysis

Related Work – Roadmaps and Other Studies

Previous roadmaps and other studies for the 10 industrial sectors and four technical areas were reviewed to: (i) determine the relationship between previous studies and the results of surveys conducted as part of this study, (ii) identify reported energy savings from the sectors for specific automation approaches, and (iii) highlight the unique attributes of specific sectors for automation-based approaches to energy savings.

Three broad categories of surveys and roadmaps were identified in conducting this background review: (i) Energy-focused industry roadmaps, generally sponsored by DOE/ITP (refs [1]-[40]), (ii) Industry surveys not primarily focused on energy (refs [41]-[52], and (iii) academic reviews addressing a variety of performance metrics, including energy (refs [53] and [54]). The documents consulted as part of this study are listed in the bibliography. Analyses of the various roadmaps are provided as appendices to this report.

Interview Protocol

The authors conducted detailed interviews across the 10 industrial sectors, including operating and vendor companies. Manufacturing operations were polled to assess current energy efficiency, discover the currently-deployed state of the art, and identify perceived needs (with emphasis on energy savings). Technology vendors were polled to identify emerging technologies in the product pipeline and evaluate the applicability of those technologies to identified needs. Finally, a gap analysis was performed to identify mismatches between research strategy and technology requirements.

The following technology vendors and operating companies were polled for detailed assessment on energy savings in all four technical area surveys:

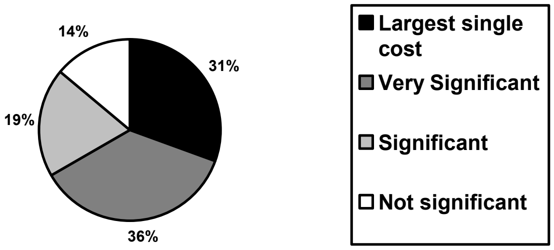
Technology Vendor Companies		
ABB	General Motors	Invensys Automation
Brandstrom Engineering, Ltd.	CSIRO	Pavilion Technologies
ActiveMedia Robotics	GE Power Systems	Solex Robotics
Free serve Corp. / Robotix, Ltd.	Honeywell Automation	Red Wing Technologies

Operating Companies		
ALCOA	Eastman Chemical	Matway
ASAE (Amer. Soc. of Agri. Eng.)	Ecolab, Inc.	MeadWestvaco
Basell Polyolefins	Exxon Mobil Chemical	Neenah Foundry
BASF	Fabcon	Owens Corning
Belmont Foundry	Federal Mogule	Praxair
Bush Brothers & Company	Foundry Group	Proctor & Gamble
Cargill	Furnace Corp.	Seacat
Cement Nik Corporation	General Mills, Inc.	Solutia
Cemstone	John Deere	Steel Manufacturing Association
Dow Chemical Company	Glass Manufacturing Association	Thunder Bay
DuPont Company	IBM Corp.	Weyerhaeuser
	Lockheed Martin	

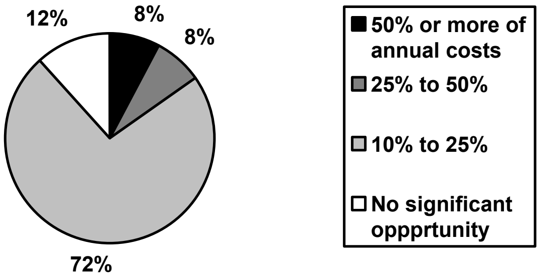
Survey Summaries – Generic Questions

The following questions are a subset of the generic questions that were included in all four technical area surveys. They provide a baseline for quantifying the opportunity for improvements in energy utilization through increased use of general automation technology. As seen in the answers to the first two questions, there are substantial opportunities to make improvements (on the order of 10-25%, in general), with specific recommendations (question 3) varying widely across the industries surveyed.

1. Please rank the significance of energy consumption as a contributor to manufacturing costs in your organization



2. How much opportunity do you see for improved energy efficiency/consumption in your organization, due to improvements in operations, automation, control, or other factors?



3. Can you identify operational, process, or tooling changes that would realize significant energy savings?

Identified operational changes
Better system-wide decisions (groups of plants vs. individual plants)
Waste reduction and yield improvements for most intermediate operations
More efficient control of boilers, lime kilns, and refining
Boiler efficiency improvement projects
Through optimization, modeling and equipment design
Improve inspection of leaks for aboveground storages
Better management of power & electric loads
Advanced control strategies such as model predictive control, improved measurement devices and sensors, multivariate data processing and analysis, better scheduling optimization strategies
Centralized purchasing, deregulation, and conservation.
Centralized purchasing of electricity and gas would reduce energy costs. On the process side, the largest opportunity is energy efficient lighting and electricity demand charges.
Regular and disciplined application of electrical and thermal energy assessment/auditing tools
Electrical supply-side (and demand-side) monitoring/advisory/decision support tools
Use of information tools (advisory/monitoring) to improve decision making with respect to thermal energy use
Use of on-line modeling/optimization tools to reduce process energy demand
Thermal optimization based on process integration technology (e.g., pinch technology)
For us, without a doubt the biggest volatility in energy costs is price (canning/cooking is a federally regulated process, highly controlled, highly documented, it is probably one of the most controlled and automated processes in the food industry and usage is highly monitored) but the swing in commodity costs and transportation costs to our plant are the biggest factors in influencing the price.
Scheduling

Identified process changes
Foundry temperature control
Fuel substitution technologies and projects (e.g., substituting waste fuels for purchased fossil fuels
Improving plant performance from new chains to improve air flow in cement wet processes.
Tracking “Energy to Capital” ratio and making changes when this ratio favors capital expenditure to improve energy efficiency
Melting of scraps technique
Increase efficiency of compression equipment
Improvements in furnace and reheat technology
Greater/improved use of combined heat & power technologies; expanded use of condensing power generation where warranted
Optimized pumping & fan systems based on appropriately sized/specified equipment and often relying on variable speed drives
Soot blower optimization technologies (e.g., in recovery furnaces)
Using submerged combustion melting➔ 40% reduction on per ton melted basis
Oxyfuel for both types of combustion processes (submerged combustion melting, forehearth delivery)
Better use of waste heat /use of waste heat recovery technologies
Technology change in glass furnaces: using submerged combustion melting and/or Forehearth delivery. In conjunction, changing fuel type, from Fuel/Air combination to Oxyfuel (Fuel/Pure O_2 combination)
Use of variable speed motors rather than throttling valves to control process flow
Electric for materials handling, metal pouring, dip coating
Ladling and material handling
Some are still in testing stages like wireless robots.
Advanced process technologies (e.g., advanced refining technologies)
Down to 0.03 mm grindings while and universal custom fixturing of samples
Automated inspection of casting or 0.01% scrap is required

This study was undertaken by four discrete teams, each addressing one of the four technical areas. The following sections address each area in turn, starting with a detailed definition of the area and an introduction to current industrial applications. For each area, specific research and development needs are identified, with an emphasis on uncovering “grand challenge” opportunities. The potential energy savings to be gained in each of these areas is calculated as well, with assumptions and ties to previous studies or roadmaps clearly identified.

2. Industrial Controls

i. Definition

Industrial controls can be classified as algorithms that respond to sensor information with some level of computation, generating a signal that drives an actuating mechanism. The sophistication of industrial controls varies widely across the IOFs considered in this study.

ii. Introduction

Industrial controls incorporate algorithms that respond to sensor output, perform some level of computation and generate a command signal to drive a process actuator. The sophistication in industrial controls varies widely across the IOFs considered in this study. Some IOFs rely on low-level regulatory controllers with modest levels of manual intervention, while others have invested heavily in advanced process control technologies, such as model predictive control.

The need for significant advances in industrial control systems are described in many roadmaps, visions and other documents. With few exceptions, these studies focus on productivity and the overall economic competitiveness of the IOFs and their corresponding process equipment. There are relatively few reported instances of control design explicitly for energy savings; rather, a number of studies, recommendations, and tools have been proposed to increase the overall *productivity* of an operating process, thereby indirectly achieving energy savings. End users envision potential energy savings ranging from about 2% to 25%, and vendors suggest savings on the order of 1-5%.

The following industrial control needs have been identified in the relevant IOFs to increase process energy efficiency. In general, this study refers to opportunities that cut across all the IOFs and avoids specific recommendations pertinent only to one IOF or one specific unit operation in a given IOF. Potential grand challenges are designated by an asterisk (*).

- *Integrated Control of Plant/Mill, Including Cogeneration Plants**

  Coordinated control of unit operations across an entire plant or mill is a significant opportunity for energy savings; of particular value would be the coordinated control of power plant operations with the main plant-wide distributed control system (DCS). Typical pulp mills in the forest products sector have the additional complexity of producing on-site energy from biomass burning, further tightening the integration between power plant operations and energy efficiency of the overall mill

- *Real-time Control of Process Energy Utilization**

  Though it would require tight integration with business planning models and the higher level decision-making processes of scheduling and planning, a real-time energy savings controller would directly address utility costs, with suitable compensation for overall operability and profitability. A potential spin-off application would be the real-time management of environmental emissions, offering a possible indirect energy effect by allowing tighter, more energy-efficient operations near to regulated limits and constraints

- *Next Generation Intelligent Control*

  One of the largest problems with automating rules and heuristics from so-called intelligent control is the problem-specific nature of each implementation. Such a formulation can be cast using logical variables in a hybrid systems framework for optimization. One of the largest problems with automating rules and heuristics from so-called intelligent control is the problem-specific nature of each implementation. This not only automates the implementation of rules and heuristics in a formal control framework, but also facilitates a seamless integration of continuous variable control algorithms with rule-based methodologies

- *Inferential Control of Product Quality and Soft-Sensing*

  The design of estimation schemes for key quality variables (as a surrogate for measurements obtained directly from hardware sensors) is a significant opportunity for energy savings. A more formal methodology for estimation would facilitate direct control of the inferred variables, and thereby allow both direct and indirect energy savings

- *(Nonlinear) Model Predictive Control of Individual Unit Operations*

  Model predictive control (MPC) continues to be a primary technical opportunity for increased efficiency (including energy) across the IOFs. It is clear that there are direct and indirect energy savings associated with MPC designs and from an energy perspective, the initial targets for application should be the most energy intensive unit operations in the industry: kilns, furnaces, dryers, boilers, extruders, distillation columns, and reactors. Most of these units have intrinsically inherently characteristics, and the development of a nonlinear algorithm would be expected to yield substantial improvements in energy savings

- *Control of Particle Processes*

  Breakthroughs in particle characterization and modeling are likely to occur in the next several years. Direct energy savings can be achieved in unit operations that deal directly with particle property control in energy-intensive equipment (e.g., drying in chemicals and food sectors), though the more likely route to energy savings is in indirect control of particulate properties (such as particle size distribution) leading to quality improvement and more efficient operations

iii. Assessment

An examination of existing literature, roadmap documents and benchmark studies, was undertaken to outline opportunities for advanced control. The compilation of this information describes energy savings as a direct opportunity for advanced control design, with consideration given to indirect means for achieving energy savings (e.g., productivity improvement, reduction of recycle). Appendix 1 of this document details the roadmap analysis for both the industrial controls and information processing areas, highlighting synergies between the two technology areas. In addition, Appendix 2 lists survey questions specific to industrial controls.

The literature review showed that several sectors rely on low-level regulatory controllers with modest levels of manual intervention, while other sectors are investing heavily in advanced process control, such as model predictive control. There are relatively few instances reported of control design for explicit energy savings; rather, there are a number of studies, recommendations, and tools that have been proposed to increase the overall productivity of an operating process, and, by indirect methods, achieve energy savings. The potential energy savings estimated by end users for the widespread adoption of advanced control systems ranges from about 2% to 25%, and vendors suggest possible savings of 1% to 5%. Calculated across the IOFs, one might expect that the achievable energy savings, normalized against the theoretically attainable energy savings would amount to approximately 1000 Trillion Btu (or1 quad) per year; this assumes 100% implementation and complete realization of savings. Individual assessments of specific technologies are described in detail below.

Basis of energy savings calculations

The exact calculation of energy savings resulting from the implementation of industrial controls is a difficult task. Some of the survey respondents (notably the vendors) were specifically questioned about the manner in which they calculate the projected energy savings of a new project. A variety of answers were received, ranging from "every application is unique and the energy savings are not easily generalized" to "can not really predict the savings until the technology is implemented in the actual unit operation." Several companies reported the use of detailed simulation models to evaluate proposed control technology, and based projected productivity and energy savings on the simulations.

The surveys offer a range of responses from approximately 10% to 25% energy savings for advanced control installations. In addition, the following case studies were identified that documented energy or productivity savings from advanced control, or identified the opportunity for energy improvements in specific sectors:

- One documented study (Qin & Badgwell, 2003) [53] described $220,000 per year energy savings from the installation of a model predictive control (MPC) controller on distillation units in a PVC plant
- Energy used in steel production by U.S. electric arc furnace plants was 9.6M Btu/shipped ton in 2001. Best practice is likely to be 9.0M Btu/shipped ton; an approximately 5% improvement opportunity [survey response].
- Based on the Energetics report on energy efficiency in the chemical industries, an order of magnitude estimate of opportunities in chemical sector are: total energy use of 7414 Trillion Btu (1997), and theoretical energy requirements lead to gaps of 4-15 Million Btu/ton (sub-sectors with greatest opportunities: ethylene, vinyl chloride, ethylene glycol, propylene) [13]
- From the same Energetics report, the potential for cogeneration opportunities in chemicals is great (second to only forest products); chemicals cogeneration supply (fraction of total energy) is increasing at 14% per year [13]
- A typical refinery or olefin plant can save tens of millions of dollars per year through advanced control technology (proprietary Weyerhaeuser study on MPC, 2002) [48]
- The Forest Products division projects savings of 10% through advanced control applications [11]

- In a highly publicized study from DuPont (1988), the company identified that $500 million per year was at stake for advanced control implementation; best process opportunities were up to 15% improvement, average was about 7%
- Pulp digesters also present opportunities for advanced control; 5% steam reduction (proprietary vendor source)
- An AspenTech / Celanese case study reported several million dollars of productivity savings and a corresponding amount of energy savings from model predictive control application
- Vendor report included 5-10% more chemical recovery and throughput (chemical recovery, lime kiln, recausticizer, paper machine); 5-15% more throughput (metals and mining); and 5-10% higher production (Food – drying and evaporator) [survey respondent]
- Vendor case study with Capitol Cement increased production by 10%, reduced specific power consumption by 4%, and increased product consistency by 30% [survey respondent]
- Vendor case study with major chemical company used an integrated approach to boiler control, which led to an overall savings of 10% in energy efficiency [survey respondent]

Clearly there is no uniform metric for predicting energy savings. Based on these case studies and the survey respondents, reasonable estimates characterize control technology in the chemicals sector as the most advanced, offering modest improvements of 2-5%; the glass and steel industries present the most significant gaps, offering savings on the order of 10%; and the other sectors considered were assessed at 5% potential savings. Calculated across all sectors, potential energy savings total approximately 1 quad/year, assuming 100% implementation.

An important additional consideration is the adoption rate or penetration of a particular control technology in the industrial sectors. Adoption rates ranging from 10-40% will be reported for the specific control technologies discussed below, based on the level of deviation from current implemented strategies: those that are most narrowly confined (e.g., particle control) will have generally low adoption rates, while those that require larger scale implementation (e.g., plant-wide) will have lower adoption rates than technologies that only require single unit implementation (e.g., intelligent control).

iv. Current Research

The research efforts in industrial controls are relatively mature with respect to individual unit operations. While model predictive control (MPC) emerged as an industrial solution in the 1970s, the academic research community contributed to this area over the past 20-30 years with contributions in estimation, model identification, on-line solution, and stability analysis.

It is also reasonable to state that, for linear MPC, the research field is relatively mature. The open challenges, from a research perspective, are largely in the areas of nonlinear MPC analysis and synthesis, hybrid (mixed logical and continuous variable) MPC formulation, and large scale MPC (including plant-wide formulation). While the problem of plant-wide control enjoys rich literature on classical low level methodologies (i.e., decentralized solutions), fewer solutions address large scale implementations of centralized strategies such as MPC.

In the areas of adaptive control, gain scheduling, and inferential control, the research problems are relatively well understood and the technical challenges are largely of an applied nature. “Intelligent” control describes a range of approaches, but again, the significant amount of academic literature on fuzzy control, expert systems, and artificial intelligence methods suggests that the hurdles are largely application-related.

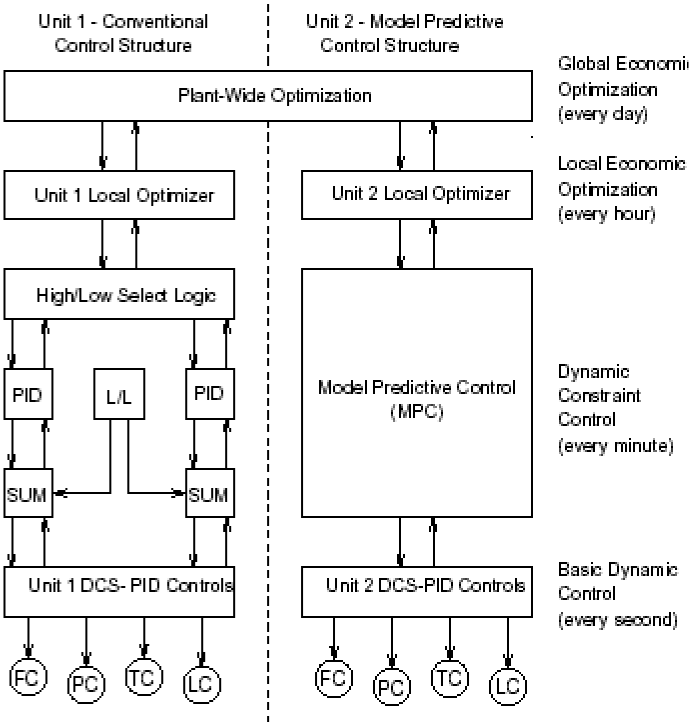
Relatively little academic research addresses direct energy savings; the closest activities are in the area of real-time optimization, in which explicit utility costs are factored into overall cost functions that lead to resetting of set points for advanced process controllers. These can be updated on intervals ranging from a few hours to a few weeks, depending on the needs of the specific sector and the volatility of the implicit pricing information.

The gap between research results and industrial implementation

As noted previously, a common gap in research (adaptive, estimation, intelligent, linear MPC) is tailoring the solution of the problem to specific applications. This suggests that a collaboration of operating companies, technology vendors, and academic researchers are needed to successfully solve these problems. There are already a large number of research consortia in process control working in such partnerships.

In the area of large-scale integrated solutions, numerous technical challenges in theory and application remain. While many technology vendors are promoting the availability of “enterprise-wide” tools for optimization and control, the manufacturing sector reports that the tools are not relevant for their problems and/or are not sufficiently developed to allow utilization. There is a clear opportunity to address systematic solutions to generic classes of problems, including the class of plants that include cogeneration capability (e.g., chemical and forest product sectors).

Figure 2.1 *– Hierarchical levels of control in process industries, showing interface between regulatory control (in DCS) and global optimization (from Qin & Badgwell, 2003) [54].*



v. Industrial Needs and Opportunities

The following needs have been identified for industrial controls, with the intent of increasing process energy efficiency in the respective IOFs. These refer to general opportunities that cut across all the IOFs, avoiding specific recommendations. The first two opportunities are discussed in greater detail than the following four, and constitute the major findings for the area of Industrial Control. As such, they are also candidates for a "Grand Challenge."

1. Integrated Control of Plant/Mill Including Cogeneration Plants

The coordinated control of unit operations across an entire plant or mill remains a largely elusive goal; current practices range from completely decentralized structures to partial centralization (see Figure 3), though a fully centralized system has been tested at a facility in Georgia. The coordinated control of power plant operations in a plant/mill with the main plant-wide DCS (distributed control system) is particularly valuable for energy savings; integrated control of the power plant alone would yield substantial benefits, notably in turbine control. Typical pulp mills in forest products as well as plants in other sectors have the additional complexity of producing on-site energy from biomass, further tightening the integration between power plant operations and energy efficiency of the overall mill. Tight management of grade transitions as the product "front" propagates down the processing line would also be a benefit. Several IOFs identified this problem as a high priority for energy savings, and one industry vendor (see survey suggestion) suggested that plant-wide integration could offer savings on the order of 5% of the total energy costs. Additional savings on product quality control would also be expected, with indirect benefits for energy consumption via reduced recycle, more efficient utility usage, and higher productivity.

Truly integrated plant/mill-wide operations would be as technologically daunting as model predictive control was for unit-based control in the 1970s: MPC addresses uncompensated interactions between variables in a unit in the same manner that plant/mill-wide integrated control would address interactions between units. MPC was initially advocated for efficiency and energy savings in distillation control in the 1970s, and is now the standard for unit-based advanced control in most industrial sectors.

As described previously, there are significant technical challenges that preclude the routine extension of current model-based strategies (such as MPC) to the scale of complete plant/mill-wide control. Some open challenges include: (i) reliability and maintenance for a completely centralized solution (e.g., how to allow specific unit controllers to fail and not bring down the entire plant control system), (ii) horizontal vs. vertical hierarchical approaches (e.g., flowsheet-based decomposition vs. temporal decomposition), (iii) identification of plant-wide models for control design, notably the "bridge" models that would link unit-level model descriptions, (iv) coordinated management of setpoint transitioning across the plant/mill as rate and grade changes propagate through the flowsheet.

