MANUFACTURING PROCESS CONTROLS FOR THE INDUSTRIES OF THE FUTURE

Panel on Manufacturing Process Controls
Committee on Industrial Technology Assessments
National Materials Advisory Board
Board on Manufacturing and Engineering Design
Commission on Engineering and Technical Systems
National Research Council

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Presenters at the second workshop on technology opportunities included Tariq Samad of Honeywell; Yoh-Han Pao of AIWARE, Inc.; Frederick Proctor of the National Institute for Standards and Technology; Rush Robinett of Sandia National Laboratories; David Holcomb of Oak Ridge National Laboratory; Arlene Garrison of the University of Tennessee's Measurement and Engineering Control Center; Michael Carrabba of EIC Laboratories; and Mel Koch of the University of Washington's Center for Process Analytical Chemistry.

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This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist

the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report: James J. Solberg, Purdue University; John A.S. Green, The Aluminum Association; Arlene A. Garrison, University of Tennessee; Daniel J. Maas and Tony Haynes, National Center for Manufacturing Sciences; Karen Markus, MCNC; and James Wagner, Case Western Reserve University.

While the individuals listed above have provided many constructive comments and suggestions, responsibility for the final content of the report rests solely with the authoring committee and the NRC.

Finally, the panel gratefully acknowledges the support of the staff of the National Materials Advisory Board and the Board on Manufacturing and Engineering Design, including Thomas E. Munns, study director, Aida C. Neel, senior project assistant, and Bonnie Scarborough, research associate.

Preface

In 1993, the U.S. Department of Energy (DOE) Office of Industrial Technology (OIT) established a group of seven industries designated as Industries of the Future (IOF). These industries were selected for their high energy use and large waste generation. The original IOF included the aluminum, chemicals, forest products, glass, metal castings, petroleum refining, and steel industries. Each industry was asked to provide a future vision and a road map detailing the research required to realize its vision. In November 1994, the forest products industry was the first of the IOF industries to enter into an agreement with DOE. At this writing, six of the IOF industries have prepared vision statements and signed agreements with DOE.

OIT asked the National Research Council's National Materials Advisory Board (NMAB) to evaluate their program strategy and to provide guidance for OIT's transition to the new IOF strategy. A Committee on Industrial Technology Assessments (CITA) was formed for this purpose with the specific tasks of reviewing and evaluating the overall OIT program, reviewing selected OIT-sponsored research projects, and identifying cross-cutting technologies (i.e., technologies applicable to more than one industry). CITA was asked to focus on three specific areas: intermetallic alloys, manufacturing process controls, and separations. A separate panel was formed to study each area and publish the results in a separate report. This report describes the activities and recommendations of the Panel on Manufacturing Process Controls (MPC).

The MPC panel's objectives are listed below:

- identify key processes that would benefit most from improved manufacturing process controls for each of the IOF

- identify control technology needs that are common among the IOF industries
- identify research opportunities to address these needs
- suggest criteria for identifying and prioritizing research and development to develop improved manufacturing controls technology
- suggest means for transferring advances in control technology to the IOF industry sectors

The MPC panel was composed of experts knowledgeable in sensors, measurement technology, and/or process control. The panel held two meetings. At the first meeting, on October 22, 1996, representatives of six of the IOF industries discussed the needs of their industries for sensing and process controls. As a result of this meeting, the panel was able to identify common needs among the IOF industries. On May 29, 1997, the MPC panel met with experts on cutting-edge sensing and control technologies to identify opportunities for the development of technologies to meet the IOF industries' needs. The conclusions and recommendations of the MPC panel can be found in Chapter 4 of this report. In general, the panel found ample opportunities for research on cross-cutting technologies, in both sensing and manufacturing control, that apply to several IOF industries.

The chair wishes to thank the MPC panel members for their enthusiasm and dedication, as well as the experts from the IOF industries and experts on process control and sensors for their excellent presentations. The chair thanks all of the participants for their insights and stimulating discussions and the staff of the NMAB for their coordination and assistance throughout the entire process, including the publication of this report.

Comments and suggestions can be sent via electronic mail to nmab@nas.edu or by FAX to NMAB (202) 334-3718.

GARY A. BAUM, *chair*
Panel on Manufacturing Process Controls

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Executive Summary

Manufacturing process controls include all systems and software that exert control over production processes. Control systems include process sensors, data processing equipment, actuators, networks to connect equipment, and algorithms to relate process variables to product attributes.

Since 1995, the U.S. Department of Energy Office of Industrial Technology's (OIT) program management strategy has reflected its commitment to increasing and documenting the commercial impact of OIT programs. OIT's management strategy for research and development has been in transition from a "technology push" strategy to a "market pull" strategy based on the needs of seven energy- and waste-intensive industries—steel, forest products, glass, metal casting, aluminum, chemicals, and petroleum refining. These industries, designated as Industries of the Future (IOF), are the focus of OIT programs. In 1997, agriculture, specifically renewable bioproducts, was added to the IOF group.

The National Research Council Panel on Manufacturing Process Controls is part of the Committee on Industrial Technology Assessments (CITA), which was established to evaluate the OIT program strategy, to provide guidance during the transition to the new IOF strategy, and to assess the effects of the change in program strategy on cross-cutting technology programs, that is, technologies applicable to several of the IOF industries. The panel was established to identify key processes and needs for improved manufacturing control technology, especially the needs common to several IOF industries; identify specific research opportunities for addressing these common industry needs; suggest criteria for identifying and prioritizing research and development (R&D) to improve manufacturing controls technologies; and recommend means for implementing advances in control technologies. The panel's responses to these tasks are described below.

KEY PROCESSES AND CONTROL TECHNOLOGY NEEDS

The panel identified common industry needs for process sensing and manufacturing process controls (Chapter 3) based on key IOF process attributes, including (1) high processing volume and production rates, (2) large-batch or continuous processes, (3) commodity-grade products (low value per unit), (4) harsh processing environments,[1] and (5) serial processing sequences (i.e., the output from one process becomes the feedstock for the next).

Common needs for process sensing include

- measurement of temperature profiles in harsh processing environments
- measurement of chemical composition/stoichiometry in harsh processing environments
- measurement of physical attributes at high line speeds and high temperatures
- monitoring of combustion processes

Common needs for process controls include

- methodologies to enable in-situ-level process controls
- optimization at the plant or enterprise level
- open-architecture software tools
- adaptive control systems
- methods and diagnostic tools for condition-based maintenance of process equipment

To address all of these needs, the OIT program should include (1) a cross-cutting R&D initiative to develop fundamental technologies that address common IOF needs, (2) industry-specific R&D to validate and implement advances in technology, and (3) an interagency government initiative to coordinate plans and research objectives.

RESEARCH OPPORTUNITIES

The panel recommends that OIT establish a cross-cutting R&D initiative to address the common needs of the IOF industries. Examples of specific research opportunities (Chapter 4) include (not prioritized)

- the development of sensor materials with significantly improved thermal and chemical resistance
- the compilation of a comprehensive database of candidate sensor material properties to accelerate the design and development cycle for the fabrication of new sensor systems

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[1] A harsh processing environment has one or more of the following characteristics: high processing temperature (with respect to sensor and control capabilities), steep thermal gradients, corrosivity, erosivity, high particle content, combustion, or high processing speeds.

- the development of methods to measure temperatures accurately and reliably
- the development of low-cost, miniaturized, integrated analytical instruments that directly and easily measure process chemistry for a wide range of process flow-streams and conditions, including harsh environments
- the application of new processing science for the fabrication and packaging of integrated sensor/data processing/actuation modules
- the development of measurement technologies for the rapid characterization and evaluation of physical properties for wide-sheet and web processes
- the application of wireless telecommunications technology to advanced wireless sensors
- the development of process control methodologies, including process measurements, intelligent control algorithms, and reliable process models, to enable the transition from environmental-level (energy transport) to in-situ-level (material behavior) controls
- the development of techniques and control architectures for using multiple, disparate process models in a cohesive and integrated way
- the development of technology for process optimization and the plant-wide integration of process controls
- the evaluation of open-architecture control systems for large-batch and continuous processes typical of IOF industries
- the development and implementation of machine learning and adaptive controls

CRITERIA FOR IDENTIFYING AND PRIORITIZING RESEARCH AND DEVELOPMENT

The panel recommends that OIT focus its research on the development of process sensors and control technologies that address the needs of the IOF industries. In addition to the common IOF needs, the organizational objectives of DOE and OIT—to reduce the consumption of raw materials and energy, to increase labor and capital productivity, and to reduce waste—must be considered. The panel recommends the following criteria as a basis for comparing and selecting technologies for the cross-cutting program:

- the potential for reducing the consumption of energy and raw materials and for reducing waste
- consistency with the technology road maps of the IOF industries
- potential cross-cutting benefits for more than one industrial sector (common needs and opportunities are described above)
- the potential for commercial application

One of the key challenges for OIT is to manage the cross-cutting program in a way that facilitates the development of specific R&D performance goals based on the common needs of several industries. To identify and prioritize research that meets IOF's needs, the panel recommends that OIT take the following steps:

- Establish an IOF coordination group to develop short-term and long-term goals and to monitor the progress and results of work on cross-cutting technologies. The group would review process attributes and control needs in each IOF industry and establish a consensus on specific goals for the most beneficial cross-cutting R&D.
- Facilitate interaction between the researchers developing improved process control technologies and potential IOF users. These interactions could include technical progress reviews of cross-cutting R&D programs and technology workshops to discuss technical developments and identify opportunities for validating and implementing them.

TECHNOLOGY TRANSFER AMONG INDUSTRY SECTORS

The panel identified cross-cutting R&D that could benefit several industries without redundancy. However, the process development and implementation phases are unique to particular processes or conditions and could be best addressed by the interested IOF groups. Some industry-specific tasks are listed below:

- the development of road maps to identify technology needs and implementation plans
- interaction with cross-cutting technology programs (e.g., technical workshops and R&D progress reviews)
- the development and validation of process models related to specific key processes that would facilitate moving from environment-level to in-situ-level control schemes
- the development of actuators to control specific key process variables
- the optimization of process control systems, especially using supervisory controllers and plantwide integration
- the validation and implementation of improved sensor technologies and process control systems in large-scale processes

Finally, the panel recommends that OIT program managers continue to coordinate interagency and intra-agency progress and plans in complementary technologies to avoid duplications. In addition to monitoring complementary programs, the panel recommends that OIT collaborate with four other organizations. The first is the National Institute of Standards and Technology, which is developing standards for open-architecture systems; IOF industries should evaluate and validate system standards for large-batch and continuous operations. The second is the National Science Foundation, which is sponsoring research centers to develop improved process sensing and process modeling capabilities (e.g., the

Measurement and Control Engineering Center at the University of Tennessee-Knoxville; the Center for Process Analytical Chemistry at the University of Washington; and the Center for Industrial Sensors and Measurements at Ohio State University); IOF industries should coordinate the implementation and application of process modeling and advanced sensor technology. The third is the U.S. Department of Defense (DOD), especially the Defense Advanced Research Projects Agency (DARPA), which is developing microelectromechanical (MEMS) devices, fabrication processes, and applications; IOF industries should evaluate MEMS devices for sensing/control of industrial processes. Finally, OIT should collaborate with DOD programs (especially Army, Navy, and DARPA), which are developing condition-based maintenance approaches; IOF industries should evaluate sensors and diagnostics developed to monitor processing equipment and machinery.

1

Introduction

The U.S. Department of Energy (DOE) Office of Industrial Technology (OIT) sponsors research and development projects to improve energy efficiency and resource utilization in energy- and waste-intensive industries. The research and development projects focus on materials processing industries and are aimed at developing technologies that reduce the use of raw materials and energy, reduce the amount of waste generated, and increase industrial productivity and global competitiveness.

Since 1993, the OIT has been undergoing a transition from a "technology push" program strategy, in which research projects are selected and prioritized primarily for their potential to reduce energy consumption or waste generation, to a "market pull" strategy, in which identified industry needs and priorities are the primary criteria for selecting projects. To pursue the new strategy, the OIT focused on seven energy- and waste-intensive materials processing industries: aluminum, chemicals, forest products, glass, metal casting, steel, and petroleum refining. These industries, designated "Industries of the Future" (IOF), use about 80 percent of the energy (Figure 1-1) and produce more than 90 percent of the manufacturing waste in the entire U.S. industrial sector. The petroleum refining industry elected not to participate in the IOF program, and, in 1997, the agriculture industry, specifically renewable bioproducts, was added to the group.

