CHEMICAL ENGINEERING

August
2011

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Process
Automation

PAGE 30

CAPITAL COST ESTIMATION:

Understanding the Software Options

PAGE 22

Focus on
Pressure Relief

The Bio-Based
Economy

Inline
Analyzers

Facts at Your Fingertips:
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AUGUST 2011

IN THIS ISSUE

VOLUME 118, NO. 8

CHEMICAL ENGINEERING

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Our redesigned website featuring: Extras from our **Cover Story**, **New Products**; **Latest News**; and more

COVER STORY

22 Cover Story **Evaluating Capital Cost Estimation Programs** Five capital cost estimation programs are compared using a set of case studies

NEWS

9 Chementator A new grinding mill achieves finer, more uniform particles; A promising new forward-osmosis membrane; The commercial launch of a new asymmetric hydrogenation catalyst; Gold nanoparticles for adsorbent foam; A U.S. power plant goes dry for handling bottom ash; An energy-saving desalination process moves ahead; and more

14 Newsfront **The Bio-Based Economy** Bio-based technologies are being developed around the world. Here, we focus on one country's advances on this front

17 Newsfront **Analyzers Keep Watch Inline** Keeping an 'eye' on every step of the chemical process is possible — and profitable — thanks to new inline analyzers

ENGINEERING

20a Facts at Your Fingertips **Heat-transfer system cleaning** This one-page reference guide describes the steps required in effective filtration, flushing and cleaning processes for heat-transfer systems

30 Feature Report **Today's Process Automation Worlds** An overview of the current and future direction of process control

40 The Fractionation Column **How long does it take to reach steady state?** Various factors affect the time it takes to reach steady state, including how you define it

41 Environmental Manager **Practice Green Chemical Engineering** Chemical engineers have countless opportunities to apply their talents to environmentally related improvements, specifically in R&D, plant design and operations

45 Solids Processing **Preventing Self-Heating and Ignition in Drying Operations** Incident investigation reveals that the most common root cause is lack of understanding

EQUIPMENT & SERVICES

20I-1 New Products & Services (International Edition) A fine way to separate solids from slurries; Detect oil leaks with this alarm system; An infrared thermometer with a USB interface; New valve design for both control and on/off position; This patented system discharges drums safely, and dust-free; Avoid downtime from unexpected pump failure with this system; and more

20D-1 Show Preview — ChemInnovations 2011 (Domestic Edition) The 2nd annual ChemInnovations Conference and Tradeshow will take place in Houston in September. This preview provides a guide to the features of the event

20D-6 New Products and Services (Domestic Edition) A data collector with longterm storage; This sifter achieves vibration-free separation; These couplers automatically shut off in disconnections; This screener can dry on-size particles; A digital remote level sensor; and more

48 Focus on **Rupture Discs and Pressure Relief** The lowest K_R values for rupture discs; A system that manages all overpressure relief devices; Reverse-acting rupture discs for aggressive sanitary applications; Two layers deliver added benefits with this rupture disc; and more

COMMENTARY

5 Editor's Page **Boiling uncertainty** A major regulatory hurdle for many U.S. boiler owners is on hiatus for now, and the ultimate outcome is up in the air

DEPARTMENTS

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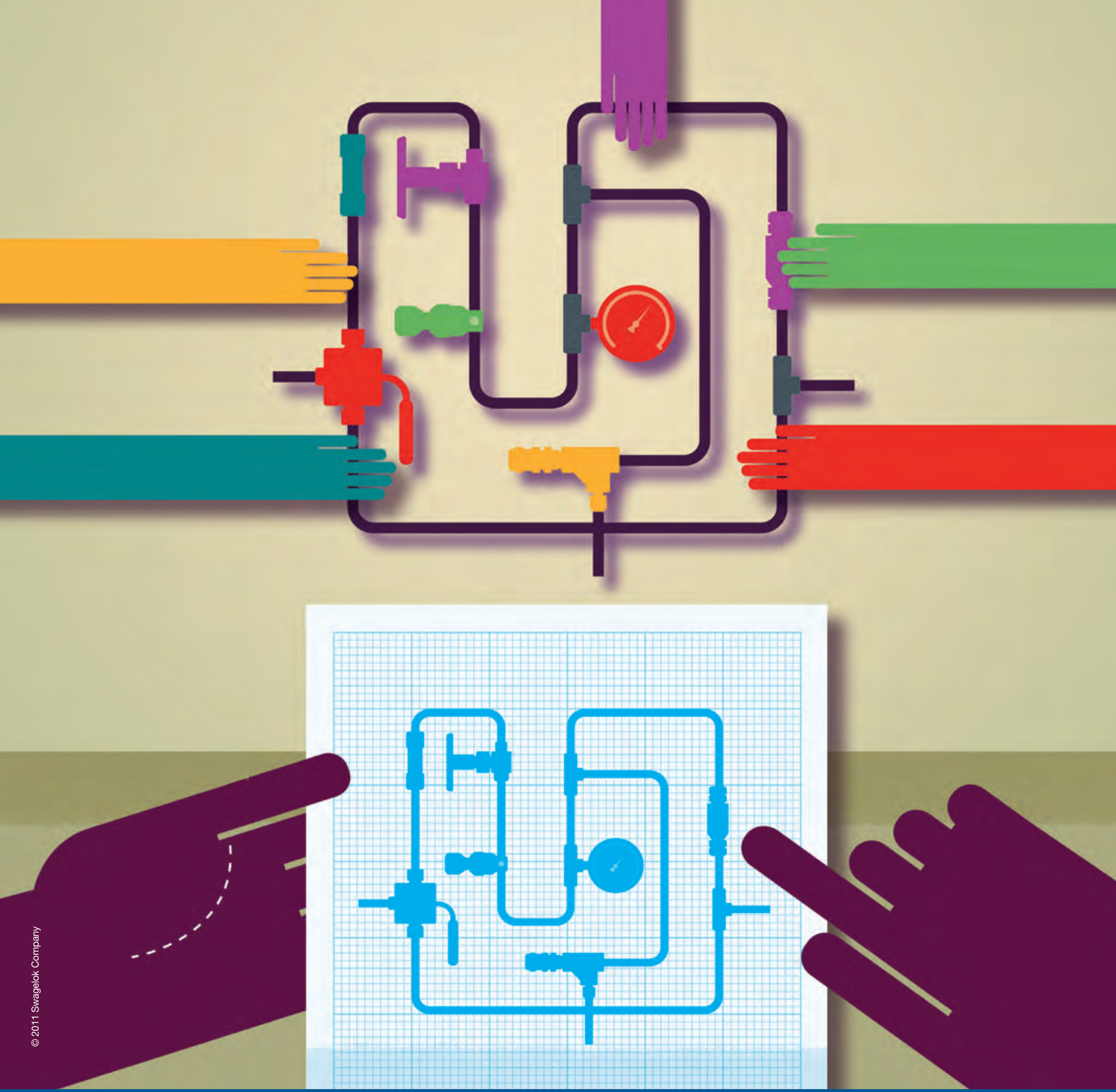

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Access Intelligence

BPA

Editor's Page

Boiling uncertainty

Last year, the U.S. Environmental Protection Agency (EPA ;Washington, D.C.; www.epa.gov) proposed new emissions standards for hazardous air pollutants (HAP) emitted by industrial boilers and solid-waste incinerators (CISWI) based on the performance of the maximum achievable control technology (MACT). The so-called "boiler MACT" final rules were signed by the EPA Administrator on February 21, 2011. On May 18, 2011, however, EPA published a notice delaying the effective date of the major source rule, pending the completion of reconsideration or judicial review, whichever is earlier.

Fueling the postponement was a plea by a range of interests — small businesses, lawmakers, even the U.S. Small Business Administration — with a convincing list of complaints. EPA acknowledged problems with its methodology and data and is reconsidering the standards. The reasons for the objections are many. "These rules, if implemented, will be costly to a broad spectrum of industry — both to capital and operating budgets," explains Tom McGowan, president of TMTS Associates (Atlanta, Ga.; www.tmtsassociates.com) and an expert in the field of air pollution control (APC). "Many of the boiler owners have not had experience with the complex CEMS (continuous emissions monitoring systems) that will be required under the regulations." Making matters worse, some of the initial standards, like 1 ppm CO, would not be achievable when you take into account both combustion issues and CEMS drift, he adds. Furthermore, the limits in the latest set of regulations have caused concern with equipment vendors about whether they can be met at all. Like most of his peers, McGowan expects to see some further loosening and rationalization of the very tight emission limits, but the rest is up in the air.

"With everything that is happening in the courts and on 'the Hill', there continues to be considerable uncertainty with regard to what will actually come out and when," says Robert D. Besette, president of the Council of Industrial Boiler Owners (CIBO; Warrenton, Va.; www.cibo.org). Among his concerns is the possibility that once a final rule is enacted, there could be unreasonable competition for engineering and equipment supplies with the utilities who may have to comply at the same time with their MACT and Cross States air pollution rules. As such, CIBO is still looking at and suggesting to its members a decision-making timeline, which can be found with the online version of this article.*

For now, McGowan says, "Smart companies are studying the regulations and comparing them to past stack data, and in some cases, running tests tuned to assure test data have detection limits that are at or below the planned stack limits. If boilers are way out of compliance, it might be better to replace the boiler and add the new APC system, rather than retrofit the existing one. In other cases, the extra cost will result in a shutdown of the facility due to lack of capital and loss of profit due to higher ongoing operating costs." There is no motivation to replace APC now, he warns, because one could find out later it was not required, or worse yet, more additional regulations could render the improvements ultimately inadequate. Unfortunately, he says, "There are no easy rules of thumb in evaluating this, as boiler age, efficiency, type of fuel, fuel cost and capital cost all have to be factored in."

There is, however, a very important limit that should not be overlooked. Minor HAP sources that operate boilers with <10 ton/yr of a single HAP or <25 ton/yr of a combination of HAPs have not been relieved of impending deadlines* for the Boiler Area Source NESHAP, 40 CFR 63 Subpart JJJJJJ. ■

Rebekkah Marshall

*Suggested decision making timeline for major sources and deadlines for area sources can be found in the online version of this article at www.che.com.

Letters

Prevent short circuiting in cyclones

The May cover story, Harnessing the Power of a Cyclone, is a very fine article and the graphics are excellent, as usual. The phenomenon "short circuiting" is mentioned once, at the bottom of Table 3. Short circuiting is more readily encountered in long-cone cyclone collectors (cyclones) like the Stairmand design. My doctoral research [*1*] investigated collection efficiencies of the Stairmand design with variations of cone length and outlet-pipe diameter. My research took an unexpected turn when flow in the experimental cyclones short circuited. Once this had occurred, I was able to repeat the event and characterize the flow and conditions inside the cyclones. Spiral patterns were observed in the cylinders and upper sections of the cones, followed by ring deposits in the lower half to one third of the cones, when short circuiting had occurred.

At the time that I conducted the research, I found only one published paper describing observed short-circuit flow [*2*]. The short-circuit conditions in the experimental cyclones correlated with intermediate- and laminar-flow Reynolds number ranges for the outlet pipes. When the outlet pipe-flow Reynolds number dropped below 3,000, the long cone cyclones were in jeopardy of short circuiting. In the intermediate range, flow began normally, but any disturbance, such as briefly covering the inlet, would cause the flow to short circuit. Once short circuiting had occurred, turbulent flow could not be reestablished without increasing the flowrate. The research results have been referenced [*3–5*]. Lippman and Chan [*6*] investigated the 10-mm Dorr Oliver cyclone and confirmed short circuiting as the normal flow pattern when the cyclone is used as a respirable dust presampler. Further research by Lidén and Gudmundsson [*7*] expands Dr. Lidén's cyclone-theory doctoral research and discusses how physical characteristics affected flow patterns in their experimental cyclones.

If the cyclone has a long cone, it is susceptible to short circuiting. Preventive measures have to be taken in the design, application and operation of long-cone cyclones to avoid short circuiting.

1. Hochstrasser, John M., The Investigation and Development of Cyclone Dust Collector Theories for Application to Miniature Cyclone Presamplers, Ph.D. Dissertation, University of Cincinnati, 1976.
2. Alexander, R., Fundamentals of Cyclone Design and Operation; *Proceedings Austral. Inst. Min. Met. N.S.*, pp 203–228, N. S. Nos. 152–153, 1949.
3. Ayer, Howard E. and Hochstrasser, John M., Cyclone Discussion in "Aerosol Measurement", University Presses of Florida, 1979.
4. Lippman, Morton, Use of Cyclones for Size Selective Aerosol Sampling, in "Aerosol Measurement", University Presses of Florida, 1979.
5. Saltzman, Bernard and Hochstrasser, John, Design and Performance of Miniature Cyclones for Respirable Dust Sampling, *Env. Sci. & Tech.*, 17, 7, pp. 418–424, July 1983.
6. Lippman, Morton and Chan, Tai, Cyclone Sampler Performance, *Staub-Reinhalt Luft*, 39, 1, pp. 7–11, January 1979.
7. Lidén, Göran and Gudmundsson, Anders, Semi-empirical modelling to generalise the dependence of cyclone collection efficiency on operating conditions and cyclone design; *J. Aerosol Sci.*, 28, 5, pp. 853–874, July 1997.

John M. Hochstrasser
EHS Engineering, LLC, Union, Kentucky

Postscripts, corrections

June, Chementator — CO_2-capture technologies move ahead, p. 15: Testing for the Vattenfall facility began in 2008, not 1968. The online version of the article has been corrected.

Calendar

NORTH AMERICA

ACS Fall National Meeting & Exposition. American Chemical Soc. (Washington, D.C.). Phone: 202-872-4600; Web: acs.org
Denver, Colo. **August 28–September 1**

ChemInnovations 2011 Conference and Exhibition, co-located with ISA's Houston Section Annual Conference & Exhibition, the Texas A&M Turbomachinery Laboratory's 40th Annual Turbomachinery Symposium, and the 27th International Pump Users Symposium. *Chemical Engineering* and The TradeFair Group (both Access Intelligence companies; Rockville, Md.). Phone: 713-343-1891; Web: cpievent.com
Houston **September 13–15**

Using WirelessHart Communication in the Process Industries. HART Communication Foundation (Austin, Tex.). Phone: 512-794-0369; Web: hartcomm.org
Nashville, Tenn. **September 19**

2011 ACEEE National Conference on Energy Efficiency. American Council for an Energy-Efficient Economy (ACEEE; Washington, D.C.). Phone: 202-507-4000; Web: aceee.org/conferences/2011
Denver, Colo. **September 25–27**

Directed Self-Assembly of Materials Workshop. Materials Research Soc. (Warrendale, Pa.). Phone: 724-779-3003; Web: mrs.org
Nashville, Tenn. **September 28–October 1**

Gasification Technologies Conference 2011. Gasification Technologies Council, (Arlington, Va.). Phone: 703-276-0110; Web: gasification.org
San Francisco, Calif. **October 9–12**

WEFTEC 2011. Water Environment Federation (Alexandria, Va.). Phone: 703-684-2492; Web: weftec.org
Los Angeles, Calif. **October 15–19**

IEEE West Coast Cement Industry Conference and Tour. Inst. of Electrical and Electronics Engineers (IEEE; New York, N.Y.). Phone: 909-635-1824; Web: ieeewestcoast.com
Texarkana, Tex. **October 13–14**

SWE11 — The Annual Conference for Women Engineers. Society of Women Engineers

(Chicago, Ill.). Phone: 877-793-4636; Web: societyofwomenengineers.swe.org
Chicago, Ill. **October 13–15**

2011 AIChE Annual Meeting. AIChE (New York). Phone: 800-242-4363; Web: aiche.org
Minneapolis, Minn. **October 16–21**

EUROPE AND ELSEWHERE

Nanopolymers. Smithers Rapra Technology Ltd. (Shropshire, U.K.). Phone: +44-1939-250383; Web: polymerconferences.com
Düsseldorf, Germany **September 13–14**

2011 Annual FEICA Conference. Assn. of the European Adhesive and Sealant Industry (Brussels, Belgium). Phone: +32-267-673-20; Web: feica-conferences.com
Valencia, Spain **September 15–16**

8th European Congress of Chemical Engineering. Dechema e.V. (Frankfurt am Main, Germany). Phone: +49-69-7564-333; Web: ecce2011.de
Berlin, Germany **September 25–29**

Extractables & Leachables for Pharmaceutical Products 2011. Smithers Rapra Technology Ltd. (Shropshire, U.K.). Phone: +44-1939-250383; Web: polymerconferences.com
Dublin, Ireland **September 27–28**

WTT Expo for Industrial Heat and Cooling Technology. Karlsruher Messe und Kongress GmbH (Karlsruhe, Germany). Phone: +49-721-370-2304; Web: wtt-expo.com
Karlsruhe, Germany **September 27–29**

The PPMA Show — Processing and Packaging Machinery. Reed Exhibitions (Surrey, U.K.). Phone: +44-20-8910-7189; Web: ppmashow.co.uk
Birmingham, U.K. **September 27–29**

ISEC 2011 — 19th International International Solvent Extraction Conference. Gecamin Ltda. (Santiago, Chile). Phone: +56-2-652-1575; Web: isec2011.com
Santiago, Chile **October 3–7**

Powtech. Nürnberg Messe GmbH (Nürnberg, Germany). Phone: +49-911-86-060; Web: powtech.de
Nürnberg, Germany **October 11–13** ■

Suzanne Shelley

CHEMENTATOR

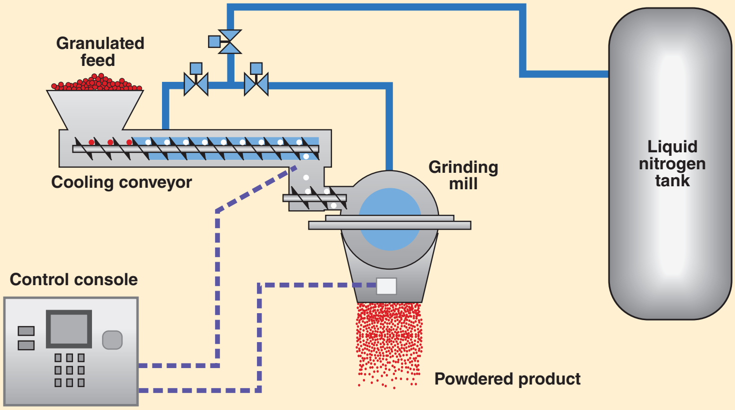
Edited by Gerald Ondrey August 2011

Three-mechanism grinding mill achieves finer, more uniform particles

A newly introduced cryogenic grinding mill from Air Products and Chemicals Inc. (Allentown, Pa.; www.airproducts.com/ultrafine) can generate consistent yields of particles between 45 and 250 µm, and in some applications can achieve particle sizes of 10 µm. The ultrafine grinding mill also achieves narrower particle size distributions than conventional impact mills.

Known as the PolarFit ultrafine-grinding mill (diagram), the cryogenic grinder employs a combination of size-reduction strategies — impact, particle attrition and particle-particle collisions — in one machine to reach finer particle sizes and raise yields within a particular size range. "We set out to design a highly flexible machine," says technology manager Jon Trembley, "and one that both lowers energy input and makes efficient use of liquid nitrogen" (to remove heat generated by the grinding process). The PolarFit mill has an easily adjustable grinding gap, and is intended for low-maintenance operation.

Before being launched at last month's PTX Canada tradeshow in Toronto, the PolarFit mill had undergone an internal analysis program, processing 2–3 tons of material at a time while being compared to competing products. The product performed well for various cryogenic size-reduction applications, including plastics, pigments, powder coatings, thermoplastic elastomers, spices and other food products. The PolarFit mill is available with grinding rotors in three standard sizes — 200, 400 and 800 mm, as well as in custom-made sizes.



A promising new forward-osmosis membrane

Forward osmosis (FO) has been recognized as a valuable technology for many applications including wastewater reclamation, seawater desalination, and energy production, due to the low energy input required. The osmotic pressure gradient across a semipermeable FO membrane causes water to diffuse naturally through the membrane, leaving impurities behind. However, when water diffuses through the selective layer of the FO membrane, the draw solution at the permeate side is substantially diluted, while the back diffusion of draw solutes through the support layer works to compensate the diluted draw solutes. The compensation process is severely hindered by the tortuous, dense and thick support layers of conventional FO membranes. As a result, the competing process between dilution and back diffusion equilibrates at a transverse draw-solute concentration profile, leading to an internal concentration polarization (ICP) problem.

To overcome this problem, researchers from the School of Civil and Environmental Engineering, Nanyang Technological University (Singapore; www.ntu.edu.sg) fabricated a novel nanocomposite FO membrane with a scaffold-like nanofiber layer that, the researchers claim, possesses remarkable advantages over conventional sponge-like support layers, such as low "tortuosity", high porosity and extreme thinness. This structure guarantees direct paths for salt and water diffusion, which could also eliminate the ICP bottleneck, the researchers say.

An electrospinning technique is used to fabricate the membrane. A rotating drum is employed to fabricate a large-area polyethersulfone nanofiber support on a nonwoven fabric, where the diameters of the nanofibers are in the range 50 to 150 nm. The thickness of the support layer can be adjusted by controlling the electrospinning time. The water permeability of the new nanocomposite membrane was observed to be about 3.5 times higher than that of a commercial FO membrane.

Graphene from dry ice

Researchers at Northern Illinois University (NIU; DeKalb, Ill.; www.niu.edu) discovered a new method for producing graphene that involves burning pure magnesium metal in dry ice. The method, which is capable of producing large quantities of graphene in sheets less than ten atoms thick, is simpler than conventional methods for generating graphene, and avoids hazardous chemicals. The NIU scientists knew that burning Mg metal in carbon dioxide produced carbon, but the structure of the resulting carbon had not been studied carefully before, says NIU researcher Amartya Chakrabarti. Graphene, two-dimensional carbon arranged in hexagonal lattice, has been the focus of extensive research because of its electrical and mechanical properties.

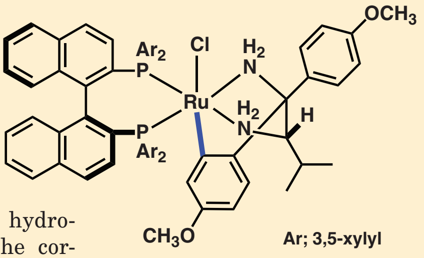
A new thermophile

Scientists from the University of Calif., Berkeley (UCB; www.berkeley.edu) and the University of Maryland School of Medicine have discovered a microbe in a Nevada hot spring that metabolizes cellulose at a record-high temperature of 109°C. The hyperthermophil-

(*Continues on p. 10*)

Note: For more information, circle the 3-digit number on p. 54, or use the website designation.

Commercial launch of a new asymmetric hydrogenation catalyst



The Fine Chemicals Div. of Takasago International Corp. (Takasago; Tokyo, Japan; www.takasago.com) has commercialized a new, highly efficient asymmetric hydrogenation catalyst for producing chiral alcohols — key chemicals for the production of pharmaceuticals, fragrances and agrochemicals. The ruthenium-complex catalyst is tradenamed RUCY after its molecular structure, ruthenabicycle. When combined with the company's BINAP ligand [2,2'-bis(diphenylphosphino)-1,1'-binaphthyl], RUCY is said to have a higher activity compared to conventional $RuCl_2$(diphosphine)(diamine) catalysts, enabling the catalyst loading to be reduced by one ninth, which directly influences the catalyst costs and the residual Ru in the product, says the company.

For example, the asymmetric hydrogenation of acetopheneone into the corresponding chiral alcohol required just 6 min when catalyzed by RUCY-XylBINAP (diagram) — half the time needed with a conventional catalyst — with better than 99% conversion and an enantioselectivity of more than 99% ee. The turnover frequency for the new catalyst (35,000 min^{-1}) is also significantly higher than that of a conventional catalyst (700 min^{-1}) — which directly affects production time and energy costs, says the company. The residual Ru-metal content in the final product was very low at 8.3 ppm.

The company says the new catalyst will "open doors" to new substrates where conventional catalysts could not be used.

A touch of gold makes a swell absorbent foam

The properties of gold nanoparticles could be combined with those of polydimethylsiloxane (PDMS) to provide a sustainable and practical solution for water treatment, according to a team from the Jawaharlal Nehru Center for Advanced Scientific Research (Bangalore, India; www.jncasr.ac.in). The team, headed by professor Giridhar U. Kulkarni, has synthesized low-density, highly compressible, porous foams of PDMS with incorporated Au nanoparticles (10–50 nm) by a single-step process, with water as a medium. The foams exhibited high swelling ability (about 600%) against benzene, toluene, ethylbenzene and xylene (BTEX) — a property that can be exploited in the removal of oil spills from water.

The team prepared three samples of AuPDMS using 0.1-, 0.5- and 1-mM aqueous solutions of $KAuCl_4$. The weight percentage of Au nanoparticles in the foam was 0.01, 0.03 and 0.06%. Higher Au content resulted in uncured, sticky AuPDMS gels. The particles are formed inside the PDMS matrix at the cross-linking Si-H sites.

The foams regained shape following decompression and did not disintegrate. The pore volume (5.52 cm^3/g) is much higher than that of just PDMS.

The foams exhibit high resistance to harsh chemical environments, such as concentrated ammonium hydroxide and sulfuric acid. One of the foams prepared by the team had a diesel oil uptake capacity of 25% of its weight. Upon regeneration of the foam by heating in air to 300°C for 30 min, the foam gave up the adsorbed diesel oil. The team has also investigated the foams' capacity to remove odorous compounds such as thioanisole.

(Continued from p. 9)

lic microbe, dubbed EBI-244, is said to be only the second member of the Archaea group known to grow by digesting cellulose, and the organism's cellulase is the most heat-tolerant enzyme found in any cellulose digesting microbe, including bacteria, says UCB.

Fuel-cell milestone

Last month, Nedstack B.V. (Arnhem, the Netherlands; www.nedstack.com) reached an important milestone by completing 10,000 h of operation with its PEM (proton-exchange membrane) fuel-cell stacks. The stacks are running in industrial conditions at AkzoNobel's (Amsterdam, the Netherlands) chlor-alkali plant in Delfzijl, the Netherlands. The fuel cells convert byproduct H_2 into electricity (see *CE*, March 2008, p. 25–27). Nedstack says the performance loss over the past 10,000 h is only 5%, which suggests that this generation of cells will reach a lifetime of over 20,000 h.

Nedstack is also finalizing the construction of a second PEM power plant for Solvay S.A.'s (Brussels, Belgium) chlor-alkali plant near Antwerp. This PEM power plant has 12,600 fuel cells that will generate 1 MW of electricity and 1 MW of heat.

Fuel-cell anode

A new anode material with nanostructured interfaces between barium oxide and nickel prevents deactivation by coking in solid-oxide fuel cells (SOFCs) using carbon-containing fuels. The material offers a path to low-cost, low-emission SOFCs that can convert gasified carbon fuels to electricity at temperatures below 850°C, where SOFCs become more economically competitive. Led by scientists at the Georgia Institute of Technology (Atlanta; www.gatech.edu) and Brookhaven National Laboratory (Upton, N.Y.; www.bnl.gov), the research team used vapor deposition technology to coat the surface of Ni-YSZ (yttria-stabilized zirconia)-based electrodes with BaO, which reduces to form nanoscale BaO islands on the Ni surface when exposed to fuel. The nanostructured surface layer adsorbs water and plays a vital role in facilitating carbon removal, making it possible for an SOFC containing the material to utilize higher-order hydrocarbons, CO and gasified carbon fuels without carbon buildup at relatively low temperatures, the group says.

Green honors

In June, the U.S. Environmental Protection Agency (EPA; Washington, D.C.; www.epa.gov) announced the winners of the 2011 Presidential Green Chemistry Challenge Awards. Winners of the Challenge, which promotes R&D of less hazardous alternatives to existing technologies that reduce or eliminate waste in industrial production, are selected by an independent panel convened by the Americal Chemical Soc. This years honorees include the following (source, EPA):

Academic Award. Professor Bruce Lipshutz, University of California, Santa Barbara (www.chem.ucsb.edu), for the design of a safe surfactant, TPGS-750-M, which forms nanomicells (50-100-nm dia.) in water to serve as nanoreactors for organic reactions, such as cross couplings. Reactants and catalysts dissolve in the micells in high concentrations, which leads to increased reaction rates at room temperature.

Small Business Award. BioAmber, Inc. (Minneapolis, Minn.; www.bio-amber.com), for the first large-scale production facility for biobased succinic acid (for process details, see *CE*, April 2007, p. 18).

Greener Synthetic Pathways Award. Genomatica (San Diego, Calif.; www.genomatica.com), for developing a microbe that produces 1,4-butanediol by fermenting sugars.