The *process automation* and *information processing* technologies will require tight coordination in the design of real-time controllers for energy utilization. As with the major finding of the previous section, *Integrated Plant/Mill-wide Control,* automation functions at higher levels (including planning and scheduling) would be beneficial, as would tighter management of process data streams. The Information Processing section recommendation of “energy informatics” is directly relevant here; the energy quantities estimated using the techniques described in that section of the report become the controlled variables that drive the control calculations for energy optimization. As noted previously, there are a number of technical challenges, including the assurance that a real-time energy-optimized process will be easy to operate, and would be minimally sensitive to perturbations.

Energy savings projection:

Benefits of this technology were evaluated, taking into consideration the individual energy consumption across the industrial sectors, employment numbers (reflecting automation level and receptivity to control technology), and a projected adoption rate of 30-50% (based on high technological barriers of implementing system-wide technology). It is assumed that 85% of the theoretical benefits of control could be realized from this technique, where this is implemented, and assuming the previously mentioned figure of 1000 Trillion Btu/year as the maximum achievable benefit from industrial controls (based on survey responses of 10%), then 85% of this theoretical savings, corrected for adoption rate as indicated in the table, is projected to be achieved via integrated plant-wide control or 317 Trillion Btu/yr.

***Figure 2.2** – Benefits of Integrated Control of Plant/Mill Including Cogeneration Plants*

IOF	Energy Consumptions (Trillions/BTU/Yr) Total	Employment (Millions)	Income/Revenues/Shipments (in billions)		Revenue per worker	Estimated Derived Automation Level (Worker Productivity)	% of Operations Disposed to Technology Aplication	% Market Acceptence	Potential Energy Savings 9%
Agriculture	663.1	21	54.6	$	2,600	Low	20%	30%	3.38
Aluminum	314	0.143	39	$	272,727	Medium	60%	50%	8.01
Cement	446	0.01748	8.3	$	474,828	Medium	60%	50%	11.37
Chemicals	5074	1	454	$	454,000	Medium	60%	50%	129.39
Food	1685	1.1	270	$	245,455	Medium	20%	30%	8.59
Forest Products	4039	1.3	262	$	201,538	Medium	60%	50%	102.99
Glass	372	0.1485	29	$	195,286	Medium	60%	50%	9.49
Metalcasting	235	0	3170	$	-	Low	20%	30%	1.20
Mining	1283	0.225	19	$	84,444	Low	60%	50%	32.72
Steel	2056	0.335	0	$	-	Low	20%	30%	10.49
Total	16167.1								317.62

Sources:
U.S. Department f Energy Office of Industrial Technologies, Congressional Briefing,
Nancy Margolis: IOF Energy Footprints
DoE/OIT Energy, Environment & Economics (E3) Handbook, www.oit.doe.gov/e3handbook/f.shtml
Cement Industry Overview, Portland Cement Association website,
http://portals.learninginsights.com/pca/index.cfm
OIT/IOF/Industry Profiles
Energy Information Administration/Monthly Energy Review (June 20030)
Energy Consumption Series, Measuring Energy Efficiency in the United States' Economy: A Beginning (October 1995), DOE/EIA-555(95)/2

2. Real-time Control of Energy Utilization in Processes

Current control design involves an (often implicit) optimization of some aspect of dynamic operability in the given process unit (or sequence of units). Coordination with costs (utility costs, raw material costs, and sales forecasts) often occurs at the level of Real-Time Optimization (RTO), which, contrary to its name, is often invoked at periodic intervals ranging from hours to weeks. Research studies have shown that "performance optimized" advanced controllers will often lose their benefits (e.g., faster transition times) when the energy costs of utilities are factored into the transient response. A real-time energy savings controller would address utility costs directly, with some suitable compensation for operability and overall profitability; this would effectively eliminate the need for a separate RTO function, though it would require tight integration with business planning models, and the higher level decision-making processes of scheduling and planning. The real-time management of environmental emissions is a potential spin-off application, offering an indirect energy effect by allowing tighter, more energy-efficient operations near to regulated limits and constraints.

As the target goal is immediate energy savings, it is difficult to conceive of a more effective approach to energy savings via process control than RTO. Owing to the interactions of process units via recycle, the management of several unit operations simultaneously may be required to achieve the full immediate benefit, as well as the indirect energy benefits arising from increased productivity, and improved operability.

There are a number of risks associated with direct real-time control of energy utilization. Among these are potentially reduced operability owing to propagation of disturbances and setpoint changes at the expense of overall energy efficiency. Also, market volatility is likely to result in unanticipated consequences for the system (overnight changes in energy markets can lead to substantial changes in plant operations). Developing stability limits under such conditions will be challenging, and require some tradeoff formulation between dynamic operability and real-time energy savings.

Energy savings projection

Benefits of Real-time Control of Energy were examined considering individual energy consumption across the industrial sectors and employment numbers (reflecting automation level and receptivity to control technology). A projected adoption rate of 30-50% is suggested (based on high technological barriers of implementing energy-based control technology), and it is assumed that 75% of the theoretical benefits of control could be realized from this technique. Assuming the previously mentioned figure of 1000 Trillion Btu/year as the maximum achievable benefit from industrial controls (based on survey responses of 10%), then 75% of this theoretical savings, corrected for adoption rate as indicated in the table, is projected to be achieved via direct energy control or 280 Trillion Btu/yr.

Figure 2.3 *– Benefits of Real-Time Control of Energy Utilization in Processes*

IOF	Energy Consumptions (Trillions/BTU/Yr) Total	Employment (Millions)	Income/Revenues/Shipments (in billions)		Revenue per worker	Estimated Derived Automation Level (Worker Productivity)	% of Operations Disposed to Technology Aplication	% Market Acceptence	Potential Energy Savings
									8%
Agriculture	663.1	21	54.6	$	2,600	Low	20%	30%	2.98
Aluminum	314	0.143	39	$	272,727	Medium	60%	50%	7.07
Cement	446	0.01748	8.3	$	474,828	Medium	60%	50%	10.04
Chemicals	5074	1	454	$	454,000	Medium	60%	50%	114.17
Food	1685	1.1	270	$	245,455	Medium	20%	30%	7.58
Forest Products	4039	1.3	262	$	201,538	Medium	60%	50%	90.88
Glass	372	0.1485	29	$	195,286	Medium	60%	50%	8.37
Metalcasting	235	0	3170	$	-	Low	20%	30%	1.06
Mining	1283	0.225	19	$	84,444	Low	60%	50%	28.87
Steel	2056	0.335	0	$	-	Low	20%	30%	9.25
Total	16167.1								280.26

Sources:	
	U.S. Department f Energy Office of Industrial Technologies, Congressional Briefing,
	Nancy Margolis: IOF Energy Footprints
	DoE/OIT Energy, Environment & Economics (E3) Handbook, www.oit.doe.gov/e3handbook/f.shtml
	Cement Industry Overview, Portland Cement Association website, http://portals.learninginsights.com/pca/index.cfm
	OIT/IOF/Industry Profiles
	Energy Information Administration/Monthly Energy Review (June 20030)
	Energy Consumption Series, Measuring Energy Efficiency in the United States' Economy: A Beginning (October 1995), DOE/EIA-555(95)/2

3. Next Generation Intelligent Control

The term "intelligent control" can be used in two ways, either to describe an advanced methodology (deemed inherently intelligent), or else to describe a methodology that is based on rules, heuristics, and/or some element of artificial intelligence. All methodologies considered in this report could be viewed as "advanced," so in the context of this "industrial need," we will concentrate on the latter interpretation.

The automating of rules and heuristics demands a level of specificity that limits cross-cutting applications; this not only restricts applicability to other sectors, but often of limits applications to other processes within a given sector. This is being addressed in the form of "hybrid" formulations of control strategies, in which rules are embedded as logical constraints in the problem formulation (implement adjustment X if the process conditions are in regime Y). As an example, one could imagine the hierarchical operating objectives of (i) run reactor safely, (ii) minimize effluents, and (iii) maximize profitability. One could pose this in an optimal framework in which multiple variables were controlled to their set points, subject first to the satisfaction of safe operation. If this objective can be satisfied, then adjustments are made to minimize effluents. Finally, if both of these objectives can be met, then focus can shift to maximization of profit. This not only automates the implementation of rules and heuristics in a formal control framework, but also facilitates a seamless integration of continuous variable control algorithms (MPC, PID, etc.) with rule-based methodologies.

Energy savings projection
The benefits of intelligent control are great in scope, and savings are expected to be high. A projected adoption rate of 40% is suggested (based on low technological barriers) and an achievable realization of 40% is projected, leading to a combined multiplier of 16%. Assuming the previously mentioned figure of 1000 Trillion Btu/year as the maximum achievable benefit from industrial controls (based on survey responses of 10%), then 16% of this theoretical savings is projected to be achieved via next generation intelligent controls or 160 Trillion Btu/yr.

4. Inferential Control of Product Quality and Soft-Sensing

Estimation schemes for key quality variables as a surrogate for hardware sensors has been identified as a critical need by the industries surveyed. (Note: the issue of sensor technology is not addressed in this study). Preliminary studies with neural networks have led to monitoring applications, notably in emissions regulations; a more formal methodology for estimation could enable the direct control of the inferred variables. This would allow both direct and indirect energy savings. Calculation of confidence intervals and management of highly nonlinear operating regimes will require future investigation.

Clearly connected to the information processing item describing "anticipatory product quality assurance," the information processing element yields the predictive attribute (or estimate), and describes the action that one would take, based upon that prediction. As a hypothetical example, one can consider the control of taste in a food process. A number of correlated variables to be measured would be identified, and the resulting model could be realized as a time-series mathematical model. The resulting model can be implemented in a so-called state-estimation framework for control, which builds refined estimates of the inferred variable (taste) as new measurement information is collected (color, moisture) and the adjustments (water addition, heat lamps, etc.) are made to optimize taste.

Energy savings projection
The benefits of inferential controls are widespread, and moderate savings would be expected. A projected adoption rate of 50% is suggested (based on low technological barriers) and an achievable realization of 30% is projected, leading to a combined multiplier of 15%. Assuming the previously mentioned figure of 1000 Trillion Btu/year as the maximum achievable benefit from industrial controls (based on survey responses of 10%), then 15% of this theoretical savings is projected to be achieved via inferential control or 150 Trillion Btu/yr.

5. (Nonlinear) Model Predictive Control of Individual Unit Operations

Model predictive control (MPC) represents a primary opportunity to achieve greater efficiency across the IOFs. In effect, this control approach utilizes a mathematical model to make predictions of the controller variable along a horizon; an optimization problem is solved to yield the adjustments that allow the predicted controlled variables to lie "close" to the target, in some formal mathematical sense (e.g., least-squares). MPC has made only limited penetration into the sectors, owing to a number of factors: the need for customization of algorithm to individual processes, maintenance of model and model-based algorithm as process changes with time, and cost/benefit ratio as perceived by plant managers. It is clear that there are direct and indirect energy savings associated with MPC designs and from an energy perspective, the initial targets for application should be the most energy intensive unit operations in the industry (i.e., kilns, furnaces, dryers, boilers, extruders, distillation columns, and reactors). Most of these units display nonlinear characteristics, and the development of a nonlinear algorithm would be expected to yield substantial energy savings. The vast majority of the industry roadmaps identified the need for development of intelligent control designs that can estimate the unknown process dynamics, though the determination of suitable models for use in nonlinear model predictive control remains an issue.

Energy savings projection

The benefits of Nonlinear MPC are limited to highly nonlinear process unit operations; however potential savings are still expected to be relatively high. A projected adoption rate of 20% is suggested (based on a fraction of nonlinear processes) and an achievable realization of 50% is projected, leading to a combined multiplier of 10%. Assuming the previously mentioned figure of 1000 Trillion Btu/year as the maximum achievable benefit from industrial controls (based on survey responses of 10%), then 10% of this theoretical savings is projected to be achieved via nonlinear model predictive control or 100 Trillion Btu/yr.

6. Control of Particle Processes

The area of particulate process control is ripe for new developments; the next several years are likely to see breakthroughs in particle characterization and modeling. Several IOFs deal with intermediate or final products in a particulate form, and invariably the final product quality is strongly correlated with the attributes of the particles. This spans the IOFs, including those with direct quality connection (mining), and those with implicit quality connections (food, agricultural and chemical). Direct energy savings can be achieved in unit operations that deal directly with particle property control in energy-intensive equipment (e.g., drying in the chemicals and food processing sectors), although the more likely route to energy savings is in indirect control of particulate properties (such as particle size distribution) leading to quality improvement and more efficient operations.

Examples of particulate process control include the use of granulation to create food particles of a desired size and the use of emulsion particles to make polymer latex. In each of these cases, adjustments are made to the process inputs to achieve a target distribution of particle sizes; creating food particles of a given size affects the taste (or solubility in a mix), and latex particles of a given size impact the end-use properties such as the optical properties of paint.

Energy savings projection

The benefits of Particulate Control are somewhat narrowly focused, and, where implemented, the savings would be expected to be moderate. A projected adoption rate of 20% is suggested (based on high technological barriers) and an achievable realization of 20% is projected, leading to a combined multiplier of 4%. Assuming the previously mentioned figure of 1000 Trillion Btu/year as the maximum achievable benefit from industrial controls (based on survey responses of 10%), then 4% of this theoretical savings is projected to be achieved via particulate process control or 40 Trillion Btu/yr.

3. Information Processing

i. Definition

Embracing the notion that "data" is *not* synonymous with "information," information processing in industrial applications spans data acquisition; transforming raw data to useful information; and utilizing such information for quality assurance, process control, improved process design, process operation and energy minimization.

ii. Introduction

Though information processing can be employed as a strategic technology for saving energy directly or indirectly (through significant product quality improvement), the IOFs are not currently exploiting its potential. Rather, "Information Processing" is still perceived in the more restricted context of sensors and other ancillary monitoring systems. Information processing technologies can deliver much more than what is currently perceived by industry practitioners as possible. Significant opportunities exist for the development of novel information processing technologies to deliver energy savings across the IOFs.

An examination of the survey results (Appendix 2) shows the potential IOF energy savings via the implementation of novel information technologies average 5% across the majority of the IOFs, and range from 2-5% in the Chemical Industry to as much as 10% for Glass and Metal Casting. The sum of annual potential savings is approximately 2 Quad Btu/year across all the IOF's. These estimates are likely to be conservative since they are based on the current perception and state-of-the-art of information processing technologies. The penetration rate of new information processing technology is difficult to estimate; however, a modest average 10% realization of this potential translates to 200 Trillion Btu/year, worth about $2 billion not including savings to come through the elimination of the "energy cost of poor quality." A good estimate for this is not currently available.

On the premise that, in addition to direct energy savings, "quality savings" ultimately translate into energy savings, the following is a summary of the concepts worth pursuing for exploiting Information Processing in the IOF's. Potential "grand challenges" are designated by an asterisk.

- **Process Data Mining and Machine Learning for Predictive Modeling and Anticipatory Product Quality Assurance***
  While ultimate product quality and end-use product characteristic parameters are hardly ever available for direct measurement, massive data records of on-line process measurements contain information that, when properly processed, can be used for predictive modeling of expected product quality as a function of process operating conditions. This will allow the assurance of quality control well in advance of the actual, but infrequent and delayed, lab analysis or customer feedback

- **Energy Informatics***
  Hailed as a new paradigm, a dedicated information technology system is utilized to monitor and regulate energy consumption while maintaining product quality and safety objectives. Implementation requires a **Process Energy Management System** to collect,

interpret, integrate, store, visualize and generally transform raw process data into a form that is readily useful to (a) determine the true state of energy utilization in the overall process for each unit operation, (b) identify and categorize the sources of inefficiency, and (c) recommend appropriate corrective action to rectify energy inefficiencies

- **Chemometric methodologies for causal analysis and adaptive control**
  Chemometric analyses quantify the (linear) correlations hidden in massive data sets. Taking chemometric methods beyond their current use for passive process monitoring would require "machinery" to establish truly causal relationships amidst identified correlations. Such upgraded techniques can then be used to develop a data-based controller technique capable of adapting to plant operating conditions automatically (using on-line data)
- **Sensor network design for energy efficient operations***
  Decisions about sensor types, number to install, and location in the manufacturing process are typically made before the manufacturing plant is built; these issues are seldom revisited afterwards. With the availability of sensors of all types, including novel specialized sensors, selecting sensors to determine and affect process operational efficiency should now be achievable

iii. Assessment

An examination of existing literature, roadmap and related documents and benchmark studies, was undertaken to outline opportunities for advanced control (model predictive control, gain scheduling, adaptive, nonlinear, and other methodologies). The compilation of this information describes energy savings as a direct opportunity for advanced control design, with consideration given to indirect means for achieving energy savings (e.g., productivity improvement, reduction of recycle). Appendix 1 of this document details the roadmap analysis for both the industrial controls and information processing areas, highlighting synergies between the two technology areas. In addition, Appendix 4 lists survey questions specific to information processing.

The concept of "information processing" as an encompassing technology that combines data acquisition and storage with the appropriate systems to convert the data into useful information is still not well-established in virtually all the IOF's surveyed. In most cases, sensors measure critical process variables and store the data in process historians (software systems used to store process data as they become available), to be consulted later to monitor overall process performance. The use of information processing as a means of achieving energy efficiency is much less familiar overall, with only a few companies (mostly in the chemical industry) indicating any experience in this context.

The research specifically focused on current industrial practices, current research capabilities, the gap between research results and industrial implementation, and industrial needs and opportunities for upgrading industrial practice. In addition, the conditions in each case will be discussed with respect to the following topics as necessary:

- Data Acquisition and Storage (Data rectification, Data Compression, On-line process data management, Quality Control Lab Systems, etc)

- Process Operations & Performance Monitoring (Sensor and Analyzer fault detection, identification and correction; sensor and analyzer failure detection; process performance analysis etc.)
- Sensor System Design and Implementation (Robust sensor system designs; Sensor Fusion; Soft sensor systems)
- Data Analysis (multi-scale, high-, low-, and medium frequency data analysis; continuous, discrete and categorical data analysis; image processing and analysis)
- Empirical Process modeling with applications
- Infrastructure (Software and hardware issues)

iv. Current Research

The advent of the computer has significantly impacted industrial data acquisition and storage capabilities, and all the IOF's are adequately equipped with process data computers. However, virtually all the IOF's use Process Data Management systems exclusively to provide information required for process control; process information is not often used to directly assess the energy status of the process. Thus, though data acquisition and storage are well established in the IOF's, the data are currently used almost exclusively to monitor process operation and performance - the primary focus is on product quality attainment, and seldom for energy efficiency. The key limitation in most IOF's (in particular Glass, Aluminum, Mining, and Metal Casting) is a lack of specialized sensors: in-situ sensors; robust and "smart"—self-calibrating, self diagnosing—sensors; on-line product quality sensors. The Chemical industry, due to its relative size and the complexity of its typical processes, is an exception with the most sophisticated data acquisition and storage systems.

Sensor design and implementation is most often determined when a manufacturing plant is built, and is seldom revisited afterwards. However, selecting sensors for the express purpose of being able to determine energy efficiency effectively is becoming more of an issue in IOF's such as Glass and Metal Casting. The general consensus is that, apart from the need for novel sensors to better enable process operation, the hardware infrastructure and data historian systems are adequate for industry needs.

As the general view holds that the research capabilities in computer hardware and data storage and retrieval is more than adequate for industry needs, no direct examination was conducted. In terms of process operations and performance monitoring, most of the information processing research has been carried out in support of the Chemical industry, though nearly 3 decades ago the glass industry pioneered research into information processing techniques for monitoring energy utilization - the work was discontinued after fuel costs began to decline (Brown, 2001). The use of Principal Component Analysis (PCA) and Partial Least Squares (PLS) for process and controller performance monitoring continues to receive research attention, and digital imaging for on-line monitoring and control is becoming a well-established capability. Very sophisticated research capabilities in data rectification and data compression, have not found their way to industrial practice.

Though research into sensor network design has produced some noteworthy results, as yet only a few actual industrial implementations have been realized. Techniques based on Bayesian Belief Networks, Kalman Filtering, and Information Theory may translate into industrial practice, and, while we are not aware of any novel research being carried out by software vendors to provide new generation data analysis software, such information is usually proprietary.

The gap between research results and industrial implementation
Many industry representatives indicated that the issue of ascertaining data integrity remains a major obstacle to employing process data for anything "serious". Automated fault detection was also identified as an area of need. It thus appears as if research results on data reconciliation, data rectification, sensor fault detection and diagnosis, etc. will be useful in these industries.

v. Industrial Needs and Opportunities

The following is an annotated compilation of the most critical needs—as well as potential solutions—to upgrade the effective employment of information technology for energy savings, both directly and indirectly. Research areas appropriate as "grand challenges" are designated with an asterisk.