Representatives of the selected industries, including industry organizations and trade associations, developed technology "visions" that identify their high-priority needs, including their strategic goals and research priorities. Table 1-1 shows the status of the vision documents for each industry. Based on these visions, the industry groups have developed technology "road maps" (research agendas), devised implementation strategies to meet their high-priority needs,

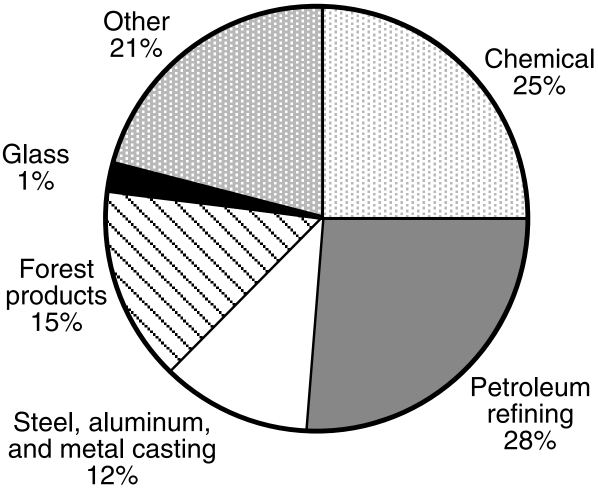


FIGURE 1-1 Manufacturing energy use (1994). Total energy use is 22.4 Quads (quadrillion BTUs). Source: Office of Industrial Technologies (DOE, 1997) (based on Energy Information Administration data).

and committed resources to conduct and manage the research projects. OIT facilitates the process by assisting and planning, by coordinating participants and catalyzing interactions, by providing access to the DOE-administered national laboratories, and by sharing the costs of selected projects.

COMMITTEE ON INDUSTRIAL TECHNOLOGY ASSESSMENTS

The OIT requested that the National Research Council (NRC), through the National Materials Advisory Board, conduct a study to (1) evaluate their program strategy, (2) provide guidance during the transition to the new "market pull" IOF strategy, and (3) assess the effects of the change on cross-cutting technology programs, that is, programs to develop technologies applicable to several industries. The Committee on Industrial Technology Assessments (CITA) was established to review and evaluate the program and plans of the overall OIT program, review the plans and progress of selected OIT-sponsored research programs, and conduct site visits and laboratory evaluations, when appropriate, to supplement program assessments. The committee will suggest improvements to the technical programs, methods of coordinating research with other agencies, and mechanisms for transferring technology to industry.

To help the committee review the overall OIT program, CITA establishes and oversees topical panels to review selected aspects of the program, conduct site visits if necessary, and bring in additional members with topical expertise.

TABLE 1-1 Status of IOF Vision Documents

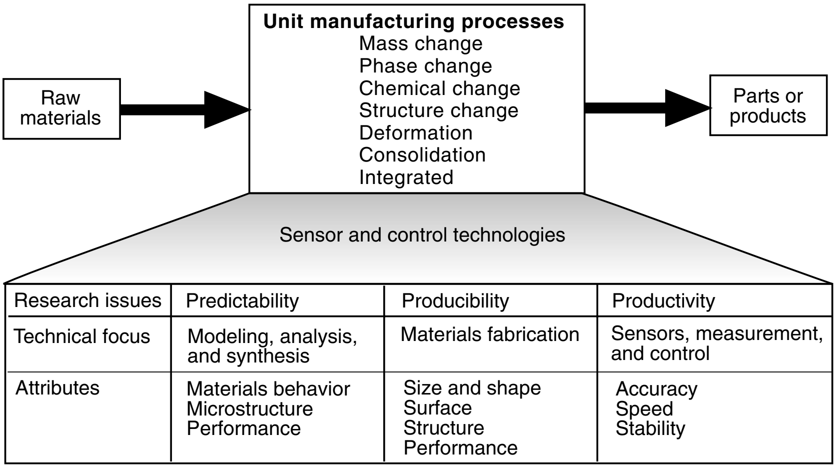
Industry Sector	Vision Document	Date Released
Forest Products	Agenda 2020: A Technology Vision for America's Forest, Wood, and Paper Industry	November 1994
Metal Casting	Beyond 2000: A Vision for the American Metalcasting Industry	September 1995
Steel	Steel: A National Resource for the Future	May 1995
Aluminum	Partnerships for the Future	March 1996
Glass	Glass: A Clear Vision for a Bright Future	January 1996
Chemicals	Technology Vision 2020: The U.S. Chemical Industry	December 1996
Agriculture	Plant/Crop-Based Renewable Resources 2020	Draft

The first panel evaluated the intermetallic alloy development program at the Oak Ridge National Laboratory (NRC, 1996a). This program was selected because it is mature and already focused on cross-cutting research and development. The emphasis of the report was on lessons that could be derived from the development of nickel aluminide alloys and processes, which have been the focus of the OIT intermetallics research program at Oak Ridge National Laboratory. The report included a review and assessment of the intermetallic alloy development program and recommendations for the future focus of the program, as well as an assessment of implications for the entire OIT program and the transition to the IOF strategy.

PANEL ON MANUFACTURING PROCESS CONTROLS

The second topical panel established under CITA was the Panel on Manufacturing Process Controls. The objective of this panel was to identify opportunities for technological development that could improve process controls in the materials processing industries of the IOF and to recommend areas of emphasis for a sensors and controls initiative. The study tasks included

- the identification of key processes and needs for improved manufacturing control technologies, especially the needs common to several IOF industries
- the identification of research opportunities to address these needs
- suggested criteria for identifying and prioritizing research and development projects for improved manufacturing controls technology
- the identification of mechanisms for transferring advances in control technologies to IOF industries



Research issues	Predictability	Producibility	Productivity
Technical focus	Modeling, analysis, and synthesis	Materials fabrication	Sensors, measurement, and control
Attributes	Materials behavior Microstructure Performance	Size and shape Surface Structure Performance	Accuracy Speed Stability

FIGURE 1-2 Research issues, technical focus, and attributes of process sensors and controls. Unit manufacturing process categories are taken from NRC (1995).

Much of the information used to develop the research recommendations was the result of two workshop sessions conducted by the panel. The first workshop included representatives of six of the IOF industry groups[1] (aluminum, chemicals, forest products, glass, metal casting, and steel), who discussed their needs for process control and sensing technologies and identified the common needs of multiple industries. The second workshop included experts on advanced sensing and control technologies, who identified opportunities for developing technologies to meet the industry needs. Workshop agendas are included in Appendix A. This report is a summary of the panel's findings and contains recommendations for future research.

CHALLENGES

Sensor and control technologies are integral components of all modern processing industries. These technologies are essential to the evaluation and monitoring of the material properties, quality (of machines, processes, and products), process safety, and energy efficiency of industrial processes. In general, sensors and controls are used by process industries to address three operational issues—predictability, producibility, and productivity—in various manufacturing processes (Figure 1-2). Sensors supply the data that are used to monitor and control product and process variables. The process controller uses real-time control strategies and algorithms to relate sensory feedback to process decision making.

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[1] Two IOF groups did not participate in the workshop, the petroleum refining industry and the agriculture industry, which had not yet joined the IOF.

With recent advances in computing, communications, advanced materials, and microelectronics, sensors and process controls can now be more effectively integrated with real-time control models on both the component and system levels. However, as discussed in Chapter 2, the operation of sensors and process control technologies is limited in harsh environments.[2] At the same time, increasing environmental constraints and regulations have made it imperative that industries be able to use state-of-the-art sensors and process controls. In addition, industries require manufacturing processes that can be quickly, easily, and affordably adapted to meet current and future production needs.

Technical Challenges

The factors driving the development of sensors and manufacturing process control technologies are (1) the need to reduce variability and improve quality, (2) environmental constraints, and (3) the need for easier servicing and maintenance. Figure 1-3 shows how these factors have created a general need for the development of intelligent sensors and control systems (NSF, 1997) to improve energy efficiency and resource utilization in energy-intensive and waste-intensive materials processing industries.

Reducing Variability and Improving Quality

Advanced sensors and process control systems that could monitor process variations would make high-quality operations feasible at lower costs. These will require the development of software engineering tools for the design and development of intelligent process control software that is both adaptable and reliable. Process control software includes real-time, embedded software that can compensate for the variability in machine performance, processing conditions, and materials properties. Advanced controllers for the process industries must offer features such as reconfigurability, reusability, self-learning, and knowledge transferability to minimize process variations.

Environmental Constraints

Innovative, robust sensory devices could improve energy efficiency and reduce waste while bringing down the costs of development and installation. Advanced sensors would be able to monitor process parameters and acquire process information directly, accurately, and quickly. In addition, innovative sensor materials and coating technologies could make the use of sensory devices in extreme high temperature and chemically corrosive environments feasible (NRC, 1996b).

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[2] A harsh operating environment has one or more of the following characteristics: high processing temperature (with respect to sensor and control capabilities), steep thermal gradients, corrosivity, erosivity, high particle content, combustion, or high processing speeds.

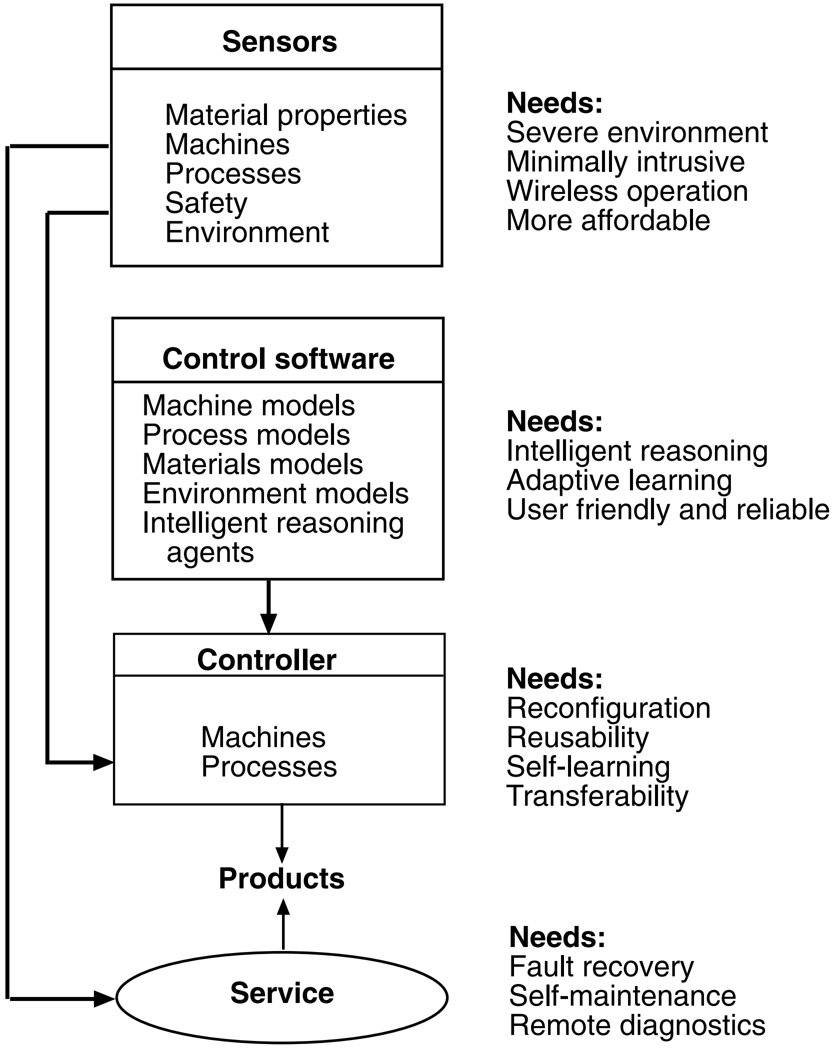

FIGURE 1-3 Research needs and technical challenges for intelligent sensors and control systems.