Greener Reaction Conditions Award. Kraton Performance Polymers, Inc. (Houston; www.kraton.com), for developing its Nexar family of halogen-free, high-flow polymer membranes, which are made using less solvent. Nexar polymers have a high water flux — up to 400 times higher than current reverse osmosis (RO) membranes — and thus can save 70% in membrane costs and about half the energy costs in RO plants.

Designing Greener Chemicals Award. The Sherwin-Williams Co. (Cleveland, Ohio; www.sherwin-williams.com), for developing water-based acrylic alkyd paints with low volatile organic compounds that can be made from recycled PET bottles, acrylics and soybean oil.

Cellulase enzymes

Last month, Codexis, Inc. (Redwood City, Calif.; www.codexis.com) announced the first scaleup of its proprietary cellulase enzymes to commercial scale. These enzymes are used to convert non-food biomass into fermentable sugars.

Enzyme production is being performed at Fermic S.A. de C.V. (Mexico City, Mexico) — a contract fermentation and synthesis company. Production has been sucessfully completed at the 20,000-L scale, and represents the first manufacture of an enzyme product using Codexis CodeEvolver directed-evolution technology.

Membrane copolymer

Last month, BASF SE (Ludwigshafen, Germany; www.basf.com) launched a new Luvitec (polyvinylpyrrolidone) product that is suitable for making membranes for food production and medical devices.

U.S. power plant goes dry for handling bottom ash

Practically all of the coal-fired power plants in the U.S. collect ash from the bottoms of their boilers using a wet system — the ash falls into hoppers that are partially filled with water, and once or twice per shift the slurry is pumped to a settling pond or solid-liquid separation tanks (dewatering bins). In a break from that norm, Seminole Electric Cooperative, Inc. is switching its two 650-MW units in Palatka, Fla., from a wet to a dry bottom ash system. The change is expected to increase boiler efficiency and reduce operation and maintenance costs in comparison with wet systems.

Scheduled for startup during 2012, the project marks the first U.S. installation of a dry bottom ash system manufactured by Clyde Bergemann Delta Ducon (Malvern, Pa.; www.deltaducon.com), although in the last four years the company has installed over 30 systems in 16 plants and five countries elsewhere, mostly in Asia. Ron Grabowski, vice-president sales, says U.S. utilities are generally slower to make changes. However, he says the company has received a lot of inquiries recently because of pending Environmental Protection Agency (EPA; Washington, D.C.) proposals to regulate settling ponds.

In the process, called Drycon, hot ash falls onto a dual chain-driven line of pans that moves continuously underneath the bottom of the boiler. There is little or no gap between the pans for ash to fall through, says Grabowski. The pan line takes the ash away from the boiler and dumps it onto a secondary transfer conveyor that feeds a storage silo.

Compared to a wet system, Drycon saves energy costs by emitting residual heat from the hot ash, whereas a wet unit quenches the ash, says Grabowski. Operation and maintenance costs are lower because slurry transportation tends to result in high wear, he says. Also, pumping slurry to a pond may take as much as 700 hp, versus 15–20 hp for dry ash transportation. Engineering, procurement and construction services for the Seminole project are being provided by Roberts & Schaefer, a subsidiary of KBR (Houston; www.kbr.com).

Biopolymers

Last month, The Dow Chemical Co. (Midland, Mich.; www.dow.com) and Mitsui & Co., Ltd. (Tokyo, Japan: www.mitsui.com/jp) announced the formation of a joint venture (JV) and execution of a memorandum of understanding (MoU) to develop sustainable products for the high-performance flexible packaging, hygiene and medical markets. Under the terms of the agreement, Mitsui would become a 50% equity interest partner in Dow's sugarcane growing operation in Santa Vitória, Minas Gerais, Brazil.

The initial scope of the JV includes production of sugarcane-derived ethanol for use as a renewable feedstock source. When completed, Dow and Mitsui will have the world's largest integrated facility for the production of biopolymers made from sugarcane-derived ethanol. Biopolymers produced at this facility will be a "green" alternative and drop-in replacement for high-performance flexible packaging.

The first phase of the project includes construction of a new sugarcane-to-ethanol production facility in Santa Vitória. Construction is slated to begin in the 3rd Q of 2011. ❐

A step forward for an energy-saving desalination process

An alternative desalination process that reduces energy consumption by over 50% compared to "best available technology" (BAT) has been successfully piloted by the Industry Sector of Siemens AG (Munich, Germany; www.siemens.com), in collaboration with Singapore's national water agency, PUB, and Singapore's Environment and Water Industry Program (EWI). Results of the Siemen's demonstration unit, which has been operating since December 2008 and treating 50-m^3/d of seawater, were presented last month at the Singapore International Water Week (Singapore; July 4–8). Siemens, in cooperation with PUB, plans to build a full-scale system by 2013.

Instead of using reverse osmosis (RO), which requires high-pressure pumps to force water through semipermeable membranes, Siemen's process combines electrodialysis (ED) and continuous electrodeionization (CEDI), both of which draw sodium and chloride ions across ion-exchange membranes. Because the process runs at low pressure, power consumption is lower than that required for RO.

Seawater is first pretreated with a self-cleaning disk filter, followed by Memcor ultrafiltration modules. The pilot desalination plant is composed of three ED units in series to handle the high concentrations of salt. These are followed by three parallel CEID units to remove the lower salt concentration, to produce drinking water that meets standards of the World Health Org. (Geneva, Switzerland). The energy demand of the entire process, including pumping, pretreatment, desalination and post treatment is less than half of that used by today's BAT for desalination, which is typically between 3.4 and 4.8 kWh/m^3, says Siemens.

A new HPCA monomer

Last month, BASF SE (Ludwigshafen, Germany; www.basf.com) launched a new crosslinking acrylate monomer, hydroxpropl carbamate acrylate (HPCA), which is said to shorten the processing time for the manufacture of carbamate-based polymers. HPCA enables crosslinkable carbamate units to be incorporated into the polymer in one step instead of the usual two required by existing processes, says BASF.

The specialty monomer is synthesized by a biocatalytic process. From HPCA, the carbamate-based polyacrylate can be produced in a single step. BASF is using this enzymatic process in industrial production for the first time.

In addition to proven applications in clearcoat systems for the automobile industry, the new monomer offers additional benefits for potential applications in adhesives, says the company.

This new membrane bioreactor cuts energy costs and boosts throughput

GE Power & Water (Trevose, Penn.; ge.com) has introduced an improved membrane bioreactor (mbr) technology whose productivity is said to be 15% higher than that of its predecessor for wastewater treatment plants. The new system, called LEAPmbr, was derived from innovations to GE's ZeeWeed 500 mbr.

Glenn Vicevic, senior manager, Engineered Systems, says the system has been tested on a commercial scale at three of its customers' plants and has demonstrated several improvements in addition to higher productivity. These include a 30% reduction in membrane energy costs, a 50% reduction in membrane aeration equipment and controls, and a 20% smaller footprint.

The system consists of rectangular cassettes of PVDF hollow-fiber membranes, immersed in a bioreactor in which bacteria break down pollutants. A pump draws treated water through the membranes, while solids, bacteria and colloidal material are retained in the tank.

An improved aeration method for cleaning the membranes was the key element in lowering energy costs, says Vicevic. "The conventional wisdom is that there should be a continuous air scour of the membranes," he says, "but over the last decade, we experimented with bubble-size-diffuser design and frequency of air release. From that we determined that large bubbles delivered intermittently was the most effective." He adds that the improved productivity was obtained by optimizing the manufacturing techniques, while the smaller footprint was achieved by increasing the surface area of the membrane.

Silicon passes a test in water-splitting

The use of solar energy to split water into hydrogen and oxygen is an appealing idea, given that sunlight is abundant in many parts of the world, but one of the challenges to its development is to find a suitable electrode material. Silicon, the popular photovoltaic material, seems like a logical choice, but when it is exposed to O_2 it is rapidly oxidized and fails. Researchers at Stanford University (Stanford, Calif.; www.stanford.edu) may have a solution.

Using atomic layer deposition, a common process in semiconductor manufacturing, they have deposited a 2-nm protective coating of titanium dioxide on silicon electrodes, followed by a similar, evaporated layer of iridium. TiO_2 is transparent to sunlight and the iridium boosts the rate of the splitting reaction, says Paul McIntyre, of Stanford's Materials Science and Engineering Dept. In laboratory tests the coated electrodes have shown stable operation for more than 24 h, without apparent corrosion or loss of efficiency, he says, while uncoated electrodes corroded and failed in less than 30 min.

Next, the researchers plan to scale up the process and test other semiconductor materials. The ultimate goal, says McIntyre, is the development of a commercial process in which H_2 and O_2 would be stored and used to generate electricity when the sun doesn't shine. ■

Lozowski

Newsfront

THE BIO-BASED ECONOMY

Bio-based technologies are being developed around the world. Here we focus on one country's advances on this front


FIGURE 1. Algae flow through the tubes in this horizontal algae reactor

The realization that our natural resources are not endless, and that we need to focus on sustainability is driving technology and its supporting funds toward new choices. In the chemical process industries (CPI), engineers are looking for alternatives to the traditional fossil-fuel-based chemistries, and are developing innovative bio-based routes to meet our needs. There is much evidence of this shift to a bio-based economy, including the work of two of the recipients of this year's Presidential Green Chemistry Awards in the U.S. (see p.11). Work on bio-based processing is a global undertaking, and in this Newsfront we focus on innovative bio-based technologies from the Netherlands.

The Dutch approach

Innovation, energy security and environmental concerns (particularly greenhouse gases) are some of the drivers leading to a bio-based economy, says Cornelis Mijnders, senior policy officer of the Dept. Bio-Based Economy in the Netherlands. In fact, the push to a bio-based economy is so strong that the "chemicals" sector in the Netherlands-defined "top sectors" has been re-defined to be chemicals and bio-based industry. In the Netherlands, various government agencies have a combined funding of €1.5-billion per year slated for investment in innovative technologies in nine top sectors — one of which is chemicals and bio-based industry. Each sector submits proposals for the funding through a team whose members represent industry, science and the government. Renée Bergkamp, director general of innovation at the Ministry of Economic Affairs, Agriculture and Innovation is the government official for the chemical and bio-based industry sector. She expects that decisions about the distribution of funds will be made next month.

Mijnders says that bio-based processes are moving toward second-generation feedstocks. While the distinction between first and second-generation feedstocks is usually thought of as edible versus non-edible materials, Mijnders says there are additional factors that distinguish between the two, including the type of technology used and greenhouse gas considerations. He estimates that the current investment in innovative bio-based projects in the Netherlands is about €450-million per year — approximately €150-million from government resources and €300-million from private funding. Some of that funding is going to open source pilot facilities, such as the AlgaePARC in Wageningen University.

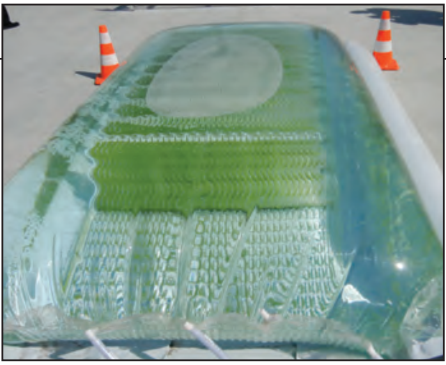
Algae reactors

Algae offer great promise as versatile and sustainable raw materials for a wide-variety of applications including biodiesel fuels, degradable plastics, natural pigments and food products (see Pond Strength, *Chem. Eng.*, September 2008, pp. 22–25). Algae transform light, carbon dioxide and minerals into a biomass that can be harvested and separated into components such as oils, protein, starch and pigments. In addition, since algae convert CO_2 to oxygen, they are attractive because large-scale cultivation can have a positive effect on the overall CO_2 balance.

The high expectations from algae as raw materials are dependent on the ability to economically produce algae in large quantities. To this end, a new research facility designed to explore the industrial production of algae was opened in June at Wageningen University & Research Centre (Wageningen UR; Wageningen, the Netherlands; www.wur.nl). Called AlgaePARC, this facility bridges the gap between laboratory research and industrial production with four different algae-reactor systems on a semi-industrial scale (24 m^2). These cultivation systems will be studied and monitored for cost, efficiency and sustainability. The goal is to raise the sustainable output of algae bioreactors while "dramatically" lowering the production costs.

René Wijffels, chair of the Bioprocess Engineering Dept. at Wageningen UR, heads the AlgaePARC program. He says that current production costs for algae are around €25–50/kg of biomass, and that with present technology that cost could be reduced to about €4/kg. Based on theoretical process designs, Wijffels expects that a level of €0.40/kg of biomass is achievable, and that is a target for AlgaePARC's work.

Wijffels explains that the four reactor designs were chosen based on current knowledge in the field, and that all have pros and cons (Table 1). The ***open pond or "raceway" ponds*** are shallow (since light does not penetrate deeply into the algae), annular



Lozowski

FIGURE 2. The flat-plate reactor contains a series of parallel flat plates

TABLE 1. ADVANTAGES AND DISADVANTAGES OF THE FOUR ALGAE REACTOR TYPES

	Raceway Ponds	Horizontal Tubes	Vertical Tubes	Flat-plate reactors
Inexpensive to build	yes	unknown	unknown	unknown
Easy to scale up	yes	yes	yes	no
Good process control	no	yes	yes	yes
Maintain purity	no	yes	yes	yes
Optimum light intensity	yes	no	yes	yes
Low footprint	no	no	yes	yes
Maintain water level (no evaporative losses)	no	yes	yes	yes
Low-cost to circulate fluids	yes	no	no	no
Maintain good gas balance (no O_2 buildup)	yes	no	no	yes

channels that use paddlewheels for mixing. These are the most common algae cultivation systems in use today. A main advantage is that they are inexpensive to build. Disadvantages include evaporation of water, and difficulties in keeping out unwanted species and controlling the process. The open structure of these systems makes them susceptible to infections and limits the choice of algae to fast-growing, resistant strains. Another disadvantage is the large footprint needed for scaleup.

Horizontal tube reactors (Figure 1) are single layers of clear horizontal tubes through which the algae are circulated. Advantages are that the productivity per surface area is higher than in an open pond, process control is better because it is in a closed loop, and scaleup can be fairly straightforward by extending the length of the tubes. A main disadvantage with horizontal tubes is the high intensity of light on the tube surface, which can be detrimental to algae growth. Additional disadvantages are the cost of circulating the fluid in the tubes and the O_2 buildup in the closed loop that can slow algae growth.

Vertical tube reactors are basically vertical rows of horizontal tubes. This configuration greatly decreases the very high-intensity light associated with horizontal tubes, and decreases the footprint needed with horizontal tubes.

Flat-plate reactors (Figure 2) consist of a series of flat, parallel plates in a closed reactor system. These large polymeric "bags" are filled with water and form a big heat sink so that temperature control is an advantage in this system. The flat-plate reactors also afford some of the same advantages of the other closed systems, namely better process control and purity. Good mass transfer is obtained by sparging air in the panels, so O_2 buildup is not a problem. Scaleup of this system is, however, complex.

The tube diameter of the systems in AlgaePARC is 5.5 cm — "large enough to prevent blockages and small enough for good heat transfer", Wijffels explains. Density measurements are used to detect when the algae are ready for harvesting, which is typically done by circulating the biomass to a centrifuge.

While fouling can be a factor in all of these systems, Wijffels says that it depends on the type of algae used and how the algae are treated. Stresses, such as large temperature swings can cause a sticky substance to be secreted. Beads, however, can be used in circulation loops to help clear fouling.

Within a couple of years, the AlgaePARC team hopes to have learned enough from these four reactors to build a fifth, optimized system.

Lactic acid and PLA

Polylactic acid (PLA) is a bio-based plastic that is a sustainable alternative to oil-based polymers, and the demand for PLA's monomers, lactic acid and lactides, is rising (see Bio-Based Chemicals Positioned to Grow, *Chem. Eng.*, March 2011, pp. 19–23). Rop Zoetmeyer, CTO of Purac (Gorinchem, the Netherlands; www.purac.com), says that the market for PLA is estimated to reach over three million tons in the next ten years. Purac, a subsidiary of CSM N.V. (Diemen, the Netherlands; www.csm.nl) is a market leader in lactic acid production.

Zoetmeyer says that Purac's technologies comply with the cradle-to-cradle concept, and that sustainability is key for bio-based chemicals. Purac is currently working on two projects toward lowering its eco-footprint — which Zoetmeyer explains means more than just a favorable CO_2 footprint — for lactic acid production: a gypsum-free lactic acid process; and a process using alternative, non-food raw materials.

A gypsum-free process. In the current process, carbohydrates are fermented to produce lactic acid. Lime is added for pH control, and then sulfuric acid is added to convert calcium lactate into lactic acid and gypsum ($CaSO_4$) as a byproduct. A separation step removes the gypsum and biomass and a subsequent purification separates out the lactic acid residue and yields the purified lactic acid. In the new process, neither lime nor sulfuric acid are used, eliminating the formation of gypsum and the associated steps to remove it. The result is a much simplified process.

This patented, gypsum-free process has been run on a demonstration scale for two years, and scale up to a production-scale plant is planned. The site of the new plant is expected to be chosen by the end of 2011.

Non-food substrates. In order to move away from competing with potential food sources for carbohydrates and sugar, Purac is working on using non-food substrates, such as corn stover or bagasse. The company's goal is to have a commercial plant for producing PLA monomers using non-food substrates in 2015. The location of the plant will, in part, depend on the availability of the substrate chosen.

New bioplastics

Avantium (Amsterdam, the Netherlands; www.avantium.com) has developed a patented process to produce furanic building blocks, tradenamed YXY, that can be used for new, bio-based plastics. Using high-throughput experimentation technology, the company has identified catalysts that can convert carbohydrates into furanic molecules in a very selective and fast way, it says. Since the process is a catalytic one, it can utilize existing CPI infrastructures without the need for fermentation equipment.

The building block that Avantium has focused on to date is 2,5-furandicarboxylic acid (FDCA), which is a five-carbon-ring monomer that can be used for the production of the polyester polyethylene-furanoate (PEF). PEF is expected to compete with polyethylene terephthalate (PET), which is made from the six-carbon-ring monomer purified terephthalic acid (PTA), in applications such as beverage bottles, other packaging materials, diapers, carpets and textiles.

Frank Roerink, Avantium's CFO, says that PEF can compete with PET on both price and performance, while offering a better environmental footprint, in part because it is bio-based and 100% recyclable. In fact, PEF is said to be superior to PET in several properties, including lower permeability of oxygen, CO_2 and water, and an enhanced ability to withstand heat. Roerink says that the cost to produce FDCA is expected to be below $1,200 per metric ton (m.t.) when produced on a commercial scale, whereas the current price of PTA is $1,500/m.t., with a five-year trading average of about $1,200/m.t.

Avantium announced in June that it has raised €30 million for the construction and operation of a pilot plant in Geleen, the Netherlands, and for the development of materials based on YXY building blocks. This funding includes €25 million from investors, as well as a €5-million subsidy from the Dutch Ministry of Economy, Agriculture and Innovation. The pilot plant is expected to yield around 40 m.t./yr of FDCA in 2011, and a plan is under review to go to a larger scale in 2013. The goal of the pilot plant is to prove the process, as well as to supply material for application development. Roerink explains that Avantium's business model is as a technology provider, so they would not produce PEF themselves, but would license the technology for it.

The company is also looking to pursue other YXY-based materials, such as polyamides (nylons and engineering plastics), polyurethanes (foams), thermosets (resins, coatings and adhesives) and plasticizers.

Renewable paths to biomethanol

BioMCN (Delfzijl, the Netherlands; www.biomcn.eu) has developed a patented process to produce biomethanol from crude glycerin. Since crude glycerin is a byproduct of biodiesel production, and that production has been increasing, new outlets for glycerin use are welcome (For more on glycerin, see Outlets for Glycerin, *Chem. Eng.*, September 2007, pp. 31–37). According to BioMCN, they are the first in the world to produce and sell industrial quantities of high-quality biomethanol, and the largest second-generation biofuels producer in the world.

Rob Voncken, CEO of BioMCN, defines first-generation biofuels as those made from crops, and second generation as those made from waste or residue raw materials. He explains that crude glycerin is considered a residue as defined by the European Union's Renewable Energy Directive (RED) and that the RED sets an ambitious target for the E.U.: that by 2020, at least 10% of energy used in transportation will be from renewable resources. While introduced in 2008, the RED has not yet been implemented. The methanol market, however, is developing quickly in countries such as China, where most of the automobiles are multi-fuel (also called flexi-fuel) and can use methanol or ethanol, says Voncken. The biomethanol produced by BioMCN has the same specifications as methanol, so there is a low introduction barrier to users.

In 2006, BioMCN purchased a conventional methanol plant in the northern part of the Netherlands. The traditional method for making methanol at that plant was to convert non-renewable natural gas. BioMCN modified the existing steam reformers to partly replace natural gas with glycerin as a raw material.

In BioMCN's process, the crude glycerin is first purified by distillation, and then pre-heated before adding it to the steam reformer (Figure 3). After a pilot-scale demonstration in 2008, commercial-scale production started in 2009. The current capacity for methanol production at Delfzijl is 400,000 m.t./yr, half of which (200,000 m.t./yr) is biomethanol. An increased capacity to a total of 400,000 m.t./yr of biomethanol is planned by 2013. BioMCN has also developed its own catalyst, which it expects to patent.

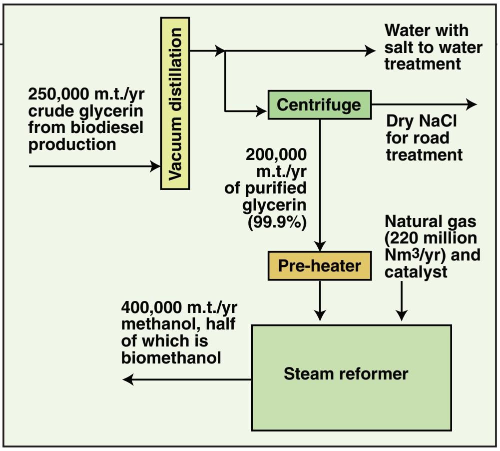


FIGURE 3. BioMCN produces industrial quantities of biomethanol from second-generation feedstocks

Woodspirit. Another project in the early stages for BioMCN involves producing biomethanol from waste wood, via a bio-syngas route. To do this, the company together with the Investment and Development Agency of North Netherlands (NOM), Linde, Siemens and Visser Smit Hanab have formed a consortium that plans to build "the world's largest" biomass refinery next to the existing biomethanol plant in Delfzijl. The planned biomass refinery will process approximately 1.5 million m.t. of residual wood to yield more than 400,000 m.t./yr of second-generation biomethanol. Termed, "Woodspirit", the project has been selected as one of three projects submitted by the Netherlands to the E.U. for the European NER300 investment subsidy program, which aims to stimulate investments in innovative, renewable energy technology and carbon capture and storage (CCS).

"We appreciate the importance that the European Committee attaches to the reduction of CO_2 emissions and the stimulus to produce and use renewable energy. With this consortium we want to make a significant contribution to the availability of second generation biofuels throughout Europe", says Voncken. He expects that decisions about which projects are chosen for the subsidy will be made in the second quarter of 2012. ■

Dorothy Lozowski

ANALYZERS KEEP WATCH INLINE

Thermo Fisher Scientific

FIGURE 1. The Prima Pro process mass spectrometer for online gas analysis was designed using advanced physical property modeling software. The analyzer also offers complete, precise and fast gas composition analysis, along with lower maintenance than gas chromatography systems

Mettler Toldeo AutoChem

FIGURE 2. The ReactIR 247 is a new generation of FTIR process analyzer, equipped with ATR fiber probes, that can be used to measure material in a solution as it disappears and crystallizes into a solid

Keeping an 'eye' on every step of the chemical process is possible — and profitable — thanks to new inline analyzers

The often-uttered phrase, "Keep your eyes on the prize," couldn't be more relevant than it is in the chemical process industries (CPI) where process optimization via inline analysis is key to producing product within specifications (specs), reducing waste, increasing efficiency and boosting safety.

"The advantage of inline analysis is that it provides instant feedback about what's going on in your chemical process," says David Joseph, senior industry manager with Emerson Process Management's Rosemount Analytical div. (Solon, Ohio). "Because the data is available in realtime, it provides information immediately, instead of having to draw a sample and send it to a laboratory to have it analyzed, which takes time. Inline analysis also trends the process nicely so you can see if there are any changes taking place."

Specifically, the ability to provide data without the wait helps chemical processors in several ways. Obviously the primary benefit is speed of results. "You're saving time by getting data in realtime at the process point," says Chris Heil, product specialist with Thermo Fisher Scientific (Waltham, Mass.). "But the real benefits are had because those immediate results can be used for feedback that can help you control, chart and trend the process right now instead of after the fact.

"When you are controlling the process in realtime, you can find a process upset or out of spec product much, much faster than when you're using laboratory analysis. In the chemical, petrochemical, polymer and food industries, ten minutes could mean thousands of gallons of product can be saved before something goes out of spec," he continues. "Point blank: Moving testing out of the laboratory and onto the production floor saves time and money in reduced waste and increased yield, higher quality and increased efficiency."

Benefits in realtime

The benefits of inline analysis, and the resultant performance optimization, are especially beneficial in very dynamic processes, such as in olefins, says Peter Traynor, product manager for process mass spectrometry with Thermo Fisher Scientific. The front end of an olefins unit is a series of cracking furnaces where various hydrocarbon feeds come in from the petroleum refinery and are cracked with steam to make products such as ethylene and propylene. The appropriate target for concentration changes on a day-by-day basis, depending on the current price for end product or if there is a downstream demand at another plant. "This means you have to optimize the product slate, which includes all the products you are getting out of a particular unit from refinery feedstocks," notes Traynor. "That product slate needs to change depending on prices and demand, as well as the current price of energy and steam. So if you're analyzing gases inline, you can see the cracking severity via direct measurement."

If inline analysis isn't used, then models based on temperature and flow must be employed to make predictions. However, models are likely to drift if regular input is not provided based on inline measurements. "In this cracking scenario, inline analysis is crucial because things change quickly during processing and the feedstocks are very valuable."

Another area where optimization is critical is in catalyst selectivity moni-

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toring, which can only be done by measuring gases into and out of a reactor. "The reason you want to monitor selectivity is that it falls off with time," says Traynor. "But if you're trending using realtime analysis, you can immediately make changes to keep product yield high and predict ahead of time when the process needs to come down in order to change the catalyst. This type of trending will also prevent processors from investing more in their catalyst than is necessary."

These instant-gratification-type results can also increase efficiency in batch processes. "If it's a batch process, the cycle time from one batch to the next must be as short as possible in order to make material as quickly as is possible," says Brian Whittkamp, reaction analysis market manager with Mettler-Toledo AutoChem (Columbia, Md.). "Using inline, realtime analysis allows processors to increase their throughput and yield in the same given period of time because they don't have to wait for results."

Other benefits, he adds, include being able to make changes on the fly. "If the chemistry should start going in the wrong direction or there's some sort of upset in the process, it can be detected with inline measurement devices as it starts to occur, and operators can see the reaction going astray and change the condition of the reaction so it can get back on course, minimizing any byproducts or degradation of the desired product," explains Whittkamp. "It is this type of upset that can cost millions of dollars, and you don't know about them until after the fact if you don't have an eye in the reaction."

Additionally, knowing when the reaction ends is also important in processes where byproducts will form if the material sits too long after the reaction, which can decrease yield and create the need for filtering to extract or separate byproducts and intermediates from the desired material. "Detecting when the reaction ends — as it ends — can be a significant benefit in terms of both higher yields and reduced time and labor," suggests Whittkamp.

Another significant benefit of inline analysis is safety. "Some units, like those for ethylene glycol, run just a few fractions of a percentage point from their explosive limit," says Traynor. "Providing realtime feedback can prevent accidents from happening by alerting operators who can take immediate corrective action and prevent a disaster."

On the other side of the safety coin is the ability to perform realtime environmental monitoring. "Many plants have the potential to emit toxic organics through fugitive emissions via failed valves," explains Traynor. "But it is possible to analyze the environment around the chemical unit and set alarms if there are fugitive emissions and have someone quickly find and fix the leak to avoid potential problems."

Besides the benefits to the process and safety improvements, spending can also be reduced due to the lack of consumables needed by other types of measurement devices. With inline equipment there are no reagents, solvents or other materials needed to conduct the analysis, says Gerald Auth, president of Midac (Costa Mesa, Calif.). Commonly used techniques like gas chromatography (GC) and high performance liquid chromatography (HPLC) usually require these consumables to quench and dilute the sample and then run analyses. And the maintenance on this type of equipment is much higher — requiring labor time and skilled technicians — than it is for inline analyzers used to take similar measurements.