1. Process Data Mining and Machine Learning for Predictive Modeling and Anticipatory Product Quality Assurance*

The product quality and end-use product characteristic parameters that determine the true acceptability of a product to the customer are hardly ever available for direct measurement, and often only become available after it is too late to rectify any indicated problems with product quality, resulting in needless waste. There is a clear recognition in the various IOFs that quality savings translate to energy savings, and conversely, there is a significant energy cost associated with poor quality.

With current sensor technology, industrial data are generally available in two categories: (i) process operation data (pressure, level, flow, temperature.), available frequently and abundantly; and (ii) product quality data (impact strength, taste, yarn tenacity, tensile strength, texture), available infrequently, often after long laboratory analyses, sometimes once every 8-hour shift or even once a week. The first category of data reflects the prevailing process operating conditions while the product quality characteristics are being determined. These records actually encode product quality information, leaving the challenge of how to "decode" (translate) and exploit this information. Thus, if properly processed, the information contained in on-line process records can be used for predictive modeling of expected product quality, as a function of process operating conditions.

To achieve this, a technique will have to be developed that goes beyond both basic statistical methods (which work best for limited data sizes, especially when the Gaussian distribution assumption must be reasonably valid) and Chemometrics (which is capable of modeling only linear relationships). The successful methodology will rely on novel applications of fundamental Information Theory to identify potential relationships among variables, and genetic algorithms for confirming and developing quantitative expressions that can be used for predictive modeling. Such models can be used to predict expected product quality hours or even days before the measurements become available. This technology will allow the assurance of quality control well in advance of the actual, but infrequent and delayed, lab analyses or customer feedback.

The heart of a significant initiative in this area would be the development of a methodology for using the data records of on-line process conditions for predictive modeling of expected product quality as a function of process operating conditions. Such a predictive model could anticipate product quality deviations well ahead of lab analyses (or customer feedback), and correct for these in a timely fashion. Some additional applications of this methodology may include:

- Identifying which combination of process conditions correspond to optimum product quality attainment
- Identifying dynamic patterns of process operation that lead to optimum (or unusually poor) energy utilization
- Characterizing process operating conditions that are indicative of the *incipience* of process upsets that regularly result in substantial loss of energy efficiency and poor product quality
- Developing "inverse models" that relate desired process operating states (optimal energy efficiency, desired product quality) to manipulated process variables, and a methodology for employing such inverse models as part of a process optimization system

This technology, which involves equal parts information processing, modeling, and industrial controls, should find application across the IOF's. However, several challenges are associated with this problem, the three most important of which are:

1. Variable frequency of relevant data: process data are real-valued measurements available on the order of seconds and minutes; direct product quality measurements, when they are available at all, are available on the order of hours; end-use physical characteristics are available perhaps once a day; and product performance in end use (manufactured part acceptability) occur in the form of binary data (acceptable or not acceptable) and often on the order of weeks.
2. Available data sets: massive nature requires a methodology that goes beyond statistical methods, which work best for limited data sizes for which the (strongly restrictive) Gaussian distribution assumption must be reasonably valid. The successful technique will also go beyond Chemometrics, which, though freed from the limitations of basic statistics, is only capable of modeling linear relationships.
3. Predictive model: must be capable of predicting product acceptability (a binary variable) on the basis of values of the mostly continuous (i.e. real-valued, as opposed to binary) process measurements.

Energy savings projection

As the proposed new technology is not restricted to any one industry, the benefits are expected to be far-reaching. If only 25% of the IOF's adopt the technology, a modest 40% market penetration (or market acceptance in each industry sector) would lead to a combined multiplier of, or 120 Trillion Btu/year. A more detailed IOF-wide analysis of these potential energy savings is shown below, employing the data and methodology described in the Automation section.

Figure 3.1 *– Benefits of Process Data Mining and Machine Learning for Predictive Modeling and Anticipatory Product Quality Assurance*

IOF	Energy Consumptions (Trillions/BTU/Yr) Total	Employment (Millions)	Income/Revenues/Shipments (in billions)	Revenue per worker	Estimated Derived Automation Level (Worker Productivity)	% of Operations Disposed to Technology Aplication	% Market Acceptence	Potential Energy Savings 5%
Agriculture	663.1	21	54.6	$ 2,600	Low	20%	20%	1.33
Aluminum	314	0.143	39	$ 272,727	Medium	30%	30%	1.41
Cement	446	0.01748	8.3	$ 474,828	Medium	30%	50%	3.35
Chemicals	5074	1	454	$ 454,000	Medium	60%	50%	76.11
Food	1685	1.1	270	$ 245,455	Medium	20%	30%	5.06
Forest Products	4039	1.3	262	$ 201,538	Medium	20%	40%	16.16
Glass	372	0.1485	29	$ 195,286	Medium	60%	50%	5.58
Metalcasting	235	0	3170	$ -	Low	20%	30%	0.71
Mining	1283	0.225	19	$ 84,444	Low	20%	30%	3.85
Steel	2056	0.335	0	$ -	Low	20%	30%	6.17
Total	16167.1							119.71

Sources:
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http://portals.learninginsights.com/pca/index.cfm
OIT/IOF/Industry Profiles
Energy Information Administration/Monthly Energy Review (June 20030)
Energy Consumption Series, Measuring Energy Efficiency in the United States'
Economy: A Beginning (October 1995), DOE/EIA-555(95)/2

2. Energy Informatics

All processes that convert raw materials to finished product use energy, and the implied energy transactions take different forms: energy input to the process and the subsequent release of energy to the atmosphere; the conversion from one form to the other before, during and after manufacturing; the amount required in terms of electricity or other utilities just to “keep the lights on”. No manufacturing process of significance operates without a formal and functioning “materials handling and management” system; similarly, all industries employ a formal product quality assurance system for monitoring the quality of the manufactured products, for detecting changes in these quality indicators and for recommending, and sometimes even automatically, implementing corrective action when necessary.

The procedures for computing energy utilization and efficiencies are often subjective and involve multiple assumptions, producing estimates that, if characterized statistically, will have wide margins of error. ***The goal of this research area is to develop a comprehensive energy system for monitoring and regulating energy consumption in a manufacturing process.*** It is to consist of two parts:

- *Energy Informatics*: a methodology that uses process data to generate a complete information map of process-wide energy utilization
- *Energy Monitoring and Regulation:* the action of collecting, interpreting, integrating, storing, visualizing and generally transforming raw process data into a form that is readily useful directly for determining (a) the true state of energy utilization in the overall process for each unit operation relative to a specified ideal target (b) identifying and categorizing the sources of inefficiency and (c) recommending appropriate corrective action to rectify energy inefficiencies and to meet the specified objectives

There are significant technical challenges associated with the development of such a system, for example:

1. Converting on-line process data to a dynamic energy information map
2. Calculating "available energy" (or useful energy) from process operating data
3. Identification of an appropriate metric to characterize overall productivity, by incorporating the amount of useful energy expended along with product quality, i.e. how much energy is being used to produce a given quantity of product that meets product quality criteria.
4. Reliable detection of a measurable change in the process energy map
5. Construction of an effective methodology to manipulate appropriate process variables to restore the process to its "optimum" desired energy state, without compromising product quality

The development of such a system has the potential revolutionize energy efficiency across all IOF's in much the same way that Statistical Process Control (or Process Chemometrics) reshaped product quality management.

Energy savings projection

Technologies to address the issues discussed above are not restricted to any one industry, and the benefits are thus expected to be broad. Nevertheless, taking into consideration the relative novelty of the concepts, we estimate that only 25% of the U.S. industry may be positively predisposed to adopting the technology. In combination with an estimated 40% market penetration (or market acceptance) leads to a combined multiplier of 10% or just over 100 Trillion Btu/year. (A more detailed IOF-wide analysis of these potential energy savings is shown below, employing the data and methodology described in the Automation section.)

Figure 3.2 *– Benefits of Energy Informatics*

IOF	Energy Consumptions (Trillions/BTU/Yr) Total	Employment (Millions)	Income/Revenues/Shipments (in billions)		Revenue per worker	Estimated Derived Automation Level (Worker Productivity)	% of Operations Disposed to Technology Aplication	% Market Acceptence	Potential Energy Savings 5%
Agriculture	663.1	21	54.6	$	2,600	Low	20%	20%	1.33
Aluminum	314	0.143	39	$	272,727	Medium	30%	50%	2.36
Cement	446	0.01748	8.3	$	474,828	Medium	30%	50%	3.35
Chemicals	5074	1	454	$	454,000	Medium	50%	50%	63.43
Food	1685	1.1	270	$	245,455	Medium	20%	30%	5.06
Forest Products	4039	1.3	262	$	201,538	Medium	20%	40%	16.16
Glass	372	0.1485	29	$	195,286	Medium	60%	50%	5.58
Metalcasting	235	0	3170	$	-	Low	20%	30%	0.71
Mining	1283	0.225	19	$	84,444	Low	20%	30%	3.85
Steel	2056	0.335	0	$	-	Low	20%	30%	6.17
Total	16167.1								107.96

Sources:

U.S. Department f Energy Office of Industrial Technologies, Congressional Briefing,
Nancy Margolis: IOF Energy Footprints
DoE/OIT Energy, Environment & Economics (E3) Handbook, www.oit.doe.gov/e3handbook/f.shtml
Cement Industry Overview, Portland Cement Association website,
http://portals.learninginsights.com/pca/index.cfm
OIT/IOF/Industry Profiles
Energy Information Administration/Monthly Energy Review (June 20030)
Energy Consumption Series, Measuring Energy Efficiency in the United States'
Economy: A Beginning (October 1995), DOE/EIA-555(95)/2

3. Chemometric Methodologies for Causal Analysis and Adaptive Control

Chemometric methodologies, techniques to analyze and quantify correlations hidden in massive data sets, have been used successfully for process monitoring and diagnosis. However, correlations do not imply causality; the fact that two variables appear to be correlated should in no way imply that one is *causing* the other to change. To take chemometrics beyond their use for passive process monitoring requires formal "machinery" to establish truly causal relationships between the identified variable correlations. For example, it may be possible to incorporate fundamental physics and chemistry into the data analysis procedure to yield a hybrid approach endowing the otherwise strictly empirical chemometric models with causal capabilities. The updated chemometric methodologies can then be combined with sensor design (see item 4 below) to:

1. Guarantee minimum information loss in the event of sensor failure

2. Develop effective control systems that will automatically adapt to plant operating conditions by using on-line data and chemometric methods capable of causal analysis

Energy savings projection
We believe that a formal methodology to achieve these objectives can lead to significant energy savings via optimized process operation, crosscuting many different industries. However, as such benefits will inherently favor industries that are already highly automated, potential benefits are not expected to be evenly distributed across the IOFs. Assuming 20% of industry may adopt the technology, coupled with a prospective 50% market penetration (since these technologies are tied to industrial controls); this leads to a combined multiplier of 10%, approximately 100 Trillion Btu/year.

4. Sensor Network Design for Energy Efficient Operations

Traditionally, decisions regarding sensors (types to use, how many of each are required for robustness, where to place them in the manufacturing process) are made before a manufacturing plant is built and are seldom revisited afterwards. With the availability of novel sensor types (in particular the emerging paradigm of "ubiquitous sensing," which may be made possible by low-cost wireless sensor networks), the concept of sensor selection and strategic placement for the express purpose of determining and affecting energy efficiency and product quality consistency will become more of an issue in many IOFs. In fact, the concept of sensor network design to achieve robustness to catastrophic sensor failure and/or other sensor faults or performance degradation has recently received attention in some IOFs.

The selection of sensors and the design of sensor networks with the explicit objective of achieving predetermined product quality specifications provides opportunities for significant energy savings. The current "practice" is limited to "engineering judgment" decisions not based on rigorous objectives. For example, the following question may be asked: *For process operating data gathered from a given manufacturing process, how many sensors, of what type, and located where in the process, are required to guarantee the "predictability" of product quality variables?* Technology developed for such sensor network design can be complementary to the data mining and predictive modeling technique discussed earlier. This will make it possible to design, select, and deploy appropriate sensors for on-line process and product measurements to generate the required data to successfully implement anticipatory product quality assurance systems.

Energy savings projection
Benefits from advances in sensor network design are not restricted to any one industry, though industries that already enjoy high levels of automation are more likely to adopt new ways of using information processing technologies. Thus, while potential benefits are expected to be broad, they are not expected to be evenly distributed across the IOFs. Supposing that 20% of industry may be predisposed to adopt the technology and given a 50% market penetration (since these technologies are tied to industrial controls), this leads to a combined multiplier of 10%, approximately 100 Trillion Btu/year.

4. Automation

i. Definition

In manufacturing, "automation" has traditionally referred only to hardware, the physical pieces of plant equipment that perform various functions: heating, cooling, transport, cutting, extruding, crushing, and rolling. The definition we use here also considers the intellectual and business components of production, and gains to be made there as well. Since these components may reside in the software (the middleware and online applications) of automated systems, "automation" will include both software and hardware systems that assist or replace human efforts in the sense-infer-act loop.

ii. Introduction

Automation of various sorts has been deployed in many of the IOFs for a number of years, and a variety of roadmap documents and multiple benchmark studies describe some of the opportunities for further automation. Typically, these have focused on themes relating the integration of results, from new and improved sensors to advancing the state of the art of automation. This report details the opportunities for energy savings both as a direct benefit of automation and through indirect means, such as reduction of waste, reduced logistics, and reduced recycle.

Automation systems that assist or replace human efforts in the sense-infer-act loop may be implemented anywhere from low-level control up to long-range planning for an entire enterprise; software is included as well as hardware. As applied to the Industries of the Future, two significant areas with grand challenge potential are recommended for future automation projects:

- **Close the loop on quality** through the application of advanced sensors and improved real-time control. This is a complex problem, requiring the development of new control models and "out of the box" thinking. It is challenging, but promises significant yields in terms of increased energy efficiency, lower production costs, and higher-quality products, leading to annual savings of an estimated 318 trillion Btu.
- **Implement automated maintenance and diagnosis** to provide significant cost savings and improved system efficiency. These technologies are mature in military applications and other areas, and are ready for adoption in commercial applications. Application of these technologies in the IOFs would result in an estimated annual savings of more than 188 trillion Btu. In addition to energy savings, this topic is of interest to industries and organizations where experienced personnel are retiring or no longer available (for example, due to layoffs). Automated maintenance and diagnostics provide a repository of corporate knowledge enabling less-experienced workers to operate at the level of more experienced technicians.

Several other areas of potentially fruitful automation projects have been identified as well, including the following:

- Supply chain optimization across the full breadth of the manufacturing-distribution-use cycle, commonly called the “value-chain”. This includes
    - Optimizing logistics to wring excess transportation, storage, spoilage and waste out of the system, thus reducing the energy associated with these wastes.
    - Real-time inventory management systems that monitor the dynamic state of the product (a chemical’s degraded efficacy over time, for example).
- Production optimization for energy use. This broad, crosscutting goal has the potential to yield significant energy savings. This could include real-time, online automated optimization algorithms implemented within and coordinating across multiple production automation systems.

In addition, indirect evidence in the data regarding the number of workers, annual revenues, and annual energy consumption strongly suggests that the industrial sectors of Agriculture, Food Processing, Mining and Steel may contain further automation opportunities leading to significant energy savings, as they currently rank lowest in terms of productivity per employee. Analyses of revenue produced per energy unit consumed indicated that the Aluminum sector may also be a particularly fruitful area for automation applications.

iii. Assessment

An assessment of data from a June 2002 Energetics report, “Measurement and Control Technology Needs Identified in Industry Technology Roadmaps” [28] illustrates that the categories of needs identified can be further grouped into two “super-categories”:

1. *Closing the loop on quality*

   Traditional production processes have used an off-line approach to quality control which eliminates any possibility of real-time control. In these processes, a batch of product is produced and several representative samples are pulled from the finished lot and examined to determine if they meet the quality criteria for production; if they are found to be deficient, the production line is halted and adjusted, and a new batch is run. Several problems are inherent to this approach, including: problems corrected “after the fact” of production render the original batch useless and contribute to increased waste; and corrections made in this manner do not guarantee that the results of the implemented corrections will be effective, potentially relegating another batch to the scrap heap.

   One approach to try to ameliorate these issues has been to instrument the production line with appropriate sensors to ensure correct operation and produce in-spec product. However, many sensors currently implemented on production lines cannot measure the actual quality. For example, a blending process with three inputs probably includes a flow sensor on each, and may include a rotation sensor on the mixing shaft and a temperature sensor in the mixture. While these sensors can ensure that an appropriate mix of ingredients is entering the mix chamber, the shaft is rotating at the proper rate, and that the mixture is attaining a certain temperature, the utilization of this specific set of sensors is based on the assumption that the metering of additives, mixing and heating process will produce an output product of a given quality (perhaps viscosity, density and molecular concentration are the key quality parameters). Unfortunately, the easy-to-measure parameters (pressure, temperature, flow, and level) may provide little direct quality information on the product.

2. *Automated Maintenance and Diagnostic Systems*

Automated maintenance and diagnostics, condition-based maintenance, and prognostic-driven maintenance are concepts that have been explored in military domains for the past 15 years. Their efficacy and cost/benefit are well understood for the military, where retirement, layoffs, a more mobile workforce, and other factors influencing the skill sets of the available labor force have been prominent considerations for many years. The same concerns are now affecting industry as well.

Figure 4.1, below, shows the composition of these "super-categories." Totaling the percentage of comments from each, we see that "Closing the Loop on Quality" accounts for approximately 74% of the comments, and "Automated Maintenance and Diagnostics" accounts for approximately 5% of the comments. Other categories beyond these fell outside the domain of this study.

Figure 4.1 *- Distribution of comments on the "Super Categories"*

	Frequency with which Comments in this Category Appear across all IOFs	Close Loop on Quality	Automated Maintenance & Diagnostics
Analytical/physical property measurements	17%	17%	
On-line/real-time measurement	16%	16%	
Modeling and simulation	14%	14%	
Sampling and Process Control	12%	12%	
Advanced control techniques	8%	8%	
Harsh environment applications	7%		
Non-intrusive/non-contact measurement	5%		
Diagnostic/maintenance applications	4%		4%
Imaging and data communication	4%	4%	
Emission/effluent measurements	3%		
Microstructure/inclusion measurement	3%		
Automation	3%	3%	
Mixed materials sorting technology	2%		
Failure sensing or self-calibration	1%		1%
Other	1%		
TOTAL	**100%**	**74%**	**5%**

Please see Appendix 6 for the detailed roadmap analysis for the automation area. The resulting findings are incorporated in the following *recommendations* section.

iv. Current Research

Quality Control

Isolated attempts to close the quality control loop exist. For example, in 1995 Maytag introduced the first "smart" dishwasher [52]. Previous models washed dishes at a predetermined temperature for a predetermined amount of time, assuming that these settings would be sufficient to clean the dishes. The smart sensor used a turbidity sensor in the water to continuously sense load conditions, process the information, and send that information to the controller for real-time control decisions. This resulted in a significant savings of energy and water (up to 35% reduction in energy use and operating cost).

Automated Maintenance and Diagnostics

Industry has begun to notice the advances made in automated maintenance and diagnostics in the military area, and is beginning to desire those automation technologies as well. Furthermore, challenging economic times, along with associated workforce reductions and increased individual productivity demands are driving industry's desire to automate maintenance and diagnostics. This was borne out by our research, where we found that automated maintenance and diagnostic issues appear across the roadmaps and vision documents for the Industries of the Future. Furthermore, industry's desire to perform remote diagnostics and provide more timely alerts is critical in the leaner operations required by a challenging economy. Finally, the ability to employ less experienced personnel to do maintenance and diagnostics tasks yields further costs savings. The goal of this project is to examine and articulate high-value-added areas for automated maintenance and diagnostics in industrial automation in the Industries of the Future.

v. Industrial Needs and Opportunities

As stated before, the results of our analysis suggest pursuing research in two major and four minor topics:

1. Closing the Loop on Quality

The goal of this project is to "close the loop" on quality by applying advanced sensors and improved real-time control to production lines and control loops, thereby taking advantage of recent technology advances in smaller, cheaper, more accurate sensors capable of directly measuring product quality. Ideally, the added sensors will keep production operations within specifications automatically by providing direct, real-time, on-line quality measures. This work dovetails nicely with findings related to information processing in the area of the "cost of poor quality." Though complex and requiring new control models, significant yields in terms of increased energy efficiency, lower production costs, and higher-quality products are anticipated.

The start of this project might consist of:

- Determining what kind of sensors would be desirable in an "ideal world"
- Explore applicable technologies that may be suitable
- Identify any existing technology barriers to implementation, create prioritized list of "early winner" areas where greatest gains can be made first, and quantify potential savings from improved sensors/controls across industries

The dishwasher example yielded an energy savings of 35%; as realized during the operation of the proposed dishwasher. Deriving the projected savings for manufacturing processes requires application of several assumptions. Since these are operational savings derived during use of the equipment, then if similar equipment is applied during the most energy-intensive portions of the operations in an industrial setting, the savings may be similar to actual deployment. Breaking this down, we projected two factors into our estimates:

1. Fraction of operations in each industry disposed to application of this technology
2. Estimates of actual market acceptance and application of this technology

The first factor was determined by analyzing the automation level of the industry, specifically based on the income/revenue/shipment numbers for each IOF (primarily from the DOE/ITP/IOF Industry Profiles and the Energy, Environment & Economics (E3) Handbook [30]). The Income/Revenue/Shipments, in billions of dollars, are divided by the number of workers in the industry to determine Revenue per Worker. This is taken as an estimate from which to derive the automation level for the industry. The assumption is that industries with the highest Revenue per Worker are deriving their greater productivity per worker from the automated tools assisting each worker in their performance. IOFs are then categorized into groups with "high," "medium," and "low" levels of automation. This is used to determine the Percentage of Operations Disposed to Technology Application. Industries with high levels of automation are assumed to be able to integrate technologies that close the loop on quality in as many as 45% of their operations. Industries with medium levels of automation are assumed to implement these technologies in up to 30% of their operations, and low-automation industries are assumed to be able to integrate these technologies in only 15% of operations.