Emerging technologies, such as microelectromechanical systems (MEMS)-based sensors (NRC, 1997; OTA, 1991) and wireless communications (Zoltowski, 1995), could be developed and optimized to meet industrial needs for sensors.

Servicing and Maintenance

Servicing and maintenance are important factors in the productivity of process industries. The recent rush to embrace computer-integrated manufacturing technologies in the process industries has increased the use of relatively unknown and untested technologies, making it difficult to identify the causes of system failures. The difficulty has been attributed to several factors, including system complexity, uncertainties, and the lack of adequate troubleshooting tools. Currently, many servicing and maintenance activities in process industries are still reactive.

Manufacturers need to emphasize manufacturing processes, equipment, and products that improve cycle time, reduce defects, and add value while accounting for process variation. Thus, process controllers will have to provide proactive maintenance capabilities, such as measurements of performance degradation, fault recovery, self-maintenance, and remote diagnostics (Lee, 1995, 1996). These features would allow process industries to develop proactive maintenance strategies that would guarantee process performance and would eliminate many system breakdowns. An example of a proactive maintenance strategy is condition-based maintenance that considers the actual condition of the equipment, rather than the more conventional strategies that consider time-based or usage-based maintenance strategies or that simply respond to equipment failures. Condition-based maintenance will require the development of sensors and diagnostic techniques to monitor critical operating conditions, such as temperature, vibration, and power consumption. The U.S. Department of Defense, especially the Army, the Navy, and the Defense Advanced Research Projects Agency (DARPA), has been sponsoring significant research and development on condition-based maintenance.

Intellectual and Infrastructural Challenges

Research resources can be used most effectively if they are focused on key intellectual and infrastructural challenges and combine analytical, computational, and experimental approaches. One goal should be to develop innovative manufacturing processes and methodologies for making useful products from both new and recycled materials. A better understanding of the behavior of materials during processing would facilitate the development of innovative technologies for analytical models and physical prototypes of next-generation machines and manufacturing equipment. Innovations could include new designs for machine components, more reliable sensing techniques, enhanced metrology, and more robust control technologies.

The major intellectual challenge will be to increase scientific knowledge that could lead to innovations in a broad spectrum of manufacturing processes and equipment. Manufacturing engineers must keep the issues involving the complete design/production environment in mind during the development of manufacturing processes and equipment. Improved process sensing and control technology will require new scientific knowledge—from material behavior to product formation for current and future manufacturing processes—and the integration of manufacturing processes with design engineering and production systems. Because the overall manufacturing structures are similar for most industries, the information could be applied to many manufacturing technologies.

The infrastructural challenge is to integrate research facilities and education curricula across institutional boundaries, to harness diverse physical resources, and to encourage collaborative innovation. One of the biggest challenges in manufacturing research has always been applying ideas developed in basic research programs to operational manufacturing industries. The true value of an innovative idea can only be determined after production attributes (cost, quality, responsiveness, and optimization) have been validated in real production through an integration process involving materials, machines, methods, maintenance, money, and personnel. In an ideal situation, researchers could leverage resources available from various institutions (even across international boundaries).

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2

Synthesis of Industrial Needs

The objective of this chapter is to assess the challenges and needs of the energy-intensive and waste-intensive industries that make up the IOF. These challenges and needs, not all of which are common among the industries, involve technology, specifically process monitoring sensors and manufacturing process controls that would improve the energy efficiency and resource utilization of industrial manufacturing processes. This assessment will be the basis for the subsequent discussion of research opportunities and the associated recommendations and conclusions for OIT's program.

SUMMARY OF INDUSTRY NEEDS

The panel reviewed the needs identified by several of the IOF industries in a working session with representatives of the industry groups and in subsequent discussions with key experts. The purpose of the working session was (1) to synthesize and organize specific technology needs identified by IOF working groups and (2) to identify common process attributes and needs for process controls and sensor technologies among the industries. This section includes descriptions of key manufacturing processes and the needs specific to six of the IOF industries. Subsequent sections describe common attributes and common technology needs of these industries.

Glass

The glass industry has national importance to the U.S. economy. Its annual sales are $22 billion, and the industry employs 150,000 people. The industry, which produces 21.5 million tons of glass per year, is a significant energy consumer. The glass industry produces four major types of products:

- flat glass—windows, automobile windshields, mirrors, and tabletops
- container glass—glass packaging, jars, and bottles
- specialty glass—tableware and ovenware, flat panel display glass, lightbulbs, television tubes, optical fibers, and scientific and medical equipment
- glass fibers—fiberglass insulation, reinforcing fibers, and textiles

A typical glass furnace is 25 to 30 feet wide, 200 feet long, and 4 to 6 feet deep, and contains enough molten glass for one to two days of production. The typical production rate is 250 tpd (tons per day) for a container-glass oven and 550 tpd for a flat-glass oven. Glass is produced in integrated factories—from raw material to finished products. Most of the needs identified by the industry representative focused on measuring and/or controlling temperatures and composition in large-scale, high-temperature (and steep-temperature-gradient) environments (Ross, 1996).

The glass industry's needs for improved sensors and controls are based on four key factors:

- improving energy efficiency (energy accounts for 10 to 15 percent of manufacturing costs)
- improving product quality and productivity
- improving environmental compliance
- maximizing recycling and reducing waste (approximately 35 percent of glass is recycled from postconsumer waste)

Specific needs include the following (Ross, 1996):

- Process instrumentation for the advanced control of
  - — temperature profiles in furnace operations and forming operations
  - — uniformity of temperatures in furnace and glass streams
  - — thickness
  - — fiber diameter
- Sensors to measure physical properties, including
  - — the real-time variations of composition (currently determined by offline sampling/laboratory testing)
  - — viscosity (currently inferred from composition and temperature)
  - — cullet[1] composition and color (plus contamination detectors) for sorting processes
  - — oxidation state (indicative of contamination and compositional variability)

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[1] Cullet is defined as broken or refuse glass, which is usually added to new materials to facilitate melting.

- Methods to control combustion processes, including nitrous oxide (NO_x) emissions, temperature, heat transfer, and gas composition
- Improvement and validation of process models

Chemicals

The chemical industry is a large component of the U.S. industrial sector. In 1995, the chemical industry shipped $367.5 billion worth of products. The industry has more than a million employees. The chemical industry is diverse, with eight standard industrial classification (SIC) codes:

- industrial inorganic chemicals
- plastics, materials, and synthetics
- pharmaceuticals
- soaps, cleaners, and toilet goods
- paints and allied products
- industrial organic chemicals
- agricultural chemicals
- miscellaneous chemical products

The vision document for the chemicals industry, *Technology Vision 2020: The U.S. Chemical Industry*, identifies three principal areas for advancing chemicals manufacturing—process science and technology, chemical measurement, and computational technology—all of which are critically dependent on improved process modeling, control, and sensing. Process science and technology includes process software, tools for real-time measurements, and flexible manufacturing (disassembly and reuse, solids processing, and smart processing). Chemical measurement involves process analytical chemistry, standards for data acquisition and control systems, analytical measurement techniques, and real-time analysis capability. Computational technologies include process modeling, simulation, optimization of operations, and process control.

Koch (1996) identified the chemical industry's needs for process sensing and control that can improve the understanding of process relationships and improve chemical sensing technologies. Specific needs include

- the chemical analysis of stack emissions (for compliance with environmental regulations)
- the detection and analysis of fugitive emissions (to prevent pollution)
- the detection and analysis of low levels of organic compounds in water (to improve product quality)
- the measurement of moisture content in organic compounds, corrosive gases, and liquids (to improve product quality)
- the physical and chemical characterization of polymers (to improve product quality)

The specific needs identified by Koch (1996) for process control equipment include

- information technology for the collection and analysis of complex, high-volume process measurements in real time (to replace the current time-consuming sample-test-adjust approach)
- combining the sensing of chemical composition with the sensing of physical properties (for process controls based on more than the traditional flow, pressure, and temperature characteristics)
- interface standards (to facilitate networking of different types of sensors)

Metal Casting

The U.S. metal casting industry is a $25 billion per year industry that employs 210,000 people (about 170,000 in production) and produces about 13 million tons of castings per year. The domestic industry is made up of 3,100 metal casting establishments, most of which are small companies (38 percent have fewer than 20 employees, and 79 percent have fewer than 100 employees). Ferrous metal castings account for 85 percent by weight (61 percent by value) of shipments; nonferrous castings, primarily aluminum, account for the rest.

Metal casting is an important process in the fabrication of net-shaped or near-net-shaped components from a variety of metals and alloys. Casting processes can be used to produce complex shapes ranging in size from a fraction of an ounce to hundreds of tons (ASM, 1988). The selection of casting processes depends on a range of factors, including required mold strength, component size, variations in the thickness of cast sections, required surface finish and dimensional accuracy, production rates, environmental factors (e.g., reclamation of sand and type of sand binder), and cost. Casting processes include the following:

- Sand casting. Temporary molds are produced by compacting sand around a reusable form. Molten metal is poured into the cavity. After the casting cools, the mold is destroyed, and as much sand as possible is reclaimed and recycled.
- Permanent-mold, low-pressure casting. Molten nonferrous metal (usually aluminum) is poured into reusable steel molds.
- Investment casting (lost-wax process). Temporary ceramic molds are produced from a wax pattern. The wax is removed (usually by melting) leaving a mold cavity. Molten metal is poured into the cavity, and the mold is broken off.
- Die casting. Molten metal is injected at high velocity and high pressure into permanent steel molds. This process generates little waste and has particularly rapid cycle times.

Because most casting companies are small, the industry does not have much capability to conduct innovative research. Consequently, the industry relies on government-sponsored research, such as programs resulting from the Cast Metals Competitiveness Act of 1990 (P.L. 101-425), for the development of generic process technologies.

Specific process sensing needs for the metal casting industry include (Green, 1996; Walkington, 1996)

- robust sensors for measuring the temperature of molten metals
- sensors for determining alloy composition, including dissolved-gas composition (i.e., chemical sensing in molten metals)
- remote monitoring for sensing in hostile environments
- chemical sensors to monitor the quality of recycled sand (for sand-casting molds)
- pressure and temperature sensors for die-casting processes
- sensors to measure solidification rates and the locations of solid-liquid interfaces
- sensors for measuring mold filling and tilt profile

The driving factors for improving process control technologies are reducing the high scrap rates (the reject rate for sand casting is currently as high as 4 to 5 percent) and improving the quality of castings, including surface finish, dimensional accuracy, and porosity. Casting processes characteristically include complex process variables—velocities, flows, temperatures, and pressures—that must be controlled to minimize shrinkage and to control temperatures, cooling rates, and cycle rates. The industry has a critical need for improving the fundamental understanding of solidification processes and for accurate solidification models (Kenchington et al., 1997).

Forest Products

The U.S. forest product industry employs 1.4 million people and produces products worth approximately $200 billion per year. The forest products industry consists of two major segments: wood products (e.g., lumber, studs, and plywood) and pulp and paper products. This section of the report focuses on the pulp and paper segment of the industry.

The papermaking process has three major steps: separation of individual fibers from wood, fiber treatment, and recombination. The separation step, which can be performed by chemical or mechanical means, involves a number of processes. For example, chemical separation processes include digestion, cleaning, and bleaching. In the digestion process, wood chips are combined with chemicals under pressure and at high temperature to dissolve the lignin binder. Recovering heat and spent chemicals, including the combustion of organic compounds in a recovery boiler and the recaustizing of sodium carbonate to sodium hydroxide, is essential to the chemical digestion process. In the cleaning process, the pulp is passed through screens and cleaners to remove oversized or unwanted particles.

The bleaching process is used for producing white paper. The pulp is bleached, typically using chlorine dioxide, although ozone and oxygen can be used.

The treatment step involves two processes: refining and cleaning. During refining, fibers are subjected to mechanical impacts that disrupt the multilayer fiber structure to increase their flexibility. After refining, the fibers are screened (sorted by size to remove clumps of unseparated fibers or shives) and cleaned as in the separation step.

The recombination step involves three processes: web processing, pressing, and drying. During web processing, a slurry of fibers and water is delivered to a forming fabric to create a continuous web; water is removed by gravity and a vacuum assist. Pressing involves applying pressure, via a series of rolls, to further consolidate the web and remove additional water. During drying, the web is typically passed over a series of heated rolls to remove water through evaporation.