Gas analysis

One of the biggest areas of concern in the CPI is gas analysis. In the past this may have been monitored using GC or HPLC, but inline analyzers based on more current technology are presently replacing traditional methods because of the many benefits they provide.

For instance, Midac's online FTIR (Fourier transform infrared) gas-analysis systems measure both contaminant concentrations at very low levels and

COST-EFFECTIVE SENSORS

While analyzers may have grabbed the headline, let's not forget that they wouldn't work without sensors. And there have been several advances in sensor technology that are allowing analyzers to go places where they haven't gone before and, into more of those places, due to engineering that is designed to reduce the cost of ownership.

For instance, Sensorex's (Garden Grove, Calif.) S8000 Modular pH/ORP system with self cleaning sensors combines a next-generation flat-surface self-cleaning pH/ORP sensor along with modular mounting hardware and optional electronics to deliver precise measurement with reduced maintenance and low cost of ownership. The platform is a fully configurable system that allows users to purchase only the components they need, while still allowing the expansion of measurement capability to meet changing plant requirements.

The company's TCS3020 Toroidal sensor, when combined with the company's toroidal transmitters, offers a highly accurate and low-maintenance conductivity sensing solution. Designed for optimal performance, it provides a non-contacting, inductive type conductivity measurement. As an inductive sensor, it is resistant to the corrosion, coating and fouling common to contacting conductivity sensors. It is designed for longterm deployment with no maintenance and has a wide solvent tolerance and temperature stability.

Banner Engineering (Minneapolis, Minn.) also is looking to make sensors more cost effective, as is evidenced in their VSM Series of micro sensors for inspection solutions. The sensors, for hygienic applications, are miniature photoelectric sensors that deliver high-performance in a compact package. They offer the ability to function in washdown environments that use a variety of liquids and chemicals and provide an alternative to proximity sensors and optical fibers in high flex environments.

And, Micronor's (Newbury Park, Calif.) fiber-optic, absolute-position sensor is an all-optical design immune to any electro-magnetic interference, such as lightening, radiation, magnetic fields and other harsh environmental conditions. The fiber optic aspect of the sensor also makes it suitable for long-distance position sensing over hundreds of meters, without being affected by ground loop problems. ❑

Mettler Toledo AutoChem

FIGURE 3. The FBRM D600R uses focused beam reflectance measurement to provide realtime quantitative measurement, tracking the rate and degree of change to particles, particle structures and droplets as they actually exist in process

process gases at very high levels. The FTIR analyzes aggressive gases and delivers realtime results in applications previously considered intractable. Using cells that can be heated to 250°C, the FTIR can be used to measure stack gases, carbon sequestration processes, perfluoro/perchloro carbons and highly reactive streams such as sulfur and ammonia or hot wet HCl. The systems can be housed in intrinsically safe enclosures for robust performance in hazardous environments. "While the cost of our equipment can be much more than a GC, the overall cost is much less due to the lack of consumables and maintenance," says Auth. "And because it provides instant results and helps eek a better performance from the reactors and the plant, it generally pays for itself in three to five months."

Thermo Fisher Scientific recently introduced its Prima Pro process mass spectrometer (Figure 1) for online gas analysis. Designed using advanced physical-property modeling software, the analyzer also offers complete, precise and fast gas-composition analysis, along with lower maintenance than GC systems. In addition, the new Sentinel Pro is designed to monitor the environment around a process and alert technicians if a toxic emission or leak is detected. A single system is said to, on average, do the job of ten GCs, which lowers total cost of ownership and maintenance expenses. Both analyzers require an annual four-hour maintenance session that can be performed without any special training.

Process analysis

In addition to gas analysis, other

measured in realtime, so equipment providers are coming up with inline versions of these analyzers, as well.

Mettler Toledo AutoCam's React IR 247 (Figure 2) and FBRM D600R (Figure 3) work hand in hand to control process chemistry. The ReactIR 247 is a new generation of FTIR process analyzer equipped with ATR fiber probes that can be used to measure material in a solution as it disappears and crystallizes into a solid, which can then be measured using the FBRM (focused beam reflectance measurement) D600R. FBRM provides realtime quantitative measurement, tracking the rate and degree of change to particles, particle structures and droplets as they actually exist in process. This inline measurement enables engineers to quickly link particle system dynamics to processing conditions. What's unique about this instrumentation is the software. "It has the ability to take the infrared data and transform it into chemical data that chemists not trained in spectrometry can understand," says Whittcam.

Thermo Fisher Scientific

FIGURE 4 **Thermo Fisher Scientific's Antaris EX FT-NIR processor analyzer combines the power of near-infrared, fiber-optic-based sampling with manufacturing-based materials testing, monitoring and control applications**

And for areas such as hazardous or remote locations, inline process analyzers are also available. Thermo Fisher Scientific offers the Antaris EX FT-NIR processor analyzer (Figure 4), which is a robust, simultaneous multiplexing analyzer designed for hazardous environments. It combines the power of near-infrared, fiber-optic-based sampling with manufacturing-based materials testing, monitoring and control applications. It features truly simultaneous measurements of up to four process points, making it a complete, fit-for-purpose solution.

And, Emerson's Rosemount Analytical offers solutions for areas that were previously too difficult, remote or expensive to instrument via their Smart Wireless series of instrumentation. Within the family, pH, conductivity, residual chlorine, dissolved oxygen and other instruments are available and able to send a wireless signal to a gateway or control system without wires to provide realtime trendable data. ■

Joy LePree

CHEMICAL ENGINEERING
FACTS AT YOUR FINGERTIPS
Department Editor: Scott Jenkins

Heat transfer system cleaning

A well designed and operated heat-transfer-fluid system is a key feature of a safe, reliable and cost-effective heating design. However, problems can arise if the heat-transfer fluid becomes heavily degraded or the system is allowed to accumulate solids and other process contaminants. These problems include the following:

- Reduced heat-transfer rates
- Diminished fuel efficiency
- Flow blockage in small-dia. or low-velocity areas
- Extended startup times at low temperatures
- Fouling of heat-transfer surfaces
- Overheating, damage or failure of heater tubes

Avoiding heat-transfer fluid degradation and contamination often requires the use of the following filtration, flushing and cleaning techniques.

Filtration

In many cases, filtration can effectively remove solids that, if left unchecked, may result in the need to drain and flush a system. In general, glass-fiber-wound filter cartridges work well for in-system filtration of organic-liquid heat-transfer fluids. These filters are generally available from numerous manufacturers, are usable at temperatures up to 400°C, typically have adequate solids-holding capacity and are usually economical and disposable. The filter housing should also be specified for the desired temperature and pressure. The filter should be installed where there is a 20–40-psi pressure drop, and should have a maximum throughput of 1% of the system flowrate. For initial startup, a 100-μm-nominal particle removal rating is acceptable, and can be gradually reduced to a 10-μm-rated filter element for ongoing use. For heat-transfer fluids containing high concentrations of solids, bag filters or other high-surface-area designs may be preferred.

When intensive system cleaning is necessary, it is recommended to incorporate sound environmental, health and safety principles into the job plan to protect against exposure to hot fluid and vapors.

System drain

Adjust the fluid temperature to 93°C and shut down the heater. Continue operating the circulating pumps as long as possible during pump-out to keep loose solids and sludge in suspension. Drain the system through all low-point drains. If gravity draining is not sufficient or possible, compressed nitrogen can be used to effectively blow additional fluid from the system. Remove as much degraded heat-transfer fluid as possible to maximize the following cleaning techniques. Caution must be exercised to avoid contact with hot fluid and piping. Once the fluid has been drained from the system it should be stored, handled and disposed of according to the product MSDS (material safety data sheet) and your environmental, safety and health professionals' guidance. The system may then be cleaned using one or more of the techniques in Table 1.

System flushing

If a strainer is not already present in the system return line that runs to the main circulating pumps, consider the addition of a fine-mesh strainer to protect the circulation pumps from solids that may be dislodged during cleaning.

When choosing a flushing fluid, ensure that it is compatible with the system components and the new replacement fluid. This can usually be determined by contacting the fluid manufacturer. In addition, avoid flush fluids that contain chlorine, as this may cause corrosion issues if a portion is left in the system.

Fill the system from the low points with the flushing fluid, including the expansion tank, to a normal operating level. Start circulating the entire system at ambient conditions to begin dissolving the organic solids and residual heat-transfer fluid. Periodically check the return line strainer for plugging and buildup of solids that may have been released during system cleaning. In accordance with the manufacturer's recommendations, increase the fluid temperature to maximize cleaning potential and continue circulating for the directed time period. Cool the flushing fluid, then drain it from the system through low points, ensuring that as much fluid is removed as possible, then dispose of it properly.

Chemical cleaning

In some situations, alternative cleaning methods are required, such as cleaning of a vapor-phase heat-transfer system. In these situations, chemical cleaning may be used as an alternative. In general, chemically cleaning a heat transfer system requires extra steps, higher cost, additional time and producessignificantly more waste. A general outline of a chemical cleaning procedure may include the following:

- Drain heat-transfer fluid from system
- Solvent flush circulation
- Drain solvent flush
- Acidic solution circulation
- Caustic and detergent solution circulation
- Flush with water
- Dry thoroughly

TABLE 1

Contaminants	Cleaning techniques
Solids	• Filtration
Sludge, high-viscosity fluid or residues	• System drain • System flushing • Chemical cleaning
Process contamination	• Unique procedure
Hard coke	• System drain • Mechanical cleaning

CONTAMINANTS AND THEIR SOURCES

Rust, dirt and pipe scale: In most cases these are introduced into the system during construction or maintenance.

Oxidation: Occurs when hot heat transfer fluid comes in contact with air to form weak organic acids. Excessive oxidation can cause the formation of solids and high viscosity compounds which impair system effectiveness.

Thermal degradation: Rate of thermal degradation for any organic thermal liquid depends on the fluid chemistry, system operating temperature and time. When degradation does occur the outcome typically includes higher molecular weight compounds and carbonaceous solids.

Process contamination: If the heat transfer fluid is contaminated with process-side fluid, the contaminant may form solids, sludge, decomposition and even reaction products.

Mechanical cleaning

In some cases, such as when the system has been severely fouled by hard coke deposits or the lines are completely blocked, the above methods are inadequate for cleaning the system. In these cases, mechanical cleaning is most likely required. Mechanical cleaning methods can include high-pressure water jetting, wire brushing, mechanical scraping and sand or bead blasting.

After cleaning

Once the system has been drained completely, it should be inspected for solids that may have fallen out of suspension, especially in low-velocity areas. Ensure that a side-stream filter is operational and properly maintained. If a side-stream filter is not present in the system, consider installing one to aid in solids removal during normal operation.

Refill the system with fresh heat-transfer fluid and start up using normal procedures. Residual moisture may be present from the drain, cleaning and start up procedures. Care should be taken to vent any moisture from the system by allowing flow through the expansion tank where the moisture can flash and then vent. It is also suggested to employ inert gas blanketing of the expansion-tank vapor space to prevent moisture and air contamination of the fluid. This is usually put in place after moisture has been vented and the system is brought up to operating temperature.

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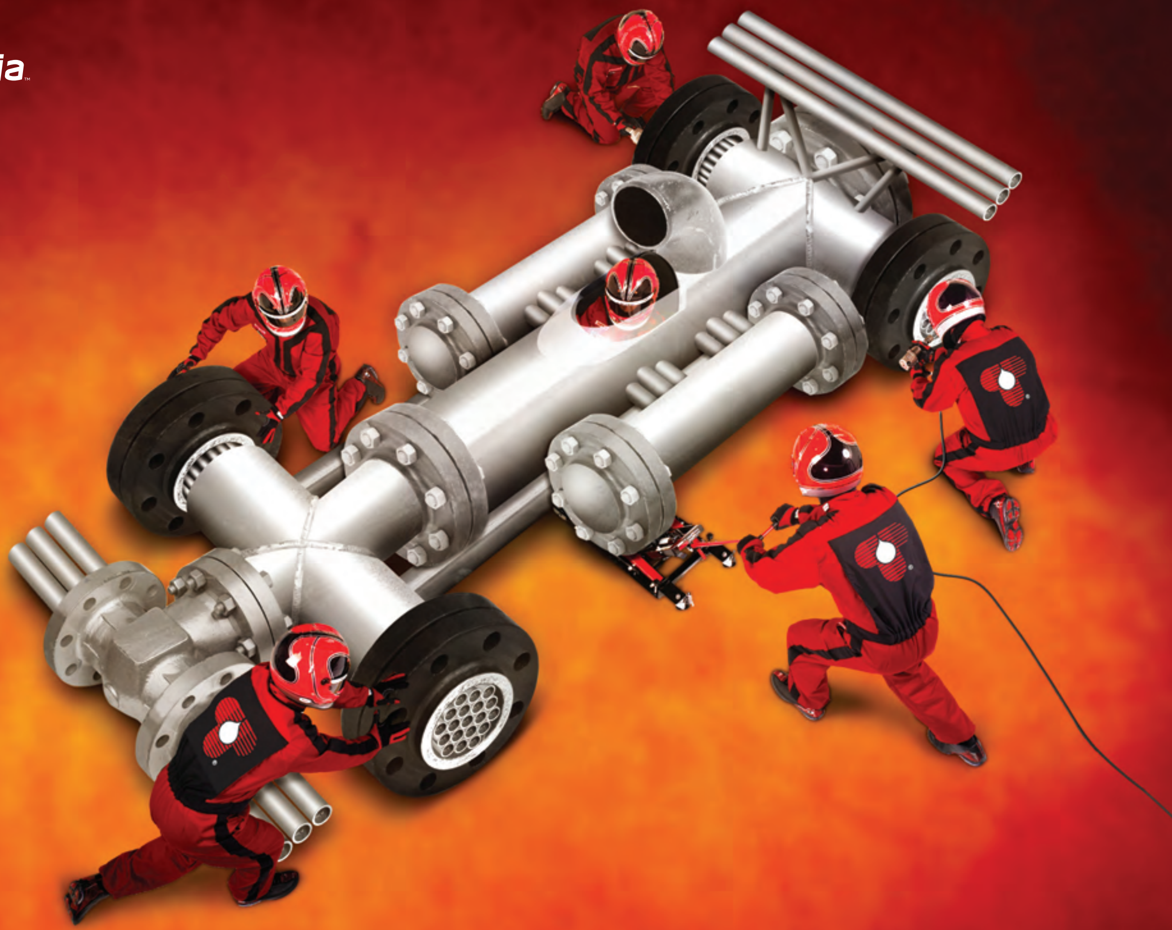

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CHEMINNOVATIONS

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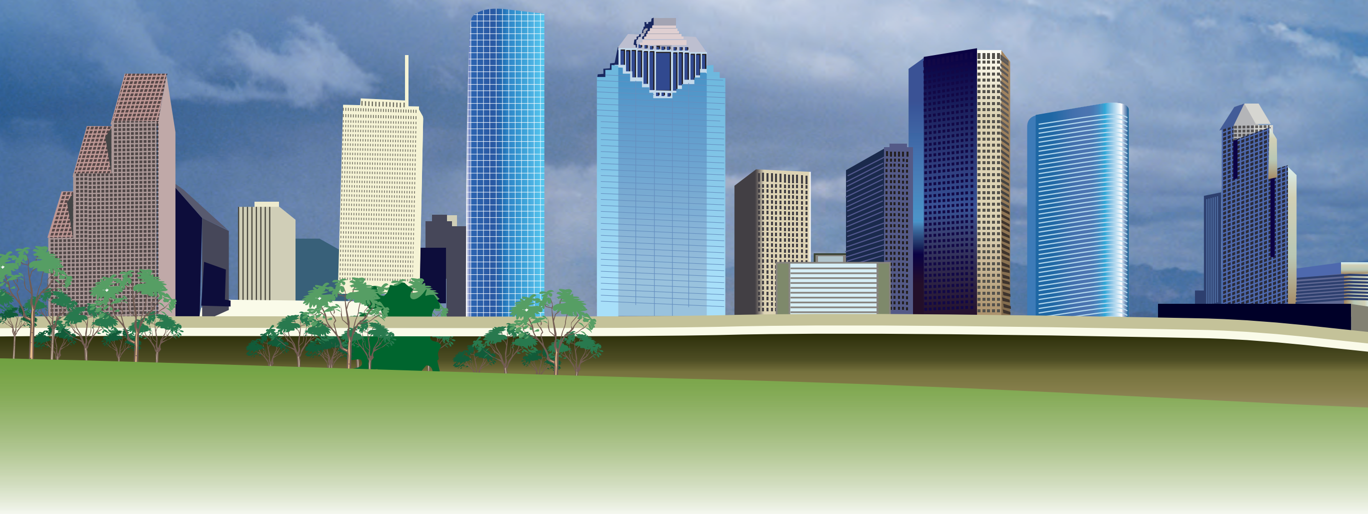


The second annual ChemInnovations Conference and Expo will take place at the George R. Brown Convention Center in Houston from September 13–15. Billed as the ultimate venue to discovering breakthrough ideas, emerging technologies and game-changing solutions in the chemical process industries (CPI), the event offers the most comprehensive conference content for the chemical engineers in North America. Over 150 exhibitors and more than 2,500 attendees are expected at the event.

ChemInnovations (CI; www.cpievent.com) is organized by the TradeFair Group (Houston; www.tradefairgroup.com), along with *Chemical Engineering*. The event will be kicked-off with a keynote address by Jim Peters, head of downstream consulting in the Americas at Wood Mackenzie (Edinburgh, U.K.; www.woodmacresearch.com), a global consulting and research firm serving a range of industries, including energy, mining, metals, oil and natural gas. Peters will discuss the outlook for oil, natural gas and natural gas liquids, and their impact on the chemical industry over the next 8–10 years.

The second day's keynotes will also take a forward view, with Peter Zorino, chief strategic officer at Emerson Process Management (Chanhassan, Minn.; www.emersonprocess.com), speaking about the future of automation. In addition, Marty Edwards, director of control systems security at the U.S. Dept. of Homeland Security (DHS; Washington, D.C.; www.dhs.gov) Control Systems Security Program, will talk about the evolving security landscape for control-systems security and the relationship between DHS and the chemical industry.

Conference tracks

The ChemInnovations 2011 conference program is organized into six tracks, plus the Chementator Lightning Round. The six conference track titles are the following:

- **TRACK 1:** Business insights, outlook and regulatory issues
- **TRACK 2:** Process, design and operations
- **TRACK 3:** Environmental, health and safety
- **TRACK 4:** Energy efficiencies and the use of Alternative Energy Sources
- **TRACK 5:** Equipment maintenance and reliability
- **TRACK 6:** Instrumentation, controls and automation

The Business insights, outlook and regulatory issues track will examine critical areas that, although non-technical, are key enablers of effective business operation in the chemical industry. In session 1A, conference speakers will take a look at the global energy outlook for the next 20 years, with the intent to give attendees an improved understanding of alternative energy sources, consumer demand trends, and energy efficiency approaches. The track continues in session 1B, which will address modern workforce issues and how to retain years of accumulated knowledge in a rapidly changing environment. Session 1C is a two-part segment that discusses two important regulatory challenges for the CPI — the U.S. EPA's revised boiler MACT rule, and its data collection requirement. The track wraps up with a session on how to protect intellectual property and a separate session on engineering ethics that satisfies the Texas Board of Professional Engineers requirement for continuing education on ethics related to the engineering profession.

Track 2, on process, design and operations, will allow attendees a glimpse of several innovative approaches for improving chemical processes. Specifically, a track session will be dedicated to each of the following: process intensification, fractionation, innovative materials of construction, modeling, automation and control.

Note: For more information, circle the 3-digit number on p. 54, or use the website designation.

Track 3 features a wide-ranging series of sessions with environment, health and safety (EHS) concerns as the unifying theme. Water treatment and reuse, clean-air strategies and sustainability are among the session topics, as are risk analysis and safety-system operation.

With a focus on energy efficiency and the use of alternative energy sources, Track 4 offers attendees a chance to learn about emerging technological options for getting the most out of chemical processing facilities.

Track 5 on equipment reliability has two sessions, one of which will cover strategies to reduce plant rental-equipment costs, ways to deal with corrosion underneath insulation, and others. The second session in Track 5 will focus on tank polymer liners and electromagnetic flowmeters.

Process automation and control links the talks in track 6, which encompasses sessions on fieldbus innovation, new approaches to gas analysis, the evolution of SCADAs and manufacturing automation.

Co-located events

A new aspect of the second annual ChemInnovations event is the co-location of several other CPI-related conferences — namely, the International Society of Automation (ISA) Houston Section Conference and Exhibition, the 40th Turbomachinery Symposium, and the 27th International Pump User's Symposium. The co-located events will allow attendees to maximize their travel dollars and time, as they can connect with a wider range of vendors and colleagues than would be possible at each individual event.

Organized by the Texas A&M University System Turbomachinery Laboratory, the Turbomachinery Symposium offers short-courses, hands-on tutorials, discussions and solutions-based case studies, as well as an exhibit floor. Texas A&M's Turbomachinery Laboratory also hosts the International Pump User's Symposium, which offers similar conference session formats, but will focus specifically on pump maintenance, troubleshooting, operation and purchasin.

At its conference, the Houston section of ISA (www.houstonisa.org) — the organization's oldest and largest — offers highly focused educational sessions on the future of instrumentation and process control, as well as opportunities to connect with vendors on its exhibit floor.

Chementator Lightning Round

A unique aspect of the ChemInnovations event is the Chementator Lightning Round, a namesake of the popular monthly department in *Chemical Engineering*. Initiated at the inaugural ChemInnovations in 2010, the Chementator Lightning Round will be brought back for 2011 with new technologies. Using a fast-paced, interview-style format, the Lightning Round will provide a look at newly demonstrated technologies and approaches that could help others in the CPI improve their operations. The interviews will be led by members of the *Chemical Engineering* editorial staff. The following are brief descriptions of some of the technologies that will be discussed in interviews within the Chementator Lightning Round sessions.

Genomatica. At ChemInnovations 2011, Genomatica (San Diego, Calif.; www.genomatica.com) chief technology officer Mark Burk will discuss the company's process technology and progress toward commercial production of biologically derived 1,4-butanediol (BDO).

The Genomatica process produces the same BDO product that is currently made from a variety of petroleum-derived feedstocks, but uses 100% renewable feedstocks. Genomatica's executive vice president Dennis McGrew says the company expects its process to have costs lower than petroleum-based BDO production processes.

Genomatica has used its considerable microbial metabolic engineering technology to develop an *E. coli* strain capable of producing bio-based BDO from a wide variety of sugars. BDO, an intermediate chemical with a $4-billion market worldwide, is used to make spandex, automotive plastics, running shoes, insulation, and high-value downstream derivatives.

Genomatica recently signed a joint development agreement with Tate & Lyle (London; www.tateandlyle.com) for the demonstration-scale production of Genomatica's biologically derived BDO. Under the agreement, Tate & Lyle will dedicate a demonstration-scale production facility in Decatur, Illinois for exclusive use by Genomatica for the scaleup of the bio-based BDO process. The company has ramped up its process to use 13,000-L fermenters, followed by an integrated downstream process for BDO recovery and purification. The demonstration plant is co-located with a corn wet mill owned and operated by Tate & Lyle, providing ready access to a cost-effective, renewable feedstock.

Genomatica is a 2011 recipient of the Presidential Green Chemistry Challenge award from the U.S. Environmental Protection Agency (Washinton, D.C.; www.epa.gov) (see p. 11).

Resource Development Co. (RDC). RDC (Birmingham, Mich.; www.resourcedev.com) executive Brian Cormier will discuss his company's industrial training program, called KnowledgeWeb, an e-learning program focused on knowledge transfer. KnowledgeWeb is an optimized learning environment for operators working in highly regulated and high-risk industries, including many sectors of the CPI.

The dynamic, Web-based environment is designed to provide a "consistent methodology where critical process knowledge can be captured, transferred, measured and validated," the company says. Through an on-demand, user-initiated format, KnowledgeWeb focuses on knowledge transfer efficiency and reducing the time to competency. A key feature of the system is a differential learning methodology, which provides learners with specific knowledge requirements for maintaining proficiency.

The service also allows cost-effective integration of best practices with job-specific plant knowledge requirements, and provides comprehensive benchmarking and learning management support tools.

Environ International Corp. Carl Adams, lead researcher and global practice leader for industrial wastewater management at Environ International Corp. (Arlington, Va.; www.environcorp.com), will also be on hand at

ChemInnovations to discuss his company's system for biological treatment of volatile organic compounds (VOCs). The system utilizes existing biological wastewater-treatment facilities for destruction of biodegradable VOCs and other organic hazardous air pollutants (HAPs). Environ's technology has been demonstrated at three U.S. petroleum-refining and chemical facilities, and the company has plans to extend the U.S. patent-pending treatment approach to eight additional facilities in coming months.

Environ developed the treatment method, known as VOC BioTreat, as an alternative to incineration or to systems involving activated-carbon VOC treatment. The VOC BioTreat protocol has demonstrated the ability to meet VOC and HAP handling requirements in U.S. state and federal emissions regulations.

VOC BioTreat works by piping VOC offgases into an existing wastewater treatment tank that contains activated sludge at depths of greater than 18 ft. Microbes in the tank break down VOCs as they bubble up through the tank. VOC BioTreat can be retrofitted into existing wastewater treatment facilities for somewhat lower capital costs than those associated with installing thermal oxidizers or activated-carbon VOC-treatment systems, but the annual operating costs are less than 10% of conventional systems.

In addition to the VOC BioTreat technology, Environ has developed a test method to confirm the performance of the proprietary technology within a plant setting. "The ability to reliably test for VOCs is critical for acceptance from the regulatory authorities," Adams says.

The VOC BioTreat technology recently received the grand prize for research excellence in the American Academy of Environmental Engineers' E3 competition.

Environ's VOC technology has also been recognized as one of four finalists for *Chem Eng*'s Kirkpatrick Chemical Engineering Achievement Award, which will be presented during the ChemInnovations event. Descriptions of the other three finalists, which involve process intensification, process monitoring and "green chemistry," respectively, follow.

Kirkpatrick Award presentation

On Monday evening (Sept. 13) of the conference, the Kirkpatrick Award will be presented to a company that has demonstrated exceptional innovation in commercializing a new product, process or chemical engineering tool during 2009 or 2010. The biennial award has been presented continuously by *Chemical Engineering* since 1933. Award winners were selected by an independent panel of experts in the CPI. In addition to Environ Corp., the list of Kirkpatrick Award finalists

includes Invensys, Oxford Catalyts Group / Velocys, as well as NSR Technologies Inc.

Velocys/Oxford Catalysts. Velocys Inc. (Plain City, Ohio; www.velocys.com) has developed small-scale, modular synthetic fuel facilities for the economically viable conversion of natural gas into synthetic gas-to-liquids (GTL) fuels. The microchannel technology has also been deployed to convert biomass to fuels (BTL) and to make coal-to-liquids fuels (CTL).

The Velocys technology, which uses microchannel reactors and specially designed catalysts from Oxford Catalysts Group Plc. (Abingdon, U.K.; www.oxfordcatalysts.com), is intended for use with natural gas that comes from crude oil wells (associated gas) or that has been physically or economically difficult to extract (stranded gas).

Currently, most associated gas is either flared or reinjected into the oil well. Velocys says existing GTL technology becomes economically viable when it can process 300 million ft^3/d of natural gas (equivalent to 30,000 bbl/d), which few natural-gas fields can sustain. Further, the costs of concentrating biomass have thus far prohibited conventional BTL processes.

Velocys' approach has been to focus on accelerating reactions using microchannels. The company owns the world's largest microchannel patent portfolio (over 750). By speeding up reactions by a factor of up to 1,000, microchannel reactors can produce synthetic fuels economically from only 5 million ft^3/d, or 500 ton/d biomass or coal. Velocys' Microchannel Process Technology "can achieve productivities orders of magnitude greater than conventional plants, making distributed production viable," Velocys says.

The company has designed microchannel reactors that support both Fischer-Tropsch (F-T) chemistry and steam-methane reforming (SMR). The reactors foster rapid reaction rates and intensify processes by removing some of the heat- and mass-transfer limitations of conventional SMR and F-T reaction environments. Velocys says the microchannels demonstrate efficient heat transfer in both highly exothermic reactions, such as F-T, and endothermic reactions, such as SMR. The two combine in the Velocys GTL process. The microchannel reactors involve precisely stacking a series of shims that are photochemically machined. This is followed by a diffusion bonding or brazing step to produce the final reactors.