Based on the Estimated Derived Automation Level, we anticipate that industries with high and medium levels of automation are more likely to adopt new technologies industry-wide (perhaps achieving as much as 80% market acceptance for new technologies) , while industries with low levels off automation may only achieve market acceptance of 50%.

These factors, along with an estimated 10% (far more conservative than the dishwasher example) savings from closing the loop on quality are multiplied by the energy consumption numbers to estimate Potential Energy Savings. Based on IOF energy use, expected savings could be as follows:

Figure 4.2*– Benefits of Closing the Loop on Quality*

	Energy Consumptions (Trillions/BTU/Yr) Total	Employment (Millions)	Income/Revenues/Shipments (in billions)		Revenue per worker	Estimated Derived Automation Level (Worker Productivity)	% of Operations Disposed to Technology Aplication	% Market Acceptence	Potential Energy Savings
IOF									**10%**
Agriculture	663.1	21	54.6	$	2,600	Low	15%	50%	4.97
Aluminum	314	0.143	39	$	272,727	Medium	30%	80%	7.54
Cement	446	0.01748	8.3	$	474,828	Medium	30%	80%	10.70
Chemicals	5074	1	454	$	454,000	Medium	30%	80%	121.78
Food	1685	1.1	270	$	245,455	Medium	30%	80%	40.44
Forest Products	4039	1.3	262	$	201,538	Medium	30%	80%	96.94
Glass	372	0.1485	29	$	195,286	Medium	30%	80%	8.93
Metalcasting	235	0	3170	$	-	Low	15%	50%	1.76
Mining	1283	0.225	19	$	84,444	Low	15%	50%	9.62
Steel	2056	0.335	0	$	-	Low	15%	50%	15.42
Total	16167.1								318.10

Potential Energy Savings (Trillions/BTU/Yr)

Sources:
U.S. Department f Energy Office of Industrial Technologies, Congressional Briefing,
Nancy Margolis, IOF Energy Footprints
DoE/OIT Energy, Environment & Economics (E3) Handbook, www.oit.doe.gov/e3handbook/f.shtml
Cement Industry Overview, Portland Cement Association website,
http://portals.learninginsights.com/pca/index.cfm
OIT/IOF/Industry Profiles
Energy Information Administration/Monthly Energy Review (June 20030)
Energy Consumption Series, Measuring Energy Efficiency in the United States' Economy: A Beginning (October 1995), DOE/EIA-555(95)/2

This research has a variety of risks and rewards, including:

Challenges

1. Inspire operational, plant-oriented personnel to “think outside the box” about what they would ideally like to measure and then drive that need through a survey of available sensors, and a technology pull to improve insufficient ones
2. Incite operational, plant-oriented personnel with large investments in current plant equipment to consider a new paradigm.
3. Ensure that proper marketing research is done to ensure applicability of system features to user’s needs.
4. Develop direct quality measurements that may push the limits of existing sensor technologies.

Rewards

1. "Revolutionary" (as opposed to evolutionary) increases in energy savings, "disruptive" cost savings to maintain competitiveness with third-world labor manufacturing markets. The revolutionary aspects of closing the loop on quality derive from the cross-cutting effects of closing the loop on quality in conjunction with data mining and machine learning for predictive modeling and anticipated product quality assurance as found in the information processing sections.

There is significant complexity in approaching this technical problem. Online sensing technology is rather poorly developed to monitor many important quality attributes, for example: taste, feel, texture, smell and other human senses; physical material properties (hardness, corrosion resistance, modulus of elasticity, molecular composition, etc.); and thermodynamic properties, such as thermal conductivity, enthalpy, or other energy content measurements. Many of these measurements are conducted in laboratory environments or by subjective means, so the challenge is to translate these subjective assessments into objective product characteristics.

2. Automated Maintenance and Diagnostics

Providing significant cost savings and improved system efficiency, automated diagnosis, assisted maintenance, and related technologies are ready for commercial applications. Military examples have yielded 50-80% reduction in diagnostic effort, and shown over a 30% reduction in faulty repairs stemming from incorrect problem diagnosis. Since these figures together lead to higher system availability, which correlates directly with production line productivity, energy efficiency is thus affected.

Maintenance and diagnostics in the military domain have always carried a unique set of operator considerations: a military flight-line technician may be 19 years old with an 18-month tour of duty. Consequently, advanced support technologies may be required to help the technician adequately diagnose and repair high tech equipment. Further complicating the military maintenance task is the fact that no two pieces of equipment may be the same. Military aircraft, for instance, are constantly being upgraded with new equipment, so it is possible that no two individual aircraft have exactly the same configuration; each one may have any of a series of upgrades installed on it that others do not.

Automated maintenance and diagnostics has not seen the widespread adoption in industry that it has gained in the military. In the past there has been less of a driving need in industry, where maintenance technicians are allowed time to develop personal expertise, and new technicians are not constantly rotating in, requiring training and automated tools.

A more conservative 5% reduction in energy use attained by automated maintenance yields the following energy savings, using similar estimation techniques as before:

***Figure 4.3**– Benefits of Automated Maintenance and Diagnostics*

IOF	Energy Consumptions (Trillions/BTU/Yr) Total	Employment (Millions)	Income/Revenues/Shipments (in billions)	Revenue per worker	Estimated Derived Automation Level (Worker Productivity)	% of Operations Disposed to Technology Aplication	% Market Acceptance	Potential Energy Savings 5%
Agriculture	663.1	21	54.6	$ 2,600	Low	15%	50%	2.49
Aluminum	314	0.143	39	$ 272,727	Medium	30%	80%	3.77
Cement	446	0.01748	8.3	$ 474,828	Medium	30%	80%	5.35
Chemicals	5074	1	454	$ 454,000	Medium	30%	80%	60.89
Food	1685	1.1	270	$ 245,455	Medium	30%	80%	20.22
Forest Products	4039	1.3	262	$ 201,538	Medium	30%	80%	48.47
Glass	372	0.1485	29	$ 195,286	Medium	30%	80%	4.46
Metalcasting	235	0	3170	$ -	Low	15%	50%	0.88
Mining	1283	0.225	19	$ 84,444	Low	15%	50%	4.81
Steel	2056	0.335	0	$-	High	45%	80%	37.01
Total	16167.1							188.35

Potential Energy Savings (Trillions BTY/Yr)

Sources:
U.S. Department f Energy Office of Industrial Technologies, Congressional Briefing,
Nancy Margolis, IOF Energy Footprints
DoE/OIT Energy, Environment & Economics (E3) Handbook, www.oit.doe.gov/e3handbook/f.shtml
Cement Industry Overview, Portland Cement Association website,
http://portals.learninginsights.com/pca/index.cfm
OIT/IOF/Industry Profiles
Energy Information Administration/Monthly Energy Review (June 20030)
Energy Consumption Series, Measuring Energy Efficiency in the United States'
Economy: A Beginning (October 1995), DOE/EIA-555(95)/2

In addition, a variety of other recommendations can be derived from the analysis of study and survey results:

3. **Exploitation of technologies leveraging existing infrastructure:** an example for agriculture would be combining satellite data, GPS data, and self-guided vehicles for autonomous production of row-crops. Satellite data could be used to signal existing irrigation equipment with added chemicals (herbicides, for example) for real-time, on-demand application of chemicals and water.
4. **Supply chain optimization advances across the full breadth of the value-chain:** this is a grander vision of "closing the loop on quality," across the entire manufacturing-distribution-consumption cycle or value chain (and perhaps across industries), and for more cross-cutting technology applications, including:
    - Logistics components across a variety of IOFs (make product at the right time, controlling quality and production quantity, and deliver it directly to the consumer) for reduced storage, waste, and transportation (and subsequent energy) costs.

- Real-time inventory management systems that monitor the dynamic state of the product and lead to better analysis of incoming ingredients and online monitoring of ingredient quality. This is significant for agricultural raw materials for the Food Processing industry where ingredients dry out in storage (water content is the single largest variable affecting milling operations and the food products derived from them, and it persists through the value chain from flour into mixing and baking operations for packaged food goods), or in pharmaceuticals where product efficacy degrades over time in storage.
- Optimized production of fine chemicals (ultra-pure benzene, acetone, and direct derivatives thereof), by only producing required amounts, producing it just prior to use (and minimizing risks associated with storage), and producing it close to the consumer. These result in energy savings by reducing waste due to spoilage and consequent remanufacture.

5. **Energy savings in automating high energy-use crushing operations** in the Glass, Steel, Aluminum, Mining, Forest Products (chipping), and Cement industries, and energy savings in automating high energy-use heating and annealing operations in the Glass, Steel, Aluminum, Forest Products, and Cement industries.
6. **Automated scheduling and planning technologies:**
    - Reduce energy waste at changeovers (e.g., in the manufacture off fibers, polymers, or edible oils).
    - Optimize production for energy usage – like “closing the loop on quality,” “Real-time Control of Energy Utilization,” and “Energy Informatics,” this broad, crosscutting group of applications has the potential to yield significant energy savings and requires further study. As a secondary benefit, this provides environmental benefits through reduced waste. This could include real-time, online, automated, optimization algorithms implemented within and coordinating across the automation systems

5. Robotics

i. Definition

Robotics is a multi-disciplinary area of technology which has direct integrating relation with many fields including sensing, control, information technology, automation, and artificial intelligence (AI). A robot is classified as a reprogrammable, multifunctional manipulator designed to move materials, parts, tools, repair or specialized devices through various programmed motions for the performance of a variety of tasks.

ii. Introduction

Flexible and taskable, robots constitute a class of reprogrammable, multifunctional manipulators designed to move materials, parts, tools, or specialized devices through programmed motions to perform a variety of tasks. A multi-disciplinary field, robotics holds far-reaching applications in industries, medicial surgery, planetary exploration, and the handling of hazardeous materials, to name a few; this clearly goes beyond simply replacing a human being in an industrial setting.

A subset of robotics more closely associated with automation, "industrial robotics" is defined as any use of robots or other similar hardware and complementary technologies in an automated setting to make the production, conversion, transmission, or utilization of energy more efficient. Direct energy savings can be found through decreases in manufacturing defects, reduced waste, increased efficiency of existing processes via sensing and information technology (IT) systems where demand and automated production modeling can be integrated, and even in reduced energy requirements for automation, remote operations, and robotics itself. In addition, some robotics effects on energy efficiency are *indirect*; robots can solve an industrial problem which would make collateral expenditure of energy unnecessary, e.g. mining robots, extreme temperature labor robots, automatic guided vehicle (AGVs).

The identification of key areas within the Industries of the Future for application of robotics can prevent energy waste in almost all cases, provided that the robots are not energy intensive in their own right.

- **Extreme Temperature Robotic Systems**
  As the main benefits of robots are to replace human labor for consistent quality and perform laborious and high-risk work where human should not risk their lives (e.g. in boilers and furnaces, mines, etc.), the key is to redesign many components, foremost of all sensors, which, can operate in such environments and sense data from key locations and application areas. For example, tasks such as monitoring, maintenance, and repair of such equipment in high-temperature environments typically require dexterity. The cumulative energy savings across all IOFs is estimated at 2.02 Quads for 10 years and 7.18 Quads for the next 10 years. This estimate has used a 10% adaptation for first 3 years, 30% for the next 2 years and 50% for the next 5 years.

- **Energy Efficient Robots**
  A critical issue is the energy efficiency of robots themselves; essentially, how to redesign various components of robots, from materials, links, joints, sensors, actuators, wireless communication source of power (electricity, batteries, fluid), for energy efficiency. A very important robot subclass, hydraulic robots, is dominant among IOFs but much less efficient compared to electric robots. The Energy Information Administration projects that industrial energy usage by 2010 will be 39 Quads; assuming that just 15% of this energy is used in fluid power operations across all IOFs and petrochemical industry, control of fluid processes will total approximately 5.8 Quads by 2010. Unlike the electric motor industry, the state-of-the-art in hydraulic actuation is based on 1960's technology.

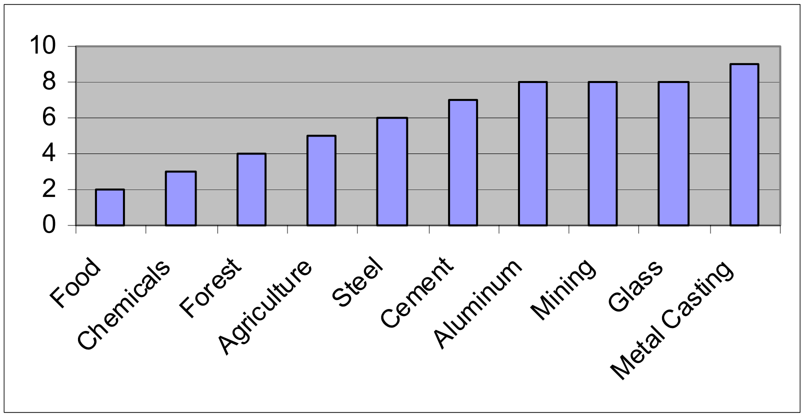
  The energy savings for redesign of other (non-hydraulic) industrial robots is now estimated as well. With approximately 109,750 industrial robots in use in the United States as of 2003, and assuming that 65% of these robots are non-hydraulic, there are an estimated 65,850 electric industrial robots in use. If new redesign of electric robots links, joints, batteries, actuators and sensor, can save 250,000 Btu per industrial robot per year, or 0.016 Quads annually.

- **Energy-efficiency through labor robots**
  Robotic technologies present enormous opportunities for energy savings and decreased labor requirements across many U.S. industries, especially forest products, steel, aluminum, and mining. Increased precision and standardization and simultaneous decreases in required labor force and time offers marked direct and indirect savings over current processes. In some cases, lessons can be learned from other nations where tangible progress has already been made. The potential energy savings, across all IOFs, has been estimated at 2.02 Quads for the first 10 years, then increasing to 7.18 Quads for the following 10 years; considerable savings that offers great improvements in techniques and processes.

iii. Assessment

The potential roles of robots in IOFs include many which target the energy efficiency of existing practices. Figure 5.1 shows the *Need Index* of all IOFs, with index zero (0) representing lowest need for robotic technologies and index ten (10) represents highest need. As shown here among IOFs, food, chemicals, and forest are among those IOFs where robotic technologies have penetrated fairly significantly and hence they have low need indexes. Agriculture and steel industries seem to be in a medium degree of need for the robotic technologies, indicating that a reasonable amount is already being done. Next are cement, aluminum and mining industries, which can stand to benefit from such industries. The metal casting industry is in dire need for such technologies and comes down with the highest need for this technology. As can be seen, there is a general inverse relationship between "need for robotics" as noted here and the "automation level" used in other sectors of report.

Figure 5.1*– Degree of Need for Robotic Technologies for 10 industries of the future in DOE study.*



iv. Needs and opportunities

The key research and development need areas of the 10 IOFs are summarized in Figure 5.2 with the industry with the highest need coming first.

Figure 5.2 *– Robotic Technology Research and Development Needs for 10 IOFs*

IOF Industry	**Robotic Technology R&D Needs** (From highest to lowest)
Metal Casting	Furnace combustion, Foam casting, Die casting robots
Glass	Glass furnace, Cyberglass robots, Flat glass robotic handlers, Sheating robots, High-temperature furnace inspection and repairs.
Mining	Mining robots, Multi-robot cooperative mining, Coal waste reduction, Hydraulic Separation.
Aluminum	Safety-related robots, scale management
Cement	Demolition robots, X-ray spectrometry robots for mineral sampling
Steel	Real-time melt temperature robots, Inspection and repair robots in extreme temperatures.
Agriculture	Picking and irrigation robots
Forest	Weed killing robots, Walking robots, Wood sanding, Kiln drying stacker
Chemicals	Chemicals – Leak inspection robots, measurement robots
Food	Picking, Precision meat and fish cutting robots, Material handling, Poultry processors

Below are three especially recommended areas of R&D; the first two can be considered as robotic Grand Challenges.

1. Extreme Temperature Robotic Systems

Many of the IOFs have operations and environments that are characterized by high-temperatures, e.g., smelters, boilers, petrochemical refining processes, energy conversion units, mining operations, furnaces. Tasks such as monitoring (sensing), maintenance, and repair of such equipment in high-temperature environments typically require dexterity (i.e., precision in placement and force control) and are currently unsolved problems in robotics. Solution to these problems would produce a revolutionary and pervasive new paradigm and would be available to a broad range of industries with significant energy savings.

The energy savings in this area are twofold. One is that a new generation of robots could be used to repair extreme-temperature components with high energy consumption such as boilers, furnaces, smelters, and heaters, thereby reducing downtime of the units. Typically these units must cool down before a worker can enter the heated chamber to make the repair. The use of extreme temperature robots could sharply decrease this waiting period and the unit could return to service faster. The other is if high-temperature robots can repair such components, further energy is also saved by not having to air condition or prepare for human labor, or having to re-heat the units after a repair team finishes its job. Therefore, this area has both a direct and many indirect effects on energy efficiency of the IOFs.

The direct energy savings potential here can be illustrated with an example typical of a wide class of maintenance and repair problems associated with a high temperature environment; it is commonly accepted that leaks in boilers at any of the IOF plants would cause an average unavailability of around 5%, as leaks develop in the boiler, their severity is monitored based on water loss through the system. When the leaks become severe enough, the unit has to be brought down. For example, electric industry data indicates that over a third of the down time for such repairs is spent waiting for the boiler to cool (so that human repair team can enter the boiler) and then reheating back to operating temperatures. A remote/robotics system that could operate in the 600°F range therefore has the potential for providing significant savings.

The electric industry estimates that the average unavailability as a result of tube failures is an industry-wide 5% [57]. As an example, electrical consumption in the United States is roughly $1.62\text{x}10^{12}$ kWh with 52.5% of it produced by coal and lignite based fuel. Thus, assuming that during the normal outage a less efficient generation (e.g., diesel) would be used that has an efficiency drop of 5% compared to a fossil plant, the energy savings of reducing the outage time due to tube failure from 5% to 2.5% (i.e., a 50% reduction) would be $1.62\text{x}10^{12}$ kWh x 0.525 x 0.05 x 0.025 = 1.06×10^9 kWh.

Noting that, since there are 8,766 hours per year, the above would be the equivalent of a 121 MW power plant running the entire year! This energy savings corresponds to 412,852,000 Btu. While this energy savings example is for just one industry, it is clear that this technology could impact many U.S. industries, including several of the IOFs and could result in overall energy savings orders of magnitude greater than the number calculated above. The potential energy savings is immense since it has applications in steel, metal casting, aluminum, glass, mining, etc. The cumulative potential savings for all industry is estimated at 2.02 Quads for the first 10 years and 7.18 Quads for 10 years after that, assuming that there is a potential of an average of 2500 adaptation, where there is a 10% adaptation for the first 5 years, 30% for the next 5 years and 50% for the next 10 years.

2. Energy Efficient Robots

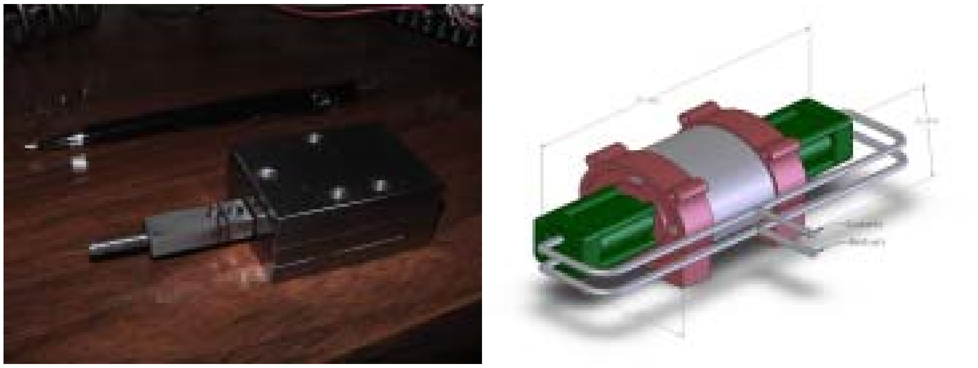
The energy efficiency of current generation hydraulic robots is a key target for improvement. How can various components of robots, from materials (fluid, composite materials, etc.), links, joints, actuators, sensors, source of power (electricity, batteries, fluid), can be redesigned to improve their energy efficiency? The improvement of robotic energy efficiency would no doubt make great impact on the robotic applications in all IOFs

The first stage of this R&D area can be an energy audit of the current robots – fluid-power (hydraulic) and electric in energy-intensive applications like those in glass, steel, and metal casting. The payload capability of most hydraulic robots is higher than electric robots, so simply substituting electric for hydraulic robots is not an option. However, from energy efficiency point of view, hydraulic robots are much less efficient than electric counterparts. One of the most common operational activities is material handling, be it food items, wood items, ore samples in mining, and iron ores in steel and metal casting. One of the most effective approaches to automate this operation in IOFs can be done by robotic hydraulic actuation with dexterous end effectors in a robotic R&D framework. This area has potential application in IOFs like agriculture, cement, chemicals, food, and forestry. For example, harvesting and silviculture (caring and managing the forests) operations in the forest industry are labor intensive, slow, and hazardous and employ outdated and energy-inefficient mechanical technologies. Incorporating hydraulic robots for such operations as logging, planting, weeding, brushing, and timber handling will greatly improve the efficiency of these operations, particularly with regard to energy efficiency.