The American Forest and Paper Association has formed a task group to develop a list of industry needs in the area of sensors and controls. At a workshop sponsored by the Technical Association of the Pulp and Paper Industry, participants identified seven high-priority needs (out of 67) specifically related to process sensing and measurements (Bareiss, 1996; TAPPI, 1996):

- measuring the characteristics of wood chips, including moisture content, chip size and size distribution, species, chip density, and age variables (i.e., acidity, extractive content, and cellulose degradation)
- monitoring pulping chemistry to measure lignin, hemicellulose, and cellulose concentration; also important are the composition of pulping liquors (i.e., effective alkali, residual alkali, and total titratable alkali)
- measuring fiber properties and characteristics, including the degree of refining, drainage loss, coarseness, length, cell wall thickness, density, flexibility, conformability, surface oxidation, and surface carboxyl groups
- measuring the consistency (percentage of solids) of the fiber stream
- measuring colloidal charge, the pulp net surface charge resulting from charges on fibers (usually negative) and additives (often positive)
- physically inspecting the fiber web (approaching 100 percent inspection)
- evaluating printability, a complex characteristic that depends on the characteristics of paper sheet (e.g., smoothness, absorbency, moisture content, formation, opacity, brightness, receptivity to ink, compressibility, surface energy, and mottle)

In general, the challenge for process controls in the forest products industry is to design and implement control systems that provide for the intelligent optimization of processes and total mill control. Specific needs include (Bareiss, 1996)

- control strategies for black-liquor evaporators
- control strategies for dimensional stability, color, humidity in drying processes, and web tension in papermaking operations

- expert systems and smart systems for process diagnostics
- techniques to predict upsets in mill systems (proactive maintenance)
- techniques to reduce the total installed cost of measurement and control systems

Aluminum

The aluminum industry employs more than 130,000 people and annually produces more than 20 billion pounds of ingot and fabricated mill products and contributes $30 billion to the gross domestic product. The major processing steps used by the aluminum industry are listed below (Green, 1996):

- mining
- alumina refining
- aluminum reduction
- metal casting
- thermal treatments
- fabrication processes
- production of fabricated products
- secondary processes (recycling)

The first processing step, after mining, is *alumina refining*, during which bauxite is refined to Al_2O_3 using the Bayer process. The primary issue in the Bayer process is productivity (i.e., yield and rate), which is limited by the rate of trihydrate precipitation and by pressure and temperature constraints on the digestion processes (Aluminum Association, 1997). The needs for sensors and controls are listed below:

- rapid, on-line measurement of particle size in precipitators and settling tanks
- rapid, on-line measurement of chemical concentration in caustics
- effective control of long-lag-time chemical processes
- measurement of temperature gradients, especially in the calcining furnace (1,700°C)

The second processing step is *aluminum reduction*, during which alumina is electrochemically converted to metal using the Hall-Héroult process. The intense use of electric energy is the major factor in the efficiency of the aluminum reduction process. Key needs for sensors and controls are listed below:

- on-line sensors to monitor bath conditions in the extremely severe fluoride melt environment (conditions that need to be monitored include alumina concentration, bath ratio, bath temperature [approximately 950°C], metal depth level, and metal-bath dynamics)
- cryolite freeze profiles

- techniques to measure wall thickness to monitor the buildup of side crust
- prediction and control of anode effects

Aluminum *fabrication processes* include casting, heat treatment, spray forming, semisolid forming, superplastic forming, rolling, foil production, extrusion, forging, stamping, wire production, and powder production.

The needs of the metal casting industry listed above are also appropriate for aluminum casting. In addition, the aluminum industry uses *continuous casting* processes to produce ingots and slabs. The particular needs for sensors and controls for the continuous casting of aluminum are listed below:

- measurement of the temperature gradients in melting furnaces (approximately 730°C)
- in-line measurement of alloy composition
- detection of inclusions
- continuous monitoring of hydrogen content

The needs for sensors and controls in *thermal treatment* processes are listed below:

- in-line chemistry measurement
- in-situ combustion analysis for furnace control
- accurate noncontact temperature sensors

The key needs for sensors and controls for the remaining fabrication processes and for *fabricated products* include

- noncontact measurement of temperature (from 65 to 540°C)
- in-line texture analysis
- control of sheet shape and work roll temperature profiles
- measurement of physical dimensions
- high-speed, noncontact sensing of surface quality
- control of metal flow in extrusion and forging processes (requires measurements of temperature gradients, surface contours, and residual stress, as well as accurate process models)
- wide-area, rapid-scan, nondestructive evaluation methods to detect manufacturing flaws
- measurement of quality, strength, and integrity of welds and joints

The steady growth of the *secondary processing* industry, particularly castings for the automotive industry, has sustained the demand for mixed aluminum alloy scrap. The diversity of aluminum alloy specifications and the restrictions imposed on the chemistry of scrap remelts require that mixed aluminum alloy streams be segregated by alloy type (e.g., separate alloy 1100 from 5XXX series and from 6XXX series). On-line sensors are needed that can rapidly identify alloy chemistry on a rapidly moving conveyor so that scrap can be segregated by alloy type.

Steel

The steel industry employs more than 170,000 people and ships approximately 100 million tons of steel per year valued at $60 billion. The major processes in the steel industry are coke making, iron making, steelmaking, hot mill processes, pickling and cleaning, cold rolling, annealing, galvanizing, welding, and slitting.

The steel producers, including integrated mills and minimills, along with industrial and academic researchers, participate in collaborative research and technology development projects sponsored by the American Iron and Steel Institute (AISI). The objectives of the research on process sensing are to develop on-line, noncontact, multifunctional process and product monitoring sensors that approach 100 percent product coverage. On the basis of these objectives, the AISI subcommittee on sensors, which includes representatives from Armco, Bethlehem, Dofasco, Inland, Timken, Alcoa, and LTV, has identified needs for sensors in the steel industry. Process sensing in the steel industry must accommodate several key factors, including very harsh processing environments, the need for extremely accurate measurements, and, in some cases, the speed (acquisition, measurement, and reporting response time) at which some of the sensor systems must function. Specific sensing needs are listed below (Brusey et al., 1996):

- measurement of thickness gage and profile (some companies need the capability to detect ridges 0.0004 in. high and 0.25 in. wide)
- measurement of mechanical responses, including yield strength, tensile strength, and formability
- microstructural characterization, including grain size and orientation
- surface inspection (defect detection/classification and roughness measured at 6,000 ft/min line speeds)
- on-line chemical measurements (e.g., oxygen content in the iron-making process and carbon content in the steelmaking process) that can feed forward to thickness control
- accurate, emissivity-independent measurement of bulk temperature
- detection and classification of internal inclusions
- multifunctional sensors in a single sensor package (e.g., to measure thickness, product orientation, alloy composition, and temperature)
- characterization of full product width and length, compensating for variations in flatness
- measurement of flatness or camber (as little as 0.25 in in 10 ft of strip length)
- characterization of coatings, including thickness, integrity, and adhesion

In general, the challenge for improved process controls in the steel industry is the design and implementation of intelligent control systems that can work in large-scale batch processes and semi-continuous (high-rate batch) processes. Specific needs for process controls are listed below (Brusey et al., 1996):

- improved utilization of data to enhance process understanding (e.g., real-time use of data in process simulation and modeling)
- self-maintenance of controllers, including on-line monitoring of performance, fault diagnostics, and automatic self-tuning
- robust controllers that can tolerate long-term sensor degradation or key sensor failures
- improved data integrity and reconciliation of spurious data
- control technologies applicable to batch processes and high-rate continuous processes
- optimization of the supervisory controllers that control scheduling and queuing for mixed batch and continuous processes

Process models are a key component of control systems for the steel industry. In many cases, improvements in process control systems depend on the long-term goal of improving first-principle process models (Balchen, 1997). In the short term, tools that combine process models with empirically derived relationships would facilitate improvements to model-based controls. Ideally, developments in modeling and simulation technologies will expand the control and decision-making capabilities of both business and manufacturing processes (Henriksen, 1996).

COMMON NEEDS AND ATTRIBUTES

Many of the factors that are driving the need for sensors and control technologies for continuous and large-batch processes are common to all of the industries represented in the IOF. These factors include efficient energy use, reduced process waste, increased productivity, the continued need for reliable processes that produce high-quality products, and reduced costs. These factors are also common to other energy-intensive processing industries.

Significant barriers to the development and implementation of new sensors and manufacturing process control technologies are listed below:

- the cost and time required to develop, validate, and implement advances from prototypes to reliable process control systems
- the risk to existing production environments, schedules, and rates from the introduction of new process technologies
- the lack of materials and fabrication processes for advanced sensors capable of operating in the harsh processing environments described above for each of the IOF industries
- incomplete understanding of process physics

Industries may require validated simulative process models, or “plant models,” before they invest in new advanced sensors or process control technologies. The purpose of these models would be to determine the impact of new control technologies and to establish the reliability and optimal utilization of the data via "response-time engineering." (Response-time engineering takes into account variations in sensor signal-to-noise ratios, instrument precision and signal processing [e.g., because of sensor placement, time of day, and frequency], and data handling and reporting.)

A long-term challenge must also be considered. Current development programs are being driven by near-term trends in process control technologies and related sensor technologies (e.g., advances in process-specific control software and standardized hardware). However, long-term development will have to meet the challenge of managing large data sets associated with the increased number of parameters (analyzed on an hourly, daily, or weekly basis) monitored by improved process controls and sensors. The cumulative investment for data recording, archiving, and visualization, in addition to the cost of maintaining analysis software, could exceed the periodic reinvestment by industry in new control hardware and software.

Process Attributes

All of the IOF industries are high-volume processors that use large-batch or continuous processes to make commodity-grade products. The products generally have low value per unit but are produced at high production rates. Production line speeds include: glass at 600 fpm; steel at 6,000 fpm; aluminum at 6,000 fpm; paper at 1,000 to 6,000 fpm, depending on basis weight; and plastic films/fibers at more than 6,000 fpm. The most widely shared attributes among the IOF processes are: (1) they are performed in harsh environments, and (2) they require control of large mechanical equipment. Most of the IOF processes considered in this report are serial processes (i.e., the output from one process is the feedstock for the next). A generalized process flow for material processing industries is described below:

- the preparation of raw materials (refining, separation, etc.)
- mixing, blending, digesting, or melting of the prepared materials
- handling of multiphase flows
- consolidation or solidification of the material leading to discrete products

In general, IOF industries use a large amount of recycled materials as feedstock, including both home scrap (in-plant waste) and postconsumer waste.

Process Sensing Requirements

The panel identified the following common requirements for sensing technologies for monitoring and controlling manufacturing processes:

- the measurement of temperature profiles in three physical dimensions and over time in harsh processing environments
- the measurement of chemical composition/stoichiometry in three physical dimensions and over time in harsh processing environments
- the measurement of surface, interfacial, and dimensional attributes at high line speeds and in high-temperature environments
- the monitoring of combustion processes with an emphasis on emissions and particulates

The IOF industries are all anticipating the development of noncontact sensors that can measure process variables (especially temperature, chemical composition, and physical attributes) in environments that are too harsh for immersion sensors. Measurements and analyses must be rapid enough to allow feedback control of high-speed processes with minimal waste.