The microchannel reactors require superactive F-T catalysts, which are made by Oxford. Oxford's patented OMX method provides superactive, selective, stable F-T catalysts that are optimized for microchannel reactors.

In 2010, Velocys engineers successfully demonstrated the microchannel BTL technology in a 1-bbl/d facility at Güssing, Austria. Velocys says a 6-bbl/d facility will demonstrate its integrated microchannel GTL process at Fortaleza, Brazil during 3rd quarter of 2011. With more than 900 microchannels, the FT reactor at Güssing "is proving highly efficient at controlling the reaction and maintaining isothermal conditions," the company says. The plant is demonstrating four to eight times the productivity of conventional systems with high selectivity and good responsiveness to start-up and shut-down. Velocys has deployed microchannel process technology at a BTL facility in Brazil, and has several other orders for the technology pending.

NSR Technologies Inc. NSR (Decatur, Ill.; www.nsr-tech.com) has developed a "green" chemical pathway to potassium hydroxide (KOH) solution using membrane separations technology and ion-exchange chromatography. The manufacturing process, which yields 45–50% KOH solutions and 7% hydrochloric acid, is the first environmentally friendly, cost-effective alternative to electrolysis (chlor-alkali) in decades, NSR says. The process generates high-purity products free of mercury and oxidizing species. Also, it does not produce chlorine gas.

The strong base KOH is used for the manufacture of potassium-containing products, such as the food additive potassium citrate and the water-treatment agent potassium permanganate. It is also a key ingredient in soap and detergent processes, as well as agricultural fertilizers and pharmaceuticals.

NSR's process uses a multipass design that reduces the fluid recirculation requirements, allowing a smaller plant size and lower costs. The company also designed filter cells that minimized internal leaks and shunt/stray losses. Finally, NSR's chromatographic purification process removes 95–99% of the salt from cell-stack KOH product.

NSR's process consumes 40% less energy than a conventional process per unit of product manufactured.

Invensys Operations Management. Along with ConocoPhilips (Houston; www.conocophillips.com), Invensys Operations Management (Plano, Tex.; www.invensys.com) has developed a method for online monitoring of hydrofluoric acid (HF) catalyst in the production of octane. The non-spectroscopic method, called ACA.HF Alkylation Measurement Solution, lowers the cost of online HF monitoring while simplifying the measurement and reducing risk to plant workers.

To measure HF levels, the Invensys approach involves analyzing differential responses from online sensors. The system takes readings of water concentration from electrode-free, non-contacting conductivity sensors, as well as simultaneously measuring density and mass-flow levels with a Coriolis flowmeter. The company has developed specialized software to calculate HF levels from the readings.

HF alkylation is a widely used process to produce isooctane for blending into gasoline. In the process, HF catalyzes the reaction between isobutane and four-carbon olefins to form octane. There are three main components in the alkylation catalyst stream, Invensys explains: HF (usually around 90%); water (about 1%); and acid-soluble organic molecules (ASO; which make up the rest). "Tight control of these constituent concentrations, which can save millions of dollars per year, requires accurate monitoring of the levels of all three components," the company says. Using the formula %HF + %water + %ASO = 100%, the Invensys system can correct for temperature effects and for second-order influences of interactions between ASO and water.

Early approaches to HF monitoring involved manual samples and laboratory analysis, which offers limited accuracy and can expose laboratory workers to toxic substances. More recent Fourier-transform near infrared (FTNIR) techniques are very accurate, but their adaptation for realtime online monitoring is complex and costly, Invensys says.

The new HF monitoring system costs about half as much as an FTNIR system, and it requires minimal maintenance because its core components are built from rugged materials long-proven in industrial HF applications. The sampling system amounts to a continuously flowing sample from a slipstream of the process, Invensys says. "Based on established industry methods, estimated mean time between failures of the technology exceeds 29 years," the company adds. Additional advantages include minimized potential for corrosion and greatly reduced potential for plant and laboratory workers to be exposed to the sample.

The system's hardware is a sampling panel, located in the hazardous area, that contains all fluid-handling components, sensors and signal transmitters. Data are transmitted from the panel to a distributed control system (DCS), with which users interact via a human-machine interface in the nonhazardous area.

Special events and workshops

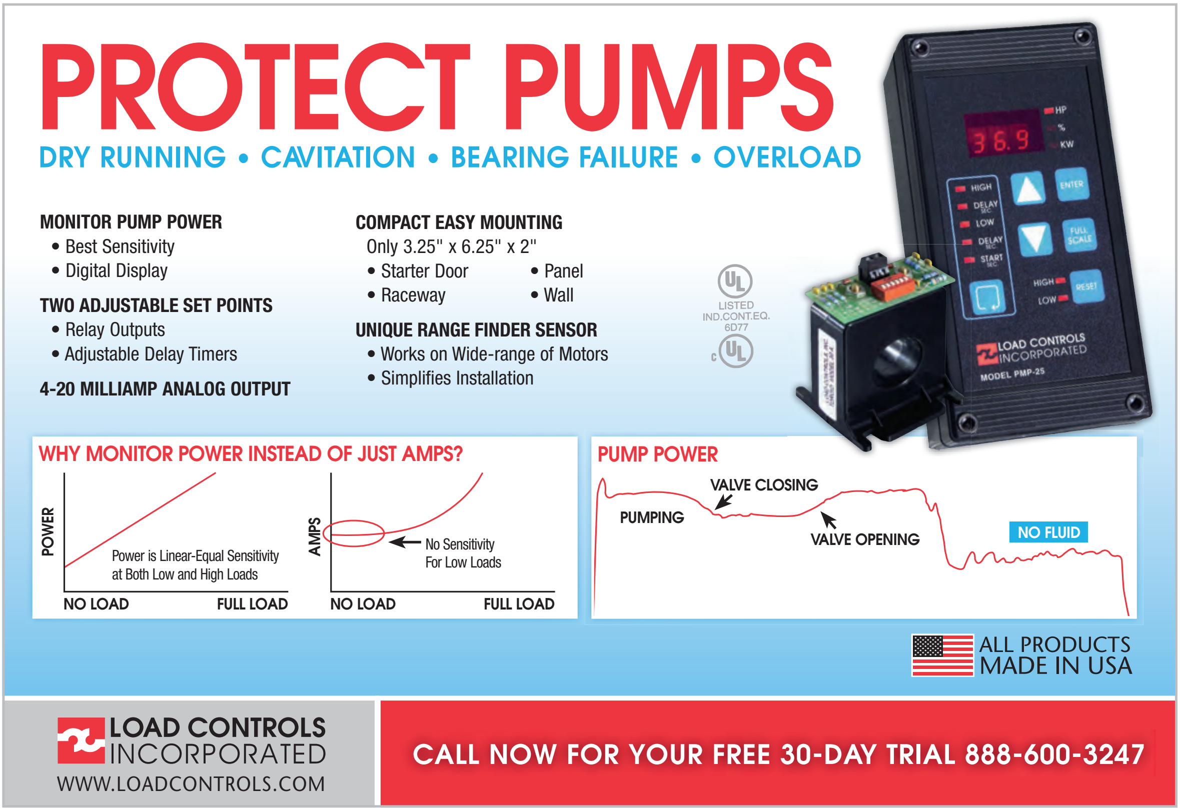
There are a number of workshops and special events occurring alongside ChemInnovations 2011. Pre-conference workshops on Monday, September 12 include one-day programs on 21st-century catalysts for the petrochemicals industry, powder and bulk-solid storage, improving control loop performance, pneumatic conveying fundamentals, and mixing and blending. The events co-located with ChemInnovations also have various offerings for Sept. 12.

Special events associated with the ChemInnovations conference include a tour of NASA's Johnson Space Center (Houston, www.nasa.gov/centers/johnson/home) and a tour, hosted by the Port of Houston Authority (www.portofhouston.com), of the Barbours Cut Container Terminal, as well as the *Chemical Engineering* Awards Reception on Sept. 12.

For additional information about ChemInnovations 2011, and for a complete conference program and schedule details, including speakers, visit the ChemInnovations conference website at www.cpievent.com.

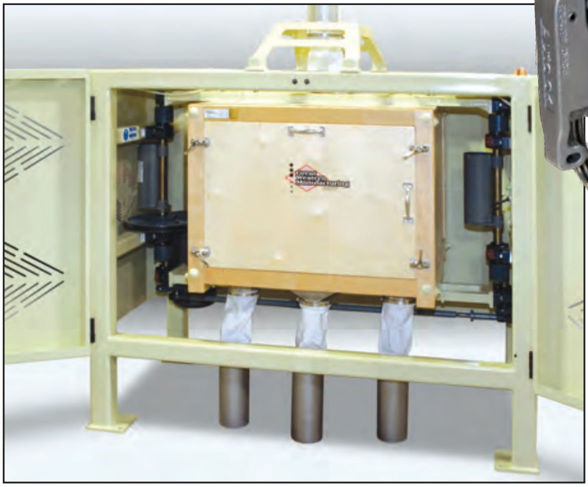
Also, further information about ChemInnovations will be available in the September issue of *Chemical Engineering,* which will include the second part of the show preview. This preview will comprise brief descriptions of products and services that attendees will be able to see on the ChemInnovations exhibit floor. ■

Scott Jenkins



AUGUST New Products

Kistler North America



Great Western Manufacturing

OPW Engineered Systems

A data collector with longterm storage

The 5630M Series of high-performance data collectors (photo) is designed to provide manufacturers and OEM machine builders with enhanced manufacturing-data storage, process visualization and longterm analysis capabilities. The instrument assigns a unique serial number to each data file, so a user can quickly search, locate and view all historical process data. In engine manufacture, users can also search by engine part. In addition to manufacturing of automotive components, the 5630M Series is also suitable for plastics and medical manufacturing operations. — *Kistler North America, Novi, Mich.*

www.kistler.com

This sifter achieves vibration-free separation

The Tru-Balance sifter (photo) can screen any dry, free-flowing product, ranging in size from 0.25 in. to 400 mesh, and accurately separate sizes with a gentle, gyratory motion. Its drive achieves perfectly balanced, vibration-free performance by straddling the sifter's center of gravity with counterweights that offset the rotating sieve housing. The custom-designed sifter can be configured for up to six separations. Models of the Tru-Balance sifter are available with between four and 14 sieve frames in four different sieve sizes. Other key features include its ability to be floor- or ceiling-mounted, and its ability to be easily opened for maintenance and cleaning of the sieves. — *Great Western Manufacturing, Leavenworth, Kan.*

www.gwmfg.com

Lower costs with this mobile water treatment system

A jointly developed Containerized Dosing System is a mobile unit for water or waste treatment designed for situations where a building would otherwise have to be erected. Dubbed the "Dosing System in a Box," the unit houses a solids-additive handling system, a dosing ejector system and all controls, including safety and alarm systems, in a 20-ft ISO intermodel container. The unit is flexible and mobile, allowing transfer of the equipment to any location on short notice to handle seasonal changes or emergencies. The box combines solids conveyors from one company that can transfer additives, such as hydrated lime or powdered activated carbon, to an ejector, made by another company, that introduces the additives into the water flow. — *Spiroflow Systems Inc., Charlotte, N.C.*

www.spiroflowsystems.com

These couplers automatically shut off in disconnections

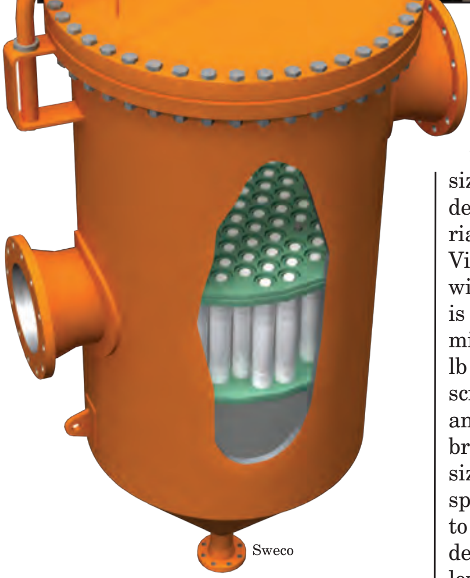
The new Kamvalok 1700D Series Dry Disconnect Couplings (photo) will automatically shut off in the event of an accidental disconnection of the coupling and adaptor. The 1700D Series couplers feature a unique spring-loaded, poppet-action design that virtually eliminates spillage of any residual liquid contained in transfer lines after disconnection. Designed for total closed-loop loading, the 1700D couplers connect and disconnect easily, and have an open/close lever to ensure that liquid flow can begin only after a secure connection is made. In addition, the lever allows a smooth opening and closing, even in high-pressure applications. The coupler and adaptor are used at transfer points where product loss is unacceptable, and are suitable for petroleum products, solvents, vegetable oils, detergents, and many acids and caustic chemicals. — *OPW Engineered Systems, Lebanon, Ohio*

www.opw-es.com

Separate 4–100-µm solids with this hydrocyclone

This company's hydrocyclone systems (photo, p. 20D-7) are designed to provide an economical method for removing solid particles in the 4 to 100+ µm range from slurries in a variety of ap-

Note: For more information, circle the 3-digit number on p. 54 or use the website designation.



Sweco

plications. The separation equipment is available in either an open-manifold or packed-vessel configuration. Manifolds can have a linear or radial orientation and utilize 2-, 4-, 5-, or 10-in.-dia. cyclones, while packed vessels contain 1- or 2-in dia. cyclones. Both configurations, the company says, can process feedrates from 10 to 3,000 gal/min, depending on the number and size of the hydrocyclones in the system. — *Sweco, Florence, Ky.*
www.sweco.com

Kason

This screener can dry on-size particles

A new dewatering and drying system from this company (photo) can remove both oversized and undersized particles, while simultaneously dewatering and drying on-size material. The system, which combines a Vibroscreen model K30-2-SS screener with a model K40/48-1FBD-SS dryer, is capable of removing up to 50 gal/min of water, and can dry up to 700 lb of on-size particles per hour. The screener is equipped with an imbalanced-weight gyratory motor that vibrates the screening chamber. Oversized particles travel in controlled spirals outward on the upper screen to a discharge port, while the on-size, dewatered pellets that fall on to the lower screen spiral outward to a spout, taking them to the fluidized-bed dryer. — *Kason Corp., Millburn, N.J.*
www.kason.com

These gloves are cut-resistant

Two models of ProFlex gloves are lined with 100% Kevlar to provide cut-resistant hand protection. The 710CR glove features a gel-polymer palm to dampen shock and impact, and the Model 820CR provides textured PVC on the palm and fingertips for a more

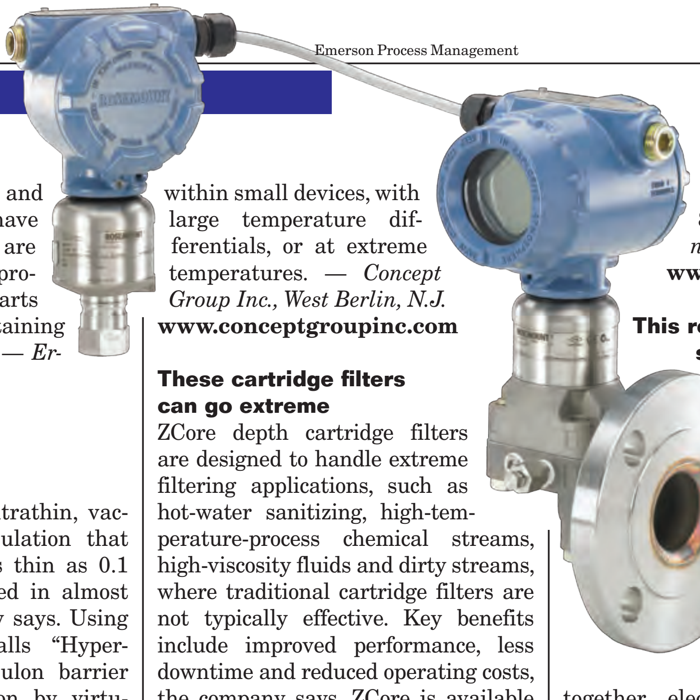
secure grip in both wet and dry conditions. Both have the Kevlar lining, and are designed to provide cut protection throughout all parts of the glove while maintaining dexterity and flexibility. — *Ergodyne, St. Paul, Minn.*
www.ergodyne.com

A vacuum insulation that is ultrathin

Insulon barrier is an ultrathin, vacuum-based thermal insulation that can be manufactured as thin as 0.1 mm, and can be supplied in almost any shape, this company says. Using what the company calls "Hyper-Deep Vacuum," the Insulon barrier stops thermal conduction by virtually eliminating molecule-to-molecule energy transfer. The company can manufacture the vacuum barrier in custom shapes and sizes for use in a wide range of applications, including within small devices, with large temperature differentials, or at extreme temperatures. — *Concept Group Inc., West Berlin, N.J.*
www.conceptgroupinc.com

These cartridge filters can go extreme

ZCore depth cartridge filters are designed to handle extreme filtering applications, such as hot-water sanitizing, high-temperature-process chemical streams, high-viscosity fluids and dirty streams, where traditional cartridge filters are not typically effective. Key benefits include improved performance, less downtime and reduced operating costs, the company says. ZCore is available in several micron ratings and lengths, and can achieve a 90% efficiency rate for particles as small as 0.5 µm. ZCore filters operate reliably at maximum pressure differentials from 1.03 bars at 180°F to 4.14 bars at 86°F. — *GE Water Technology, Trevose, Pa.*
www.ge.com



Emerson Process Management

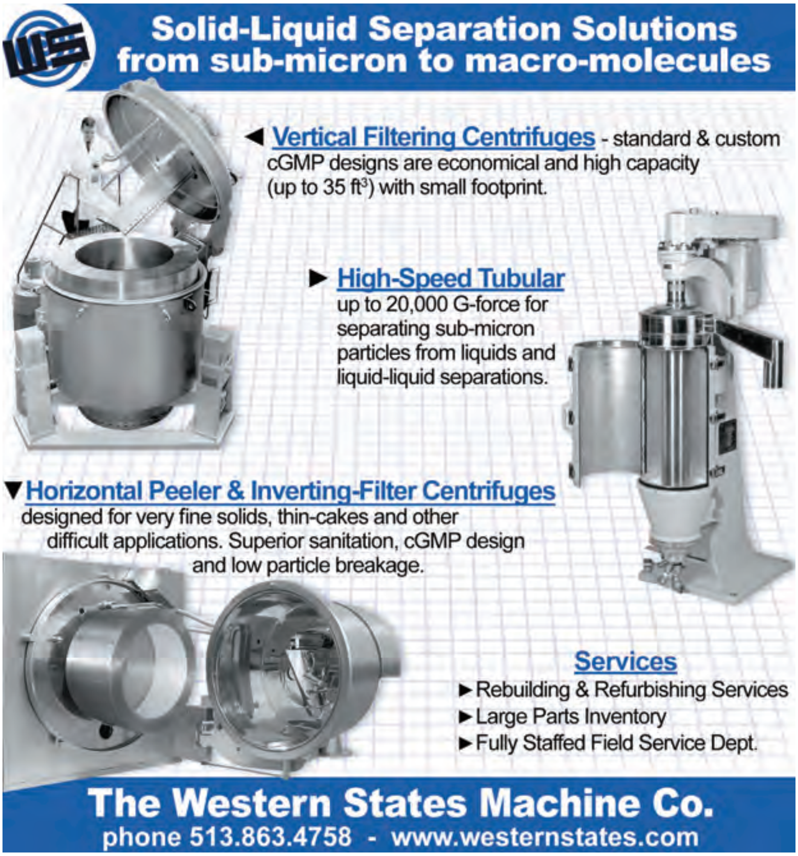
This remote level sensor is digital

The 3051S ERS (electronic remote sensor) system (photo) is a digital-based, differential-pressure level technology that replaces mechanical impulse piping with two of this company's pressure sensors linked together electronically. Differential pressure is calculated in one of two sensors and transmitted using a standard two-wire, 4–20-mA HART signal. Ideal applications for the 3051S ERS system include tall vessels, distillation towers and other installations that have traditionally required excessive lengths of impulse piping or capillary, the company says. The system can provide faster response times and more repeatable measurements, even with wide varying temperatures. — *Emerson Process Management, Chanhassan, Minn.*
www.rosemount.com

Precision fluid measurement on a budget

The TM Series flowmeter is a high-output flowmeter offering durable, high-precision fluid measurement at a much lower price than comparable systems, says this company. These water flowmeters have a 0.5-in. digital display with a battery life of 5,000 h, and can be field-calibrated. The digital display of the TM Series shows flowrate, as well as two flow totals (one can be reset; the other is cumulative). TM Series flowmeters are available in line sizes of 0.5 to 4 in. with NPT, spigot and 150-lb ANSI flange fittings. They are suitable for applications including commercial water mixing tanks, geothermal heating and cooling towers, agricultural sprayers and cement mixers. — *Assured Automation, Clark, N.J.*
www.assuredautomation.com ■

Scott Jenkins



WHO'S WHO


Büchner


Brodersen


Lewis


Comerford


Lopes

Ton Büchner, president and CEO of Sulzer AG, will become CEO of **AkzoNobel NV** (Amsterdam) in January 2012, when current CEO *Hans Wijers* steps down.

Sönke Brodersen, head of research for **KSB Group (Frankenthal, Germany)**, will serve as president of Europump (Amsterdam), an umbrella association of European pump manufacturers, for the next two years.

Vanton Pump & Equipment Corp. (Hillside, N.J.) promotes *Lawrence Lewis* to president and *Kenneth Comerford* to vice president.

Aaron Miller becomes vice president of environmental affairs for **The DOE Run Co.** (St. Louis, Mo.), an operator of mining, milling, smelting and recycling facilities.

AvantorT Performance Materials (Phillipsburg, N.J.) promotes *Sushil Mehta* to executive vice president to lead the global laboratory and clinical business and *Paul Smaltz* to executive vice president to lead the pharmaceuticals business, and names *Brian Wilson* executive vice president of operations.

Dow Performance Materials (Buffalo Grove, Ill.) names *Carlos Silva Lopes* strategic marketing director.

Mark Witcher joins engineering firm **Integrated Project Services** (IPS; Lafayette Hill, Pa.) as senior biotechnology consultant. *Jeff Odum* joins IPS as senior technical consultant and director of N.C. Operations. ■

Suzanne Shelley

Evaluating Capital Cost Estimation Programs

Five capital-cost-estimation programs are compared using a set of case studies

Ying Feng and Gade P. Rangaiah
National University of Singapore

TABLE 1. CLASSIFICATION OF CAPITAL COST ESTIMATES
AACE International Recommended Practice No. 18R-97 cost estimate classification system

Class / type	Purpose	Accuracy	Level of project completion
Class 5: Order of magnitude estimates	Initial feasibility study or screening	L:-20 to -50% H: 30 to 100%	0–2%
Class 4: Study or preliminary estimates	Concept study or feasibility	L: -15 to -30% H: 20 to 50%	1-15%
Class 3: Definitive estimates	Budget, authorization or control	L: -10 to -20% H: 10 to 30%	10–40%
Class 2: Detailed estimates	Control or bid/tender	L: -5 to -15% H: 5 to 20%	30–70%
Class 1: Check estimates	Check estimate or bid/tender	L: -3 to -10% H: 3 to 15%	50–100%

TABLE 2. PURCHASE COST (C_{PCS}) OF COMPRESSORS

Compressor			CapCost	DFP	CCEP	EconExpert	AspenPEA
	Power, kW	Material	C_{PCS}	Δ%	Δ%	Δ%	Δ%
CS7-G-101	58	CS	217,350*	278%*	-4%*	-65%*	-27%
CS4-C-101	183	CS	217,350*	226%	-16%	-27%	-24%
CS5-C-101	364	CS	217,350*	454%	78%	92%	33%
CS6-C-101	3,100	CS	1,113,200	162%	128%	174%	-37%

*cost of minimum size, as size is less than the minimum size

Capital cost assessment is an integral part of process design when building or expanding a chemical process plant. It is required to provide project analysis and evaluation, to select among alternative designs, to plan the appropriation of funds and to serve as a basis for project cost control. Capital cost estimation is also important for an engineerng student's final design project.

The accuracy of capital cost estimates depends on the available design details, the accuracy of the cost data, as well as the time available to prepare estimates. The generally accepted classification of capital cost estimates (Table 1) is published by the Association for the Advancement of Cost Engineering (AACE International). Currently, several methods and associated computer programs exist for estimating capital cost, and they provide mainly study or preliminary estimates (Table 1; Class 4).

An evaluation and comparison of the computer programs available for capital cost estimation provides a better understanding of both their use and the methods behind them. This article arose out of a systematic effort by the authors to apply and analyze several programs available for capital cost estimation. The goals of this effort were to evaluate available cost estimation programs, apply the programs to case studies of plant design and to analyze the cost estimates for different types of equipment.

Five programs are discussed here — CapCost, EconExpert, AspenTech Process Economic Analyzer (AspenPEA), Detailed Factorial Method (DFP) and Capital Cost Estimation Program (CCEP). They were evaluated using seven case studies taken from textbooks. The selected case studies involve petroleum refining, petrochemical and biopharmaceutical processes. The cost estimates are compared and analyzed at both the equipment and plant levels to uncover the relative strengths of each of the programs used.

Estimation methods

Capital cost estimation methods in various process design reference books range from simple order-of-magnitude schemes to more detailed module costing and factorial methods. Common methods for preliminary capital cost estimation are based on the Lang factor method, the detailed factorial method and the module costing method. Most available cost estimation programs in the open literature use one of these methods.

In the Lang factor method [1], plant capital cost is determined by multiplying the sum of the purchase costs of major equipment by a lumped factor called the Lang factor. Since the Lang factor is used across the whole plant, it applies the same installation factor to all equipment types in the plant, irrespective of material of construction and pressure. Sinnott and Towler [2] proposed a modified Lang factor method to estimate inside battery limit cost (C_{ISBL}) and fixed capital cost. This modified method accounts for varying installation factors in different processes, but not for different types of equipment. However, material of construction is considered through a material factor in calculating C_{ISBL}.

Another cost estimation method is the module costing method originally introduced by Guthrie [3]. This method is well accepted for estimating the cost of a new chemical plant in the preliminary stage. It is detailed, and includes a breakdown of cost categories for de-

TABLE 3. PURCHASE COST (C_{PCS}) OF HEAT EXCHANGERS

DFP ESTIMATE FOR ALL SHELL-AND-TUBE HEAT EXCHANGERS IS FOR U-TUBE TYPE; CS=CARBON STEEL; SS=STAINLESS STEEL

Heat exchanger – shell and tube (Floating-head type)			**CapCost**	**DFP**	**CCEP**	**EconExpert**	**AspenPEA**
	Area, m^2	Material	C_{PCS}	Δ%	Δ%	Δ%	Δ%
CS4-E-102	4.62	CS/CS	28,750*	–3%*	–28%*	–75%*	–37%
CS2-E-104	18.2	CS/CS	26,680	10%	–21%	–66%	50%
CS3-E-101/ 102/103/104	26.4	CS/CS	26,680	11%	–18%	–59%	–22%
CS4-E-103	28.2	CS/CS	26,795	12%	–17%	–58%	–24%
CS5-E-106	76.7	CS/CS	33,120	10%	–14%	–43%	–6%
CS5-E-107	127	CS/CS	40,940	8%	–15%	–38%	–3%
CS1-E-103/104	150	CS/CS	44,620	8%	–16%	–37%	–3%
CS4-E-101	405	CS/CS	87,055	11%	–26%	32%	–3%
CS5-E-101	541	CS/CS	111,320	13%	–16%	–39%	–7%
CS5-E-109	680	CS/CS	138,000	14%	–34%	–42%	11%
CS1-E-102	740	CS/CS	149,500	14%	–34%	–43%	–25%
CS5-E-108	902	CS/CS	181,700	15%	–38%	–35%	0%
CS5-E-104	2130	CS/CS	430,100	9%	–40%	–42%	-4%
CS5-E-105	2900	CS/CS	587,650	19%	–39%	–43%	-2%
CS6-E-106	11.7	SS/SS	27,945	0%	–26%	–73%	–31%
CS6-E-101	14.6	SS/SS	27,140	5%	–23%	–69%	–29%
CS4-E-106	41	SS/SS	28,060	12%	–15%	–52%	–17%
CS6-E-102	61.6	SS/SS	30,820	11%	–1%	–46%	–13%
CS6-E-105	131	SS/SS	41,515	9%	–4%	–38%	–4%
CS6-E-107	192	SS/SS	51,290	8%	–7%	–36%	–1%
CS4-E-105	269	SS/SS	63,940	9%	–21%	–36%	3%
CS5-E-102	456	SS/SS	96,025	12%	–28%	–38%	–5%
CS6-E-104	1090	SS/SS	224,250	4%	–45%	–40%	–8%
CS6-E-103	1760	SS/SS	355,350	31%	–28%	–45%	12%
CS5-E-103	2010	SS/SS	405,950	15%	–27%	–41%	–4%
Heat exchanger – shell and tube (Fixed-head type)							
CS2-E-101	14.3	CS/CS	22,540	28%	–52%	–72%	49%
CS1-E-101	20	CS/CS	26,565	9%	–19%	–64%	–22%
CS7-E-102	100	CS/SS	34,155	20%	–36%	–32%	–15%
CS7-E-103	240	CS/SS	48,990	34%	–29%	–16%	–3%
Heat exchanger – kettle reboiler							
CS2-E-102	85.3	CS/CS	120,750	–58%	–67%	–73%	67%
CS4-E-104	37.3	SS/SS	59,340	–36%	–47%	–78%	–61%
Heat exchanger – double pipe							
CS2-E-103	5.41	CS	4,796	–35%	–42%	26%	21%
Heat exchanger – plate							
CS7-E-101	57	SS	95,450	–88%	n/a$^+$	–80%	–41%

*cost of minimum size as size is less than the minimum size

$^+$ not available in this program and so taken from another program

riving installed costs from purchase costs. For each piece of equipment, Guthrie provided factors to estimate the direct costs of field materials, such as piping, concrete, steel, instruments, controllers, electrical hardware, insulation and paint, as well as the direct costs of field labor used for their installation. These factors include material erection and equipment setting, as well as the indirect costs involved in installation, such as insurance, construction overhead and contractor engineering expense. The bare module cost (C_{BM}) for a given piece of equipment i is thus defined as:

$$C_{BM,i} = C_{DE,i} + C_{IDE,i} = [C_P^o + C_M + C_L + C_{FIT} + C_O + C_E]_i \quad (1)$$

where $C_{BM,i}$, $C_{DE,i}$, $C_{IDE,i}$ and C_P^o are, respectively, bare module cost, direct cost, indirect cost and purchase cost of equipment i in base conditions (that is, carbon steel material and atmospheric pressure). C_M is the cost of field materials required for installation, C_L is the cost of labor to install equipment and materials, C_{FIT} is the cost of freight, insurance and taxes, C_O is the cost of construction overhead and C_E is the cost of contractor engineering expenses. For the whole plant, Ulrich and Vasudevan [*4*] propose to find the total module cost (C_{TM}) by multiplying $C_{BM,i}$ for all equipment types by the factor 1.18 to account for contingency and contractor fee.

$$C_{TM} = \Sigma\,(C_{BM,i} + C_{Cont,i} + C_{Fee,i}) = 1.18\,\Sigma\,C_{BM,i} \quad (2)$$

where $C_{Cont,i}$ is contingency fee and $C_{Fee,i}$ is the contractor fee.