In order to prioritize the R&D areas here, it is important to distinguish the dominant role that hydraulic robots are playing in today's IOFs. According to the 1998 Manufacturing Profile from the U.S. Census Bureau, the U.S. market for fluid power products, which includes hydraulic robots, was $11.9 billion, one billion dollars larger than that for electric motors and generators [60]. Furthermore, DOE research has found that pumping systems (which include not only pumps, but all associated hardware to control the flow of materials) account for nearly 20 percent of the world's electrical energy demand and range from 25-50% of the total energy usage in certain industrial plant operations. The Energy Information Administration also projects that industrial energy usage by 2010 will be 39 Quads [61].

Assuming that just 15% of this energy is used in fluid power operations [61], across all IOFs and petrochemical industry, control of fluid processes will account for approximately 5.8 Quadrillions by 2010. The state-of-the-art in hydraulic actuation component design and control is based on 1960's technology, and is in dire need of improvements in energy efficiency. For example, conventional constant pressure hydraulic servo control has, at best, a maximum efficiency of 67%, which further drops off rapidly as the load conditions vary. Because very little effort has been devoted to improving the efficiency of hydraulic systems, the potential exists for significant energy savings and economic impact. As an example of R&D activities, energy-efficiency of fluid power components and controls are Oak Ridge National Laboratory's "quasi-hydrostatic controls" and "plate valves" concepts that have shown the potential for significantly lower power requirements (50% in some cases) and energy savings in fluid control systems. Figure 5.3 shows two generations of hydraulic valve and pump which can be incorporated in the new designs of next generation hydraulic robotic actuators [61].

Figure 5.3 - *A valve and a pump design for next generation hydraulic robotic actuators, (Courtesy, Oak Ridge National Laboratories).*



<u>3. Energy-efficiency through labor robots</u>

Robotic technologies present enormous opportunities for increasing energy efficiency through labor-saving roles in industrial processes. For instance, in the forest products industry robots and robotics can help energy conservation and efficiency in harvesting, weed killing, packaging, wood machining and sanding, planting, furniture manufacture, pulp and paper processing, kiln drying, cutting, finishing, and felling. Robots can also increase energy conservation and efficiency in steel manufacturing through sensors, furnace combustion, and automated central laboratory.

Turning to the aluminum industry, technical challenges hinder further improvements in melter system efficiency and ensuring a steady and reliable scrap stream [66]. Furthermore, the aluminum industry is not as advanced as the chemical and some other industries in its use of process management techniques, particularly models and control systems. Increased use of Bayer-specific models and automation would reduce process variation and human exposure to the caustic environment. The push for full automation is a common goal throughout the industry and would promote the awareness of aluminum plants as well run, modern, and safe. Industry-wide standards and criteria for safety in plant design and operation, as well as standardized training, would help establish a culture of operating safety within the refining industry [66].

For mining operations, robotics is concerned with "safe and efficient extraction and processing" and "superior exploration and resource characterization" [108]. Research is needed to design technologies for a range of applications, including: repair and maintenance using robotics, and automated slurry wall technology (a new system or special slurry) to eliminate open-pit mining. Robotics for exploration is a mid-term (4-10 years) project, as is cooperative multi-robot mining, and repair/maintenance for underground mining. For surface mining, autonomous technology for imaging, sensing, and blasting and data, communication, and positioning systems are two near-term (1-3 years) projects, and slurry wall technology is a long term (11-20 years) project

[103]. Lessons can be learned from other nations, where tangible progress in this area has been made [104-106].

As is evident, this technology could impact many U.S. industries, including several of the IOFs, and could result in overall energy savings orders of magnitude greater than the number calculated above. The potential energy savings is immense since it has usage in steel, metal casting, aluminum, glass, mining, and can be estimated as 2.02 Quads cumulative for the first 10 years, and 7.18 Quads for 10 years after that, assuming that there is a potential of an average of 2500 adaptation, where there is a 10% adaptation for the first 5 years, 30% for the next 5 years and 50% after that till 10 years.

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Appendix 1 – Roadmap Analysis:

A variety of roadmaps for the Industries of the Future were reviewed for this survey. Many of them had been compiled into a related report entitled "Measurement and Control Technology Needs Identified in Industry Technology Roadmaps" produced by Energetics in June, 2002. The individual roadmaps, which appear on the DOE/ITP websites, were also reviewed to ensure coverage for automation. In addition, the Aluminum and Mining industries had online roadmaps that superseded the Energetics report. These roadmaps were reviewed individually and in greater detail. In addition to the summary report, each of the IOF roadmaps was examined for key requirements and needs. Agriculture and Cement presented challenges since no formal roadmaps exist for these industries.

In order to highlight apparent synergies between Industrial Controls and Information Processing, a joint approach was taken in the literature analysis. This is in part due to the prevailing perspective that Information Processing addresses sensors, in conjunction with other ancillary systems, which are used to provide the information needed to implement Industrial Controls.

AGRICULTURE

Industrial Controls and Information Processing

The recent industrial roadmap does not directly address the role of process controls or information processing in the Agriculture Industry. Some relevant issues discussed include: process design for energy efficiency: there is significant potential for Biosynthesis using solar energy, which will require careful process engineering to develop an adequate solar-powered process; and materials standards and analytical instruments/methods to monitor heterogeneous process conditions and product quality.

Automation

The agriculture and crop-based renewable resources industry can be divided into four sections: Plant Science, Plant/Crop Production, Processing, and Utilization. While there are significant scientific and technological challenges in each of these areas, the primary opportunities for automation are in the areas of Processing and Utilization, including the development of improved separation technology, isolation/purification techniques for cost-effective capture of plant monomers and polymers, and the eventual development of new equipment for processing modified plants and components.

Robotics

Robotics and automation are not a primary focus of the Agriculture Industry, but that can change. Existing robot applications in agricultural industries have many major focuses: milking systems [62, 63], harvesting equipment, and tractor and field work [64, 65]. Additionally, robots and robotics can help energy conservation and efficiency in inspection, packaging, materials handling, milking, field work, tractors, weed killing, wrapping, labeling, spraying, tilling, and planting.

ALUMINUM

Among aluminum's compelling advantages over competing materials is its ability to be repeatedly recycled with high recovery rates and without loss of quality. Secondary aluminum production offers obvious energy and environmental benefits, as it requires only five percent of the energy use and emissions associated with primary production. The projected shift in North America toward an increased share of secondary, rather than primary, aluminum production will consequently improve the industry's overall energy efficiency.

Industrial Controls and Information Processing

In the recent industry roadmap documents [3, 4, and 5], advanced controls were identified as enabling technologies for several steps in aluminum processing:

- Electrolytic reduction processes: a lack of detailed fundamental models limits the ability to improve cell performance; given key process measurements (beyond resistance), improvements in the reduction process through real-time control are projected
- Melting, solidification and recycling: the lack of real-time control for quality and metallurgical structures, as well as a lack of control solutions for casting. Top R&D needs highlighted fundamental models for predicting microstructure, metal qualities, and economic indices
- Fabrication stages: lack of controls for dimensional properties and temperature
- Alloy development and finished products: lack of suitable control technology, including sensors and models for understanding

In the earlier reports for the aluminum sector (National Academy, 1998) [2], the following priorities were identified for information processing and process control:

- Effective control of lagged processes in alumina refining
- Prediction and control of anode effects in aluminum reduction
- In-situ combustion analysis for furnace control in thermal treatment
- Control of metal flow in extrusion and forging processes
- Control of sheet shape and work roll temperatures

Automation & Robotics

In the recent industry roadmap and technology documents [3, 4, 5, 31], automation technologies were identified as enabling technologies for several steps in aluminum processing. A top priority for electrolyte reduction processes involved the use of a systems approach to design dimensionally stable cells in the development of alternative cell concepts. Several technical barriers were listed, including: Inadequate computer design and simulation tools to link product design and optimized manufacturing (related to closing the loop on quality)

Refining procedures often use models that have not been tailored for the specific conditions found in a refinery and therefore do not work particularly well. Knowledge management systems are also critically lacking in the aluminum industry, leading to repeated mistakes, particularly at the operation level. Another technology roadmap issue, the reduction of human exposure to safety risks, can be accomplished though many topics already discussed, including reducing scale and increasing plant automation. Robots and automation can help energy conservation and efficiency in material handling, die casting, cleaning, and refinery automation.

- Crosscutting Effects: Steel, Metalcasting, Mining
- Benefits: Energy waste reduction, Saves on labor costs. Cleaner environment
- Need is strong
- Inadequate process control technology, including: the inability to conduct real-time monitoring and control, or link process models with product models; and inadequate sensors/process feedback
- Lack of integration between process and product design
- Lack of a continuous process from melting to final product
- Limited process technologies to produce advanced materials

CEMENT

Industrial Controls and Information Processing

DOE/ITP currently has no roadmap for this industry. As such, what follow are some of our own findings, mostly from the following sources:

- Commission for Environmental Cooperation (Second North American Symposium on Assessing the Environmental Effects of Trade (Report date: 21 February 2003), ref [16])
- 2003 Batelle report (ref [17]).

While each step in the cement manufacturing process consumes its own share of energy, it is the calcination process, where the limestone is converted into clinker in the kiln, which requires the greatest amount of energy. This energy, usually provided by the burning of fuels injected at the opposite end of the kiln, represents the major economic cost in cement production.

There is legislation requiring documented Cement Kiln Dust (CKD) Management; it is essential to simultaneously develop an Energy management system. The Battelle Report, concerned primarily with sustainability, provides a number of key observations and recommendations.

- Process innovations will lead to resource and energy efficiency improvements with resulting cost savings
- Rising energy and materials costs, and adverse business impacts of poor environmental performance, mean maintaining the status quo is not a viable option

Automation

Though no DOE/ITP roadmap exists for the cement industry, a vision document, “Vision 2030: A Vision For The U.S. Concrete Industry,” notes that the concrete industry is expected to make processing improvements though the widespread use of automation (using closed-loop control and closing the loop on quality) in cement plants over the next 30 years. In addition, advanced technologies are expected to improve process heating for cement making leading to increased energy efficiency. Case studies [16, 17, 21, 32, 34] of improved plant automation and water recycling have noted 20% savings in energy and 3.5% increases in production due to increased automation. Finally, a recent report, "New Materials and Technologies Available for Use in Industrial Infrastructure, An Overview," prepared for the Office of Energy Efficiency and Renewable Energy, touches on both the cement and steel industries, indicating a promise for production systems which include automated self-diagnosis, mitigation, and repair (automated maintenance and diagnosis).

Robotics

Production of cement is an energy-intensive process that produces significant quantities of greenhouse gases and consumes substantial raw materials. Innovative technologies have been developed that can simultaneously reduce the energy consumption and environmental impact of cement production, and utilize the waste products from other industries. Use of robots in cement industry has been reported in demolition [69], laboratory automation [70], flexible automation [71, 72], and robotic-based quality control systems [73].

CHEMICALS

The chemical industry faces heightened challenges as it enters the 21st century. As mentioned in "Technology Vision 2010" [75], enabling technologies, such as chemical measurement and computers in manufacturing, are central to meeting the challenges. These techniques are geared for real-time, highly reliable analysis in practical environments, and include automated analytical laboratory systems – remote device control and data interchange protocols and standards — are needed to make chemical analysis systems more reliable, accurate, and cost-effective. There is also the potential to rapidly develop new products with desired performance at lowest cost.

Industrial Controls and Information Processing

Unlike the other industries on the IOF list, the chemical industry is complex, incredibly broad, and diverse, encompassing the production of over 50,000 chemical compounds. While there are several different ways to subdivide this industry, we have chosen the following segmentation in accordance with the eight standard industrial classifications:

1. Inorganic Chemicals
2. Plastics materials and synthetics
3. Fine chemicals and Pharmaceuticals
4. Soaps, Cleaners and Personal Care
5. Paints and Allied products
6. Organic Chemicals
7. Agricultural chemicals
8. Miscellaneous Chemical Products

The importance of this industry is underscored by the following fact that it accounts for approximately 7% of global income and 9% of international trade, and uses approximately 25% of the estimated manufacturing energy used by U.S. industries. A recent report from the Lawrence Berkeley National Laboratory (ref [15]) provides a summary of energy use throughout the industry.

While there is one roadmap for each IOF, there are currently 9 separate documents in the complete roadmap for the Chemical Industry, covering the following topics: Biocatalysis; Combinatorial chemistry; Computational chemistry; Computational Fluid Dynamics; materials of Construction; Materials Technology; New Process Chemistry; Reaction Engineering; and Separations. A review of this series leads to the conclusion that the industry has not produced a clearly articulated roadmap for either process control or information processing. Of the 9 components of the roadmap, only Materials Processing, New Process Chemistry, Reaction Engineering and Separations contain any direct reference to issues related to the role of Process Control and "Sensors and Analyzers" in achieving the industry vision.

The most relevant issues related to Process Control in the current roadmaps are Integrated Process Design and Process Control for energy efficiency: the design of new processes should incorporate, from the very beginning, the concept of simultaneous control structure and control system design, not only to achieve desired product quality, but also to minimize energy expenditure

The most relevant issues related to information processing are as follows:

1. Development on-line (or at-line) sensors to determine product quality at a sampling rate faster than currently possible with quality control lab sampling systems
2. Development of "smart sensors" as part of an overall process monitoring and control system; to be part of a network of self-calibrating sensors with built-in intelligence that can be integrated for example with the "field-bus" technology
3. Novel sensors for effective bio-process control

An earlier report (ref [2]) focused much more directly on process control and process sensing for implementing process control than the Roadmap. All the key issues summarized in this report are still relevant.

1. Sensor development for acquiring both process variables as well as physical properties of the products;
2. The development of information technology for the collection, analysis and processing of high volume process measurements in real-time;
3. Robust, intelligent control systems
4. Plant-wide process optimization and control.

Issues of relevance to other technology areas

The implementation of the vision of combinatorial chemistry involves the use of *robotics, automation*, and *informatics* in combination. For accelerated discovery as well as process and product development, a large number of carefully designed, multi-dimensional experiments are performed rapidly and in parallel, typically on miniaturized and heavily automated platforms. Robotics enable the rapid and large-scale loading and unloading of chemical components into hundreds of micro-reactors with automated reagent addition and platform conditions control; the massive quantities of generated information are handled with appropriate informatics tools.

Automation

Despite the disparate nature of the Chemicals industry, common opportunities for automation improvements [35, 75] exist across these areas, including: development of tools to diagnose faults in real-time systems (automated maintenance and diagnosis), the development of improved customizable optimization techniques needed to handle the rigorous demands imposed by increasingly complex nonlinear models, and the development and maturation of those nonlinear models.

Robotics

Manufacturing processes will be operated under fully controlled conditions; automatic process control will be practiced from plant start-up to shutdown. Robotics can also be used to assist operators in tasks such as loading catalyst into the reactor; tele-operation, allowing the operator to handle field tasks without leaving the control room [75]; and other energy efficient practices including robot-aided testing [76], leak detection [77-79] and Maverick robot inspector [55]. Robots and robotics can help energy conservation and efficiency testing, leak monitoring, materials handling, packaging, and storage tank corrosion inspection crawler robots.

FOOD PROCESSING

The food and food products industry plays a vital role in the US economy and in foreign trade due to its large size, stability, growth, diverse products, and competitive nature. The food industry boasts the second highest value of shipments among all industrial sectors, and, in addition, exports currently outnumber imports and have consistently increased since 1991, making the food industry significant to US Foreign Trade.

Industrial Controls and Information Processing

As this is a suggested addition to the IOF portfolio, there are no detailed industry roadmaps that address energy operations in the context of control technology. One source of review material is the paper published by Nikolaou in 1998 [53], which is based upon extensive interactions in the food industry. In Nikolaou's report, the technology gaps identified include scheduling tools, advanced controls, statistical methods, and artificial intelligence. Two detailed case studies are provided, each of which has significant ramifications for energy savings: an extrusion cooking process, and a chip frying process. In both cases, the technology gaps included control design for time-varying, uncertain, nonlinear systems.

Automation

No DOE roadmaps exist for the Food Processing industry. Case studies [27, 33] indicate process improvements that could offer increases in productivity and energy savings at least as great as those in agriculture and beyond (up to doubling energy efficiency).

Robotics

The application of robotic systems may result in valuable gains in energy efficiency while improving product quality in such operations as harvesting, cutting, portioning, filling, packaging, inspection, and handling. Other reported efforts are meat processor and grinding [83], poultry processing [82], materials handling and wastewater purification system. Robots and robotics can help energy conservation and efficiency in meat processing, packaging, grinding, poultry processing, fish processing, cooking, drying, fruit picking, spraying, and baking.

FOREST PRODUCTS

Forestry, lumber, wood products, pulp and paper, and fuel wood constitute the Forest Products Industry. This industry employs close to 2 million workers in the United States, generates annual sales of about $250 billion (about 10% of which is through export), and represents nearly 10% of the US manufacturing output.

Industrial Controls and Information Processing

A detailed report was prepared by a process automation working group of the Forest, Wood and Paper industry in 2001 [1]. Among the program goals for the year 2020 were reductions in costs for materials, energy, labor, and maintenance by 10%. This was part of a larger overall objective to reduce unit manufacturing costs by 50%. Three focus areas were considered: sensors, decision-making tools, and process control.

The gaps in decision-making tools included a lack of detailed mechanistic models that can be fitted to mill operations and include parameters that adapt as conditions change. A related challenge was the need to present process data in an intuitive visual media to the operating personnel. To address the need, three categories of technologies were detailed:

1. First-principle dynamic models
2. Data mining and pre-processor sensor information
3. Data presentation techniques

In addition, two classes of dynamic process models were advocated: prediction of product properties and characterization of novel processing steps such as black liquor gasification. Improvements are also possible in traditional processes which are poorly understood, such as sheet forming (to address, for example, fiber-fiber interactions and retention of fines and filler particles). The data mining issue received considerable attention, with an emphasis of tapping the large volume of data typically generated at a high rate. Analysis might focus on prediction of pending upsets or preprocessing of sensor data for the purposes of asset management or real-time process control.

Gaps in control technology included:

1. Difficulties with the implementation of model-based controllers
2. Lack of methods for handling of complex grade transitions (e.g., paper machine or feedstock swings in the digester)

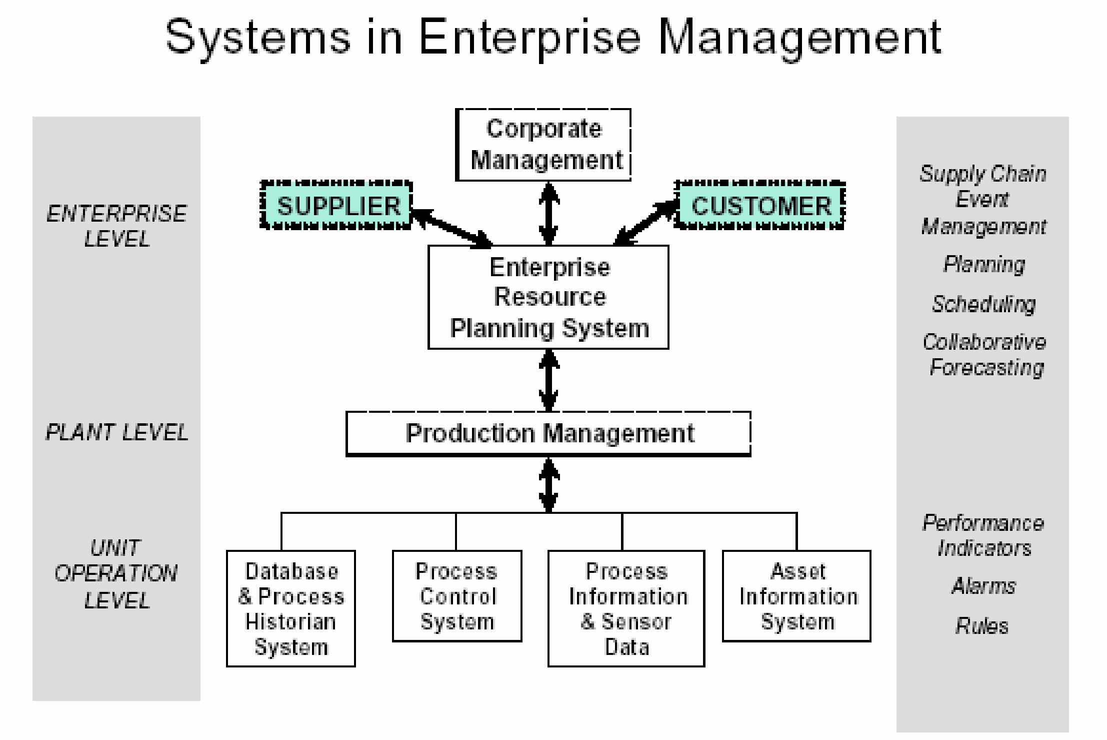
3. Lack of reliable self-tuning mechanisms
4. Lack of automated fault diagnostic tools

Gap-filling technology recommendations were:

1. Self-diagnosing, self-tuning control systems: numerous loop audits have been published that show approximately 20% of the control loops in a typical mill are actually *reducing* variability. As processes drift, there is a need to have controllers which adapt to the new conditions automatically. Robustness and diagnostic capability are largely unsolved problems
2. Transition controllers: a predictive control opportunity provided that suitable models exist for describing separate product grades.
3. Hybrid analytical/empirical models
4. Integrated process control and business systems: (see Figure 2) the integration of enterprise resource planning (ERP) systems with process control systems was highlighted as a problem area in which tools are available from the vendors, but relatively few actual demonstrations have been documented.