Process Control Requirements

As a basis for organizing requirements for sensors and corresponding process control technologies, the panel classified process controls into three levels of complexity (shown in Figure 2-1; Jones, 1997):

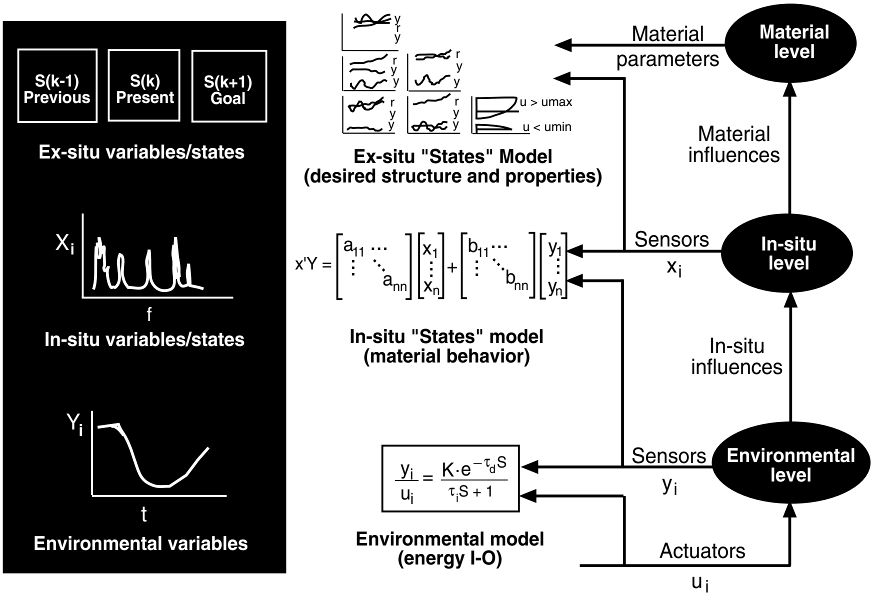

FIGURE 2-1 Three-level classification scheme for process control technologies. Source: Jones, 1997.

- the *environmental level*, where PID (proportional, integral, derivative)-algorithm controllers are used to monitor and control input-output energy variables (e.g., temperature, pressure, flow rate)
- the *in-situ level*, where materials behavior is monitored and process variables are controlled based on process models
- the *material level*, where processes are controlled by direct measurements of desired materials properties

Traditional environmental-level controls rely on feedback control algorithms that monitor primary process parameters, compare the measurements to an initial calibration, and adjust the process in response to deviations. Feedback controls have an inherent delay in making process adjustments. In-situ-level controls can compensate for dynamic delays by using feed-forward control algorithms that use process models to anticipate control settings.

In general, current process control technologies in the IOF industries are at the environmental level. The panel believes that an appropriate goal for near-term OIT-sponsored research would be to move the technology to the in-situ level. Because each industry has its unique operating characteristics, process controls will ultimately have to be tailored to meet the requirements of each industry. Implementing technologies, such as control algorithms, specific process models, and actuator systems, will have to be industry specific.

The process control requirements that are common to the IOF industries are listed below:

- effective use of process measurements
- process control methodologies that enable in-situ-level process control
  - fuzzy logic controllers that can translate expert system rules to establish control parameters
  - model-based controllers that use process models to establish control parameters
- hybrid models that allow multiple, disparate process models to be used in a cohesive and integrated way
- plantwide or enterprise-level optimization, including multi-unit controls and robust, self-diagnostic supervisory controllers
- tools for open-architecture applications, including operator/controller interfaces that allow effective control of dynamic processes by non-experts
- adaptive control systems that account for the variabilities of aging equipment, environmental conditions, or product mix

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3

Research Opportunities

The IOF industries have common needs for measurement and control technology that would lead to reductions in energy consumption and waste. The panel reviewed emerging sensor and control technologies and identified the ones that would address the IOF needs. The panel's objective was to determine which technologies were most promising, and what could be done to accelerate their development. The panel reviewed research on sensors and control systems, information extraction, delivery hardware, and software platforms. The panel also reviewed technologies in the following areas:

- emerging first-principle measurements
- data validation and information extraction from multiple high-speed data streams
- process operator interfacing, efficiency, and safety
- control systems to improve process efficiency and reduce downtime

PROCESS SENSORS

The development of the next generation of sensor technologies is being driven by the common need of IOF industries to improve product quality, processing performance, and yield while optimizing energy efficiency and reducing the adverse environmental impact of manufacturing. The lack of advanced real-time process measurements and control systems is currently considered a critically limiting factor in the realization of these objectives as industries move into the next century.

In the past, manufacturing process sensors and controls have primarily been used to maintain steady-state operating conditions through the measurement and control of fundamental variables, such as temperature, pressure, and flow (i.e., environmental-level control, as described in Chapter 2). However, developments in process measurement and control technologies are rapidly shifting the focus to sensors that can measure physicochemical parameters that are more directly related to product quality, performance, and process optimization. The realization of these next-generation technologies will require innovative sensors with new sensing techniques and transducer elements. As described in Chapter 2, the required measurements include

- the measurement of temperature profiles in harsh processing environments
- the measurement of chemical composition/stoichiometry in harsh processing environments
- the measurement of physical attributes at high line speeds and high temperatures
- the monitoring of combustion processes

For the applications that require direct immersion-type sensors in harsh environments, materials (including materials for the entire sensor system, which consists of sensor elements, packaging, leads, interconnects, and actuators) with significantly improved thermal and chemical resistance will be essential. A single comprehensive database of candidate material properties (including mechanical and physical properties; high-temperature properties; reactivity in chemical environments; and methods for deposition, formation, and patterning processing) would significantly accelerate the design and development cycle for the fabrication of new sensors and transducers for these demanding applications.

In many situations, however, severe constraints all but preclude the use of direct, invasive diagnostic sensors. Research, therefore, should focus on non-invasive diagnostics and probes, photonic, acoustic, or electrical probes that can elicit responses that indicate given states or properties of the system. Non-invasive diagnostics can be divided into two categories: *fundamental diagnostics* and *natural system behavior diagnostics*.

Fundamental diagnostics include direct measurements (e.g., temperature, composition, spectral absorbance, mass/charge ratio, electrochemical potential) and indirect measurements (e.g., impedance or optical spectrum). Indirect measurements, which are important for in-situ-level process controls, correlate sets of data values with systems performance in a way that is easily repeatable. Using indirect measurements, process performance can be controlled without directly ascertaining the property being controlled. Indirect measurements are especially useful in extremely complex systems where measurement of a property comprised of several nonlinearly interacting parameters can be used to control a process function. Direct measurements of desired materials properties, which enables materials-level process control, invariably provide the most valuable information.

With natural system behavior diagnostics, systems performance is characterized by measuring certain attributes that reflect processing characteristics, such as current signature, motor torque, circuit loading parameters, and system electrical impedance. Natural system behavior diagnostics provide complex information about a process and are application specific. Nevertheless, efficient data mining and advanced signal processing methods (e.g., time- and frequency-domain analyses) can be developed to extract valuable processing information from these large, complex, often noisy multidimensional data sets. Natural systems diagnostics are critical to monitoring the performance of processing equipment in condition-based maintenance programs. The advantages and promise of natural system behavior diagnostics are listed below:

- non-intrusive and remote process monitoring
- no need for additional cables and field sensors at the process point
- high sensitivity to a wide range of mechanical and electrical disorders
- high selectivity among disorders of processes and machines

General Research Opportunities in Sensor Technology

Among the many research opportunities identified by the panel for creating the next generation of sensor technologies are

- sensors and transducers capable of reliably measuring composition and temperature in harsh environmental conditions
- low-cost, high-volume production of sensors
- reliable, robust sensors
- integrated sensors produced using integrated circuit processing approaches (“sensors on a chip”)
- advanced wireless sensors
- miniature sensors and ancillary systems (e.g., through micromachining, spectrometer on a chip, and sensor arrays)
- reliability testing and self-monitoring of sensors
- integrated sensing techniques with monitoring modules and control software to provide a total manufacturing solution
- process spectroscopy (e.g., nuclear magnetic resonance, Raman, infrared, near-infrared, mass, optical, electrochemical, and acoustic spectroscopies)
- new materials for the production of low-cost, low-loss fibers for the remote sensing of chemical composition using infrared process spectroscopy (currently available chalcogenides are unsuitable for many infrared process applications)
- environmental sensors that can detect and characterize a wide variety of emissions/pollutants (gas or submicron particles)
- materials for new sensors that are engineered on a molecular scale for enhanced structure-function specificity and sensitivity to chemical moieties
- analysis and visualization of process measurements

Temperature Measurements

The need to measure high temperatures accurately and reliably is common to all of the IOF industries. Thus, there is a strong impetus for developing new technologies that can meet these stringent requirements. The following examples of innovative temperature measurement techniques are a few of the techniques that were discussed at the workshops. There are other emerging technologies that should also be evaluated.

Johnson-noise thermometry has the potential for producing accurate, real-time process measurements of a wide range of temperatures, from cryogenic to incandescent. Technology gaps (and thus research opportunities) in the development of new probes include problems with drift, hysteresis, and electromagnetic interference. New high-speed, low-cost silicon digital signal processor devices, although not compatible with exposure to temperatures above approximately 250°C (NRC, 1995), may provide a solution for the requisite high-bandwidth digital signal filtering required to "notch-out" bands of interference.

Using *Raman-based thermal measurements*, temperature sensors could be developed that are not influenced by the emissivity of a given material. The Raman technique is based on measuring the ratio of the Stokes to anti-Stokes intensity in a Raman signal. Research should focus on the development of holographic filters that would mask the Raman laser lines to enhance the Stokes and anti-Stokes emissions. Alternatively, development could focus on low-cost rugate notch filters that may have significant advantages over holographic notch filters because of their small size and superior environmental and thermal stability.

Phosphor thermography is a new type of sensor that was developed by a joint research project by Oak Ridge National Laboratory, the U.S. steel industry, and DOE. This technique uses phosphor thermography to provide accurate in-process temperature measurements and is being applied during galvanneal operations. Phosphor thermography has a number of key attributes, including (1) noncontact, remote operation; (2) reduced temperature errors; and (3) insensitivity to surface quality, emissivity, and electromagnetic interference. Conventional infrared pyrometry strongly depends on the emissivity values of materials (which are often not well known and can vary with temperature and surface morphology).

Self-verifying temperature sensors (SVS) have the distinct advantage of not being susceptible to the degradation of calibration and accuracy, or "drift," that is common to many other types of thermal measuring devices. The SVS probe purports to have a unique construction of proprietary materials; the associated monitoring module constantly checks the temperature calibration of the system against an established reference, thereby ensuring accurate measurements of better than ±0.4 percent. However, the current probe system has the same problems in hostile environments as conventional sensors. Protective thimble technology may be required to extend the sensor life and practical utility of SVS systems in high-temperature environments.

Chemical Composition: The Advent of Process Spectroscopies

A variety of analytical instruments to monitor process chemistry and stoichiometry are in rapid transition from the laboratory environment to the manufacturing environment. The impetus for this rapid evolution has been mostly the development of lower-cost, miniaturized, integrated systems that directly and easily measure a wide range of process flow streams and conditions. Some of the techniques OIT should consider for process measurement and control in IOF industries are Raman spectroscopy, mass spectrometry, infrared spectroscopy, near-infrared spectroscopy, UV-visible spectroscopy, electrochemical spectroscopy, and acoustic spectroscopy. Two technologies that were discussed in the panel's technology workshop, Raman spectroscopy and mass spectrometry, are described below as examples.

A growing number of optical-based absorption and fluorescence instruments are being used as remote analytical sensors. These compact *optical spectrometers* provide real-time spectral identification of chemicals in chemical process lines or in smokestack plumes. In addition, similar Fourier-transform infrared instruments are starting to be used to monitor the perimeter of industrial facilities to detect accidental releases of hazardous gases.

Another important technique, for which instrumentation is commercially available, is *Raman spectroscopy*, which has several advantages over other optical spectroscopy techniques. First, it is not affected by interference from glass or ambient water or moisture (which is critical in many industrial applications). Second, it yields a unique molecular fingerprint, which unambiguously identifies chemical species. Third, it can be deployed remotely through commercially available low-loss silica-based optical fibers.

Mass spectrometry has crossed the threshold from the laboratory to the manufacturing environment and is being used for monitoring and control of chemical compositions in low-pressure systems. Significant challenges remain, however, before this technique can be more generally used as a diagnostic tool in manufacturing. These challenges include making more accurate quantifications of chemical species, developing better sampling procedures, and creating robust calibration methods that would be transferable to different processing conditions and not require numerous samples.

In general, implementing chemical composition monitors in manufacturing will require continued research to develop innovative sensors; miniaturize sensors and ancillary equipment; develop engineered materials for chemical specificity and sensitivity (for new chemical probes); develop lower cost, more robust electro-optics; and incorporate chemometrics to improve the calibration, performance, and reliability of new and existing analyzers.