Computer programs

The five progams used in this study are CapCost, DFP, CCEP, EconExpert and AspenPEA. Most programs use a parametric-cost model for the cost estimates, which is useful in early conceptual estimates [*5*]. The cost equation constants used in these programs are obtained from vendor quotes or from past literature data. As discussed by Woods [*6*] and Walas [*7*], when cost data are assembled from vendor quotes, they exhibit scatter due to different qualities of equipment design, fabrication, market conditions, vendor profit and other considerations. Hence, the accuracy of published equipment-cost data may be no better than ±25%, and therefore the estimating method based on these data can only be used for study or preliminary estimates.

CapCost is available with the process design book of Turton and coauthors [*1*]. It is based on the module costing method, written in Visual Basic, and can be used for estimating preliminary process cost. Bare module cost (C_{BM}) is defined as the sum of the direct and indirect expenses for purchasing and installing equipment; the total module cost (C_{TM}) is defined as the sum of the bare module cost, contingency and fee; and the grassroots plant cost (C_{GR}) is defined as the sum of the total module cost and the auxiliary facilities costs. To estimate the bare module cost and purchase cost of equipment, Turton and colleagues proposed the following:

$$C_{BM} = C_P^o \times F_{BM} = C_P^o\,(B_1 + B_2F_MF_P) \quad (3)$$

$$\log C_P^o = K_1 + K_2\log(S) + K_3[\log(S)]^2 \quad (4)$$

where S represents a parameter for the equipment size or capacity. Values for the constants B_1 and B_2, equipment-specific constants K_1, K_2 and K_3, as well as correlations and plots for F_{BM}, F_M, F_P and $C^o{}_P$ of different equipment can be found in the appendices in Ref. *1*. These data are based on surveys of equipment vendors between May and September 2001. The *Chemical Engineering* Plant Cost Index (CEPCI; see p. 56 and www.che.com/pci for current value) value of 397 for this period can be used for escalating cost to a different time.

Detailed Factorial Program (DFP) is based on the detailed factorial estimates method described in Ref. *2*. For this program, the purchase cost, C_P^o, of the major equipment items is esti-

TABLE 4. PURCHASE COST (C_{PCS}) OF MIXERS

Mixer Details			CapCost	DFP	CCEP	EconExpert	AspenPEA
	Power, kW	Material	C_{PCS}	Δ%	Δ%	Δ%	Δ%
CS3-M-101	0.7	CS	37,375*	38%*	n/a$^+$	–83%*	–70%*
CS7-M-105	0.015	SS	37,375*	–94%	n/a$^+$	–99%	–97%
CS7-M-104	2	SS	37,375*	–37%	n/a$^+$	–81%	–67%
CS7-M-103B	2.5	SS	37,375*	–37%	n/a$^+$	–79%	–64%
CS7-M-103A	4.2	SS	37,375*	–37%	n/a$^+$	–74%	–57%
CS7-M-102	7	SS	40,595	–36%	n/a$^+$	–68%	–52%
CS7-M-101	146	SS	103,730	16%	n/a$^+$	56%	–13%

*cost of minimum size as size is less than the minimum size
$^+$mixer cost not available for CCEP

mated using the following:

$$C_P^o = a + bS^n \tag{5}$$

Cost constants a and b, available in Ref. *2* for different equipment items, are mainly for carbon-steel material, and correspond to January 2007 (CEPCI of 509.7). The ISBL cost and fixed capital cost are calculated according to the method in Ref. *2*.

Capital Cost Estimation Program (CCEP) uses cost correlations in Seider [*8*] for estimation of free-on-board purchase cost of equipment. The material factor and Guthrie's bare module factor are used thereafter to estimate the installed cost of that equipment. Seider [*8*] developed the purchase cost correlations for common process equipment, based on available literature sources and vendor data. A list of these cost correlations can be found in Ref. *8*, using CEPCI = 500. The purchase cost of the major equipment items is estimated using the following:

$$C_P^o = e^{\{A_0 + A_1[ln(S)] + A_2[ln(S)]^2 + \ldots\}} \tag{6}$$

Values of constants A_0, A_1 and A_2 for various equipment items can be found in Ref. *8*. In addition to size, other factors, such as material of construction and operating pressure, are also taken into consideration in estimating the purchase cost. Therefore, the cost equations are often in the following form:

$$C_p = F_M F_P C_P^o \tag{7}$$

where C_P is the purchase cost of equipment; F_M is the material factor and F_P is the pressure factor. CCEP and DFP were developed in Microsoft Excel and Visual Basic environments, by Wong [*9*] and Huang [*10*], respectively, as part of research projects supervised by the second author (these programs can be obtained from the authors).

EconExpert is a Web-based interactive software for capital cost estimation [*11*]. Similar to CapCost, the equipment module costing method is used to calculate bare module cost and total module cost from the purchase cost of equipment. The purchase cost data and bare module factors used can be found in Ref. *4*. In this textbook, the cost data are expressed in graphical form, whereas in EconExpert, the plots are represented as polynomial equations for calculation of the purchase cost. Multiple regression is used to fit the data if the purchase cost is dependent on more than one variable. The cost data and correlations in EconExpert are for a CEPCI of 400 [*4*].

AspenPEA is built on Aspen Icarus technology, and is designed to generate both conceptual and detailed estimates [*12*]. It takes a unique approach, representing equipment by comprehensive design-based installation models. AspenPEA claims to contain time-proven, field-tested, industry-standard cost modeling and scheduling methods [*12*]. AspenPEA Version 7.1 was used for this study (this version follows 2008 data, where the CEPCI is 575).

Equipment examples

Seven case studies based on process design data available in Refs. *1, 4, 8* and *13* were chosen for this study. In Case 1 from Ref. *13*, a petroleum refinery distillation column (the alkylate splitter) is employed to separate a mixture of C4 to C14 hydrocarbons into two streams. Case 2 is the monochlorobenzene (MCB) separation process in Ref. *8*. Case 3 is a crystallization process from the same source. Case 4 is the formalin production process from methanol using silver catalyst [*1*]. A styrene production process in the same reference is Case 5. Case 6 is an alternative synthesis of maleic anhydride via benzene in a shell-and-tube reactor with catalyst [*1*]. Case 7 is a ß-galactosidase batch process via recombinant *Escherichia coli* [*4*].

The five computer programs were used to evaluate capital costs for each case. A CEPCI of 575 was used throughout to allow cost estimates by all programs to be compared meaningfully. The CEPCI generally trends upward over time. An exception was 2009, when the CEPCI dropped to 525 (from 575 in 2008) so, the CEPCI seems likely to return to 575 in the near future.

The CapCost program is used as the reference for comparison, although any other program could have been used. The base condition (equipment made of carbon steel and operating near ambient pressures) purchase cost (C_{PCS}) and total module cost (C_{TM}) are compared and analyzed. In DFP, CCEP and AspenPEA, calculated purchase cost is directly based on actual material of construction and pressure. Hence, C_{PCS} in these programs is calculated by entering equipment details for the same condition as the one required using carbon steel as the material of construction and 1 barg as the operating pressure.

As the module costing technique is not used in DFP and AspenPEA, only C_{ISBL} and C_{Direct}, respectively, are available from these programs. By analyzing the cost factors, including C_{TM}, C_{ISBL} and C_{Direct}, it is observed that C_{TM} includes engineering design, contract fees and contingency fees, while the other two do not. Hence, C_{TM} in DFP and AspenPEA is calculated by Equations (8) and (9), respectively.

$$C_{TM} = C_{ISBL}(1 + DE + X) \tag{8}$$

$$C_{TM} = C_{Direct}(1 + DE + X) \tag{9}$$

Here, C_{ISBL} is the inside battery limit cost; and $DE = 0.3$ and $X = 0.1$, according to the factors stated in the detailed factorial method [*2*].

Some process equipment may have sizes outside the valid range for the cost correlations or for the program. For all programs, if a piece of equipment has a size above the valid range, it is divided into multiple units of smaller size and the costing is done by summing up C_{TM} of multiple smaller units. If equipment has a specification below the valid range, then its cost is estimated by taking the lower limit of the valid range. Similarly, for flowrates less than the minimum amount required for costing, the minimum flowrate is used instead of the actual flowrate. This causes some uncertainty in the predicted cost.

In the following sections, base condition purchase cost (C_{PCS}) and total module cost (C_{TM}) for equipment in the seven case studies are compared.

TABLE 5. PURCHASE COST (C_{PCS}) OF PUMPS

Centrifugal pumps			CapCost	DFP	CCEP	Econ-Expert	Aspen-PEA
	Power, kW	Material	C_{PCS}	Δ%	Δ%	Δ%	Δ%
CS4-P-101	0.3	CS	3,554*	152%	50%*	7%	55%
CS5-P-104	0.38	CS	3,554*	156%*	49%*	14%*	57%*
CS6-P-101	0.46	CS	3,554*	152%*	62%*	21%	57%
CS5-P-105	0.75	CS	3,554	165%	46%	39%	60%
CS2-P-102	1.12	CS	3,577	164%	48%*	57%	35%
CS1-P-102	1.7	CS	3,726	165%	27%*	73%	53%
CS4-P-102	1.7	CS	3,726	110%	46%*	73%	53%
CS5-P-102/103	2	CS	3,807	166%	54%*	79%	50%
CS2-P-101	2.24	CS	3,876	176%	28%*	83%	37%
CS5-P-106	2.65	CS	3,979	209%	53%	89%	76%
CS1-P-101	2.8	CS	4,025	251%	26%	91%	89%
CS6-P-102	5.84	CS	4,807	297%	120%	110%	123%
CS5-P-101	6.4	CS	4,934	289%	75%	112%	107%
CS1-P-103	24	CS	8,257	204%	24%	117%	10%
CS4-P-103	0.5	SS	3,554*	146%	59%*	24%	57%
CS6-P-105	1.08	SS	3,565	143%	223%	56%	57%
CS7-P-101	2.3	SS	3,887	163%	51%*	84%	50%
CS6-P-106	3.69	SS	4,267	145%	294%	99%	132%
CS6-P-104	10.4	SS	5,808	438%	140%	118%	58%
Reciprocating pumps							
CS3-P-104	0.2	CS	7,659	n/a$^+$	–25%*	11%	–9%*
CS3-P-105	0.24	CS	7,613	n/a$^+$	–24%*	11%	–8%*
CS3-P-103	0.6	CS	9,258	n/a$^+$	–55%	22%	–24%*
CS3-P-101	22.4	CS	47,380	n/a$^+$	–21%	22%	–38%*
CS3-P-102	29.6	CS	57,500	n/a$^+$	–35%	22%	–49%*
CS6-P-103	0.16	SS	7,176	n/a$^+$	–29%*	4%	–3%*
Diaphragm pumps							
CS7-P-105	1	SS	10,730	n/a$^+$	45%*	26%	–50%
CS7-P-103	1.9	SS	13,455	n/a$^+$	182%*	27%	–50%
CS7-P-102	3.7	SS	17,710	n/a$^+$	–36%	27%	–51%
CS7-P-104	60	SS	95,105	n/a$^+$	17%	25%	–87%

*cost of minimum size as size is less than the minimum size

$^+$ not available in this program and so taken from another program

Compressors

Major compressor types are trunk-piston and crosshead reciprocating compressors, diaphragm compressors, centrifugal compressors and axial compressors. Case studies 4–7 involve compressors, and purchase costs of these compressors at base conditions are presented in Table 2. Total module cost is shown in online table I.

In these and subsequent tables, the cost estimate by CapCost is given, and the cost estimate by other methods is expressed as the percent difference from that by CapCost, such that Δ = 100 × (cost using other method – cost using CapCost) / cost using CapCost). Hence, a positive (or negative) Δ value means the cost estimate by that method is more (or less) than that determined by CapCost.

Results in Table 2 indicate that compressor purchase cost estimates by CapCost, CCEP and AspenPEA are comparable, while the purchase costs given by EconExpert increase very fast with increasing size. In fact, DFP gives a very high cost compared to all other programs, which is mainly due to the cost equation given in Ref. *2*. From this equation, even the lower limit (power of 75 kW) gives a cost as high as $714,050. Such a high cost may be due to the data source for calculation of empirical constants. Differences in total module cost of compressors by different programs are larger than those in purchase costs (Table online), which is due to differences in installation and other factors used for C_{TM}.

Heat exchangers

Common heat-exchanger types are shell-and-tube, double-pipe, air-cooled fin fan, and compact heat exchangers, including plate-and-frame and spiral plate types. Because heat exchangers are common, the data available from vendors and other sources are voluminous. The wealth of data results in relatively more-accurate cost estimation. For example, the purchase cost and total module costs of floating-head and fixed-head heat exchangers predicted by all programs are comparable, with somewhat lower cost by CCEP and EconExpert (Table 3). For kettle reboilers, CapCost predicts 50 to 80% higher purchase and total module costs than the other four programs. For double-pipe heat exchangers, all programs predict comparable purchase cost. However, AspenPEA predicted a total module cost three times that by CapCost (online table II). The most significant factor contributing to the high total module cost in AspenPEA is the piping cost. While other programs calculate piping cost as a small fraction of purchase cost, AspenPEA model calculates piping cost based on respective equipment. For double-pipe heat exchangers, the piping cost is around three times the purchase cost, which contributes $10 \times C_{PCS}$ to C_{TM}.

Figure 1 shows the total module cost of floating-head heat exchangers calculated in all five programs as a function of heat transfer area. Since only the U-tube shell-and-tube heat exchanger cost equation is given in Ref. *2*, the DFP estimate in Figure 1 is for this type. Since floating-head heat exchangers are generally costlier than the U-tube type, the floating-head heat exchanger cost by DFP is expected to be slightly higher than that in Figure 1.

For smaller heat transfer areas (up to 400 m^2), all five programs predict total module cost for floating-head exchangers with less than 50% deviation using the CapCost value as a reference. As the area increases, the deviations become more significant. In the seven case studies, many of the floating-head heat exchangers have areas below 400 m^2. Hence, all five programs predicted similar costs. However, when the heat transfer area is large, CapCost and DFP predict a relatively higher cost than the other programs.

Figure 2 shows the variation in the total module cost of fixed-head heat exchangers calculated by all five programs, with heat transfer area. Since only the U-tube shell-and-tube heat exchanger cost equation is given in Ref. [*2*], the DFP estimate in Figure 1 is for this type. CCEP and EconExpert predict lower costs than the other three programs for all sizes of fixed-head heat exchanger. However, for smaller areas, (up to 300 m^2) the percent deviation is relatively small. In the case studies, most of the fixed-head heat exchangers have areas below 300 m^2. Hence, all five programs predicted a similar cost. As the area

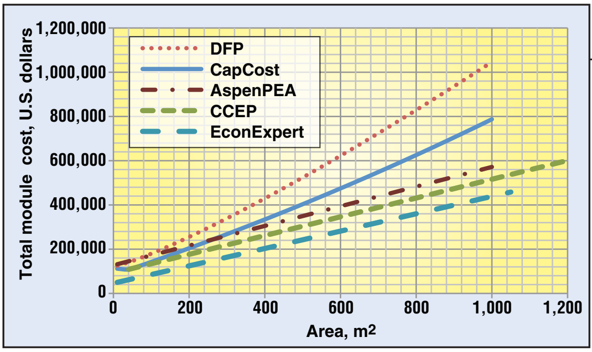


FIGURE 1. As the area of floating-head heat exchangers increases the deviation in total module cost estimates grows

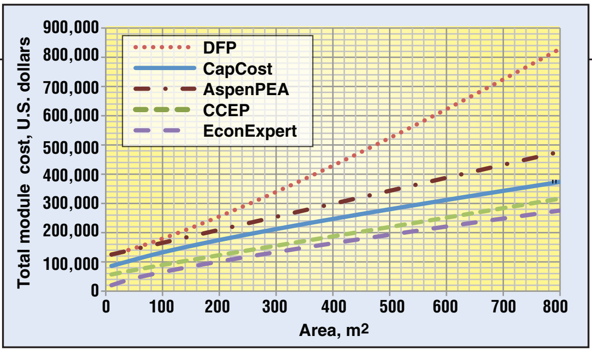


FIGURE 2. Fixed-head heat exchangers are generally less expensive, but deviations in estimates still increases with area

TABLE 6. PURCHASE COST (C_{PCS}) OF TOWERS

Tray Towers				CapCost	DFP	CCEP	EconExpert	AspenPEA
	Dia., m	Length, m	Material	C_{PCS}	Δ%	Δ%	Δ%	Δ%
CS2-T-102	0.5	12.8	CS	26,105	–9%	249%*	n/a+	0%
CS2-T-101	0.9	21.9	CS	63,135	–19%	121%	n/a+	–4%
CS1-T-101	3.0	30.0	CS	483,000	26%	29%	n/a+	76%
CS5-T-101	3.6	28.0	CS	702,650	6%	16%	n/a+	–18%
CS6-T-102	1.1	18.0	SS	78,775	25%	89%	n/a+	87%
CS4-T-102	2.5	19.0	SS	230,000	24%	48%	n/a+	21%
CS6-T-101	4.2	10.0	SS	565,800	–5%	–57%	n/a+	–51%
Packed Tower								
CS4-T-101	0.9	10.0	CS	21,045	63%	284%*	n/a+	135%

*cost of minimum size as size is less than the minimum size
+ cost trays and packing are not included in EconExpert, and hence not compared

increases, the differences become more significant, with DFP predicting a significantly higher cost than all the others. This may be partially due to the mapping of fixed-head heat exchanger to U-tube heat exchanger in DFP. In general, fixed-head heat exchangers are slightly less expensive than U-tube heat exchangers [*8*] (Table 3, Figures 1–2 and online table II).

The total module cost of double-pipe heat exchangers is plotted against heat transfer area in Figure 3. AspenPEA predicts a significantly higher cost than all other programs (again, mainly due to the higher cost of piping predicted). For double-pipe exchangers, EconExpert and CapCost predicted similar costs, while DFP and CCEP predicted slightly lower cost (Figure 3).

Mixers

Of the huge variety in mixer designs available, common types are ribbon and tumbler mixers, kneaders and mullers. Mixer costing is not included in the CCEP program. Mixer purchase costs differ by 50–100% among different programs (Table 4). The deviation in total module cost (online table III) is similar to that for the purchase cost for EconExpert and AspenPEA. However, the total module cost given by DFP is higher due to a large installation factor for mixers in this method. The cost estimate by DFP and EconExpert increases faster than that by CapCost, and so the former two predict significantly higher cost than CapCost for large mixers. For example, the total module cost of CS7-M-101 by DFP and EconExpert are, respectively, 193% and 160% of that by CapCost, even though the purchase costs are comparable. This is due to the limitation of mixer size in DFP, which requires its costs to be estimated as that of two smaller mixers. Such a mapping increases the cost significantly. Also, selection of materials of construction is not available in CapCost, which results in similar costs for mixers of different materials in that program.

Pumps

Commonly used pumps in chemical processing plants are radial-centrifugal, plunger-reciprocating, diaphragm and external-rotator-gear pumps. For centrifugal pumps, the four other programs predict higher purchase and total module costs than CapCost, with DFP giving costs up to three times of those predicted by CapCost (Table 5). One reason for this difference may be due to using different input data. While CapCost and EconExpert programs require only pump power for cost prediction, DFP requires flowrate and liquid density, in addition to pump power, and CCEP and AspenPEA require flowrate and pump head. Hence, two pumps with the same power, but different flowrates due to design pressures, will have the same cost in CapCost and EconExpert, but different costs in the other three programs. However, even though both CapCost and EconExpert use pump power to predict the cost, they have rather different results. This difference is due to the variation in cost data used in these two programs to calculate purchase cost.

For centrifugal pumps, purchase and total module costs by AspenPEA deviate by 50–100% and 100–400%, respectively, from those of CapCost (Table 5). The high total module cost is mainly due to the higher piping cost given by AspenPEA. Reciprocating pumps are not available in DFP. The other four programs give similar purchase costs (Table 5 and online table). However, CCEP predicts 50% lower total module cost than CapCost (online table). This is due to different module factors used in the two programs. For diaphragm pumps with small power, the deviation in total module cost between different programs is within 70%. However, when the power is large, the deviation between different programs increases further (online table IV).

In Figure 4, the total module costs of centrifugal pumps are plotted against their power. In general, DFP and AspenPEA predict higher cost than the others. For low-power pumps, DFP and AspenPEA predict similar costs. However, as the power increases, DFP predicts a higher cost than AspenPEA. CapCost gives the lowest, and EconExpert predicts a cost in the middle range. This observation coincides with the results obtained in case studies above. Compared to other programs, the cost

TABLE 7. PURCHASE COST (C_{PCS}) OF VESSELS

All vessel pressures less than 10 barg except CS1-V-101 with pressure = 60 barg

Vessel – horizontal				CapCost	DFP	CCEP	EconExpert	AspenPEA
	Dia., m	Length, m	Material	C_{PCS}	Δ%	Δ%	Δ%	Δ%
CS2-V-101	0.9	1.4	CS	5,014	155%*	372%*	1%	21%*
CS6-V-101	1.2	3.5	CS	9,212	308%*	188%*	1%	89%
CS5-V-102/103	1.3	3.9	CS	10,603	52%	183%	2%	105%
CS1-V-102	1.6	4.7	CS	14,490	38%	87%	4%	78%
CS1-V-101	2.7	8.0	CS	38,640	–10%	93%	–4%	14%
CS6-V-103	1.3	3.9	SS	10,787	552%*	180%*	2%	104%
CS4-V-101	1.7	6.9	SS	9,718	173%	345%	5%	111%
CS7-VS-105	2.0	3.2	SS	15,295	44%	189%	27%	80%
CS7-VS-106	2.5	6.1	SS	29,670	19%	135%	30%	43%
CS6-V-102	4.4	13.2	SS	136,850	260%	–14%	–45%	–28%
Vessel – vertical								
CS2-V-102	0.9	3.7	CS	6,992	629%	441%*	102%	40%*
CS3-V-101	1.8	3.7	CS	15,985	12%	191%	58%	72%
CS5-V-101	2.5	7.4	CS	40,135	–14%	130%	35%	17%
CS5-V-104	4.0	34.5	CS	386,400	–56%	–13%	–31%	–27%
CS7-V-102	0.4	6.0	SS	4,025	291%	923%*	276%	151%
CS7-VS-102	0.5	1.0	SS	2,841	430%*	1301%*	71%*	127%
CS7-V-101	0.5	5.0	SS	4,761	238%	765%*	194%	144%
CS7-VS-104	1.2	1.8	SS	6,348	141%	527%	11%	56%
CS7-VS-103	1.5	2.0	SS	8,591	93%	414%	17%	26%
CS7-VS-101	3.5	10.5	SS	97,405	–44%	85%	–15%	–54%
Vessel – jacketed								
CS7-VS-110	2.0	3.8	SS	59,300+	n/a$^+$	n/a$^+$	n/a$^+$	n/a$^+$
CS7-VS-109	2.3	4.5	SS	75,600+	n/a$^+$	n/a$^+$	n/a$^+$	n/a$^+$
CS7-VS-108	3.0	4.8	SS	124,500+	n/a$^+$	n/a$^+$	n/a$^+$	n/a$^+$
CS7-VS-107	3.2	8.5	SS	199,100+	n/a$^+$	n/a$^+$	n/a$^+$	n/a$^+$

*cost of minimum size as size is less than the minimum size

$^+$not available in this program and so taken from another program

of a centrifugal pump in CCEP depends on an additional factor: the stages and split-case orientation. For lower-power pumps (up to 55 kW and flowrates up to 57 L/s), the pump is operating in one stage and vertical split case, and the cost is lower. For higher power and flowrates, the pump operates in two or more stages and horizontal split case, and the cost is higher. Hence, a jump is observed for the CCEP cost in Figure 4 due to the change of stages. The CCEP program warns the user if the pump is not operating in the appropriate stage.

When C_{TM} for reciprocating pumps is plotted against shaft power, EconExpert gives the highest cost of the four programs, followed by CapCost and CCEP, while AspenPEA predicts the lowest (reciprocating pumps are not available in DFP). This result is similar to what is observed in case studies.

Towers

Towers are vertical-pressure vessels for separation operations, such as absorption, distillation and stripping. They contain trays or packing, plus manholes and nozzles. For both towers and vessels, shell thickness is required for cost estimation in DFP. Since in most cases, the designed pressure is provided in the equipment data, the following equation from Ref. *1* is used to estimate the shell thickness.

$$t = [PD \div (2S_{max}E - 1.2P) + CA] \quad \textbf{(10)}$$

Here, t is the shell thickness in meters, P is the design pressure in bars, D is the diameter of the vessel (meters), S_{max} is the maximum allowable working pressure of the material (bars), E is the weld efficiency and CA is the corrosion allowance (0.0035 m).

For tray towers, the purchase cost given in EconExpert does not include trays and packing, while those are included in the total module cost. Hence, EconExpert's purchase cost is not compared with CapCost (Table 6). DFP gives a purchase cost similar to CapCost, whereas CCEP is higher when the diameter is small (or lower when large). When the total module cost of the tower is compared, for towers of large diameter, all programs give similar results (online table V). CCEP shows a relatively higher total module cost (+59%). For small-dia. towers, CapCost predicts a much lower cost than the others. A packed tower is also evaluated (Table 6). CapCost predicts a much lower cost than the rest. Both CCEP and AspenPEA predict the cost of this packed tower to be significantly higher than that by CapCost.

Vessels

Vessels are used in chemical processing plants as reflux drums, flash drums, knock-out drums, settlers, chemical reactors, mixing vessels and storage drums. In general, for horizontal vessels with low design pressure and small diameter, CapCost and EconExpert predict similar purchase and total module costs while the others give much higher costs (Table 7). For horizontal vessels of large diameter, CapCost, DFP and EconExpert give similar results, while CCEP predicts a higher cost. The total module cost in AspenPEA is exceptionally high due to the high instrumentation cost, which is three times C_{PCS}. This contributes to C_{TM} as ten times C_{PCS} (online table VI).