Needs that were identified in earlier reports (e.g., National Academy Study in 1998) [2] included control strategies for black liquor evaporators, multi-character (color, moisture, etc.) control in papermaking, expert systems, diagnostic systems, and proactive maintenance. These are likely to be active considerations in the industry today, but perhaps at a lower priority level than the topics identified in the more recent survey.

Figure A-1 – *Layers of hierarchical control in a typical enterprise management system [1]*



The 1998 report by Kayihan [54] also highlighted unit-operation specific recommendations, with an emphasis on: (i) pulp digester, (ii) washing and bleaching, (iii) evaporators, recovery boiler, and causticizing, (iv) refiners, (v) stock preparation, and (vi) paper machine. Technology gaps identified include fundamental modeling, model reduction, adaptive control, robust model-based controller design, and disturbance estimation.

Automation

Energy efficiency has been investigated in many areas in forest products. Issues were raised related to maximizing the value of waste (perhaps by reusing it as fuel) and otherwise improving operations through the value chain are important. To that end, industry needs include smart systems for process diagnostics (automated maintenance and diagnosis); and algorithms for multivariable adaptive control, including improved mapping of actuator responses for more effective cross-directional control, and the implementation and maturation of those algorithms (all of these closing the loop on quality).

Robotics

Robots and robotics can help energy conservation and efficiency in harvesting, weed killing, packaging, wood machining and sanding, planting, furniture manufacture, pulp and paper processing, kiln drying, cutting, finishing, and felling.

GLASS

Glass products are used in food and beverage packaging, lighting, communications, transportation, and building construction. However, the glass industry needs to increase its productivity, reduce its energy use, and decrease its environmental impact [94].

Industrial Controls and Information Processing

The DOE/ITP roadmap directly addresses the role of process control and information processing in the Glass Industry. The major product types, flat glass, container glass, and fiberglass are considered jointly. "Process measurement and control" as a single entity, is identified as a means for improving process performance, but it was also identified as a technological challenge. The industry priorities are defined in terms of four technical elements, two directly relevant to industrial controls and information processing:

- Production Efficiency: research and development that will help the industry become more efficient, productive, and competitive. This is the area where advanced process control systems and advanced measurement techniques are identified as critical components required for achieving the desired objectives
- Innovative Uses: new product development, find new applications for glass that reflect a higher technical content and create a positive impact on the industry

Elements identified and summarized in the report are still relevant and resonate with the current survey; specifically, the report identifies "Intelligent Process Controls" (integrated control systems, product fabrication control processes) and "Advanced Sensors" (robust temperature sensors, smart sensors) among the high-priority activities considered critical for improving production efficiency. Information processing must play a significant role here, if we consider the following items as critical to achieving energy efficiency:

1. Limited rate of heat transfer into/out of the glass
    a. Raw materials are not optimized; higher quality raw materials are needed
    b. Glass compositions may not be optimal
    c. Combustion is not optimized
    d. Better material data is required
2. Waste heat not fully utilized
    a. Heat recovery systems require improvement
    b. Preheating systems require improvement
3. Limited use of cullet
    a. Cullet requires about 30% less energy to melt than raw materials (batch), and also reduces volatilization

An "energy management system," specifically designed to acquire and integrate process data related to all the items listed above, can, in conjunction with an appropriate energy utilization model, be used to achieve combustion and raw material optimization with respect to energy efficiency.

Under "Innovative Uses", Process Control and Measurements are also identified as priorities. Advanced Processing and Control:

1. Suboptimal measurement and control of processes
2. Lack of adequate distortion measurement technology
3. Poor understanding and control of temperature gradients during forming
4. Lack of a non-intrusive flow characteristic measurement device

The general consensus is that, while sensors and controls exist in current operations, significant improvements are needed throughout the glassmaking process. Advanced control and sensors technologies are needed to provide additional information regarding the operating environment, in order to improve control of glassmaking operations and the quality of glass products. A few examples of critical needs include viscosity sensors and robust temperature sensors.

The overall estimate of the impact of advanced process control and better information processing (sensors and systems for data analysis) on Production Efficiency is *High*; on Energy Efficiency is *Medium*; on Environmental Performance is *Medium*; and on Innovative Uses is *Low*.

The earlier report ([2]) focused much more directly on process control and process sensing for the Glass industry; the specific needs identified and summarized in the report are still very relevant today since the problems identified remain unsolved. The primary control need identified was the improved control of combustion processes in general. The key limitation to the implementation of advanced control was identified as the lack of adequate process sensors, specifically, for determining:

1. Critical process variables
    a. Temperature profiles in furnace and forming operations;
    b. Temperature uniformity in glass streams and
2. Product quality variables and other physical properties such as
    a. Fiber diameter
    b. Cullet composition
    c. Viscosity
    d. Oxidative state

Automation

Common themes among the Glass roadmap documents [2, 19, and 37] were:

1. Cognitive algorithms for process controls. "Smart" algorithms that can control a number of process parameters simultaneously to achieve better film quality would simplify operation of the coating process
2. Fuzzy logic development for process control
3. Unified PLC-based system for measurement/control of flows

Robotics

Documented successes in robotics applications in glass industry include Cyberglass robotics [95, 96], monitor operations management [97], process sheathing system [98] and flat glass production [99].

Robots and robotics can help energy conservation and efficiency inrobust sensors for harsh environments, handling, furnace combustion, and blowing and stemming.

METAL CASTING

The metal casting industry is currently improving its casting design methods to open new markets and applications, and improve the understanding and control of metal casting processes [100].

Industrial Controls and Information Processing

More than 90% of all manufactured, durable goods, and 100% of all manufacturing machinery contain castings; the casting industry is an essential building block of U.S. industry. Made up of mostly of small companies, the industry relies on government assistance to conduct innovative research. The Metal Casting Industry Technology Roadmap directly addresses the role of Process Control and Information processing; the major driving force for Process Control is scrap reduction. Improved process measurement and control technologies are identified as high priority needs in manufacturing, for both product quality and energy efficiency, especially for melting processes. The roadmap explicitly states (p. 31) "The lack of low-cost and accurate sensors and controls hurts metal-casting productivity and quality. The sensor and control equipment that is currently being used in die and sand casting is often not very effective."

Specific needs identified include the following:

1. A lack of continuous monitoring capability in sand molds
2. Existing sensors are unable to detect subtle changes in conditions in molds, gates, runners, and risers
3. Existing automated control systems are neither sophisticated enough to learn from past mistakes, nor an adequate substitute for manual controls

This last statement implies that the development of effective control schemes is of prime importance, and the potential benefits of advanced control systems are significant.

There are also significant benefits to be gained from process modeling. Model developers face several technical challenges because the casting process is extremely complex, so modeling the various process steps is particularly difficult. Additional complications arise due to a lack of consistent data for mold filling and an inability to predict the micro-structure as a function of composition and processing.

In sum, industry priorities include the general development of effective sensors and controls suited to the hostile environments characteristic of this industry. Specifically:

1. Develop smart controls and sensors for automation supervision
2. Develop a systems approach to scheduling and tracking
3. Develop a mathematical model that describes process control and can be used to control the machine

The earlier report (ref [2]) focused directly on Process Control and Process Sensing for this industry. The most critical needs were identified as novel sensors, a category that is outside of the intended scope of our work. Nevertheless, the need for such sensors is directly linked to the need for improved process control.

Automation & Robotics
The metal casting roadmap outlines key challenges to improved energy efficiency through automation, including the challenges of optimization and the lack of adequate control systems. Consequently, the primary needs highlighted in this roadmap include the development of smart controls and sensors for automation supervision, the development of smart molds for continuous monitoring, and the need for improved models and their integration for continuous process improvement. Robots and robotics can help energy conservation and efficiency in robust sensors for harsh environments, furnace combustion control and die casting.

MINING

Industrial Controls and Information Processing
In the recent IOF roadmap documents (ref [8,9,10]), opportunities for process control and information processing developments are detailed.

- Extraction and processing: automation improvements in communications, on-line analysis, and controls are identified as opportunities; worker safety has been enhanced through remote control of hauling equipment, and further developments will improve both safety and energy efficiency
- Detection of geological anomalies: significant and unique opportunities for improved utilization of image analysis tools
- Mine planning: tight integration of available sensor input (e.g., radar) and model development. Extracting knowledge from models and data for mine planning are akin to petroleum reserves modeling and control efforts in the refining industry
- Remote devices: control development will mainly occur on the exploration front.
- Overall mining operation: a data flow problem exists not unlike that in plants and mills; there are obvious opportunities for data mining and integrated control of mining operations.
- Processing: numerous gaps exist in controls and information processing technology, notably, the comminution and classification process are akin to many particle processing steps in other IOF sectors (e.g., crystallization, precipitation, emulsion, and granulation). Better characterization of particle properties and tighter control of particulate attributes would address some of the technology gaps. Many of the unit operations in the

processing stage are not under closed-loop control, hence this is a necessary condition for eventual systems-level integration with business and planning functions.

Automation and Robotics

Several roadmaps exist for the mining industry, including a mining industry roadmap for crosscutting technologies, a roadmap for mineral processing technology, and a roadmap for exploration and mining. Common themes include:

- Development of intelligent, self-building process models.
- Development and implementation of comprehensive models that support the optimization of the entire mining process by combining processes into an integrated processing system.
- Development of autonomous mining equipment.
- Automation of critical decisions related to throughput and product quality through economical on-line sensors and control methods.
- Automated communication and data transfer systems
- Repair and maintenance using robotics.
- Automated slurry wall technology (a new system or special slurry) to eliminate open-pit mining.
- Automation and robotics concerns with "safe and efficient extraction and processing" and "superior exploration and resource characterization".

Among these, robotics for exploration and mine planning constitute a mid-term (4-10 years) project; robotics for repair/maintenance for underground mining is a mid-term project while for surface mining autonomous technology for imaging, sensing, and blasting and data, communication, and positioning systems comprise two near-term (1-3 years) projects, and slurry wall technology is a long term (11-20 years) project [103].

A great deal of effort on robotic applications in mining is coming from Australia, including: ore sampling automation [101], mine field modeling [102], mining robots [103,104], ocean mining [105-107], multi-robot mining [108], Powerboss product [109], ceramic production [110], coal waste reduction, hydraulic separation, and fractal robots [111].

Robots and robotics can help energy conservation and efficiency in material handling, equipment, autonomous underground vehicles, and underwater mining:

- Crosscutting Effects: Glass, Metal casting, and Steel
- Benefits: Energy savings due to elimination of human miners (air conditioning, safety, environmental hazards, and welfare of the miners are not involved), and reduced waste
- Need: Perceived to be quite strong, with much progress taking place in Australia
- R&D Areas: Mining robots, multi-robot cooperative mining, coal waste reduction, hydraulic separation.

It is difficult to make an accurate estimate of the energy savings in this area, but with the large size of this industry, robotic technologies in mining can help save energy needs for such operations as heating, cooling and conditioning of air under the ground, and save miners' lives, an immeasurable account.

STEEL

Industrial Controls and Information Processing

In the recent roadmap document [7], a number of opportunities were identified for energy improvements arising from process control.

- Cokemaking: *"On-line data collection is required to optimize process sequencing for highest energy efficiency and lowest cost coke production. The operation of conventional by-product plants or syngas-producing plants could be improved with the implementation of modern distributed control systems. However, research is needed to develop plant simulations and sophisticated control algorithms"* (p. 11)
- Ironmaking: advanced controls for maintaining critical levels of char in the slag, control of slag formation, as well as better process models for reduction, char control, foaming, and post combustion/heat transfer for smelting systems
- Oxygen furnace operations: advanced in-situ sensors that would allow carbon and temperature control
- Electric arc furnace operations would benefit from approaches to optimize and control the electrical input, particularly with the high-voltage, high-impedance UHP furnaces and chemical energy sources
- Ladle refining operations: control improvements in temperature, chemistry, and cleanliness
- Casting and milling: minimization of defects through tight fluid flow and temperature control, as well as the utilization of diagnostic controls for prediction of operational problems and scheduling of maintenance
- Rolling and finishing: tight, integrated control of downstream processes. Given suitable microstructure sensors, there are also opportunities for improved control of heat treatment processes in rolling and finishing.

In a similar report for the steel and iron sector (National Academy, 1998) [2], the following priorities were identified for information processing and process control:

- On-line chemical measurements for feedforward control of thickness
- Improved utilization of data to enhance process understanding
- Robust and self-diagnosing controllers
- Improved data integrity and reconciliation of spurious data
- Optimization of supervisory controllers for scheduling and queuing
- Development of hybrid models that combine empirical and mechanistic understanding

Automation and Robotics

The roadmap categorized the needs as follows: sensors for on-line, real-time, or high speed measurement; sensors for harsh environment applications; analytical and physical property measurements; sensors for non-intrusive or non-contact measurement; sensors for diagnostic and maintenance applications; mixed materials sorting technology; sensors for emission and effluent measurements; sensors for microstructure or inclusion measurement; sensors with built-in failure sensing or self-calibration; advanced control techniques; imaging and data communication; modeling and simulation; sampling and process control; and automation [112].

Overall, we can categorize these between process monitoring sensors and process control systems. Process monitoring sensors measure process parameters, while process control systems include needs for advanced control techniques, image analysis, development of adequate control schemes, and emission control schemes. In fact, the need for process monitoring sensors feeds into the process control system needs because their intent is essentially to improve the process control. Among documented energy efficient practices, one needs to mention harsh environment, real-time melt temperature measurement energy regeneration [113] and temperature measurement of galvanneal steel [114].

GENERAL INDUSTRIAL RECOMMENDATIONS

Industrial Controls and Information Processing

The Miletic et al. review [46] is noteworthy; two energy-intensive industries (steel and forest products) combine to give a unified viewpoint on information processing needs. Process applications include casting and desulfurization from the steel industry, and digester and paperboard manufacturing from the forest products industry. Their recommendations for addressing current challenges in information processing include:

- Identifying and defining an appropriate scope for statistical modeling applications
- Data gathering, pre-processing, and visualization tools
- Development of methods for on-line multivariate statistical models
- Solving long term maintenance problems

In the Integrated Manufacturing Technologies Institute (IMTI) continuous processing and discrete manufacturing reports [42, 43], the following characteristics were described for effective design and implementation of intelligent controls in the future (across general industrial sectors):

- Control systems will provide total process solutions to product requirements
- Control system elements will work together in a coordinated fashion to monitor the "health" of the process, as well as product quality
- Control systems will be flexible and modular, enabling true plug-and-play functionality
- Intelligent control systems will permeate all levels of the manufacturing process, from high level planning and scheduling down to regulatory control and data acquisition

- Multi-agent architectures for process and product modeling
- A prominent role in the overall control scheme was identified for the process model, which would be captured from process knowledge
- Process control that achieves total economic optimization

In the domain of information processing, the report touched on a number of relevant goals for future manufacturing:

- Soft sensors that leverage modeling to eliminate the need for hardware sensors, achieved through inferential modeling, as well as hybrid combinations of empirical and mechanistic models.
- Sensor fusion algorithms that combine heterogeneous data sources to provide support for advanced decision-making levels in the automation hierarchy.
- Real-time sensory processing to enable continuous tuning optimization of manufacturing processes.

In one vendor survey (conducted by AspenTech) [41], the prioritized list of challenges included:

1. On-line optimization
2. (tied) Plant test for control models; on-line control; performance monitoring
3. Model identification and control
4. (tied) Control simulation; model identification and inferential sensors; on-line inferential sensors

This suggests that on-line optimization is a priority, and further analysis revealed that the desirable features of on-line optimization would be: maintainable, consistent with higher level (planning) models, reconfigurable, ability to utilize off-line, fast solution time, and ability to track key performance indicators. In the domain of performance monitoring, customers indicated that quick diagnostics were most desirable, with additional interest in: simplified user reporting, integration with controller simulation, PID performance metrics, and combination alarms. In a more general forum, cost and maintainability were common concerns raised as limitations to implementing advanced automation solutions.

Automation

Finally, the information from the online roadmaps and the DOE/ITP Energy, Environment & Economics (E3) Handbook [30], was compiled into the following table (Figure A-3). In this table, two interesting points to highlight are "Revenue per worker" and "Revenue per energy consumed." "Revenue per Worker" (a gauge of productivity), is used to compile the second to the last column, "Estimated Derived Automation level (based on worker productivity). The highest levels of revenue per worker are in the Aluminum, Cement, Chemicals, Forest Products and Glass industries. These industries appear to have the highest worker productivity, which may be linked to automation – this depends on the assumption that greater productivity is a direct result of greater use of automation. This may not be an exact correlation; however, industries that rank relatively low on this measure (Agriculture, Metalcasting, Mining and Steel) may be ripe for productivity gains if more automation is prudently applied.

Next, “Revenue per energy consumed,” shows the results of dividing “Income/Revenue/Shipments (in $billions)” by “Energy Consumption (Trillion of Btu per Year)” to give the results that appear in “Revenue per energy consumed” and lead to the rankings in “Estimated Derived Automation Level (based on Productivity per Btu).” Again, the level of automation is estimated and derived from an indication that and industry that uses energy efficiently may be well automated. The industries that rank high by this measure are Aluminum and Food. They can be said to be energy efficient industries since they harvest the greatest value yield per unit of energy. Mining, for example ranks relatively low by this standard. They may be fruitful areas to explore for “low hanging fruit” in terms of energy efficiency from automation.

Figure A-3

Industries of the Future		Employment (Millions)	Income/Revenues/Shipments (in billions)	Energy Consumptions (Trillions/BTU/Yr) Total	Consumption Data from Year	Percentage of Total Energy Consumption	Revenue per worker	Revenue per energy consumed	Est. Quadrillion BTUs 1991	Est. Quadrillion BTUs 2002	Estimated Derived Automation Level (Worker F	Estimated Derived Automation Level (Producti
Agriculture	8%	21	54.6	663.1	1996	3%	$ 2,600	0.082	1.81	2.59	Low	Medium
Aluminum	2%	0.143	39	314	1994	2%	$ 272,727	0.124	0.45	0.65	Medium	High
Cement		0.017	8.3				$ 474,828				Medium	
Chemicals	19%	1	454	5328		27%	$ 454,000	0.085	4.29	6.15	Medium	Medium
Food		1.1	270	1193	1994	6%	$ 245,455	0.226	0.00	0.00	Medium	High
Forest Products	11%	1.3	262	3165	1994	16%	$ 201,538	0.083	2.49	3.56	Medium	Medium
Glass	1%	0.149	29	225			$ 195,286	0.129	0.23	0.32	Medium	High
Manufacturing			3170		1994				0.00	0.00	Low	Low
Metalcasting	1%	0.225	19	235			$ 84,444	0.081	0.23	0.32	Low	Medium
Mining	3%	0.335		39.5			$ -		0.68	0.97	Low	Low
Other	25%			2807		14%		0.000	5.65	8.09	Low	Low
Petroleum Refining	24%			4000		20%			5.42	7.77	Low	Low
Steel	6%	0.155	86.97683	1824.3	1994	9%	$ 561,141	0.048	1.36	1.94	Medium	Medium
Totals	100%			19,794					22.60	32.36		
									1991 n	2002 numbers		
Sources:	U.S. Department f Energy Office of Industrial Technologies, Congressional Briefing,											
	Denise Swink, Deputy Assistant Secretary, April 2, 2001											
	DoE/OIT Energy, Environment & Economics (E3) Handbook, www.oit.doe.gov/e3handbook/f.shtml											
	Cement Industry Overview, Portland Cement Association website,											
	http://portals.learninginsights.com/pca/index.cfm											
	OIT/IOF/Industry Profiles											
	Energy Information Administration/Monthly Energy Review (June 2003)											
	Energy Consumption Series, Measuring Energy Efficiency in the United States'											
	Economy: A Beginning (October 1995), DOE/EIA-555(95)/2											

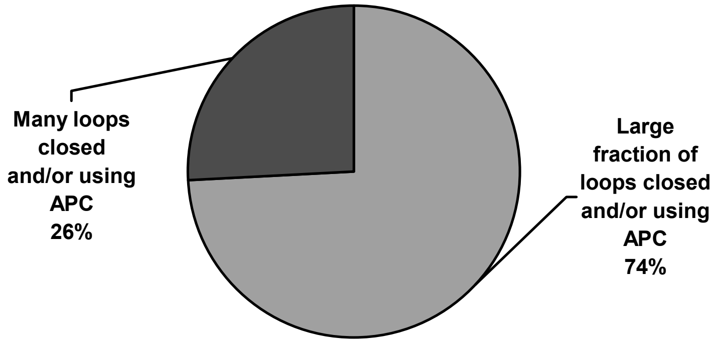
Appendix 2 – Industry Surveys

Industrial Controls

The survey results are organized in two categories: (i) operating companies in the IOFs, and (ii) vendor technology companies supporting the IOFs

Operating Company Questions and Response Summaries

1. For the energy-intensive operations within your organization, what is the degree of feedback control currently implemented?