According to Koch (1997), evolutionary advances that will affect chemical measurements include

- information processing, including data mining and fusion, artificial intelligence, neural networks, and model-based analyses
- miniaturization, including micromachined components, single-chip spectrometers, and sensor arrays
- engineered materials, including molecular-scale tailoring for selectivity and sensitivity
- electro-optics, including mid-infrared fibers, detectors, and diode lasers

Application-Specific Integrated Sensors

The realization of a fully integrated sensor, with the necessary microelectronics packaged in a single device, will require using existing silicon integrated circuit technology to produce a low-cost, high-volume product for a specific function. For example, research could be done on integrated systems that include sensors for applications involving process spectroscopies (described above) combined with solid-state photospectrometers. These integrated systems could be designed with mechanical elements (e.g., actuators) fabricated using MEMS (microelectromechanical systems) technology (NRC, 1997). The systems would be unique and powerful probes that could perform sensitive, specific functions. For example, cantilever MEMS is a promising technology for the development of tools for in-process chemical analyses, but they will require low-cost, reliable, and easily reproducible methods for depositing chemical-specific coatings. Current state-of-the-art processing methods have not addressed the formidable challenge of developing the materials and processing strategies for a sensor that gives a specific response to a chemical perturbation.

Critical areas for research in integrated sensors and MEMS devices are assembly, interfacing, and packaging. These final production steps can represent more than 80 percent of the cost of MEMS, and the failure of packaging is often the leading cause of system failure (NRC, 1997). As described above, chip technologies have developed rapidly because many of the manufacturing processes are the same as those used for conventional microelectronics. However, because integrated sensor systems must be able to interface with a range of input and output modes—including electrical, fluid, optical, chemical, and mechanical—conventional packaging and interconnection technologies cannot be used. The development of packaging and interfacing technologies that can be used in the harsh environments found in the IOF industries represents a research opportunity for OIT. Advances in packaging, assembly, and interfacing technologies could accelerate the development and acceptance of integrated sensor systems in the IOF industries.

Reliability of Sensor Measurements

One of the greatest impediments to the continued development and implementation of new sensor technologies is the difficulty of ensuring sensor reliability and performance. Because reliability is critical, improved methods of demonstrating and testing new sensor technologies under realistic manufacturing conditions must be developed. However, experiments performed on actual production lines are expensive and time-consuming and may require machine downtime. The capability of realistically simulating manufacturing conditions (e.g., in a test bed or pilot-scale manufacturing facility) would significantly reduce the time required to evaluate, qualify, and implement a new manufacturing process sensor.

Advanced Wireless Sensors

The explosive growth in wireless telecommunications has generated a wide range of new products and created a technology infrastructure that may be suitable for the next generation of advanced wireless sensors. The prospect of being able to deploy new sensors rapidly anywhere in a manufacturing plant without the costs of cabling, connections, and associated labor presents a significant opportunity for using advanced wireless sensors in the future. Research would have to address the needs and overcome the barriers listed below:

- eliminate interference from metal structures in the manufacturing environment
- use intelligent, integrated sensors
- develop reliable wireless networks for process monitoring and control
- develop remote power systems for wireless devices
- standardize communication protocols, interfaces, and software

Analysis and Visualization of Process Measurements

Even without the expected increase in the use of sensors for process monitoring and control, manufacturers face the daunting prospect of dealng with databases of unprecedented size and complexity. Considering the investment manufacturers will have made in acquiring process data, they would be wise to develop techniques for electronic documentation, electronic storage, archiving, and retrieval, as well as data analysis and visualization. Specifically, they will require methods to (1) compensate for uncertain data; (2) link measured parameters to meaningful process variables; and (3) organize observed data, models, and inferred knowledge using database technology.

Research should focus on adaptive methods involving the coupling of traditional methods, such as the Karhonen-Loeve transform, Euclidean distance clustering, and self-organizing maps, to emerging techniques, such as auto-associative neural networks, and self-training, hetero-associative neural networks. The coupling of these methods will provide the following capabilities:

- automated classification of data
- supervised and unsupervised learning methods

- knowledge discovery techniques
- image analysis and segmentation
- statistical pattern recognition
- time-series feature extraction and analysis
- trainable object recognition
- automatic image registration and change detection
- spatiotemporal data mining

PROCESS CONTROLS

Industrial process controls in the IOF industries, as in most other large-scale process industries, lag far behind the developments of the past 20 to 30 years. The process controls currently used rely extensively on manual and single-loop PID control. Recent developments in control theory have not been widely applied, with the notable exception of model predictive control concepts, which are used predominantly in refining industries. The success of model predictive control can be attributed to its heuristic model basis and its use with relatively slow, stable processes.

Adaptive control of a manufacturing process consists principally of (1) sensing variations in processes or products, (2) determining corrective action, and (3) executing a correction through an actuator. Each of these functions presents barriers that must be overcome. The requirements for process controls common to the IOF industries (described in Chapter 2) include

- methodologies to enable in-situ-level process control
- plantwide or enterprise-level optimization
- hybrid process models
- tools for open-architecture applications
- adaptive control systems

Process Control Methodologies

The principal objective for the process industries represented by the IOF is to develop technology to enable the transition of controls from the environmental level to the in-situ level (described in Chapter 2). Areas where process control technology can be significantly improved include

- effective use of process measurements
- robust on-line learning (intelligence applications)
- autonomous control reconfigurations
- automatic diagnostics and maintenance
- management of abnormal situations (e.g., start-up, shutdown, and fault recovery)
- plantwide process optimization

Control input signals must be accurate and repeatable with few variations; sensor drift, faults, and noise corruption can compromise the data. If multiple sensors are required, there may be high costs for wiring and installation. Even when reliable data are available, information must be rapidly extracted from a mass of data.

Many advanced control algorithms require more accurate process modeling than is available in most industries. Most process models do not adequately address real-world issues of process nonlinearity, instability, inaccuracies in input signals, and the number and complexity of variables. All of these factors have meant that industry now uses complex systems that have long development times and high implementation costs and risks to end users.

The panel suggests the following research areas to address these common needs:

- *Intelligent control algorithms* would address process nonlinearity, capture heuristic knowledge, and fill voids in first-principles knowledge.
- *Neural networks* would generate multivariable, nonlinear, reduced-order models from process data. However, (1) the current state of knowledge makes it extremely difficult to develop process understanding from "learned" weighting factors; and (2) neural networks require large process data sets that accurately represent the entire process space over which the control is to be applied (see Box 3-1).
- *Fuzzy logic strategies* can capture heuristic knowledge but require "expert" knowledge that can be translated into rules.
- *Chaos theory* is already being applied to industrial processes, such as power generation, to extract ordered models of global behavior from apparently random signals (Garrison, 1997).

Recently, advances have been made in several technologies relevant to process controls. Business system models for scheduling production, pull systems, and flow-time minimization are being widely used, as are computer-based systems to monitor maintenance data and schedule preventive maintenance. Reliability techniques are being used to design equipment and analyze data to estimate maintenance schedules from mean time between failures and other statistics.

Improving the state of practice in the IOF industries will require both improving the technologies described above and combining them to cover the large range of issues presented by real processes. Stability criteria must be developed, for example, for the intelligent, nonlinear algorithms to reduce processing risk. Control systems must be able to "learn" on line as processes change and to reconfigure themselves autonomously. This learning must be robust to ensure process reliability. Modeling techniques (first principle, heuristic, neural network, and fuzzy logic) should be integrated into hybrid models in which each technique is applied to the part of the larger process or plant for which it is best suited.

Problems with incompatible data formats and portability of process models between equipment with different operating systems will have to be resolved. Systems must be able to detect and diagnose not only sensor degradation but also, and more importantly, performance degradation. Business objectives, such as profit, quality, downtime, and environmental impact, will have to be integrated into the control.

Hybrid Modeling

The development of hybrid modeling techniques that include multiple, disparate models in a cohesive and integrated fashion (i.e., beyond simple information sharing) is a key area for research (Samad, 1997). Many different types of process models are now used in the materials process industries, including models based on first principles, empirical knowledge, heuristic knowledge, steady-state behavior, dynamic behavior, linear behavior, and nonlinear behavior. The complexity of industrial processes and the complexity of the desired level of control and automation practically mandate that more than one modeling approach be used.

In general, process models are now treated as independent entities to be used for monitoring, control, or optimization in isolation from other models. This approach has many adverse consequences. Because no unified representation of the whole process is available, inconsistencies (or consistencies) between different models are not recognized, which means that operational functions cannot be coordinated (except in an administrative sense). Specific topics that should be pursued in the development of hybrid modeling capabilities include

- the integration of first-principle, empirical, and heuristic knowledge
- the recognition and disposition of relationships and inconsistencies between models
- the development of multiresolution and multiscale models
- the integration of heterogeneous models

Plantwide Optimization and Control

Traditional (environmental) process-control technologies are widely used by the IOF industries. With regulatory and supervisory control schemes already in widespread use, the next breakthrough is likely to be in plantwide or enterprise-level process optimization. The large scale of a process facility poses daunting challenges in this regard. Plants may have tens of thousands of monitored variables, feedstock-to-product delays may be measured in weeks, and, perhaps most critical, plantwide optimization requires the coordination of the process and business aspects of plant operation.

Plantwide optimization technology would provide a decision support system

BOX 3-1

A Neural-Network Controller for Adaptive Annealing of Rolling Sheet

Need. Recrystallization annealing is a process of reheating steel strip in thermal zones to reorder grains physically to decrease internal stresses and hardness. Annealing is a necessary step in the cold rolling process to counteract the effects of grain deformation and brittleness. Variations of Rockwell hardness in rolling sheet are caused by changes in the tensile stresses on sheet stock while it is being reshaped (in width or thickness). These variations can be correlated with changes in the mechanical load of the motors that spin the rollers (see Figure 3-1).

Solution. A survey of continuous annealing lines by Jeong and Ha (1992) showed that very little information is available indicating how line temperatures and process conditions interact to influence strip hardness. Gibson et al. (1992) presented improvements in the annealing process but did not have quantitative algorithms or methods. The lack of the necessary algorithms prompted the development of ANNEAL-NET (Garrett and Reddy, in press) for modeling continuous annealing processes, including appropriate zone temperatures, to minimize strip hardness and variations. A feed-forward neural network was used to approximate a model of the process with 3,519 data points obtained from product strip coupons (and associated process parameters) for back-propagation training. One of the 3,519 data points (with Rockwell hardness rating) is shown below.

Gauge	0.0119 in.
Width	31.371 in.
Speed	500 ft/min
Zone 1	1,295°F
Zone 2	1,300°F
Zone 3	1,420°F
Zone 4	1,450°F

for bridging planning and scheduling systems and supervisory controls (see Figure 3-2). The goal is to optimize manufacturing operations in terms of process efficiency and business considerations. Plantwide optimization has proved to be very beneficial to the petrochemical industries. Applicability of these optimization systems to the other IOF industries will depend on the availability of accurate hybrid models for both large-batch processes and continuous processes and compatibility with existing controllers.

BOX 3-1 Continued

Zone 5	1,445°F
Zone 6	1,330°F
Zone 7	1,205°F
Zone 8	1,200°F
Zone 9	700°F
Zone 10	605°F
Rockwell hardness	59

Data from 879 separate coupons were tested to evaluate the ability of the neural network to predict hardness. Training time involved 4,000 epochs with a mean error of approximately zero and a standard deviation of 1.58 Rockwell hardness units. A gradient descent algorithm then used the model to predict the line conditions necessary for annealing with minimum Rockwell variation for a target Rockwell hardness of 50.

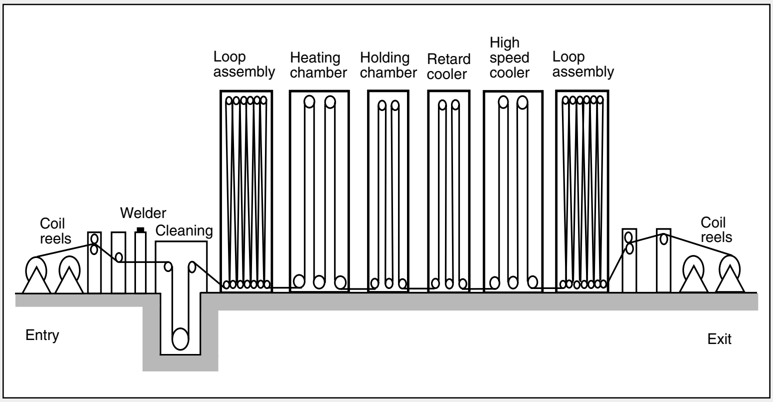

FIGURE 3-1 Continuous annealing process roller sequence.