For vertical vessels, CapCost gives significantly lower costs than the other four programs. However, when the design pressure of the vessel is very high (CS1-V-101), CapCost predicts a very high pressure factor according to:

$$\log_{10} F_P = C_1 + C_2 \log_{10} P + C_3(\log_{10} P)^2 \quad \textbf{(11)}$$

where C_1, C_2 and C_3 are constants that can be found in Ref. *1*. Hence, although the purchase cost from CapCost is comparable or even lower than in other programs, the total module cost in CapCost is much higher than that by the other four programs.

The plot of total module cost of horizontal vessels against volume (Figure 5) shows that CapCost and EconExpert predict similar total module costs for horizontal vessels. DFP predicts a slightly higher cost, whereas AspenPEA and CCEP predict the highest costs. Also, CCEP's cost of horizontal vessels increases faster with increasing volume than that by AspenPEA. When volume is large, CCEP predicts a much higher cost than AspenPEA, and the deviation becomes more significant as the volume and size increase. The horizontal vessels evaluated in the case studies are all below 100 m^3 (Table 7), and their costs follow these trends.

For vertical vessels of small diameter, CapCost predicts lower purchase and total module costs than the others (Figure 6, Table 7 and online table VI). However, for large-diameter vertical vessels (CS7-VS-101), the cost given

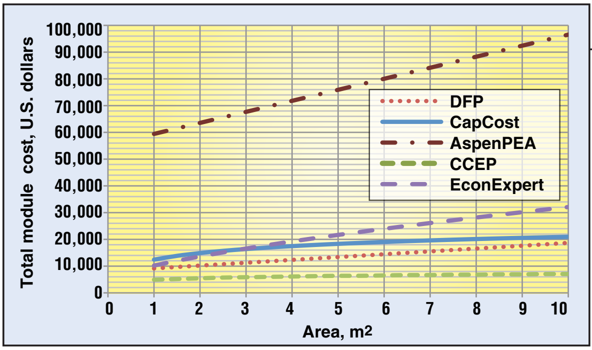


FIGURE 3. Due to its treatment of piping, DFP predicts a higher total module cost for double-pipe heat exchangers

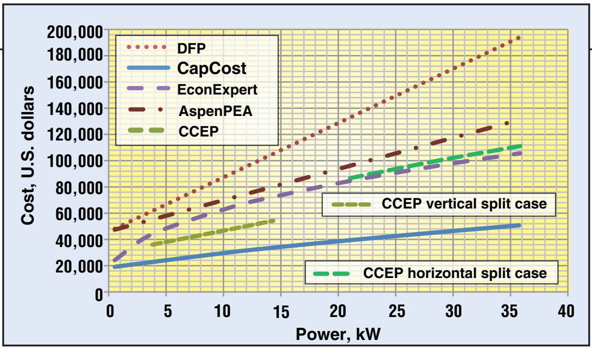


FIGURE 4. DFP and AspenPEA predict higher total module costs of centrifugal pumps than other programs

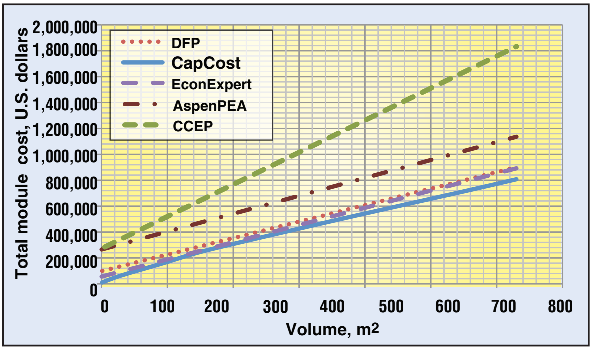


FIGURE 5. Total module cost predictions for horizontal vessels are lowest for CapCost

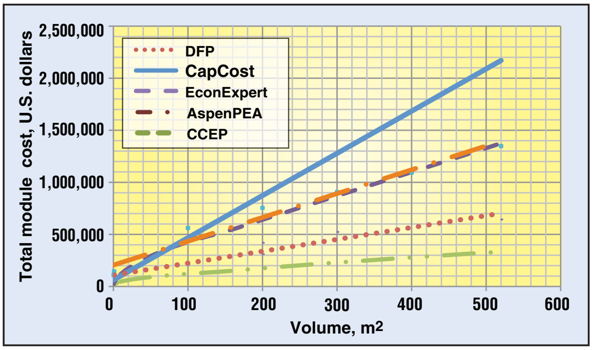


FIGURE 6. The rate of increase in predicted total module cost for vertical vessels is greatest with CapCost

by CapCost is lower than CCEP only. The rate of cost increase by CapCost is faster than that by other programs. While CapCost's cost is low for small volumes, its predicted cost is the highest for volumes more than 200 m^3.

Other equipment

In this section, other pieces of equipment, such as centrifuges, crystallizers, fired heaters, mills, filters and jacketed and agitated reactors are discussed (Table 8). Crystallizers and centrifuges are not listed in DFP and EconExpert. AspenPEA gives high purchase and total module costs compared to CapCost and CCEP for both crystallizers and centrifuges. The deviation is mainly due to differences in the C_{PCS} predicted based on different correlations in the programs.

In case studies five and six, fired heater cost is evaluated. For CS5-H-101, all programs give similar purchase and total module costs with DFP giving a relatively higher cost than the rest. However, the cost of CS6-H-101 shows significant deviation for different programs. Due to limited data, the trend of fired heater cost is not clear.

In case study seven, there are equipment types that are not present in earlier case studies. The first is a mill, whose costing is available only in EconExpert and AspenPEA. Comparing the results in Table 8 (and online table VII), both purchase and total module costs predicted by EconExpert are half that predicted by AspenPEA. This is mainly caused by the different approach in calculating the purchase cost of the mill in different programs. Filters and filtering centrifuges can only be found explicitly in CapCost, EconExpert and AspenPEA. In AspenPEA, there are more types of filters and centrifuges to which to map the process equipment, compared to fewer choices for CapCost and EconExpert. Due to the mapping to different type of filters, the costs predicted deviate from one another. However, the deviation is within the acceptable range for those which are within the size range. Furthermore, jacketed

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TABLE 8. PURCHASE COST (C_{PCS}) OF OTHER TYPES OF EQUIPMENT

Centrifuges			CapCost	DFP	CCEP	EconExpert	AspenPEA
	Dia., m	Material	C_{PCS}	Δ%	Δ%	Δ%	Δ%
CS3-Ct-101	2	CS	303,600	n/a^{+}	n/a^{+}	n/a^{+}	49%
CS3-Ct-102	2	CS	303,600	n/a^{+}	n/a^{+}	n/a^{+}	49%
Crystallizers							
CS3-Cr-101	21.9	CS	139,150	n/a^{+}	–76%	n/a^{+}	210%
Fired heater							
CS6-H-101	26,800	CS	1,078,700	63%	112%	–46%	59%
CS5-H-101	360,000	CS	6,405,500	–23%	–15%	–13%	–35%
Mills							
CS7-C-101	0.00035	SS	67,100+	n/a^{+}	n/a^{+}	–90%	n/a^{+}
Filtering centrifuges							
CS7-S-103	0.00002	SS	53,900+	n/a^{+}	n/a^{+}	181%	n/a^{+}
Filters							
CS7-S-104	0.0075	SS	18,600*	n/a^{+}	n/a^{+}	–99%*	–98%
CS7-S-101	1.5	SS	18,600*	n/a^{+}	n/a^{+}	–89%	–47%
CS7-S-102	55	SS	131,000	n/a^{+}	n/a^{+}	n/a$^{\#}$	–37%
CS7-S-105	80	SS	170,200	n/a^{+}	n/a^{+}	n/a$^{\#}$	31%
CS7-S-106	90	SS	184,000	n/a^{+}	n/a^{+}	n/a$^{\#}$	33%
CS7-S-107	90	SS	184,000	n/a^{+}	n/a^{+}	n/a$^{\#}$	33%
Reactor-jacketed agitated							
CS3-R-101	28.4	CS	109,135	n/a^{+}	n/a^{+}	–70%	n/a^{+}
CS3-R-102	28.4	CS	109,135	n/a^{+}	n/a^{+}	–70%	n/a^{+}

*cost of minimum size as size is less than the minimum size

$^{+}$ not available in this program and so taken from another program

$^{\#}$ purchase cost not available in EconExpert

TABLE 9. TOTAL MODULE COST (C_{TM}) OF EQUIPMENT

Total module cost	CapCost	DFP	CCEP	EconExpert	AspenPEA
Case study	C_{TM}, $\$$million	Δ%	Δ%	Δ%	Δ%
1	4.3	–6%	–4%	–36%	–3%
2	1.0	16%	71%	–5%	68%
3	2.5	6%	–11%	–14%	81%
4	4.1	79%	19%	–29%	28%
5	33.3	27%	–23%	–28%	–36%
6	17.0	94%	14%	2%	–11%
7	9.4	34%	7%	8%	14%

and agitated reactors are only available in CapCost and EconExpert. The results obtained from these two are comparable (Table 8).

Total purchase and module cost

We also compared total purchase and total module costs for all pieces of equipment in each case study given by the different programs. For all programs, if a piece of equipment had a size above the valid range, it was divided into multiple units of smaller size and the costing was done by summing C_{TM} for multiple smaller units. If a piece of equipment had a specification below the valid range, then its cost was estimated by taking the lower limit of the valid range. Similarly, if the flowrate was less than the minimum required for costing, the minimum flowrate was used (not actual). Since layers of silver wire gauze inside the reactor cannot be mapped to any equipment in the programs, it is not evaluated in case four. For similar reasons, the cost of catalyst pellets is also excluded in the total fixed capital cost in case five.

The five programs give comparable purchase and total module costs for the whole plant in each case study (Table 9 and online table VIII), with DFP giving a slightly higher cost in some cases. In case study two, both the purchase and total module costs obtained by ApenPEA are more than 60% higher than those by CapCost. This is mainly due to the high costs of towers and vessels in AspenPEA. In case three, there is good agreement among different programs except for AspenPEA, which shows higher purchase and total module costs due to the high costs of crystallizers and vessels. In case studies four and six, the high deviations (more than 80%) in both purchase and total module cost in DFP are mainly due to cost differences in vessels and packing towers.

Conclusions

Although based on different methods and developed in different platforms, all five programs are user friendly and are useful tools for estimating the capital cost of chemical process plants. AspenPEA has the most equipment types available out of the five programs. DFP is the most limited in that regard. Based on our analysis, the overall plant cost does not deviate much among the different programs studied. However, equipment capital costs for different programs may not be comparable. There is generally good agreement for the purchase costs of floating-head heat exchangers. For fixed-head heat exchangers and pumps, there is greater deviation in both purchase and total module costs among different programs studied. Also, there is significant deviation for most vessels and towers in total module cost. Since material, pressure and installation factors vary in different methods in calculating total module cost, capital cost estimates may differ. Hence, while evaluating plant design alternatives, it is important to use only one program for cost evaluation of process design options to maintain consistent results. ■

Edited by Scott Jenkins

Editor's note: Additional tables for total module cost of equipment are included in the online version of this article (www.che.com).

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Today's Process Automation Worlds

An overview of the current and future direction of process control

Cecil L. Smith, Cecil L. Smith, Inc.

Modern industrial-automation systems rely entirely on digital technology, that is, computers. And as is typical of digital products, suppliers love to add features — data collection, alarm management, and so on — that are very useful for process operations but are not process control in the purest sense. This is continuing, the result being that process control systems are evolving to enterprise management systems.

We like to think that industrial automation is special, but in reality it follows the trends dictated by other segments of the computer industry. Adding features to process control systems is no different than the evolution of cell phones. Products such as the Android, iPhone, and so on, provide a plethora of functions, including navigation, Web browsing, playing music, morning wakeup (alarm clock), ad infinitum, and almost incidentally, a function that permits the user to have a verbal conversation with someone else — that is, what was at one time the sole function of a device called "a phone".

This article focuses on the control capabilities of modern process control systems. This is like focusing on the phone capabilities of modern cell phones. Although the cell phone has changed dramatically, the "phone" feature is pretty much what it always was — you talk and the other person hears you; the other person talks and you hear him or her. Perhaps the quality is somewhat better, but as long as you can understand each other, the technology is "good enough".

Similarly, the PID (proportional-integral-derivative) control equation is still the workhorse in process control. Academicians extol the virtues of MPC (model predictive control), but as long as our plants make salable product, any control technology is, in a sense, "good enough". Digital technology facilitates implementing more sophisticated control schemes, but only when the improvements in plant performance justify the additional expenditures.

Automation practices within the process industrieslargely involve four types of control architectures:

1. DCS (distributed control system)
2. PLC (programmable logic controller)
3. Microprocessor-based single-loop controllers
4. PC-based controls

Being based on computers, all are subject to trends in the computer industry.

The computing business

A consequence of relying almost entirely on digital technology is that trends in other segments of the computer industry often dictate what we see in industrial control systems. Practices in the computing business are not entirely compatible with traditional practices in industrial automation, but the computer industry is like a torrent — swim upstream and you drown.

Change. Perhaps the dominant characteristic of the computing business is change. The consumer electronics business is dynamic and exciting; by comparison, industrial control, process control included, is stogy and dull. An industrial practice with a five-year success record is considered proven technology and revered. Any practice in the computer industry with a five-year track record is viewed as suspect — there must be a better way and let's find it.

This rapid rate of change impacts both suppliers and customers. Pneumatic and electronic controls had a life of 30 years or more. But digital electronics older than 15 years are difficult to maintain — some of the chips are no longer manufactured and new ones cannot be purchased at any price. Very old systems can only be maintained by "harvesting" certain components from equipment that others are retiring.

Only the nuclear power industry has managed to swim upstream. Suppliers of equipment for nuclear power must commit to a 30-year life. In effect, the supplier commits to redesign each component at least once within the 30-year life of the product. The redesigned component must be plug-compatible with the original component and provide exactly the same functions — even if there is now a better way to perform any of these functions. Mandated by the regulatory environment, this comes at a noticeable additional price and with a side-effect of replicating obsolete technology.

Volume. From the computer industry's perspective, the industrial controls market is tiny. If the entire industrial control market evaporated, its effect on the computer industry would be like the Queen Mary losing a deck chair. We can be demanding, but we can also be ignored.

The mentality of the manufacturers of conventional pneumatic and electronic controls was simple: if you did not make the hardware, you did not make any money. But with digital technology, this attitude proved to be totally out of step. Adapting from this perspective led to a bumpy evolution for the process control suppliers — a couple even tried to develop their own line of computers. Just swimming upstream in a torrent.

With each passing year the process control system suppliers are manufacturing less and less hardware. Instead, they incorporate components manufactured in volume for other markets into their process control systems.

Standards. Industrial automation likes standards. The computer industry does not. Computer people are clever at inserting language into standards that essentially defeats the customary objectives for having a standard. In the computer industry, standards do not drive the technology; they always follow. By the time the formal standard appeared, Ethernet was the de facto standard for networking.

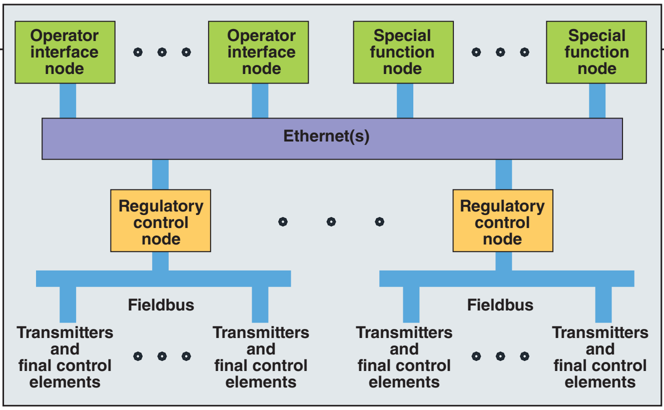

FIGURE 1. Architecture of a typical process control system

Those familiar with standards in the computer industry were not at all surprised by the standard that eventually appeared for Fieldbus. The ISA (Instrument Society of America) took the lead to develop a standard, one complication being that the standard had to be a world-wide standard and not just a U.S. standard.

But in addition, the approach effectively envisioned the standard driving the technology — again, trying to swim upstream. Everyone was on board until the deliberations started to converge to a single architecture, but then the wheels started to come off. In order to get a standard for Fieldbus, five networking architectures were incorporated into the standard. So much for the notion that a standard should provide one — and only one — way to do something.

Ever wonder why the various control system suppliers use different units for PID tuning coefficients? Want a standard? Following the practices in the computer industry, the standard would be as follows:

1. The proportional mode tuning parameter can be controller gain, proportional gain, or proportional band.
2. The integral mode tuning parameter can be reset time, reset rate, or reset gain.
3. The derivative mode tuning parameter can be derivative time or derivative gain.
4. The units for time may be seconds, minutes, hours, or fortnights.

The benefits? Specification writers could demand compliance, suppliers could promise compliance, and the ISA could make money selling copies of the standard — clearly a win-win-win proposition.

Customary architecture

Figure 1 presents a generic block diagram for process control systems. The central component is a communications network that enables information to be quickly and reliably transferred between nodes. Each node consists of a computer whose function falls into one of the following categories:

Regulatory control node. In a continuous plant, this is provided by PID function blocks complemented by various algorithms. In a batch plant, the simple and repetitive sequences (pulling vacuum, transferring a material, and so on) are implemented in the regulatory control node. Except for a few LEDs that indicate power, run/halt, fault status, and so on, a regulatory control node conveys no information directly to humans. Redundancy is usually available for these nodes.

Operator interface node. This node presents information to the process operator and accepts commands from the process operator. In the ideal world, no other functions are implemented in an operator interface node, but in practice, other functions are sometimes "piggy-backed" onto the operator interface node. Usually the easiest way to address failure issues is to provide multiple operator interface nodes.

Special functions node. A common special function is data collection (historian). An individual node can be dedicated to a special function, or one or more special functions can be implemented in a general purpose computer. Failure is usually not an issue, as most processes can be operated (perhaps not very well) without these nodes.

In Figure 1, the various nodes are connected by a communications network. This raises the specter of a rather nasty failure situation. A total failure of the communications network results in the dreaded "loss of view" — each node continues to function, but the operator interface nodes cannot acquire data from or send data to the regulatory control nodes. There are numerous consequences, most of which are bad. This must be addressed using options such as redundancy for the communications network, multiple communications networks with the operator interface nodes spread over two or more networks, or otherwise.

As the computer industry evolved, Ethernet became the default standard for networking. For control applications, concerns about collisions and predictability were raised. But what can compete with a 1 GHz Ethernet whose components are readily available and very cost competitive? As always, you will be amazed at our flexibility when we see the price. Apparently a few collisions aren't that bad after all.

The initial installations of both smart transmitters and smart valves relied on the traditional 4–20-mA current loop to interface to the control system. Configuration was via a hand-held programmer that either plugged directly into the field device or transmitted via a signal superimposed on the 4–20-mA current loop. This approach permitted the advantages of both smart transmitters and smart valves to be realized, but networking the field devices would make much more possible.

Such a network became known as Fieldbus and is included in the configuration in Figure 1. In process control, the competition appears to have narrowed to two:

Foundation Fieldbus. This technology is more common in the U.S.

Profibus. This technology is more common in Europe.

These are well on the way to displacing the traditional current loop interfaces.

DCS architectures

DCSs date from the 1980s, with the initial products designed primarily for petroleum refining. However, they quickly expanded to other industries, including specialty batch.

The early products tended to be focused in one of the following directions:

Continuous control. An extensive set of algorithms complemented the PID control function to provide whatever was required to automate a continuous process.

Sequence control. Although these also provided the PID control function, the extensions were mainly features to facilitate operating a batch process through the appropriate sequence of steps to make the desired product.

The increasing capabilities of the microprocessors soon enabled both to be implemented in the same product, along with a variety of supporting functions. At one time certain suppliers were preferred for continuous applications and other suppliers for batch applications. This disappeared more than a decade ago.

From the very beginning, the DCS products were designed with those working in instrumentation and control in mind. Conventional electronic control systems were hardwired — measurements devices and final control elements were connected to the controls via physical wires. DCSs rely on a corresponding approach, but in software. Controllers are implemented as software function blocks. The source of the measured value and the destination of the controller output are specified via pointers, which are the software counterpart to wires. A logical term for this methodology is "softwiring". To ease the transition to digital technology, capabilities of the DCS were presented in a form familiar to those working in instrumentation and control.

The current direction of the DCS suppliers is to expand upward. The concept of hierarchical control was proposed more than fifty years ago, long before the computers realistically had the capabilities to provide it. Figure 2 presents a hierarchy consisting of four layers:

Regulatory control. The PID loops, simple sequences, and so on comprise this layer. Once implemented, changes at this layer should be infrequent.

Supervisory control. These functions depend on the type of plant:

- In a continuous plant, small setpoint adjustments are required to maintain process operations at or near optimum conditions
- In a batch plant, the basic sequences must be executed in the proper order and with the proper targets according to the product being manufactured

Traditionally provided by process operators, supervisory control functions have proven to be far more effective via computers. However, changes to these functions are more frequent (new products are introduced in a batch plant; optimum conditions in a continuous plant must reflect product demands and prices). The continuing costs associated with these changes often draw the scrutiny of plant management.

Middle ground. This encompasses a variety of functions performed by people like production supervisors, inventory managers and so on.

Business systems. This comprises the various functions (accounting, supply chain management, and so on) implemented at the corporate level.

Most companies have systems in place at the two ends of the hierarchy:

- Business systems. This is the realm of the corporate information-technology (IT) department
- Regulatory and supervisory control. Traditional DCSs provide both

The functions required for both are generally well-defined and largely automated. But the middle ground is generally not so well defined, often with each site developing procedures to suit its purposes.

The DCS suppliers are now taking on the middle ground and introducing terms such as management, enterprise, and others into their product descriptions to reflect their efforts in this direction. The term MES (manufacturing execution system) encompasses the functions in this middle ground. In a batch facility, MES includes the following functions:

Production scheduling. Long-term scheduling is often implemented as part of the supply chain management function within the business systems. But the production quantity from the business system must be converted into some number of batches. Most equipment suites in batch facilities provide multiple types of process units (reactors, decanters and filters, for example) and provide more than one process unit of each type. Short-term scheduling involves deciding specifically which process units will be used for each batch. Sometimes this is referred to as routing, and is a challenging problem to both define (involving numerous production rules) and solve.

Production control and supervision. This involves dispatching a production order to a suite of process equipment and monitoring the progression of the manufacturing process. For example, should a batch be lost, the decision must be made to either accept a reduced amount of the final product or to schedule another batch, which requires equipment, raw materials, and so on.

Material tracking. For each batch of product (identified by a lot number), the lot number of each raw material consumed to manufacture that batch is recorded. This involves lots of data with numerous possibilities for complications (for example, a raw material might be taken from two or more lots).

Performance monitoring. Most batch control systems capture the necessary data to compute yields, energy consumption, equipment utilization time, and the like for each batch. But there is a layer above this that deserves attention. For example, what percent of the time is a given item of process equipment being used to produce some type of product? This must reflect idle times, cleaning cycles, maintenance requirements and so on.

To address this middle ground, the DCS suppliers are integrating components provided by other parts of their organization or by third-parties, or by both. And similar to their activities at the hardware level, the ability to integrate multiple software systems into a coherent and functioning product is critical to success.

PLC configurations

The PLC was the first digital technology to compete on a cost basis with conventional technology. Developed for the automotive industry, the early PLCs were discrete logic devices designed to replace the hardwired logic required to operate stamping machines and the like. The hardwired logic was represented by rungs of ladder logic; the early PLCs could then be programmed directly from ladder diagrams, the desire being that electricians could work with PLCs in the same manner that they worked with hardwired logic.

The early PLCs were digital machines that predated microprocessors. But with the introduction of microprocessors, the capabilities of PLCs expanded rapidly. The early PLCs supported discrete I/O (input/output)

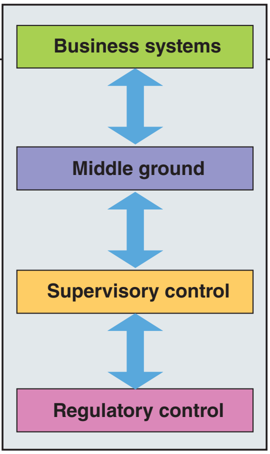

FIGURE 2. The control hierarchy shown here consists of four layers

only, but quickly gained a reputation for robust I/O that could stand up to the abuses in facilities like sawmills. By 1980 the upper-end PLC products supported analog I/O, and the software included a PID function (or at least what some automotive engineer understood a PID function to be).

Ladder logic represents one thing very, very well: discrete logic. Most process interlocks are expressed entirely by discrete logic. PLCs are also very efficient at executing discrete logic. Most execute the logic as rapidly as possible — one scan is immediately followed by another scan. Scan times on the order of 10 ms (100 scans per second) or faster are typical.

Any application with a heavy requirement for discrete logic is very likely to include a PLC in its control equipment. Most DCS products provide an interface to a PLC, effectively making the PLC a node within the DCS configuration. The PLC provides the discrete logic; the traditional DCS nodes provide the PID and other continuous control functions.

But since PLCs can also provide PID functions, math capabilities, and so on, why not also implement the continuous control functions within the PLC? This question is most relevant in small applications where only a "few" PID loops are required. Initially, "few" meant two or possibly three; today "few" may be a misnomer — most PLCs can do 16, 32, or even more PID loops.

In a sense, adding PID and related functions to a PLC created a marketing nightmare — who do you sell this thing to? PLCs were traditionally marketed to two departments:

The electrical department. The discrete logic required in-motor control applications and the like transitioned from hard-wired logic to logic within a PLC.

The safety department. PLCs are the product of choice of most plant safety organizations. If required, triple redundancy with voting logic can be purchased.

Neither of these departments has any interest in PID control. Furthermore, purchasing such a device could become a political "hot potato" — PID is within the realm of the instrument department.

Trying to sell the enhanced product to the instrument department proved to be an uphill slog. Ladder logic is not required to implement a piping and instrumention diagram (P&ID), and most instrument departments quickly note that they implement continous control logic and not discrete logic. Most of the PID implementations in the early PLCs were rather basic, and often not described in the customary terminology of the process industries. The PLC suppliers learned that just having a PID function did not instantly make them a process control supplier.

But there were exceptions. Some processes require discrete logic within their automation systems. For example, food processes often include conveyors, packaging lines, and so on. These requirements involve ladder logic, and in practice, this means a PLC. Adding PID and related functions to the PLC greatly enhanced its utility, and the resulting product continues to be favored in these industries.

Most PLC-based control systems start out as a single PLC, often with only one PC-based operator interface connected via Ethernet. But applications grow. Most PLCs provide the possibility for multiple Ethernet interfaces, with one network interface on the processor board and additional ones obtained by installing one or more communications processors. This enables several possibilities:

1. Communicate with one or more PCs providing the operator interface.
2. Exchange data between the various PLCs on the network.
3. Transfer data to and receive data from a host computer.

As these are pursued, the PLC-based control system evolves to the architecture illustrated in Figure 1.

To date, PLC manufacturers have not shown much appetite for implementing MES functions. The reason may be simple — most took a bath in prior ventures into factory automation. Encouraged by companies like General Motors, most pursued capabilities to automate all aspects of a manufacturing process for automobiles, appliances, and so on. They quickly learned that success in controlling the individual machines did not assure success in integrating them.

This should give the DCS suppliers cause for caution. Hopefully they will be more successful — computers are more powerful, networks are more capable, and so on. But this is not a sure bet — integrating complex software packages from a variety of sources so that they function in a seamless manner remains challenging, especially if the user's definition of the middle ground is also evolving.

The 'Haves' and the 'Have Nots'

When considering DCSs versus PLCs for an application, the availability of money is clearly a major determinant of the approach selected. Big oil, big pharma, and so on, have deep pockets, herein being referred to as the "Haves". They generally favor the DCS products. But those operating cotton gins, rendering plants, and so on, have to pinch every penny, and are herein referred to as the "Have Nots". These generally favor the PLC products.

The Have Nots are sometimes tagged with derogatory terms such as "low on the food chain", often by those with little to be arrogant about. The past two decades have witnessed much industry moving off-shore — just take the river road from Baton Rouge to New Orleans to see the consequences. And how much penicillin is now manufactured in the U.S.? But cotton gins and rendering plants are staying put — their options are stark: either survive or go out of business.