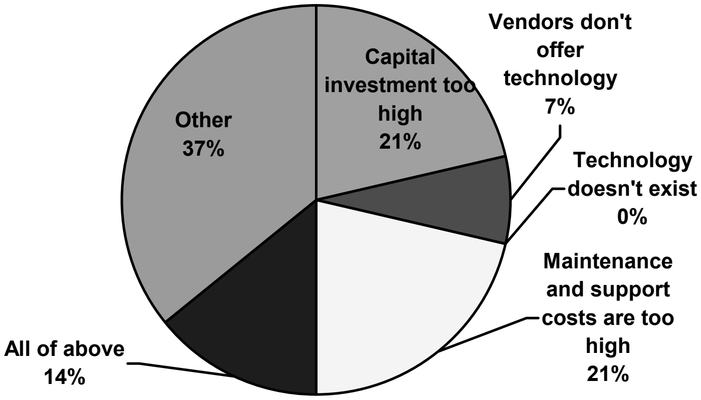
2. If the level of control is inadequate, what are the opportunities for improvement? We are particularly interested in opportunities for large-scale, large-impact improvements in energy efficiency and consumption.

Opportunities for Control Improvement
Optimization
Control of inputs (scrap, fluxes, cycle times)
Model Predictive Control (MPC) technology itself is reasonably adequate, but there's still room to improve model identification and fit-for-purpose model adaptation technology
Current state-of-the art of real-time optimization is really an idea that industry has been running with for about 40 years, I suspect that we'll see an evolutionary trend in the upward growth of the scope and capability of MPC applications to supercede "classical" real-time optimization
Nonlinear MPC
System-wide control
There are opportunities for improvement. (Not sure process control will get this, but optimization may)
More investments; better equipment; focus on Intelligent Control
Huge volumes of low temperature waste heat sent to the air and water. Electric utilities are even larger sources of low temperature waste heat than the pulp and paper sector which uses at least some of the waste heat before dumping it to the air or water.
Low cost variable speed electric motors and their controls as an alternative to pressure reducing valves for flow control is a large potential source of energy savings for U.S. manufacturing.
Opportunities in drying are possible (largest energy (natural gas) use in plant)
Sometimes, when the weather is especially cold, the logistics for utilities get complicated – home heating gas (local utilities) – coordination would be helpful here.

3. What types of control technologies are currently in use in your organization?

Control Technology
PID
Cascade/Ratio/Model-based Control (other than MPC)
MPC
Real-time Optimization
Smith predictor
Adaptive control
Visual Image-based control

4. If the current level of industrial control is insufficient, where, in your opinion, are the bottlenecks to achieving better performance?



Other responses included: organizational inertia, lacking on-site process engineers, and cost/benefit not favorable

5. Is your company involved in any federally supported research program? (e.g., with an academic collaborator, such as NSF Grant Opportunities for Academic Liaison with Industry (GOALI) program)

Federally Supported Programs
NSF/GOALI program
Yes - limited basis
Member of several academic consortia on process control
Grantee on DOE contracts (fossil fuels program) for MPC
Subcontractors on DOE project; other NIST ATP programs
DOE: Part of a DOE $100B US National Labs contribution to members of Glass Manufacturing Industry Council

6. Can you think of any significant opportunities for DOE investment in R&D in the area of industrial control as it relates to energy efficiency/consumption in your organization and similar operations?

DOE Opportunities
Measurement of furnace variables for process optimization (energy input)
Advanced integrated global control
Automatic sensor corrections
Nonlinear control
Multi-plant, system-wide planning (almost operations research issue) – solving large mixed integer problems (improved optimization)
Integration with planning/scheduling
Statistical forecasting (they are effectively a utility operation) – predicting customer demand
On-line sensor development: Nylon autoclave, HMD loss to the vent is a major issue; if we could measure gas vent flow and composition on-line: benefit ripples downstream; make less waste). Energy efficiency is directly related to yield
Better tools for tie-line control, tools for dealing with electric power make/buy decisions in the context of complex (e.g., real-time) pricing contracts; tools for dealing intelligently with electric power demand curtailment in the face of complex electrical contracts (e.g., real-time pricing); use of on-line (perhaps model-based) optimization tools geared toward energy optimization objectives
Better tools for tie-line control, tools for dealing with electric power make/buy decisions in the context of complex (e.g., real-time) pricing contracts
Tools for dealing intelligently with electric power demand curtailment in the face of complex electrical contracts (e.g., real-time pricing)
Use of on-line (perhaps model-based) optimization tools geared toward energy optimization objectives
Development of inexpensive analyzer technologies would enable a significant improvement in process control for the distillation area
Use of MPC for better modeling and control in resin manufacturing and polymer extrusion would be useful
Biggest driver for efficient use of energy is to increase throughput capability with the current or slightly modified equipment – energy savings would be a side benefit
There are environmental issues: in designing a process to minimize impact on the environment, we will almost always end up with a process with insufficient degrees of freedom. This might only be made operable by advanced control. This is a potential opportunity for achieving indirect benefits through control, perhaps

Vendor Company Questions and Response Summaries

1. Are any of your offerings (in process and automation tools) specifically targeted for, or primarily employed for, improving energy efficiency and utilization?

Energy Targeted Tools
Yes. There are specialized control and optimization applications, and auditing and engineering services for the improvement of energy efficiency and for the reduction of plant overall fuel and power costs.
All products contribute to reduction of energy use by helping minimize energy use to manufacture the required products, avoiding rework/recycling and minimized energy use during abnormal situations.
Specialized versions of ROMEO (PowerX – power generation), ARPN (On-line Monitoring tool for equipment performance) → many other tools from Foxboro

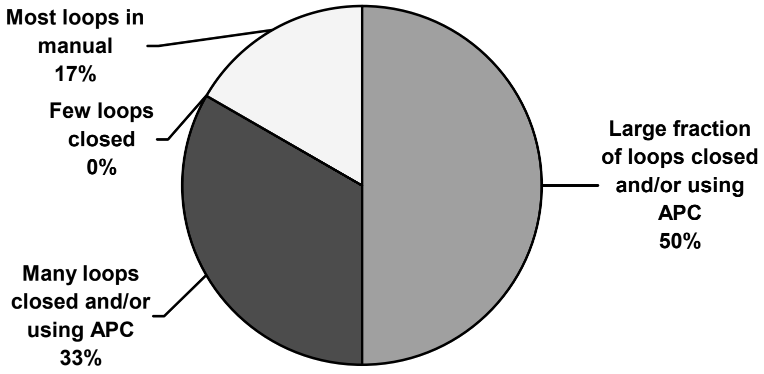
2. Do you have new technologies or product offerings under consideration or under development, relevant to improving energy usage? Please describe them.

New Tools for Energy
Model predictive controls for energy demand and supply side control improvements
Various energy management software applications
Novel energy forecasting and equipment scheduling and real-time optimization/control solutions for control of boilers and power generation equipment.

3. Have you worked with any of these customers on energy usage? If so, what are the projected energy savings from these projects, as a percentage of current energy use?

Energy Savings
The projected energy savings are typically 1-5 % of the fuel and power costs.
1-3% in profitability, with approximately 1/3 of that is energy related

4. For the energy-intensive manufacturing customers, what is the degree of feedback control currently implemented; was advanced process control (APC) used?

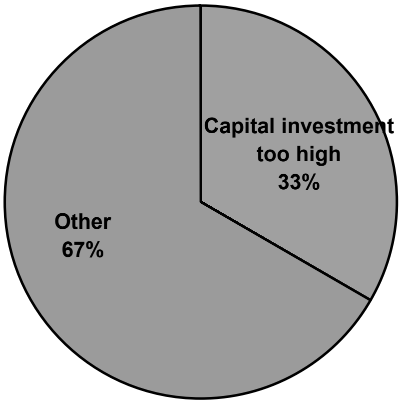


5. Is this level of industrial control adequate, or are there opportunities for improvement? We are particularly interested in opportunities for large-scale, large-impact improvements in energy efficiency and consumption.

Opportunities for Improvement
Energy metering system (steam and water flow measurements, electric power) is generally very poor, difficult to know the actual energy usage breakdown.
Boiler combustion process is difficult to optimize and emissions are difficult control due to the poor condition of combustion air actuators, and poor air flow instrumentation (not sufficient number flow sensors, air ducts poorly designed –especially in North America - with no straight sections for flow meter placement).
Lack of control coordination between the different power plant components. Biggest problem is often the turbine control system. Typically, turbines have their own stand-alone, isolated control systems provided by the turbine manufacturers. It is extremely difficult to integrate these controls to the plant coordinated control strategies. The turbine control manufacturers usually offer standard solutions for all customers, with little customization to actual plant conditions and requirements. An integrated turbine control system allowing coordinated control of multiple turbines, pressure reducing valves, etc. can be extremely beneficial, savings potential can be 5% of the overall energy costs. Even better improvement would be a total integration of the plant DCS and the turbine controls.

Plant information systems seldom reveal much about the actual performance of the energy supply and demand. The information systems typically produce routine reports. Potential areas of improvement: data reconciliation systems, model based performance assessment.
Moving from old control to MPC for turbines, could be up to 5% improvement in heat rate (at low loads), at higher loads (no incentive). Lower loads are more common (emissions requirements). 50lb/s natural gas is typical consumption for a turbine.
They partner with operating companies on operation (Optimization Services). Roughly 5-10% of turbine power can be consumed by operating equipment in plant. Optimize with utility cost scheduling. Scheduling the energy for grid pricing variations (evenings, off-peak, etc.).
Big opportunity for improvement: for example, optimization is only local (small units, e.g., cat cracker) – therefore plantwide optimization. Pricing information come from LPs that is highly inaccurate. No good interface between refinery LPs and local optimizers.
Increased use of real-time optimization
Increased use of scheduling
Increased deployment of solutions to prevent, detect, and manage abnormal situations whether caused by equipment problems or caused by human error
Increased use of equipment health solutions
Increased use of Key Performance Indicator (KPI) Management and continuous improvement solutions

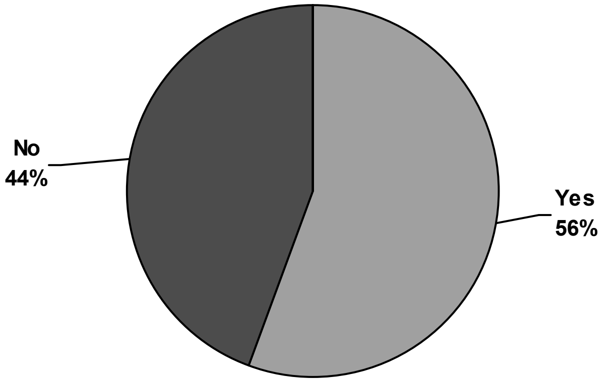
6. In those industry segments where the current level of business and process automation is not sufficient, where, in your opinion, are the bottlenecks to achieving better performance?



Other responses included: Lack of engineering resources in the customer organization. All resources currently fully occupied with day-to-day operations. Distrust of advanced control or Abnormal Situation Management when the decision-maker doesn't understand it.

Information Processing

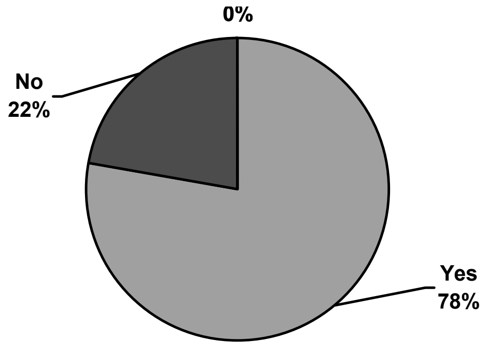
1. Does your organization have any specific system for *directly* monitoring energy usage or energy efficiency in its manufacturing operation?



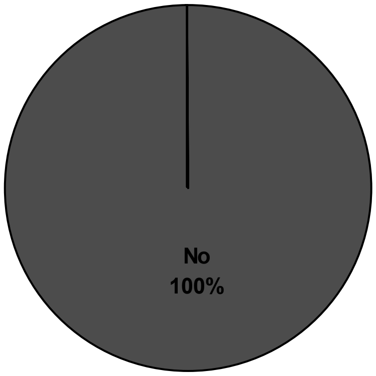
Which system is used?

Systems used for Directly monitoring energy usage/efficiency
Homegrown
Standard Process historian
Excel Spreadsheets

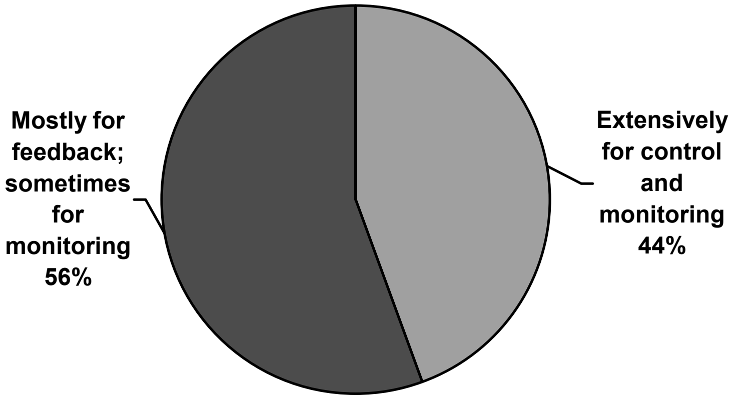
2. Are you, (or anyone else in your organization) aware of the term EXERGY?
(EXERGY refers to the quality of energy - as energy is used in a process it loses quality)



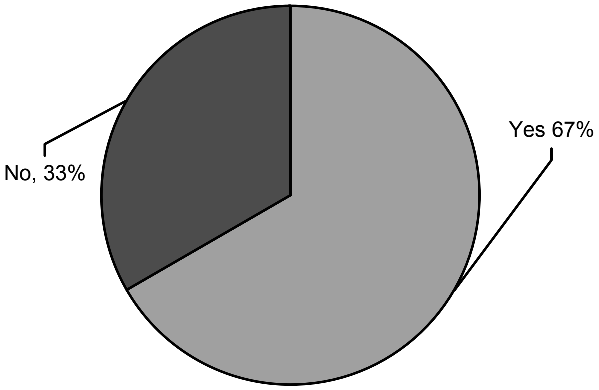
3. Does your organization have access to and/or make use of Exergy Analysis software?



4. For the energy-intensive operations within your organization, what is the extent to which routine process data is used for actively monitoring overall process performance?



5. Does your organization use routine process data to infer energy consumption (or efficiency)?



In what fashion?

How routine process data is used to infer energy usage/efficiency
Compute QPU (Quantity per unit of production) where Q = Energy utilized (among others).
Compute Energy cost/lb.
By-product of economic optimizer
Compute fuel value and fuel use (periodically: weekly and monthly)
Compute (and predict) energy per unit production.
Generate Energy use per ton of production versus time trends.

6. Does your organization employ a laboratory quality control system? If so has this information ever been related in any form to energy consumption? (There were only two respondents to this question)

Use of quality control system and relation to energy consumption
Quality control system used exclusively for product quality; no link yet for determining the energy cost of poor quality
Quality measurements available on-line; no need for a QC lab; no direct link to energy consumption.

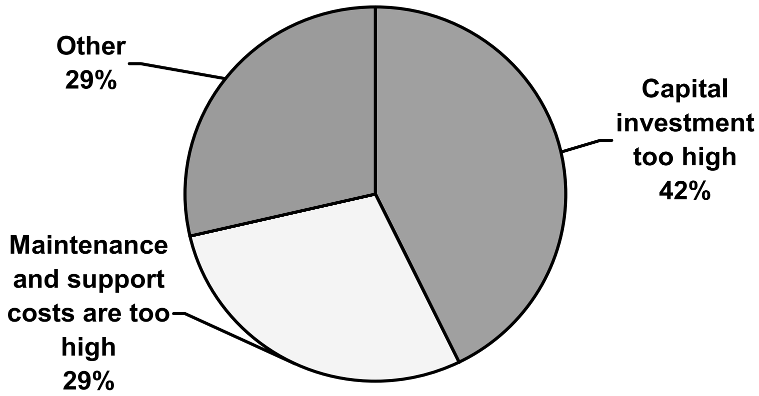
7. Is the current level of information gathering and processing adequate, or are there opportunities for improvement? We are particularly interested in opportunities for large-scale, large-impact improvements in energy efficiency and consumption.

Opportunities for Information Processing Improvement
Maintain meters properly first so that information will be reliable and then use for energy monitoring.
Conversion of process data to more useful information could be done better.
New classes of sensors (intelligent, self-diagnosing, etc.)
More data than we know how to handle; need systems for converting to useful information.
Inadequate data processing
Significant opportunities for improvement in how process data is used in the context of energy efficiency, but first, data reliability must improve.

8. What types of information processing technologies are currently in use in your organization?

Control Technology
Principal Component Analysis (PCA) and Partial Least Squares (PLS)
Kalman Filtering
Statistical process control
Data Compression
Empirical modeling
First Principles Models

9. If the current level of information processing is not sufficient, where, in your opinion, are the bottlenecks to achieving better performance?



Other includes: Knowing what to do; inability to quantify expected benefits a-priori; hurdle rate on return on investment (ROI) too high; no buy-in from businesses.

10. Is your company involved in any federally supported research program? (e.g., with an academic collaborator, such as NSF Grant Opportunities for Academic Liaison with Industry (GOALI) program)

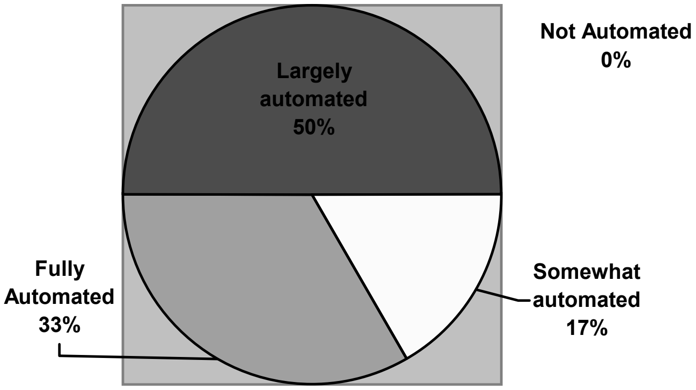
Federally Supported Programs
Not on any program on information processing in direct relation to energy.

11. Can you think of any significant opportunities for DOE investment in R&D in the area of information processing as it relates to energy efficiency/consumption in your organization and similar operations?

DOE Opportunities
Real-time QPU (Quantity per unit production) monitor where Q = Energy
Real-time energy management system
PLS/PCA for energy purposes, with addition of causal analysis.
Monitoring and analysis tools for Batch processes; better linkage between Lab, process, product and end-use customer resulting in overall optimal supply chain.
Data mining for learning energy efficient process operating conditions

Automation

1. For the energy-intensive operations within your organization, what is the degree of business and process automation currently implemented?



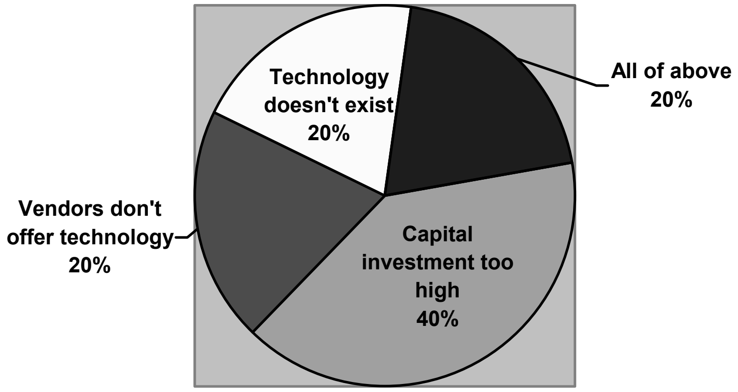
2. Is this level of automation adequate, or are there opportunities for improvement? We are particularly interested in opportunities for large-scale, large-impact improvements in energy efficiency and consumption.

Opportunities for Control Improvement
This level of control is dictated by the FDA regulations of the food industry specifying cook times and temperatures.
Adequate in some facilities – opportunity in others. All energy opportunities will be incremental, not breakthrough large scale.
Due to the varying levels of automation, there are opportunities to automate those that are not, plus opportunities to integrate different "islands" of automation.