Specific research should be focused on the areas listed below:

- automated data analysis to identify key process variables that affect profitability, energy consumption, and waste generation
- integration of process controls with maintenance operations and monitoring of equipment health (see Box 3-2)
- approaches to optimization that increase profitability while minimizing energy consumption and environmental impact

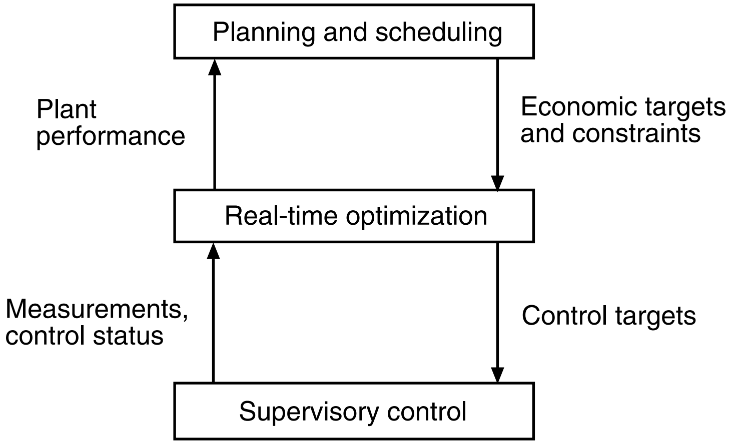

FIGURE 3-2 Decision support hierarchy for plantwide optimization. Source: Dudzic, 1997.

- large-scale, nonlinear optimization algorithms (a refinery model, for example, may consist of more than one million nonlinear equations)
- techniques to compensate for model uncertainties
- the dynamic reconciliation of incompatible data for large-scale models

Open-Architecture Controls

In open-architecture control systems (1) control software can be "ported" between controllers from different suppliers (or with different operating systems) with few modifications, and (2) data can be easily and reliably transferred between system components while maintaining a "friendly" and consistent user interface (Owen, 1995). Factors in determining the "openness" of a control system include (Proctor, 1997)

- the ability of two or more components to exchange information and use the information that has been exchanged (interoperability)
- the ease with which a module can be made to interface with a controller based on another platform (portability)
- the ease with which an existing system performance can be increased or decreased with changes in demand (scalability)
- the ability of users and third parties to add functions incrementally to a module without replacing it (extensibility)

The development of open-architecture controllers promises to advance control technology in the IOF industries because standard platforms allow more rapid implementation of new technologies and controllers based on commercial "off-the-shelf" technology. However, the ease with which second parties can modify vendor-supplied, open-architecture software could result in deleterious effects on system reliability and could ultimately affect machine and operator safety.

Despite their potential effects on system reliability and robustness, open-architecture controllers are replacing proprietary "black box" systems in industrial applications. De facto standards, such as Microsoft Windows NT operating systems and real-time extensions, Pentium processors, and DeviceNet network interfaces, are emerging (Proctor, 1997). Some features of the emerging de facto standards, however, make them less than optimal for process control applications. For example, real-time extensions have to be (and are being) developed and tested because Windows NT is not a real-time operating system. This is an example of why industry participation in the development of open-architecture standards is important.

The National Institute for Standards and Technology has established a program to evaluate emerging standards. However, the program is focused primarily on the manufacture of discrete components rather than on the continuous or large-batch processes typical of IOF industries. The panel believes that the evaluation and implementation of emerging open-architecture standards for large-batch and continuous processes represents an important research opportunity for OIT to pursue, with the active participation of IOF.

Learning and Adaptation in Control Systems

The process industries represented in the IOF are promising candidates for the development and implementation of learning and adaptation in control systems. Many characteristics of industrial processes (time constants, stable dynamics, and operational understanding) are compatible with adaptation, and industries have been waiting for practical adaptive control technologies for decades. Recent research in artificial intelligence and nonlinear control, together with the availability of relatively inexpensive computing power, have finally made adaptive controls feasible.

Some areas for research in adaptive controls are listed below:

- distributed adaptive/learning system architectures that can be practically implemented by process industries
- appropriate roles for human operators and engineers in semi-autonomous control systems
- determination of when sensor data have sufficient excitation (signal/noise ratio) for further analysis
- ensuring that stability and safety are enhanced (not compromised) by adaptation

BOX 3-2

Optimization of Electric Motors for Finishing Mill Operations

Need. Rolling mills use direct-current motors and generators to meet the power demands of the mechanical loads. In long-term operation, these motors continue to develop power until they are current-limited or they encounter a fault from thermal runaway. Variations in load can cause the motor windings to heat up, which increases losses or work generated per unit of electric power consumed. If the average temperature of the windings could be reduced through load scheduling and augmented with stand-still cooling (monitored by on-line temperature and current measurements), then motor losses could be reduced. In a typical hot-strip finishing mill with 26 electric motors, thermal losses can be as great as 10,000,000 BTUs per year.

Solution. The objective is to minimize energy allocation while optimizing production and ensuring the condition of the equipment (Oswald, 1997) monitored by on-line measurements of thermodynamic parameters that describe heating and cooling. The solution must provide minimum product spacing ($t_{standstill}$) without exceeding maximum machine temperatures and must maintain specific product characteristics and load currents (shown in Figure 3-3). Thermal energy dissipated by an electric machine constitutes energy not converted to mechanical work.

Increased loading causes a corresponding rise in temperature, by the square of the power (Power = I^2R) (Engelmann, 1995). The temperature increase must be averaged over mill loading and standstill periods to limit the increase to 40°C above the ambient temperature. Overheating during summer operation is of particular concern. Variations in product hardness can be accounted for using simple analysis (linear regression) of $t_{standstill}$ augmented by measured product characteristic and load currents.

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BOX 3-1 Continued

$$t_{standstill} = \left[(-\tau_{fall}) \left[\ln \left[\frac{(\theta_{target} - \theta_{max}) \left[e^{\left[\frac{t_{load} - t_{load\,start}}{(\tau_{rise})} \right]} \right] + (\theta_{max} - \theta_{ambient})}{(\theta_{target} - \theta_{ambient})} \right] \right] \right] + t_{standstill\,start}$$

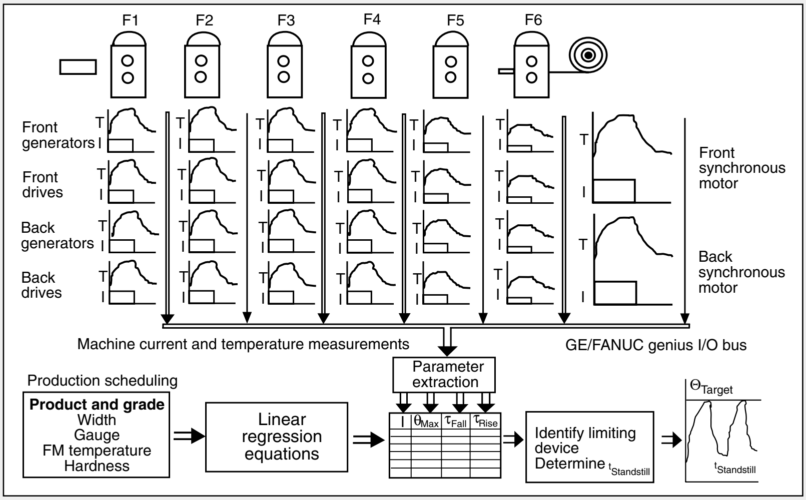

FIGURE 3-3 Monitoring system for finishing mill electric motors.

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4

Recommendations

The industries in the IOF operate in an environment of global competition. For these suppliers of raw materials and semifinished goods, quality is a requirement, rather than a differentiator. Successful companies are able to manufacture high-quality products at the lowest possible cost. In this cost-constrained business environment, in-house process control groups are becoming smaller or even being eliminated. Hence, the industries are becoming increasingly dependent on suppliers of process control systems, even for ongoing optimization. At the same time, even though process control systems can give companies a technological advantage, new process control technologies will not be implemented unless they will have an immediate effect on current operations.

The development of improved process control technologies depends on cooperative efforts by multidisciplinary teams. The capabilities required to develop and implement new process control technologies vary significantly depending on the specific process science involved and on the maturity of the technology. Success depends on the integration of several technologies, which may include the following:

- process control science and engineering
- computer science and software engineering
- signal processing engineering
- measurement science
- process engineering
- manufacturing

Although significant efforts have been made to develop process control technologies and improve sensor technologies, most of the work has focused on the manufacture of discrete parts. The technologies that can be used for large-batch and continuous processes are an area in which OIT can address the needs of important industries. This chapter presents the panel's recommended strategy for a process controls initiative by OIT to improve technologies for the materials processing industries represented in the IOF. The panel also suggests ways for OIT to coordinate research objectives and new technologies among the IOF sectors and with other programs.

TECHNICAL CHALLENGES

Industry has shown a great deal of interest in the development of sensor and control technologies for a number of applications. Substantial government-supported programs are under way at many agencies. The U.S. Department of Defense has been working on environmental sensors to protect personnel and equipment, sensing and control technology to guide autonomous and remotely piloted systems, and intelligent process controls for component manufacturing. The National Institute for Standards and Technology has been developing standards for open-architecture controllers, robotics, and intelligent process controls for the manufacture of discrete parts. The National Science Foundation has been working on integrated sensors/controllers, intelligent controls, and condition monitoring systems. DOE has been investigating environmental sensing and advanced controls to improve process efficiency.

Regardless of the specific research objectives of these projects, the following general challenges are driving the development of sensors and manufacturing process control technologies:

- Variability and quality. Advanced sensors and process controls are necessary to monitor process variations so that high-quality operations can be maintained at lower cost.
- Environmental constraints. Innovative, robust sensory devices, including innovative sensor materials and coating technologies, are necessary to monitor process parameters and provide information in extreme high-temperature and chemically corrosive environments.
- Service. Process controllers are necessary to provide proactive maintenance capabilities, such as measurements of performance degradation, fault recovery, self-maintenance, and remote diagnostics.

STRATEGY FOR A PROCESS CONTROLS INITIATIVE

The panel recommends that OIT research be focused on the development of process sensors and control technologies to meet the needs of the IOF industries. In Chapter 2, the panel identified common industry needs for process sensing and manufacturing process controls based on common IOF process attributes. The process attributes include (1) high processing volume and production rates, (2) large-batch or continuous processes, (3) commodity-grade products (low value per unit), (4) harsh processing environments, and (5) serial processing sequences (i.e., the output of one process is the feedstock for the next).

Common process sensing needs include

- measuring temperature profiles in harsh processing environments
- measuring chemical composition/stoichiometry in harsh processing environments
- measuring physical attributes at high line speeds and high temperatures
- monitoring combustion processes

Common needs for process controls include

- methodologies that enable in-situ-level process control
- hybrid process models
- plantwide or enterprise-level optimization
- tools for open-architecture applications
- adaptive control systems
- methods and diagnostic tools for condition-based maintenance of process equipment

To address these needs, the OIT program should include (1) a cross-cutting research initiative to develop fundamental technologies that address the common needs of IOF industries, (2) industry-specific (IOF) research to validate and implement advances in technology, and (3) an interagency initiative to coordinate plans and research objectives.