As summarized in Table 1, the differences in the approach to an application extends beyond the hardware platforms chosen. A major issue is systems integration, which is the integration of hardware and software components into a functioning system. The difference is who assumes responsibility for this:

The DCS offering includes system integration services for the standard components. Other components can be incorporated for a fee, but usu-

TABLE 1. COMPARING THE HAVES AND THE HAVE NOTS

	The Haves	The Have Nots
Companies	Generally the majors, such as "big oil", "big pharma", and so on	Smaller organizations, such as cotton gins, rendering plants, and so on
Equipment	Usually DCS's	Largely PLC's, although occasionally based on single-loop controllers
Source	Purchased as an integrated product from single supplier	Purchased as components and integrated in-house or by a local contractor
Process aspects	Provided by process technology supplier	Generally provided in-house, but occasionally purchased
Configuration / programming	Provided by DCS supplier	Provided in-house or by a local contractor
Maintenance	Provided by DCS supplier	Provided in-house or by a local contractor
Justification	Part of a large capital project with the automation being "the way we do our business"	Costs and benefits scrutinized very carefully

ally one that restricts this practice to components that are absolutely essential. This is especially appealing to the Haves — they are willing to pay others to assume as much risk as possible. Systems integration can be frustrating — things just do not always fit together as expected. Furthermore, management usually takes a dim view, noting that we are in the chemical (or whatever) business, not the computer business. Basically, the Haves do not want to be in the systems integration business, and can afford to pay others to do it for them.

The PLC offering is components only. The customer essentially assumes complete responsibility for systems integration. Even if a local systems integrator is retained, the customer still carries most of the risk. The systems integration business is a tough business — the competition is such that you can only make a small profit on each job, but the risk is such that you could incur a large loss. Many local systems integrators are very good, but rarely have deep pockets. And if one is dependent on an organization to deliver a system, driving it into bankruptcy is probably not advisable. You can hold their feet to the fire, but once you burn them off, now what? But if you are a Have Not with limited resources, one way to reduce costs is to carry your own risk.

The major corporations have a strong preference for outsourcing, and the DCS suppliers have responded, sometimes to the extent that only project management is required from the customer's engineering organization. The starting point was a DCS product that could be purchased as a complete process control system from a single supplier. But with time, services were added to the offering:

On-site maintenance services, first for the hardware and then for the software. Hardware maintenance initially stopped at the terminal strips, but at the insistence of customers, may extend to the measurement devices and final control elements.

Application support services, which includes defining I/O points, configuring control blocks, building graphic displays, and so on. Today's networking capabilities enable affiliates in India to perform this work using people physically located in India. In large projects, the cost reductions are significant.

Application technology, often with alliances with third parties. This has long been the case in industries such as electric utilities (all steam cycles tend to be similar), pulp-and-paper (most paper machines are Fourdriniers) and so on, and is becoming more common in petroleum refining. But in industries like specialty chemicals, foods, consumer products, and so on, the proprietary nature of the business is a major obstacle.

The service offerings are most appealing to those with large production facilities (generally the Haves). The costs get lumped with other costs for either a grass-roots facility or a major revamp of an existing facility. The last thing one wants is for the process control system to delay the plant commissioning. For this, the Haves are willing to pay a premium.

The world of the Have Nots is very different. The production facilities are generally smaller and often have been in operation for a number of years. Projects are based on a variety of objectives, such as the following:

- Replace aging measurement and control equipment
- Take advantage of a new measurement technology
- Replace an existing item of plant equipment with an improved design
- Modify the process technology

While the relatively small size is a disadvantage, there are often options that cannot be tolerated in large commodity facilities, including the following:

- Continuing to operate the process in the existing manner is an alternative. Even those with deep pockets cannot afford to operate a large commodity process at a loss for very long
- Startups and shutdowns are usually more frequent but less costly. Shutdowns in a commodity plant are few and far between
- Brief shutdowns are tolerable. Typically, no money will be spent to avoid infrequent shutdowns of two hours or less. Operators of commodity plants spend lots of money to avoid an unscheduled shutdown

To keep the costs down, the following practices are common in Have Nots' facilities:

- Maintenance is the responsibility of local personnel. When short duration shutdowns are tolerable, spare boards or even a complete spare PLC can be quickly swapped into service
- Application support services are provided by either in-house personnel or a local contractor
- Application technology is often supplied in-house, although occasionally purchased from a third party. Most are simple configurations, but surprisingly sophisticated technologies are appearing more frequently

The Have Nots scrutinize the costs and benefits of each automation endeavor on its own merits, even if it is done in conjunction with other efforts. Every effort has to pay its own way to the satisfaction of management. This inevitably places a higher scrutiny on costs and benefits.

Ask a plant manager of a Haves facility what automation is doing for him or her. The likely answer is that it is making lots of money today, and will make even more tomorrow. Then ask how it is doing this. You will get an answer, but too often the gist is "not a clue".

Ask a plant manager of a Have Nots plant what automation is doing, and

you get an explanation of the benefits followed by an "it was definitely worth it" endorsement. These are usually small projects with a limited scope, but focused on what makes money.

This is the result of the different perspective that the Haves and Have Nots take toward automation:

Haves. The installation of a process control system, usually a DCS, is not under discussion — this is just the way we do our business. Cost considerations focus on getting the DCS installed at the minimum possible cost. But this focus on costs can have an unintended side-effect. Managers view the process control system as a cost and a sink for money. Managers do what they are trained to do — manage the cost so as to minimize the cost. Spend more money on a cost? No way!

Have Nots. Not doing the automation project is usually an option. The intense scrutiny from management can become burdensome, but there is a beneficial side effect. The plant manager acquires a good understanding for what automation is doing in the plant. Automation is installed only if it is a source of revenue — the benefits exceed the costs. And if another opportunity arises to make more money with automation, the plant manager is receptive to "spending money to make money".

Recent and future directions — Hardware

Hardware evolutions largely draw on advancements from other segments of the computer industry:

Wireless. By porting the wireless technology developed for routers, cell phones and so on, into automation systems, wireless communications with measurement devices and valves is now possible. Although being aggressively promoted, how this technology will be accepted is difficult to predict. Electronic devices require power, which entails either batteries or two strips of copper known as wires. The wires that power a device can also be used to communicate with the device, so why go wireless? Wireless will prove very attractive in certain cases, but a widespread shift to wireless is not a sure thing.

Graphics. The 3D graphics technology from video games and the like are sure to appear in operator interfaces. Is this really needed in industrial automation? The answer remains to be seen.

Voice recognition. The capabilities of modern cell phones are very impressive. Voice recognition is sure to be ported into industrial automation systems and has some interesting and very beneficial possibilities.

Recent and future directions — Control practices

Being largely home-grown, control practices within modern control systems have evolved about as much as the phone component of modern cell phones.

P&ID. This continues to provide the definition for the measurement devices, final control elements, and control functions for a process. Usually these rely primarily on single-loop control structures, in the simplified P&ID in Figure 3 for a chlorine vaporizer. The organization for these loops is critical. If this structure accurately reflects the nature of the process, the controllers can almost always be successfully tuned. But if it does not, one or more controllers prove to be "untunable".

For something that is so critical, one would think that the rationale for the arrangement of the loops would be well-documented. But take one of these and ask why are we doing it this way? One answer is that it is done that way in another plant — basically ours is a copy of theirs. Then why do they do it this way? Somebody had to do the first one, which possibly was subsequently modified to give the one we are using.

P&IDs should be developed by someone with a thorough understanding of the process. The more experienced the person and the more time that person is allowed to develop the P&ID, the more successful the result. However, there are factors working against this, including the following:

- Early retirements usually mean that people with less experience are developing P&IDs
- The emphasis on shortening the design and construction cycle mean less time is allotted to developing the P&ID

For such a critical component, one would think that a rigorous methodology could be developed for translating the operating requirements for the process and the nature of the process (as expressed by models) into a P&ID. What is available? Very little. Probably the most useful is the relative gain technique for assessing the steady-state interaction between two control loops. But even this is not usually applied until problems arise during commissioning.

PID controller. The basic PID equation has not changed. Both DCSs and PLCs can execute the loop on very short intervals (or sampling times), effectively making the digital implementation equivalent to a continuous equation. In most cases, the control equation is executed on a shorter interval than really necessary.

Digital systems have permitted a number of useful options to be added, especially in the area of initialization (for a smooth or bumpless transition from manual to automatic) and preventing windup. Windup can result when some component of the loop attains a limiting condition. The standard windup protection is invoked when the PID output value attains a limit, but the more demanding case is when windup is the result of a limit being attained elsewhere in the loop.

In certain applications the nonlinear options (error gap or error squared) are very useful. However, no nonlinear function of general utility has appeared.

MPC. Although MPC can be implemented in a single-loop controller to replace the PID, this is not widespread practice. Instead, most industrial applications of MPC are in multivariable control applications with one or more of the following characteristics:

- Significant degree of interaction within the process
- Constraints on dependent variables
- Numerous measured disturbances
- Adverse dynamics, mainly long dead times or inverse response

Implementing MPC requires extensive process tests, which necessitates a significant incentive (usually some form of optimization) to justify the cost.

MPC has proven very successful in continuous commodity processes, with applications in oil refining leading the way. But to date, MPC applications outside commodity processes are rare.

A common application of MPC is distillation columns, especially complex columns with sidestreams, side heaters or coolers, and so on. For two-product towers, PID control is usually adequate provided the loops are structured properly. The most common approach is to control the overhead composition (or upper control stage temperature) using reflux and the bottoms composition (or lower control stage temperature) using boilup. However, this configuration often exhibits a significant degree of interaction. Separation models for distillation are very good, which permits techniques such as the relative gain to be applied to quantify the degree of interaction. In most cases an alternate control configuration with a low degree of interaction can be identified. However, getting the configuration changed is rarely easy, often leading to endless discussions and what is in effect a pocket veto — we agree to change it but never get around to doing it. MPC avoids this. In essence, MPC ascertains how the column should be controlled and does it "under the hood", giving the same result as changing the control configuration.

Automatic or self tuning. Virtually every supplier (PLC and DCS) offers some form of automatic tuning. It is good that these capabilities are available, but to date their overall impact has been minimal. If an automatic tuning method is properly applied (and "properly" should be stressed) to every loop in a plant, it will successfully tune most of them, with "most" usually being 90% or more.

However, the common practice is to first attempt to manually tune the loops, and apply automatic tuning only to those loops that cannot be successfully tuned manually. With this approach, the success rate will be low, usually below 10%. In effect, automatic tuning is being applied almost exclusively to the "untunable" loops. Most such loops are the result of mistakes in the P&ID, and they cannot be tuned until the P&ID is corrected. Changing a P&ID usually encounters significant resistance, the consequence being that one or more loops remain on manual.

For PI controllers, the advantages of automatic tuning over manual tuning are questionable. Anyone proficient in manual tuning can obtain comparable results in a comparable length of time. Furthermore, automatic tuning does not totally relieve the burden on the instrument technician or engineer. All automatic tuning procedures require a process test of some kind, and process tests have to be monitored in order to obtain quality data from the process.

For PID controllers manual tuning is far more challenging. Derivative is normally used in slow loops (primarily temperature) and ones whose performance significantly affect the process (repeated tries using different tuning coefficients are essentially undesired upsets to the process). All one can realistically expect from manual tuning is to get some improvement by tuning derivative, but the results are unlikely to realize the full potential of the derivative mode.

Derivative is more challenging for automatic tuning techniques as well. Model-based approaches are up to the task, and can effectively and consistently tune the derivative mode. However, these require a process test from which a model can be derived. But this raises another question — once a process model is available, why not use a single-loop MPC instead of PID?

Artificial intelligence and fuzzy logic. Despite the early promises and enthusiasm, this technology has made little inroads into process control. Few successful applications have been reported, and apparently the fu-

ture is not expected to be any brighter.

Process testing. Testing a process with a 5-min response time is usually easy, but testing a process with a 5-h response time is far more difficult. Properly conducting the test is crucial — this is "garbage in, garbage out" business. A poor test gives poor quality data; the model derived from these data does not accurately represent process behavior; control logic based on this model performs poorly.

Realistically, is it possible to conduct a test on a process with a 5-h response time? The answer is "yes, but with great difficulty". Such endeavors will be undertaken only when there is a significant incentive to do so. Commissioning MPC requires a process test to determine process behavior, which is a major component of the MPC's total cost. The potential benefits of the process optimization made possible by MPC can easily justify the cost, but when it comes to activities such as controller tuning, anything other than simple tests can only be justified in those loops critical to process operations (often temperature loops where derivative is likely to be used).

Dynamic modeling. The utility of steady-state models is well-established — all modern process designs are based on such models. However, the utility of dynamic models remains debatable. The technology to develop a dynamic model for any industrial process has been available for at least 20 years. However, dynamic modeling is usually applied to selected parts of the process (with "selected parts" sometimes being none). And even for the selected parts, the dynamic modeling is not always to the detail required to tune a control loop.

The practices are entirely different in the aerospace industry — detailed dynamic simulations are developed for each vehicle. Why is this not the practice in the process industries? There is a major difference in the ground rules. When an aerospace vehicle leaves the ground, every loop must be in automatic and working, even on the first flight. Except for a few fast loops (one example being compressor surge control), process plants can be operated with every loop in manual. This is not a popular way to do it — more people are required and the plant does not perform as well — but something that is tolerable during startup. Basically, aerospace has to start up on automatic; process can start up on manual. When will all process plants be simulated in detail? The day they have to start up in automatic mode.

Understand the process

Senior people in process control take great delight in giving this advice to new hires. And it is true. But there is a problem. This is strategic advice that works well at 30,000 ft and above. But exactly what does this mean to someone working at ground level, that is, someone with a specific problem to solve? New hires should not hesitate asking "exactly how do you do that?" The answer is often by examples (also called "war stories").

But understanding the process is crucial to process control. In some respects, artificial intelligence is an attempt to take a lot of data and let the system make sense of it. Based on the test data, MPC develops finite response models to characterize the process. But the utility of these models depends on the quality of the test data. How does one assess the quality of these models? One looks at how they respond to certain changes and assesses their behavior in light of past experiences regarding the behavior of the process. Obviously the better one understands the process, the more effective one can assess the quality of these models.

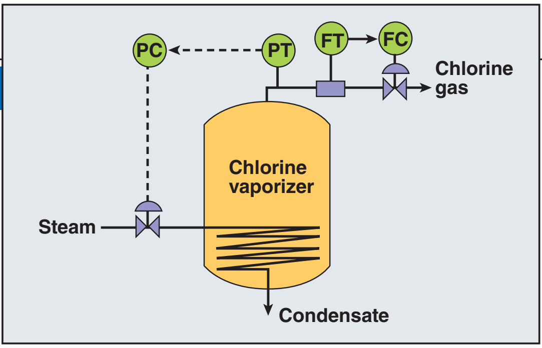

FIGURE 3. Shown here is a P&ID for a chlorine vaporizer, which is discussed in detail in the text

In the end, a P&ID that reflects the nature of the process is essential to a successful process control application. P&IDs are also developed largely based on someone's understanding the process. A steady-state model formulated from basic process mechanisms is another way to express the behavior of the process. But as previously noted, we have no technology to translate these relationships into a P&ID.

The traditional view is that the dynamic nature of a process determines the appropriate process control configurations, that is, the loops as represented on the P&ID. When developing the P&ID, this translates into the following rule: *Control every variable with the nearest valve.*

Developers of P&IDs usually deny that this is the guiding principle, but if one examines enough P&IDs, it seems to turn out that way. Probably a more accurate statement is that what one sees on P&IDs is based largely on considerations pertaining to process dynamics.

This leads to trouble, and here is a "war story". The process in Figure 3 is a batch chlorine vaporizer. The chlorine is delivered in a vessel equipped with an internal coil through which heat can be supplied from low pressure steam or hot water. The vaporizer is a pressure vessel, so a pressure relief device is required.

The process objective is to deliver the desired flowrate of chlorine vapor to the process, but in doing so, do not exceed the pressure setting on the relief device. The variables to be controlled are the following:

- Chlorine vapor flow
- Vaporizer pressure

The final control elements are:

- Control valve on chlorine vapor line
- Control valve on the steam supply

The P&ID in Figure 3 reflects thinking based on process dynamics. The chlorine vapor flow measurement is the flow through the chlorine vapor valve, so a customary flow controller is proposed. The vaporizer pressure is controlled via the steam valve, which influences the rate of heat input.

There is a fundamental problem with this control configuration. What actually determines the chlorine vapor flow? The rate of heat input to the vaporizer. To vaporize a kilogram of chlorine, some kilocalories (the latent heat of vaporization for chlorine) of heat are required. If you line out the process, switch both controllers to manual, and increase the opening of the chlorine vapor valve, what happens?

- The chlorine vapor flow initially increases
- The vaporizer pressure and the vaporizer temperature decrease
- The heat input decreases
- The chlorine vapor flow decreases

Once the transients have passed, the chlorine vapor flow returns to a value very near its initial value. At a fixed steam valve opening, the steady-state sensitivity of chlorine vapor flow to chlorine vapor valve opening is essentially zero.

These cause-and-effect relationships are the basis for the following logic:

- To increase the chlorine flow, the flow controller increases the chlorine vapor valve opening
- This decreases the vaporizer pressure
- The vaporizer pressure controller increases the steam valve opening, which in turn increases the chlorine vapor flow

The conclusion: the configuration in Figure 3 is perfectly satisfactory.

This is not necessarily the case. The chlorine vapor flow controller is totally dependent on the vaporizer pressure controller — if the vaporizer pressure controller is on manual, the chlorine vapor flow controller will drive the chlorine vapor valve either fully open or fully closed. The output of the chlorine vapor flow controller has only a nominal effect on the chlorine vapor flow.

When Loop A is totally dependent on Loop B, the following statements can be made:

- The configuration can only function when Loop B is on auto
- Loop B must be significantly faster than Loop A, preferably by a factor of about five

These statements also apply to cascade configurations, where the outer loop is totally dependent on the inner loop.

The configuration in Figure 3 does not have the required separation in dynamics. In fact, the separation is probably the opposite of what is required — the chlorine vapor flow loop is likely five times faster than the vaporizer pressure loop. The result will be major tuning problems with the chlorine vapor flow loop. This loop will only function if tuned very conservatively — so that it is five times slower than the vaporizer pressure loop. But then the resulting performance of the chlorine vapor flow loop is unacceptable.

Basically, the configuration in Figure 3 does not reflect the fundamental nature of the process. The chlorine vapor flow is determined by the heat input from the steam flow; the chlorine vapor valve must basically be used as a back-pressure regulator.

You have to understand the process. And when it comes to P&IDs, understanding the steady-state nature of the process is the crucial part. ■

Edited by Gerald Ondrey

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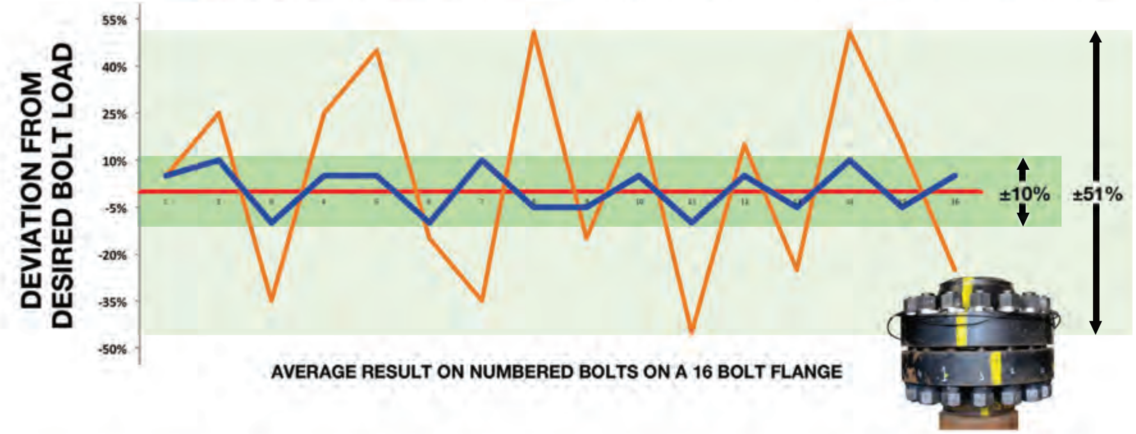
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Fractionation Column

How long does it take to reach steady state?

Mike Resetarits is the technical director at Fractionation Research, Inc. (FRI; Stillwater, Okla.; www.fri.org), a distillation research consortium. Each month, Mike shares his first-hand experience with *CE* readers

How long does it take a six-tray, 4-ft dia. deisobutanizer to achieve steady state? That depends on your definition of "steady state". Some control experts regard 95% of "ultimate value" as a good definition, but how useful is that definition?

The FRI distillation columns are located on the Oklahoma State University (OSU) campus. As a result, there is a close relationship between FRI and the OSU chemical engineering dept., particularly with professors Rob Whiteley, Jan Wagner and Ken Bell. A couple of years ago, professor Whiteley and one of his graduate students, Anand Vennavelli, performed a set of time-to-steady-state (TTSS) tests using the FRI experimental unit. They found that hydraulic equilibrium was achieved fastest when a column was operated at atmospheric pressure and two times slower at vacuum and at high pressure. They found that the key to reducing TTSS, was pressure control.

Several years ago, FRI's membership instructed the FRI staff to study the impact that reflux temperature has on packing performance. The membership wondered whether renegade condensation on the outside of liquid distributors was shifting the control of the distribution from the distributors to Mother Nature. FRI purchased and installed a new reflux heater. Professor Whiteley, and OSU, provided a new control strategy. That strategy has proven to be very effective at controlling column pressure.

Late this April, the FRI staff decided to have some "fun" — some "TTSS fun." Exactly how long would it take for steady state to be achieved after an extreme change in reboiler duty? Different staff members guessed different times. Cash bets were collected and stored in a hermetically sealed mayonnaise jar that was buried by technician Kenny Martin in the swamp behind the unit.

On April 27 the column contained 10 ft of structured packing operating at 5 psia. The reboiler duty was increased, as quickly as possible, from 20 to 80% of flood. Thereafter, liquid samples were taken every 15 min. The column's pressure was held very steady by — and thanks to — the new OSU control strategy. Hydraulic equilibrium was defined as the point when all of the levels and pressure drops steadied out. Hydraulic equilibrium was achieved within 15 min. Thermal equilibrium, as evidenced by ten thermocouples, was achieved at the same time. Mass transfer, and HETP (height equivalent to a Theoretical plate), equilibrium were achieved 30 min. after that.

At the October 2011 AIChE meeting, FRI will be giving two presentations associated with the aforementioned work. The new control strategy will be described as will the TTSS results. In fact, between now and then, several other TTSS tests are planned. Eventually, the impacts of tower pressure, tower system and trays-versus-packing will all be studied.

Meanwhile, in case you were wondering about who won the contest: Kenny claimed that he could not find the buried mayonnaise jar, but he is wearing a new watch. ■

Environmental Manager

Practice Green Chemical Engineering

Chemical engineers have countless opportunities to apply their talents to environmentally related improvements, specifically in R&D, plant design and operations

C. Delia Contreras
and **Fabio Bravo**
Specialists in plant design
and operation

Almost by definition, chemical engineering is a "green" discipline today, as it so often involves efforts to optimize chemical processes in order to reduce the amount of energy and raw materials that are used and the amount of waste that is generated. Today everybody "talks green" but in a lot of cases engineers are the most qualified people to provide the tools required to make complex chemical processes more environmentally sustainable. In fact, many types of engineers — but chemical engineers, in particular — are in an ideal position to develop solutions for some of today's most important problems, including all types of air pollution, CO_2 emissions, carbon capture and storage, improved renewable energy sources, improved food production, sustainable water supply and wastewater treatment, quick and economic mass production of vaccines and drugs, complex issues related to global warming[1] and so on.

If not properly addressed, these issues will become even more critical, as economic growth and demographic expansion invariably leads to increased consumption of fuel and natural resources and to increased production of waste streams. "Being green" has always been part of the chemical engineering profession — although in the past, such activities were not necessarily called green or sustainable.

So-called "green practices" are often considered to be expensive or unaffordable, prompting some process operators to do just what is required to comply with the minimum legal requirements. This type of thinking is not only outdated but shortsighted, as well. Today, it is increasingly recognized that green practices and economic profits are related. Technically strong and innovative teams are needed to capitalize on the opportunities to link environmentally related activities with bottom-line profitability.

Today, it's widely recognized that improvements such as reduction of energy and raw material consumption, minimization of waste production and increased process yields are critical to increase a facility's overall economic profitability. There are tremendous opportunities for technically strong and innovative chemical engineers to bring their expertise and ingenuity to bear in green endeavors, in chemical engineering roles ranging from R&D to process design and operation. A key driver for becoming greener has to do with the so-called "three key Ps": planet, people and profits. This article discusses some of the opportunities that are available for chemical engineers to lead the charge in green engineering.

Why green?

Being green is about taking care of the planet, which is in the best interest of every person regardless of profession. But, considering the special training that chemical engineers receive, it is especially applicable to members of our profession. Today, no company has much choice when it comes to taking care of the environment or investigating ways to operate in a more environmentally sustainable way.

It is not only a matter of compliance with regulations but a matter of responding to the demands and expectations of customers, employees, com-

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[1] It is understood that the concept of global warming is not universally accepted and this article does not intend to address either side of that argument.

munity, stockholders and competitors. Together, these drivers create tremendous pressure for companies to carry out their operations in a more environmentally friendly way.

'R&D FOR GREEN' — SOME IDEAS ON HOW TO FOCUS R&D ACTIVITIES ON KEY ENVIRONMENTAL CHALLENGES

- Work on issues that have a large impact to society and focus on delivering practical solutions. These include air pollution, CO_2 emissions, carbon capture and storage, renewable energy sources, food production (including pest control to minimize crop losses), water supply, and quick and economic mass production of vaccines and drugs
- Develop new production processes that provide competitive advantages from the resource-usage point of view, including higher yields, reduced waste and vent streams, reduced energy consumption, reduced raw material usage, minimized environmental impact and more
- Develop new production processes with competitive advantages from the safety point of view. These include processes that do not require dangerous raw materials or intermediates, can operate at lower pressures or temperatures and more
- Consider biotechnology-based routes or other non-traditional processes that could result in the benefits described above [*4, 5*]
- Develop new biodegradable plastics and develop processes for the commercially viable production of them [*1*]
- Develop processes that use renewable raw materials
- Consider new or improved catalyst systems to improve efficiency, reduce byproducts or costs, or provide other competitive advantages [*6*]
- Consider different technology options that could eliminate some process steps
- Consider different chemical routes, including raw material changes
- Consider utilization of byproducts from other processes as raw materials
- Consider membrane-based separation routes as an alternative to distillation and other energy-intensive separation techniques
- Include environmental considerations in the selection of any solvents required by the process
- Replace organic solvents with water [*1*], where possible ❏

For the chemical process industries (CPI), it might not be precise to talk about "clean processes" as the word "clean" implies zero emissions which, being an admirable stretch goal, is not always a practical goal for these industries. Similarly, by definition, the CPI routinely handle flammable, volatile and hazardous materials and operate at high pressures and extreme temperatures, so in spite of their accomplishments in the green arena, it is much more difficult for them to be perceived as green companies compared to, for example, a company in the software business.

Perhaps for those reasons, some people have a negative perception — or at least one that is not as positive compared to other industries — of the CPI. Unfortunately, many in the general public are relatively unaware of the contributions that these industries bring to society, and many may not fully realize that our lives would be dramatically changed if we attempted to eliminate chemicals, plastics, pharmaceuticals and other CPI products from everyday life.

However, regardless of their contributions to society, the CPI can and must talk about becoming cleaner and greener. While setting a goal of zero is achievable as far as zero personal injuries, zero process safety incidents and zero accidents are concerned, for some other metrics (such as emissions and other waste streams), setting a goal of zero might be too aggressive or even unrealistic [*1*]. Nonetheless, striving for zero is an easy-to-visualize, symbolic goal, which can give way to more-specific goals for different functions (an example of a valid goal for manufacturing would be to achieve zero waste due to operational mistakes).

For operators throughout the chemical process industries (CPI). operating in a more environmentally sustainable way also brings some intangible benefits. These include improved company image and brand recognition, better acceptance and support by customers and by society in general, enhanced trust by regulating agencies, enhanced employee morale (in general, people like to work for noble causes and companies that they can feel proud of), improved stockholder acceptance [*2*], and more. These intangibles become very important when we consider that the "book value" of most companies is typically much lower than their market capitalization — one big difference being the intangible aspects of the company's image and reputation.

Why chemical engineering?

Becoming green requires the best engineering minds, especially the best chemical engineering minds, and commitment from the entire organization. Engineering is all about practicality, improving living conditions and finding solutions to challenges. Excellent understanding of the chemical engineering fundamentals are key to helping industrial operations to become greener.