3. What types of automation tools are currently in use in your organization?

Control Technology
Closed loop process controllers.
Stork, Allen Bradley
Set back thermostats, photoelectric eyes for lighting control, timer for lighting control.
Honeywell, General Electric, Johnson Controls
PLC, HMI, DCS, MES Set back thermostats. Photoelectric eyes for lighting control, timers for lighting control
A/B, Invensys (Forboro/Wonderware/InSQL), SAP
Foxboro, Allen Bradley, Intellution and many, many others. Automatic guided vehicles Centralized command/control PLC's, distributed DDC, centralized factory control SCADA – Utility equipment (boilers, air compressors, water systems) Building HVAC controls (EMS) Process controllers/integrated and monitored

4. If the current level of business and process automation is insufficient, where, in your opinion, are the bottlenecks to achieving better performance?



Other includes: organizational inertia, lacking on-site process engineers, cost/benefit not favorable

5. Is your company involved in any federally supported research program? (e.g., with an academic collaborator, such as NSF Grant Opportunities for Academic Liaison with Industry (GOALI) program)

Federally Supported Programs
None.

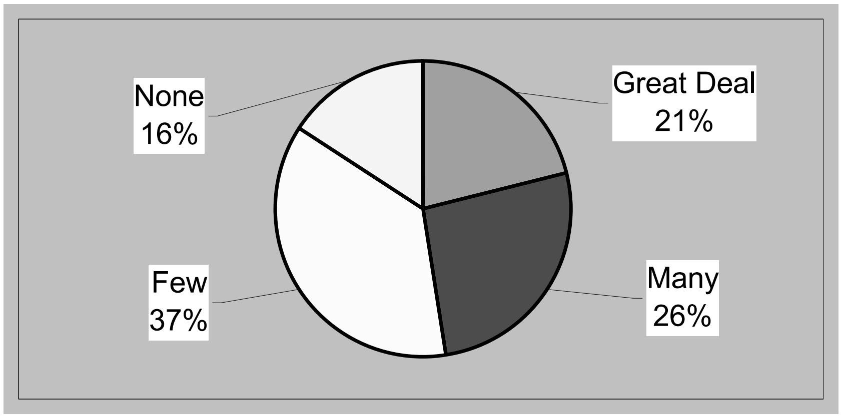
6. Can you think of any significant opportunities for DOE investment in R&D in the area of industrial control as it relates to energy efficiency/consumption in your organization and similar operations?

DOE Opportunities
Demand management systems to move electrical costs from periods with demand energy charges to off peak hours, no demand energy times.
·Process instrumentation and integration of scheduling and control to reduce energy costs due to individual plan steps (e.g., heat-treating of metals, carbon/carbon composite drying). The issue would be to add automation where none exists, integrate the existing "islands" and new automation, with a top-level control/scheduling platform to bring everything together and optimize the flow, utilization, energy consumption, and all other elements.

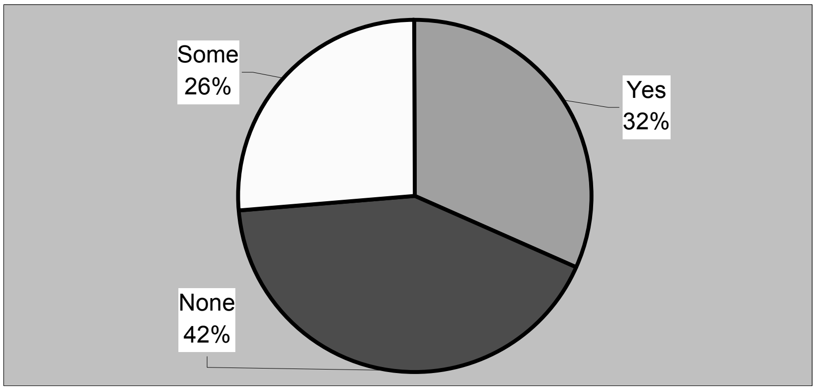
Robotics

Survey Summaries – Robotics Questions

1) For the energy-intensive operations within your organization, what is the extent of *robotics* currently implemented?



2) Is this level of industrial *robotic* adequate, or are there opportunities for improvement?



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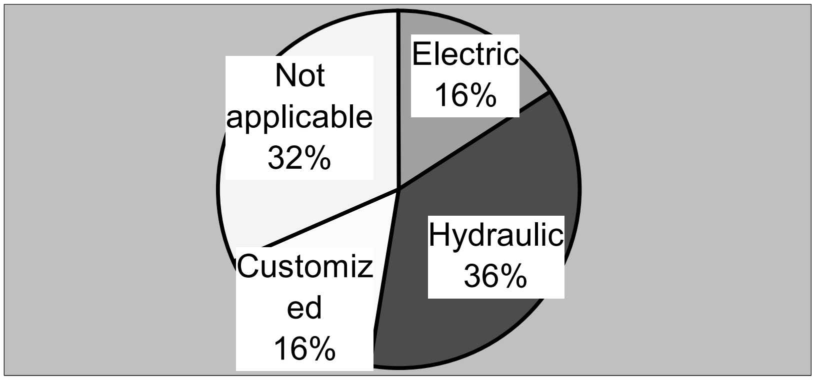
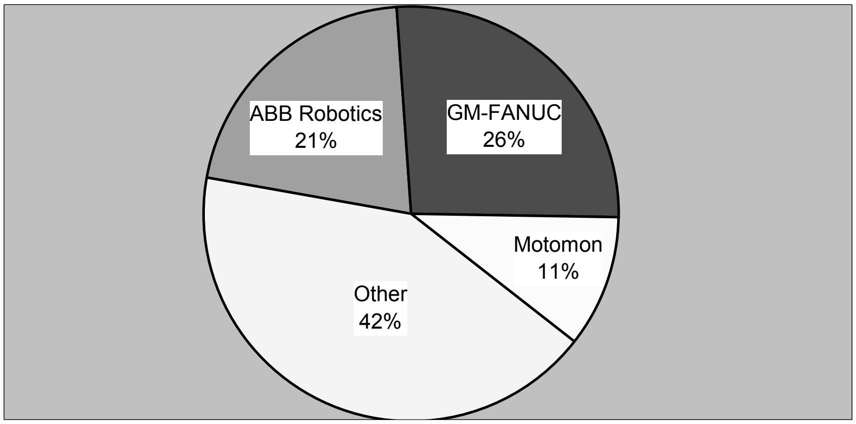
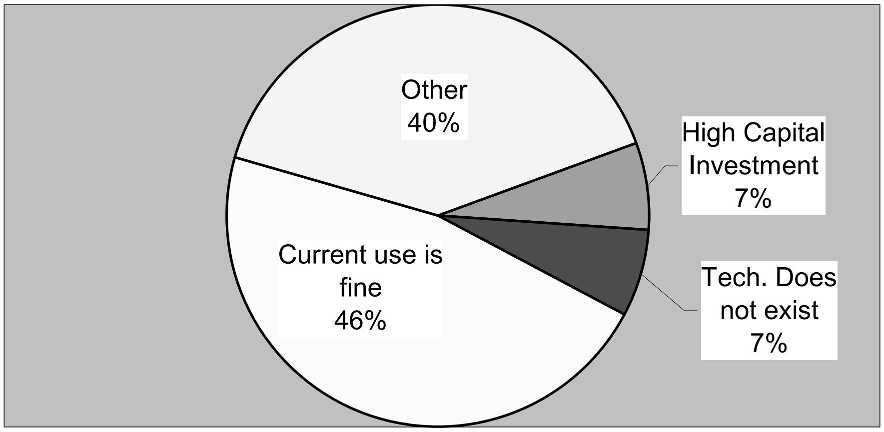
3) What types of robots (Electric, hydraulic, Customized, etc.)?



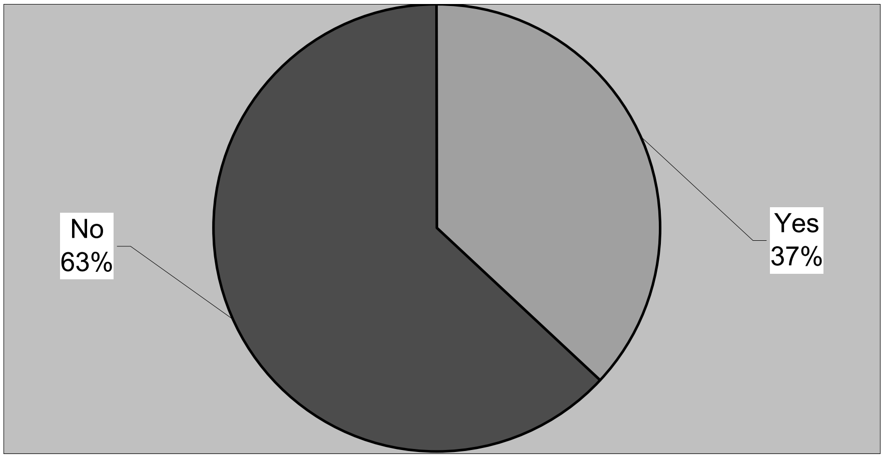
Which *robotic* vendors does your company use?



4) If the current level of *robotic* usage is not sufficient, where, in your opinion, are the bottlenecks to achieving better performance?



5) Can you think of any significant opportunities for DOE investment in R&D in the area of industrial *robotics* as it relates to energy efficiency/ consumption in your organization and similar operations?



Appendix 3 – Related Work from Other Federal Funding Sources

A survey of federally funded research in the four technology areas was carried out by Energetics, Inc., with direction from the report authors.

Industrial Controls

The projects detailed in the table below were identified as overlapping with the industrial control needs; however, there is no basis for determining the extent to which energy savings are considered as an objective.

- National Institute of Standards and Technology (NIST) has supported several industrial control projects, with an emphasis on applied results, and in some cases with targeted sector application (e.g., steel). Funding levels are generally high (multi-million dollar budgets), and project partners/investigators are generally from industrial operating companies and/or technology vendors. Technical areas of overlap with the summarized findings in this report include intelligent control and control systems architecture.
- National Science Foundation (NSF), a premier funding agency for the academic institutions in the United States, has supported a number of more academically oriented research projects, with the lead investigator typically based at a university. Funding levels are usually modest, typically $100,000 per year per investigator. Programs of note include the Grant Opportunities for Academic Liaison with Industry (GOALI) program that facilitates industrial collaborations and requires an industrial match and an industrial co-investigator. Technical areas of overlap with the summarized findings in this report include: intelligent automation, adaptive control, gain scheduled control, nonlinear control, and hybrid systems control.

Sponsor	**Project Title**	**Funding Level**
NIST, APT, Edison Materials Technology Center (sponsor)	Enabling Technologies for Lean Manufacturing of Hardened Steel Applications	Total project (est.): $11,747,000.00 Requested ATP funds: $5,871,000.00
NIST, APT, ISCA Technologies, Inc	Autonomous Pest Monitoring and Control System	Total project (est.): $2,717,693.00 Requested ATP funds: $2,000,000.00
NIST, APT, Step Tools (sponsor)	Model Driven Intelligent Control of Manufacturing	Total project (est.): $2,908,185.00 Requested ATP funds: $1,998,880.00
NIST	Critical Infrastructure Protection: Cybersecurity of Industrial Control Systems	
Sandia National Labs, Goodyear Tire and Rubber	CRADA project	
NSF, Iowa State University	Development of Adaptive Learning Algorithms for High-Performance Control of Robotic Systems	
USDOE Building Technologies Program, General Electric (sponsor)	IC-Based Controls for Energy-Efficient Lighting	
NSF, University of Kentucky	Integrated Tools for Automated Control Synthesis and Fault Diagnosis of Automated Manufacturing Systems using Discrete Condition Models	
NSF, University of Akron	ITR/AP: Reconfigurable Computing for Real-Time Control Systems	Expected Total Amount $201,910 (Estimated)
NSF, Stanford	CAREER: Hybrid Control of Complex Networked Systems	
NSF, North Carolina State University	Global/Semi-Global Stabilizing, Local Optimized Gain-Scheduling Control Design for Nonlinear Systems	Award for $195,144 received in May 2003

USDOE, FETC (Fossil Energy Technology Center), Ford	Advanced CIDI Emission Control System Development	
NSF, GA Tech Res Corp - GIT (sponsor)	CAREER: Linguistic Control of Mobile Robots	Expected Total Amount $399,980 (Estimated)
NSF, GA Tech Res Corp - GIT (sponsor)	Supervisory Control in Automated Manufacturing Processes: The Design of Human-Computer Interaction for "Lights-Out Factories"	
NIST (MEL)	Intelligent Control of Mobility Systems	
NIST (MEL)	Process Control Security Requirements Forum (PCSRF)	
NIST (MEL)	Open Architecture Controls	
NIST (MEL)	Specifications for Intelligent Control System Software Components	
NIST (MEL)	RCS The Real-time Control Systems Architecture	
NSF, ECS, University of Akron (sponsor)	ITR/AP: Reconfigurable Computing for Real-Time Control Systems	Expected Total Amount $201,910 (Estimated)
NSF, ECS, Pennsylvania State University (sponsor)	Free-Model Based Intelligent Control of Power Plants and Power Systems	Expected Total Amount $236,807 (Estimated)
NSF, DMI, Rutgers	Research on Control System/IT Design Issues	Expected Total Amount $108,277 (Estimated)
NSF, DMI, Purdue Research Foundation	Small Grants for Exploratory Research: Chaos Theory for Control of Manufacturing Systems	Expected Total Amount $15,449 (Estimated)
NSF, CMS, Duke University	Intelligent Control Strategies for Coordination of Multi-Robot Systems	Expected Total Amount $230,658 (Estimated)

Information Processing

The table below lists those projects related to information processing, all but one address the need for information processing in support of process control. There appears to be no current federally funded project that addresses the issue of information processing as a means of achieving direct energy savings.

Three of the four projects on the list have been supported by NIST, one is supported by NSF. Information processing in support of advanced industrial controls has uniformly been the emphasis of the NIST-supported projects, which have also been more application oriented; the NSF project is more theoretical, and addresses the general issue of signal processing and information theory. Funding levels are much higher for the NIST projects with project partners/investigators from industrial operating companies and/or technology vendors than the significantly lower funding levels for the NSF project. The goals of the four projects were as follows, with further information shown in the table:

1. Develop infrastructure technologies to enable low-cost manufacturing of high-capacity optical data links, which could overcome bandwidth limitations in computing and communications networks and increase productivity in many industries
2. Demonstrate the technical feasibility of collaborative decision-support technologies that can enhance the performance of operations personnel who supervise industrial process control
3. Develop the basic framework for an integrated factory-level production control environment for the semiconductor industry that will control lot production across the factory and enable real-time, automated feedforward and feedback refinement of individual process steps
4. Develop a new theory information theory that combines signal processing with information theory with the dual goals of understanding how effectively signals can present information and of quantifying how well systems process information

Project Title	Sponsor	Project Duration	Funding Level
1. Data Pipe	NIST, APT, 3M	1/1/1999 - 12/31/2002	Total project (est.): $8,454,363.00 Requested ATP funds: $4,175,976.00
2. Collaborative Decision Support for Industrial Process Control	NIST, APT, Honeywell (sponsor)	6/1/1995 - 1/31/1999	Total project (est.): $16,629,000.00 Requested ATP funds: $8,148,000.00
3. Advanced Process Control Framework Initiative	NIST, APT, Honeywell (sponsor)	2/1/1996 - 10/31/1998	Total project (est.): $10,007,999.00 Requested ATP funds: $4,906,758.00
4. Information Processing Theory and Applications	NSF, William Marsh Rice University	1/7/2001-6/30/2004	$310,610 (Estimated)

Automation

An examination of reports of federal funding for automation-related technologies yields a variety of projects funded since 1992 (and with online reports), ranging up to $8 million (the larger grants typically have a 100% match of industry R&D funds), from a variety of agencies in a variety of areas, some not industrial.

- NIST supported several automation projects with an emphasis on applying these results to commercial development. Specifically, independent living for senior citizens, improved image processing for feature extraction, and improved tools and methodologies applicable to production.
- NSF has funded cross-industry collaborations for transitioning research from universities to industry and industrial development

Sponsor	Project Title	Funding Level
NIST, APT, Perceptron, Inc., Sponsor	Robust, Fast 3-D Image Processing and Feature Extraction Tools for Industrial Automation Applications	Total project (est.): $2,083,715.00 Requested ATP funds: $1,218,503.00
NIST, APT, Precision Optoelectronics Assembly Consortium	Precision Optoelectronics Assembly (sponsor)	Total project (est.): $10,181,200.00 Requested ATP funds: $4,936,100.00
NIST, APT, Budd Company, Design Center (sponsor)	Manufacturing Methodologies for Automated Thermoset Transfer/Injection Molding (TIM)	Total project (est.): $3,067,850.00 Requested ATP funds: $2,000,000.00
NIST, Fire and Research Lab	Performance of Innovative Technologies for Automated Steel Construction	
NSF, University of California, Berkeley (sponsor)	Industry/University Cooperative Research Center for Manufacturing and Automation	
INEEL (Idaho National Engineering and Environmental Laboratory (INEEL), (Idaho Falls, ID); USDOE Office of Environmental Management (EM)	Chemical Automation Analysis	
FETC (Fossil Energy Technology Center); USDOE Office of Energy Efficiency and Renewable Energy (EE); USDOE Office of Fossil Energy (FE)	Development of Internet Based Facilities Automation System	
NSF, Texas Engineering Exp Sta	CAREER: Understanding and Supporting the Acquisition of Manufacturing Automation System Integration Skills	
NIST, APT, Step Tools (sponsor)	Model Driven Intelligent Control of Manufacturing	Total project (est.): $2,908,185.00 Requested ATP funds: $1,998,880.00
NSF, University of Kentucky	Integrated Tools for Automated	

	Control Synthesis and Fault Diagnosis of Automated Manufacturing Systems using Discrete Condition Models	
NSF, GA Tech Res Corp - GIT (sponsor)	Supervisory Control in Automated Manufacturing Processes: The Design of Human-Computer Interaction for "Lights-Out Factories"	
NSF, DMI, TPL (sponsor)	SBIR PHASE I: Machine Vision System for Automated Imaging and Process Control	(est) $99996

Robotics

An examination of reports of federal funding for robotics-related revealed:

- NIST has a wide variety of programs, which involve both academic institutions and small to medium level corporations.
- NSF has a division of Robotics and Intelligent Systems. The level of funding is mostly modest, around $100K per year. There are other programs like Grant Opportunities for Academic Liaison with Industry (GOALI) program where industrial collaboration is also sought.
- NASA has 9-field centers like the Johnson Space Center and Ames Research Center, and a critical privately owned center in the Jet Propulsion Laboratory. The levels of funding through the Jet Propulsion Laboratory, though not displayed in the following table, are usually several millions of dollars. Whether any other funding agency pays particular attention to energy efficiency with respect to robotics research and development is not clear.

Sponsor	**Project Title**	**Funding Level**
NSF, Arkansas State University	*GOALI: Mechanisms and Optimization of Laser Assisted Particle Removal*	Total project (est.): $ 250,001
NSF, Cornell University	*CAREER: Improving Information Access by Robot Learning from User Interactions*	Total project (est.): $ 400,000
NIST, APT, SEMI-North America, Austin, TX	eManufacturing Security Framework to Improve Semiconductor Robotic-assisted Manufacturing Productivity	Total project (est.): ATP funds: $10,096, 000(est.)
NASA, Carnegie Mellon University	Dead Reckoning for Walking Robots	NA
NSF, CMS, Duke University	Intelligent Control Strategies for Coordination of Multi-Robot Systems	Expected Total Amount $230,658 (Estimated)
NASA, Jet Propulsion Laboratory	The Urban Autonomous Robot	NA
NASA, Jet Propulsion Laboratory	Robotic Assistance in Brain Surgery	***NA***
NIST, Computer Motion, Inc.	A New Concept for Minimally Invasive Surgical Training Using Robotics and Tele-Collaboration	$ 4,000,000

Appendix 4 – Cross-Cutting Opportunities

A number of the recommendations and major findings described in the four technical areas are synergistic and, in multiple cases, common problems are identified. A few examples are described below:

- **Energy informatics and process energy management systems** (*information processing*) and **Real-time control of energy** (*industrial controls*) reflect two different aspects of the same problem. The former is concerned with data generation and analysis, the latter is concerned with intelligent use of the knowledge that is generated for operating the processes in a plant or mill

- **Closing the loop on quality** (*automation*) and **Data mining and machine learning for predictive modeling and anticipatory product quality assurance** (*information processing*) are directly linked. The former focuses on the control of quality while the latter includes how to generate the information and model required to achieve quality control in a predictive fashion

- **Extreme temperature robotic systems** (*robotics*) includes elements of feedback control is tightly connected to issues of servo control design (*industrial controls*), and the quality of feedback signals (*information processing*)

- **Integrated control of plant/mill** (*industrial controls*) requires detailed (and frequently updated) information from both process units and the business functions of an organization (*information processing*), and careful coordination with higher levels in the CIM (computer integrated manufacturing) hierarchy (*automation*)

- **Automated maintenance and diagnosis** (*automation*) will require the careful translation of process data into process knowledge (*information processing*) in order to identify abnormal situations, and will require coordination with control functions (*industrial controls*) to allow automated corrective response

Additional examples are noted in the sections corresponding to each of the four technical areas.