Cross-Cutting Research

The panel believes the common needs for process controls and sensor technologies warrant a cross-cutting research and development initiative in this area. The panel recommends that OIT establish a research and development program that emphasizes the common needs of the IOF industries. Some of the research opportunities, identified in Chapter 3, are listed below:

- the development of sensor materials (including materials for the entire sensor system, which consists of sensor elements, packaging, leads, interconnects, and actuators) with significantly improved thermal and chemical resistance
- the compilation of a comprehensive database of candidate sensor material properties, including mechanical and physical properties; high-temperature properties; reactivity in chemical environments; and methods for deposition, formation, and patterning processing to accelerate the design and development cycle for the fabrication of new sensor systems

- the development of methods to measure temperatures accurately and reliably, including techniques, such as Johnson-noise thermometry, Raman-based thermal measurements, phosphor thermography, and self-verifying temperature sensors
- the development of low-cost, miniaturized, integrated analytical instruments that can provide direct, easy measurements of process chemistries for a wide range of process flow streams and conditions; techniques to be considered for process measurement and control include near-infrared spectroscopy, Raman spectroscopy, mass spectrometry, infrared spectroscopy, UV-visible spectroscopy, electrochemical spectroscopy, and acoustic spectroscopy
- the application of new processing science for fabricating and packaging integrated sensor/signal processing/actuation modules
- the development of measurement technologies that can rapidly characterize and evaluate physical properties for wide-sheet processes or web processes
- the application of wireless telecommunications technology to the development of advanced wireless sensors; areas for development include reliable wireless networks for process monitoring and control, remote power systems for wireless devices, and standardization of communication protocols, interfaces, and software
- the development of process control methodologies that can facilitate the transition from environmental-level to in-situ-level control methods; areas of interest include the effective use of process measurements, intelligent control algorithms, and the development of reliable process models
- the development of techniques that can integrate disparate process models
- plantwide optimization and controls, including automated data analysis techniques to identify key process variables, integration of control with maintenance operations, process control approaches to minimize energy consumption and environmental impact, large-scale nonlinear optimization algorithms, methods to deal with process model uncertainties, and dynamic data reconciliation for large-scale models
- the evaluation of open-architecture control systems for large-batch and continuous processes typical of IOF industries
- the development and implementation of learning and adaptive controls; particular topics for research include distributed adaptive/learning system architectures that are feasible for implementation by process industries, operator interfaces in semi-autonomous control systems, and system stability and safety

In addition to the common IOF industry needs, the organizational objectives of DOE and OIT—the reduction of raw material and energy consumption, improved labor and capital productivity, and the reduction of waste—must be considered. The panel recommends the following criteria, which are compatible with

DOE and OIT organizational objectives, as a basis for comparing and selecting projects for the cross-cutting program:

- potential for reducing the consumption of energy and raw materials and for reducing waste
- consistency with the technology road maps of the IOF industries
- potential benefits for more than one industrial sector
- potential for commercial application

One of the key challenges for OIT will be managing the cross-cutting program in a way that facilitates the development of specific performance goals based on the common needs of multiple industries. The panel recommends that an IOF coordination group be established, with representation of all of the IOF teams, to develop short-term and long-term goals and to monitor progress and results. Active participation by the IOF industry teams would help ensure that cross-cutting research programs remain responsive to industry needs. The group would review process attributes and control needs in each of the industries and establish a consensus on specific goals the cross-cutting program should pursue to benefit the maximum number of processes. Examples of process attributes that should be considered include (1) process environment (e.g., temperature and chemical exposure) to establish material requirements and performance ranges, (2) line speeds and sensitivity of the processes to variations to establish required system response times, and (3) the number of sensors and frequency of measurements to establish requirements for sensor fusion and data processing for the handling of large data sets.

In addition to establishing research goals, the IOF industry teams should monitor the progress and results of the cross-cutting program to speed the transition and scaling of new technology through validation and implementation programs. The panel recommends that OIT facilitate interaction between researchers and potential users within the IOF. These interactions could take the form of technical progress reviews and/or technology workshops to discuss technical developments and identify opportunities for validation and implementation.

IOF Initiatives

All of the IOF vision documents identified manufacturing process controls and process monitoring sensors as important to the future success of their industries. The panel identified a cross-cutting initiative that would benefit multiple industries. However, the aspects of the required research and development that are unique to particular processes or conditions could be handled best by individual IOF groups, especially in the process development and implementation phases.

Industry-specific efforts could include the following:

- the development of road maps to identify technology needs and implementation plans
- participation in interactions with cross-cutting technology programs (e.g., technical workshops and progress reviews)
- the development and validation of process models related to specific key processes
- improved process models that can facilitate the transition from environment-level control schemes to in-situ-level controls
- the optimization of process control systems, especially supervisory controls and plantwide integration
- the validation and implementation of improved sensor technologies and process control systems for large-scale processes

Coordination with Other Programs

Significant efforts related to sensors and process controls have been made by other agencies in the government—especially the National Institute for Standards and Technology, the U.S. Department of Defense, the National Science Foundation, and elsewhere in DOE. The final challenge to OIT will be to coordinate the cross-cutting and industry-specific aspects of the OIT program with other government-sponsored programs. The panel recommends that OIT program managers continue to lead the interagency and intra-agency coordination of progress in complementary technologies to avoid duplications. In addition to monitoring the complementary programs, the committee recommends that OIT collaborate with four programs that are particularly important to the success of the OIT program.

- National Institute for Standards and Technology program to develop standards for open-architecture systems; IOF industries should evaluate and validate system standards for large-batch and continuous operations
- National Science Foundation programs to improve process sensing and process modeling capabilities (e.g., the Measurement and Control Engineering Center at the University of Tennessee-Knoxville; the Center for Process Analytical Chemistry at the University of Washington; and the Center for Industrial Sensors and Measurements at Ohio State University); IOF industries should coordinate the implementation and application of process modeling and advanced sensor technologies
- U.S. Department of Defense research, especially at DARPA, to develop MEMS devices, fabrication processes, and applications; IOF industries should evaluate these devices for sensing/control of industrial processes
- U.S. Department of Defense (especially Army, Navy, and DARPA) programs to develop condition-based maintenance approaches; IOF industries should evaluate sensors and diagnostics developed to monitor processing equipment and machinery

APPENDICES

APPENDIX
A

Workshop Agendas

FIRST WORKSHOP MEETING
OCTOBER 22, 1996
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C.

8:30 Introductions and Session Objectives
Gary Baum, Panel Chair

Industry Needs in Process Controls

8:45 Advanced Sensor Needs for the Glass Industry
C. Philip Ross, Creative Opportunities

9:30 Process Control and Sensor Needs: The Chemical Industry
Mel Koch, University of Washington

10:15 *BREAK*

10:30 Sensor and Control Needs for the Metal Casting Industry
Bill Walkington, Consultant

11:15 Forest Products Industry: An Overview of Needs in Process Control
Robert Bareiss, Bareiss Associates

12:00 *LUNCH*

1:00 A Compilation of Sensor and Control Needs
John Green, The Aluminum Association

1:45 Process Sensor and Control Needs in the Steel Industry
Barry Brusey and Mike Dudzic, Dofasco

2:30 *BREAK*

Discussion of Common Industry Needs

3:30 Processes (Types and Conditions)
All

4:00 Process Control Needs
All

4:30 Process Monitoring Sensor Needs
All

5:00 *ADJOURN*

SECOND WORKSHOP MEETING
MAY 29, 1997
NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C.

8:30 Study and Session Objectives
Gary Baum, Panel Chair

8:45 "Intelligent" Process Controls: An Industrial Perspective
Tariq Samad, Honeywell

9:30 Neural Net Computing: A Perspective on Its Role as an Enabling Technology for Process Control in the Industries of the Future
Yoh-Han Pao, AIWARE, Inc.

10:15 *BREAK*

10:35 Open-Architecture Controllers
Fred Proctor, National Institute for Standards and Technology

11:20 Process Optimization and Control
Rush Robinett, Sandia National Laboratory

12:05 *LUNCH*

12:45 Strategic Directions for Improving Energy Efficiency within the Manufacturing Sector through Improved Harsh Environment Process Measurements
David Holcomb, Oak Ridge National Laboratory

1:30 Advanced Sensing Technologies for Industrial Process Controls
Arlene Garrison, University of Tennessee

2:15 Applications of Raman Optical Sensing for Industrial Process Monitoring and Control
Michael Carrabba, EIC Laboratories

3:00 Advanced Sensors for Monitoring Processes
Mel Koch, University of Washington

3:45 Wrap-up Discussions
All

4:15 *ADJOURN*

APPENDIX
B

Biographical Sketches of Panel Members

GARY A. BAUM (chair) is vice president of technology for the Institute of Paper Science and Technology. His research has focused on paper physics and mechanical properties, the electrical properties of polymers, and the processing of paper and paperboard. Dr. Baum had many years of experience in industrial processing with Dow Chemical, the Institute of Paper Chemistry, the James River Corporation, and North Carolina State University before moving to his current position. Dr. Baum is a member of the Committee on Industrial Technology Assessments.

THOMAS G. DEVILLE is manager, advanced control, for Bechtel's Research and Development Group. He has 28 years of experience in process controls, integrated computer systems, and systems engineering. Mr. DeVille is responsible for the planning, analysis, design, implementation, and testing of integrated control and computer systems for the petroleum industry and other industrial clients.

RICHARD J. EBERT is manager of the Process Control Center at the Alcoa Technical Center. He is currently responsible for the development and implementation of advanced controls and measurement systems throughout the Aluminum Company of America, a fully integrated aluminum and materials company. During his 24 years at the research center, he has developed and implemented control systems for a variety of aluminum processes, including smelting, hot rolling, cold rolling, and finishing.

DENNIS K. KILLINGER is professor of physics and technical director of the Technology Deployment Center at the University of South Florida. Dr. Killinger has conducted research for the past 30 years on new lasers and optical spectroscopic sensors and their uses in medicine and industry. Before joining the University of South Florida in 1987, he was a member of the research staff at Massachusetts Institute of Technology's Lincoln Laboratory. Dr. Killinger has served on several advisory panels, at the National Aeronautics and Space Administration, the U.S. Department of Energy, and the U.S. Department of Defense. He was also a member of the National Research Council Committee on Optical Science and Engineering.

STEVEN R. LECLAIR is technical leader and chief of the Materials Process Design Branch of the Materials and Manufacturing Directorate at the Air Force Research Laboratory. In that capacity, he is responsible for developing and implementing self-directed and self-improving process design and control methods in support of Air Force materials research. His experience includes more than 20 years of research and development on materials processing systems involving metal, ceramic, polymer, and electro-optic materials and associated processes. He has been a member of the National Research Council's Committee on Materials and Processes and the Information Highway and technical advisor to the Committee on New Sensor Technologies: Materials and Applications. Since 1987, he has been a National Research Council postdoctoral advisor. Dr. LeClair's research and international collaborations include service as a member of the Computer Assisted Manufacturing Working Group of the International Federation for Information Processing.

JAY LEE is director for product development and manufacturing at the United Technologies Research Center. He is responsible for the strategic direction and research and development activities in the areas of product development process, manufacturing systems, sustainable process development, machining systems, quality systems, and life cycle product development technologies. Prior to joining UTRC, he was director for the Industry-University Cooperative Research Centers, the Engineering Research Centers Program, and the Manufacturing Processes and Manufacturing Program at the National Science Foundation (NSF). Previously, Dr. Lee had been involved in research, engineering, and program management in the areas of precision machinery, factory automation, and service productivity. Since 1992, he has been an adjunct professor of the Technical Management Program at the Johns Hopkins University. Dr. Lee is a member of the executive committee of the Manufacturing Engineering Division of the American Society of Mechanical Engineers, the Program Evaluation Board of the Japanese Ministry of International Trade and Industry, and the Academic Advisory Committee for the Programme for Industry at Cambridge University (U.K.). He received the Society of Manufacturing Engineers Outstanding Young Manufacturing Award in 1992.

FRANCIS C. MCMICHAEL is professor of civil engineering and public policy and Blenko Professor of Environmental Engineering at Carnegie-Mellon

University. His research concerns the effects of industrial processing on groundwater quality, hydrology, applied statistics, risk analysis, and solid and hazardous waste management. He has a particular interest in process control, monitoring, and in-process recycling of process waste streams. Dr. McMichael is a recognized leader in industrial ecology and has been a consultant to the steel industry. He has served on the Science Advisory Board for the Environmental Protection Agency. Dr. McMichael is a member of the Committee on Industrial Technology Assessments.

JORGE VALDES is department head of process and chemical engineering research at Lucent Technologies. He has experience in the development of advanced diagnostics for process monitoring and control, plasma processing science and technology, and the engineering of environmentally conscious processes. Dr. Valdes has conducted research on chemical engineering systems and technologies, colloidal science, materials for electrochemical reaction systems, and chemical process sensors.