In particular, when it comes to environmental health and safety (EH&S) activities — specifically those related to improving safety and minimizing all forms of emissions — chemical engineers are in an ideal position to contribute to the development and implementation of technologically sound, cost-effective solutions.

Green initiatives represent a big and growing business, so the opportunities in that area for innovative companies and innovative engineers are gigantic, with some sources saying that environmental initiatives will create a business opportunity in the order of trillions of dollars for this decade [*2*].

'Green R&D,' 'R&D for green'

"Green R&D" and "R&D for green" represent two different concepts. The former deals with making sure that green considerations are taken into account during R&D work; the latter deals with the tremendous R&D opportunities that exist to make all types of activities throughout the CPI more environmentally sustainable. There are two types of examples of R&D for green, as follows:

- In certain cases, the use of more-direct chemistry routes can reduce the number of intermediate stages required, which can, in turn, minimize or even eliminate additional reactions, additional byproducts or waste streams, and may curtail the overall number of operations required (with related reductions in waste generation and energy consumption)
- Developing innovative processes and products that address environmental problems can provide many

PLANT DESIGN STAGE – SOME IDEAS ON HOW TO BE GREEN

- Properly apply the chemical engineering principles and take an innovative approach to design the plant with some of the following benefits: higher yields, reduced waste, lower operating temperatures, reduced energy requirements and reduced utilities use
- Properly apply inherent safety principles in the design, seeking opportunities for substitution of dangerous materials, minimization of inventories, moderation of the process conditions and so on
- Brainstorm about the most effective processes to achieve the final result, including the potential for biotechnology-based processes
- Develop uses for waste streams, for instance, as raw material or as fuel in boilers
- Consider advanced control techniques that could contribute to reduced energy consumption or to increased yields
- Consider process-intensification opportunities to maximize throughput and minimize a unit's plot space
- Perform state-of-the-art heat-integration studies by using the most advanced software available
- Eliminate waste by design instead of designing for waste treatment
- Fully understand risks and previous accidents associated with the same or similar technologies or process routes, and design accordingly
- Consider highly efficient processes and equipment (for instance, the use of highly efficient boilers)
- Consider high-performance packing and trays for mass transfer operations (to improve distillation, liquid-liquid extraction, scrubbing and so on)
- Take steps to minimize or eliminate hazardous raw materials and materials that are harmful to people or the environment
- Consider variable-speed drives to minimize energy consumption
- Consider the use of CO_2 streams, either as an inert gas in the process or by binding it in the products
- Consider divided-wall columns and reactive distillation
- Consider fuel gas recovery and recompression in flare systems
- Select adequate flowmeters to ensure that no waste or inefficiencies are created because of improper flowrates
- Design plants taking into consideration potential changes to product portfolios in the future (that is, be sure to build in some flexibility)
- Consider automated blowdown for cooling towers (as reliance on manual blowdown typically results in increased production of wastewater and increased consumption of treatment chemicals or system fouling)
- Design for maximum use of local materials of construction [*1*] ❑

benefits, and there are tremendous technical and business opportunities in this area. One prime example is the parallel efforts that are underway worldwide to develop cost-effective strategies for longterm carbon sequestration (CO_2 removal and storage). Other examples where R&D for green efforts have the potential to create large-scale business opportunities include the use of renewable raw materials, the production of biodegradable plastics, the production of better batteries for electrical vehicles, improved insulation products, improved materials for wind turbine blades, better catalysts, use of CO_2 as raw material for useful products [*3*] and more.

The box on p. 42 presents some specific ideas related to "R&D for green."

Green design

Green design in this case refers to seeking opportunities for environmental improvements when designing CPI plants. Green design offers tremendous opportunities for profit and growth, but requires the right skills and the right attitude. It requires good understanding of the chemical engineering fundamentals — kinetics, thermodynamics, mass transfer, heat transfer — and the capability to think out of the proverbial box.

During chemical process design, there is a significant advantage to reducing or even eliminating waste formation, not only from an environmental viewpoint, but in terms of improving yields and reducing associated waste-treatment and disposal — improvements that could offer significant advantages in terms of profitability.

Consider the example of scrubbers, which are intended to eliminate unwanted emissions from being vented to the atmosphere [*7*]. Scrubbers also offer opportunities for further waste reduction by either reusing the resulting streams in the process or by redesigning the entire process to reduce or eliminate such vent streams. In other words, scrubber applications illustrate that there are several levels of green that could be summarized as treat, reuse, reduce and eliminate. As an example, in a recent project undertaken by one of the authors and his team, a vent stream was successfully scrubbed with a product from the unit and the stream was recycled to the process unit, which helped to minimize both emissions and material losses.

The box above lists some specific ideas on how to become greener in the plant design phase.

Green operation

When talking about the operation of chemical plants, there is a need to recognize that any efforts to be green or sustainable during R&D and design phases will be in vain if the plants themselves are not properly operated.

Additionally, in today's era of tight environmental scrutiny and high expectations from customers, stockholders and the general public, it is unlikely that any chemical process company would be able to remain competitive if it were not able to continuously improve its operations in terms of improved yields, reduced energy use and improved waste reduction. Many companies have demonstrated that operating in an environmentally sustainable manner provides a range of tangible and intangible advantages.

A typical plant manager needs to handle a large set of priorities, including objectives and requirements related to safety and environmental performance, costs, production targets, quality and so on. The push for constant improvement is often focused on helping the company or the facility to become (or remain) the most efficient producer in the market, in terms of yield and waste, emissions and energy consumption — all key metrics that signal the health and competitive position of the production process in economic terms.

There are countless examples of the payoffs that can result from the prudent implementation of green initiatives. By way of example, one of the authors (and a team of colleagues) recently received five awards related to the successful implementation of innovative ideas for waste and energy reduction, which had significant impact not only in terms of the environment but in terms of improved profitability, as well. There is always room for continuous improvement on waste reduction and energy optimization around the plants, but the right combination of attitude, creativity, motivation and

PLANT OPERATION STAGE – SOME IDEAS ON HOW TO BE GREEN

- Consistently operate the plant within optimum parameters. This may sound obvious but it is quite important from the profitability and environmental viewpoints and not always an easy task
- Continuously look for opportunities to obtain competitive advantages in terms of higher yields, reduced waste, lower temperatures, reduced reliance on dangerous raw materials or intermediates, reduced energy, reduced utilities consumption and so on
- Always consider opportunities to reduce, reuse and recycle. For example reduce raw materials consumption and waste, reuse or recycle off-specification products. If reuse or recycle is not practical, consider treating any off-specification products to a lower-value material instead of sending it to waste treatment
- Take steps to prevent waste formation instead of relying on waste treatment
- Find uses for byproducts
- Think outside of the box and challenge the traditional "that is how we have done it for 20 years" mentality
- Develop and implement relevant metrics, such as emissions and Btu (or Kcal) per ton of product
- Build a culture in which safety and environmental stewardship are top priorities and create stretch goals such as zero personal injuries, zero accidents and zero process safety incidents
- Measure, track and minimize emissions of GHGs, volatile organic compounds and regulated substances
- Minimize inventories of raw materials, intermediates and final products to minimize risks, costs and emissions
- Fully understand risks and previous accidents associated with the technology at hand, and operate accordingly
- When downsizing, make sure that the remaining employees have adequate knowledge of the technology, the processes and understand how to reduce risk and emissions
- Properly maintain insulation to support greater energy efficiency
- Repair steam and utility leaks [*4*] and replace deficient steam traps
- Change disposable filters as needed to avoid unnecessary and costly pressure drop
- Properly maintain flowmeters so that no waste or inefficiencies are created as a result of improper flowrates
- Optimize fuel gas to flares and furnaces
- Look for opportunities to reuse water
- Measure and minimize chemical oxygen demand of wastewater
- Optimize compressed-air systems to minimize energy consumption [*7*]
- Use local materials (fo raw materials and spare parts) to minimize the environmental impact due to excessive transportation ❑

chemical engineering skills is required to achieve demonstrable results. The box above presents some specific ideas on how to be greener during operations.

The energy case as an example

Energy consumption is especially relevant to this discussion considering that: a) the world's energy requirements are expected to double by 2050, b) fuel-related expenditures (in terms of both energy production and raw materials) represent a major cost incurred by the CPI, and the use of fossil fuels is also implicated in the production of greenhouse gas emissions (GHG).

The American Chemistry Council website (ACC; americanchemistry.com) provides very interesting data on the significant improvements that have been achieved by the chemical industry in terms of its reduced energy consumption. Considering that energy has a huge impact on the production costs in the CPI, it becomes quite clear that to be competitive and profitable the CPI need to find and implement mechanisms to reduce their energy consumption and become greener. Defining clear metrics, such as energy per unit of output, and setting concrete goals, are key to achieving continuous improvement. Other metrics, such as GHG emissions per ton of product, help to evaluate the potential impact of the operation on the planet and to identify the best opportunities for improvement.

More advanced metrics used by the ACC and explained on its website include the ratio of GHG savings to GHG emissions. This ratio compares "pros and cons" of a particular product in terms of GHG emissions. For example, if the production of a certain piece of insulation foam involves the generation of 1 lb CO_2 but during its useful life the same piece of foam avoids heat losses and saves enough energy to avoid the generation of 233 lb of CO_2, then the ratio for this building insulation foam is 233:1. Other examples are glass and carbon fiber for wind turbines (ratio 123:1) and so on. These advanced metrics help not only to illustrate the tremendous benefits of the CPI to society but also to identify the best opportunities for doing so.

However, while metrics are very important, they are not enough to get dramatic improvements. Meeting objectives related to environmental sustainability requires innovation and the appropriate use of technology, the application of proper engineering skills and a commitment from the entire organization (including upper management). It also requires the establishment of clear goals and objectives, and the development of a properly designed and managed energy-saving program that includes education, measurement, follow-up and recognition.

Green practices are inherent to the chemical engineering profession and promoting and implementing them is the responsibility not just of upper management but of all chemical engineering practitioners, regardless of function. With the demand for continuous improvement coming from society and all industry stakeholders, green chemical engineering offers magnificent challenges and extraordinary opportunities to innovative engineers. ■

Edited by Suzanne Shelley

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Solids Processing

Preventing Self-Heating and Ignition in Drying Operations

Incident investigation reveals that the most common root cause is lack of understanding

Pieter Zeeuwen and Vahid Ebadat
Chilworth Global

Many solid materials can exhibit self-heating, which — if unchecked — can progress to a fire or even explosion. And even if the situation does not get that far, it is likely to affect the output of the process, in terms of product quality degradation, for example. Recognizing that your product in powder or granular form can self-heat is the first step in controlling the risks associated with self-heating.

Whenever self-heating incidents are investigated, we find that a common root cause is a lack of understanding of self-heating phenomena. This article provides an introduction to self-heating phenomena and suggests measures to control this type of ignition source.

What is self-heating?

Not all particulate solids that are classified as combustible dust (in other words, pose a dust explosion hazard) will self-heat at normal processing temperatures, and conversely, some of the materials that do self-heat react too slowly to pose a dust explosion hazard. Some materials can self-heat at ambient temperatures, especially in large-scale storage, but for most materials the hazards arise when they are heated.

Self-heating can arise by one of two different mechanisms: by exothermic (heat releasing) chemical reactions and by exothermic decomposition. The chemical reactions are often the same as what occurs during a fire or explosion: an oxidation reaction with the oxygen in the air. At the start of the self-heating process, the reaction is very slow, like steel that oxidizes with atmospheric oxygen to form rust. Decomposition happens in a material that is unstable, and the material will fall apart while releasing heat. A significant difference between the two mechanisms is that decomposition does not require additional reactants and is therefore largely independent of the environment, while an oxidation reaction only happens if certain conditions are present, making it more difficult to predict its occurrence without detailed experimental studies.

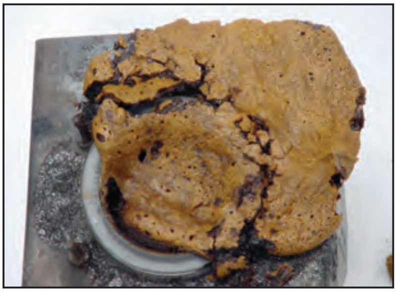

FIGURE 1. After completion of a test, in which self-heating of the product took place, the product was completely burnt. The charred and partly molten remains no longer fit inside the sample holder

What happens in self-heating?

Step 1. Rate of heat generation exceeds rate of heat loss. If a material undergoes an exothermic chemical reaction (or multiple reactions) or decomposes exothermically, the temperature of the material will rise due to the heat released from the exothermic reaction or decomposition. In the meantime, some of the heat is lost to the environment. If the rate of heat loss exceeds the rate of heat generation, the temperature of the material will be the same as the ambient temperature, otherwise, it will increase. Due to the poor thermal conductivities of many solids, a large portion of the reaction heat is retained in the powder.

Step 2. Resulting temperature rise further increases chemical reaction rate exponentially. The temperature rise of the material due to the exothermic reaction will further increase the chemical reaction rate, which in turn will cause the temperature to increase further. The increase of material temperature also results in an increase in the rate of heat loss. However, the rate of heat loss increases linearly with temperature, while the chemical reaction rate, and thus the

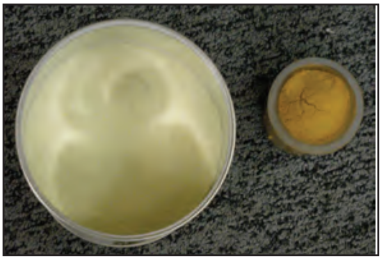

FIGURE 2. Product in the test cell (right) is discolored significantly after the test compared to the original sample (left), even though the self-heating has not led to smoldering or burning of the material

FIGURE 3. In this typical test cell for "bulk" conditions (50-mm dia., 80-mm height), air can diffuse into the sample through the open top of the cell and through the bottom of the cell, which is closed with a sintered glass disc. The sample temperature is measured continuously at various locations along the height of the cell

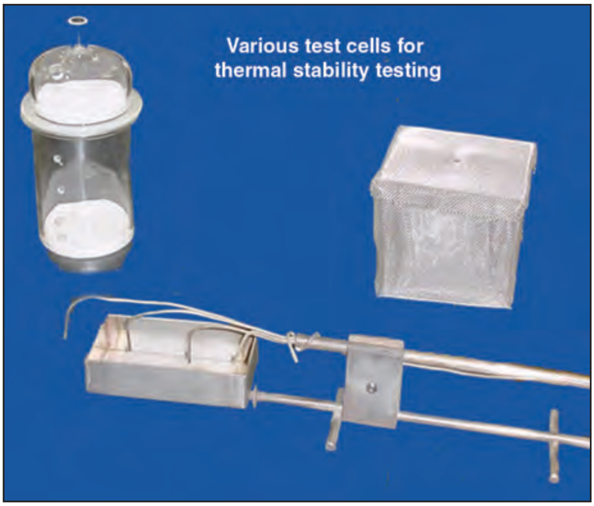

FIGURE 4. (Top left) In the test for "aerated" conditions, air flows through the sample from top to bottom, which are both closed by sintered glass discs. The cylindrical section has a 50 mm dia. and a height of 80 mm. (Bottom) For "air over layer" testing, warm air flows over the powder layer in the sample tray. (Top right) The wire basket for "basket testing" is illustrated more clearly in Figure 5

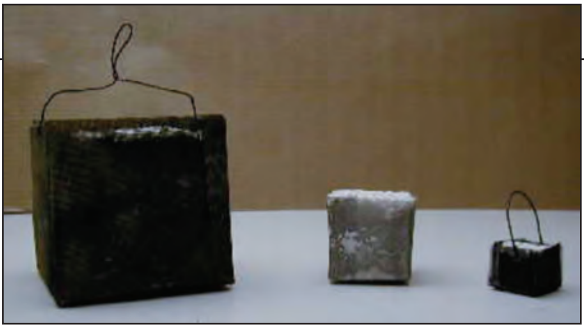

FIGURE 5. "Basket test" sample holders, for testing at different scales, allow extrapolation to large-scale storage conditions. The baskets typically have sides of 25, 50 and 100 mm

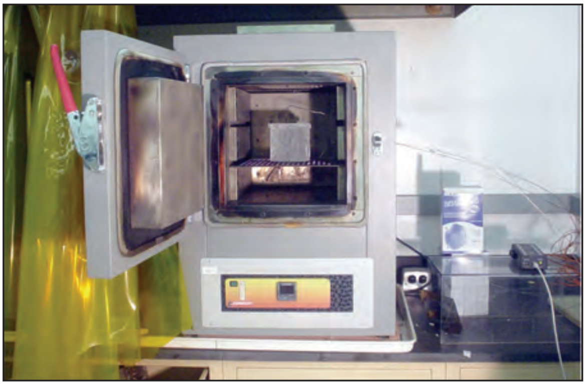

FIGURE 6. This "basket test" sample holder is prepared for testing inside a laboratory oven

heat generation rate, increases exponentially with temperature. Consequently, the heat generation rate will exceed the rate of heat loss and the temperature of the material will rise higher. This process is referred to as self-heating. Self-heating begins at a temperature at which the rate of heat generation is greater than the rate of heat loss and this temperature is called the exothermic onset temperature.

Subsequent effects

Potential smoldering. Self-heating of solid materials usually results in smoldering, which can set the material on fire or cause dust explosions, particularly when the smoldering material is disturbed and exposed to air (Figure 1). Many plants that experience self-heating incidents have a history of "near misses" where some self-heating occurs but does not progress to full-blown ignition. In such cases there may be "black spots" in an otherwise light-colored product, or a lump of charred product may be found, a so-called "smoldering nest". It is important to recognize such occurrences as indications of a potentially serious problem, rather than to learn to live with it.

Potential release of flammable gases. Self-heating reactions may also produce flammable gases, which may lead to gas explosions in process vessels or compromise product quality (Figure 2).

Testing self-heating behavior

The exothermic onset temperature is influenced not only by the chemical and physical properties, such as chemical reaction kinetics and heat of reaction, but also by other factors, including the following:

- Dimension and geometry of the solid bulk
- Ambient airflow
- Availability of oxygen in the bulk
- Additives and contaminants

Usually, the material has to be exposed to an elevated temperature for a period of time before it self-heats. This time is referred to as the induction time, which is dependent on temperature; and usually the higher the temperature, the shorter the induction time will be.

Because of the influencing factors mentioned, a single test is usually unable to predict self-heating behavior for all different drying and storage conditions. Instead, separate tests have been developed to simulate the conditions where the powder is in bulk form (Figure 3), layer form (with air flowing over the powder; Figure 4) and aerated form (Figure 4), where air is passing through the bulk of the product, increasing the oxygen availability for the reaction and also helping to remove heat from the reacting material. For large-scale storage situations tests are carried out at different scales so that the effect of the size of the bulk material can be assessed (Figure 5). All tests are carried out in temperature-controlled ovens (Figure 6) that allow screening tests (with the temperature ramped up at a defined rate) and isothermal testing (with a constant temperature controlled within narrow margins). Because of the potential for violent reactions during the self-heating process, all testing equipment needs to be fitted with explosion protection.

Learning from a real incident

In one incident, the powder in a fluidized bed dryer caught fire when the powder conveyer in the dryer was turned off in order to fix clogging in an upstream wet-product conveyer. During this period, the hot air supply was continued.

A screening test was conducted to determine whether this powder could self-heat under the conditions that ex-

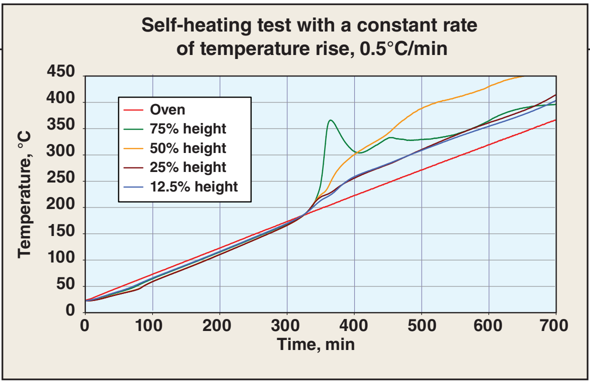

FIGURE 7. In this screening test, the oven temperature was increased from 20 to 400°C at a rate of 0.5°C/min. The exothermic onset temperature was identified to be 166°C, which was lower than the hot air temperature of the dryer, indicating that self-heating was the most probable ignition source for this incident

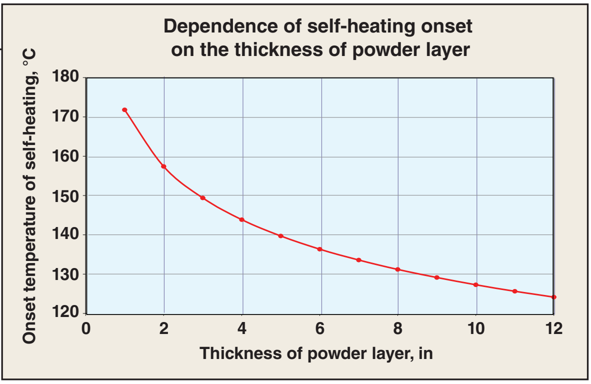

FIGURE 8. Using Equation (1), the exothermic onset temperatures of layers of the powder at different thicknesses were calculated and the results plotted here. As the thickness of the powder layer was increased from 1 to 12 in., the exothermic onset temperature decreased by 48°C

isted in the dryer before the incident. An typical powder sample was placed in a temperature-programmed oven and the temperature of the oven was increased from 20 to 400°C at a rate of 0.5°C/min (Figure 7). The exothermic onset temperature was identified to be 166°C, which was lower than the hot air temperature of the dryer. The result indicated that self-heating was the most probable ignition source for this incident.

This test provides a useful tool for a quick identification of the self-ignition hazard of materials and should be conducted for materials whose thermal stability characteristics are not known. However, to be of any practical value, the test results obtained in a laboratory-scale apparatus have to be scaled up to plant-size process. In order to establish the relationship between the exothermic onset temperature and powder layer thickness with the aid of thermal explosion theory, the sample of the powder that was being dried in the same incident batch was tested at three different layer thicknesses. In each trial, the powder sample was exposed to a constant temperature to test if self-heating would actually take place. The highest temperature at which self-heating did not occur and the lowest temperature at which self-heating did occur were determined. The average value of these two temperatures was taken as the exothermic onset temperature for each powder layer.

The exothermic onset temperatures were used to determine the unknown constants of the following equation, which expresses the relationship between the exothermic onset temperature and the thickness of the powder layer:

$$\ln\left(\frac{\delta_c T_a^2}{r^2}\right) = M - \frac{N}{T_a} \qquad (\mathbf{1})$$

Where

T_a = Exothermic onset temperature for a powder layer, K

r = One half of the powder layer thickness, m

δ_c = Frank-Kamenetskii-parameter, dimensionless

M, N = Constants determined by properties of the powder material

Using Equation (1), the exothermic onset temperatures of layers of the powder at different thicknesses were calculated and the results are plotted (Figure 8). As the thickness of the powder layer was increased from 1 to 12 in., the exothermic onset temperature decreased by 48°C.

The powder layer in the dryer before the incident was on the order of 4–8 in. This suggests that the exothermic onset temperature for the powder layer was well below the hot air temperature. Ignition would occur if the heating time exceeded the induction time.

Concluding remarks

The self-heating hazard of solid materials to be dried should be determined. Depending on the drying process, the solid materials can be tested in different shape, heating environment, with or without an airflow through the material and an airflow at the surface of the material. The exothermic onset temperatures can be used to determine safe drying temperatures using sufficient safety margins. However, the relationship between the exothermic onset temperature and the dimension of solid bulk is often needed in order to design a safe drying process. This relationship can be established from self-heating experiments based on thermal explosion theories, as demonstrated by the example introduced above. ■

Edited by Rebekkah Marshall

Suggested reading

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Rupture Discs and Pressure Relief

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The lowest K_R values in rupture discs

K_R values are used to determine the frictional flow loss in rupture discs. While the perception is that all rupture discs have high K_R values, this company's FAS (Forward Acting Scored; photo) and PRO+ (Precision Reverse Operating) discs debunk this perception by offering the best flow characteristics available in a rupture disc. Having a lower K_R value means that the FAS [$K_{RG} = 0.223$ (gas), $K_{RL} = 0.19$ (liquid)] and PRO+ ($K_R = 0.29$) rupture discs provide a larger opening that allows a greater flowrate than other rupture discs on the market, says the company. The ability of these two discs to reach such low K_R values allows for better flow and faster system relief in the event of overpressurization. The FAS and PRO+ are both used for safety-relief valve isolation. The FAS is used in high-pressure applications, while the PRO+ is ideal for situations requiring a lower burst pressure. The PRO+ is also suitable for isolation relief valves in high-cycling applications. — *Oseco, Broken Arrow, Okla.*

www.oseco.com

A system that manages all overpressure relief devices

This company has introduced Relief Device Manager (RDM; photo) for optimizing the safety, integrity and total ownership of overpressure relief devices, including rupture disks; buckling-pin relief valves; safety and pressure-relief valves; tank vents; flame arrestors; and explosion vents. This Windows-based system provides peace of mind to plant operators and owners by continuously monitoring overpressure relief devices. RDM provides warnings, alarms and performance history if events compromise the integrity of pressure safety management systems. RDM was designed because overpressure relief devices, such as rupture disks, activate instantaneously, which presents challenges to process plant owners and operators in pinpointing precise operating conditions of an overpressure event. Without RDM, inaccurate conclusions regarding the relationship between process conditions and overpressure relief devices can be made, risking repeated incidences and compromised safety. Inaccurate conclusions are frustrating, if devices are bursting frequently without the ability to diagnose causes, or if you are trying to maximize longevity of overpressure relief investments through precise replacement schedules. — *BS&B Safety Systems, Tulsa, Okla.*

www.bsbsystems.com

Reverse-acting rupture discs for aggressive, sanitary applications

The Axius reverse-acting rupture (bursting) disc (photo) is said to represent a revolutionary advancement in high-performance pressure-relief technology. The manufacturer has continued to expand Axius capabilities, since its introduction in 2005, by offering higher burst pressure, a sanitary version and a range of larger sizes. Axius is designed to be used in aggressive chemical, pharmaceutical and sanitary applications, and typically outperforms all other types of rupture discs in these applications, says the company. Axius rupture discs are unique because they have no score lines, no stress zones that can fatigue and a completely smooth process side. — *Fike Corp., Blue Springs, Mo.*

www.fike.com

Micro-scored rupture discs offer added benefits

This company has recently introduced its SCD (forward acting) and SCR (reverse buckling) rupture discs with micro-scored calibration sections. The patent-pending technology makes the discs very flexible so that scoring in six or more sections is possible instead of the usual four. This allows a better opening of the disc, reducing the risk of petal detachment, even at higher pressures, says the company. This technology is also very effective for the manufacture of high-performance reverse buckling discs for low-pressure bursting ranges. The discs react to excessive pressure in a few milliseconds without fragmentation, have a good resistance to corrosion and are especially suitable for protection of relief valves. The company has also recently tested new materials for rupture discs, such as titanium and tantalum. — *Donadon SDD Srl., Corbetta, Milan, Italy*

www.donadonsdd.com

Proportional venting assured with these relief valves

RHPS Series PRV model proportional relief valves (photo, p. 56) provide

Note: For more information, circle the 3-digit number on p. 54, or use the website designation.


Swagelok

proportional venting of overpressures for piping systems up to 1-in. size. End connections include NPT female, BSPP female and BSPP male in sizes 1/4, 1/2, 3/4 and 1 in. Available threaded adapters convert from BSPP to NPT to allow for easy product installation. Valve operation is smooth, opening gradually and reseating accurately in proportion to the increase or decrease in pressure over the set pressure. RPV proportional relief valves feature 316L stainless steel construction of the body, trim and spring housing. Fluorocarbon or nitrile seats and seals can be chosen. Available set pressure ranges are: 145 to 580 psig; 580 to 1,160 psig; 1,160 to 2,170 psig; 2,170 to 4,060 psig; and 4,060 to 5,800 psig. Depending on the body size selected, flow coefficients (C_V) range from 0.49 to 4.36. Operating temperature is from –20 to 80°C. — *Swagelok Co., Solon, Ohio*
www.swagelok.com


Rembe

Two layers deliver added benefits with this rupture disc
The double-layer KUB-V-Series (photo) adds one vital feature that other rupture discs don't offer: Due to special reinforcement of the second protecting layer, it withstands twice the pressure in the reverse direction as it does in the venting direction. The two-layer design consists of one layer that handles the burst pressure by incorporating a buckling pin element brought into the dome by high-precision laser cutting. The second layer is a sealing membrane that isolates the burst-pressure-determining layer from harsh process conditions. As a result, the KUB-V-Series eliminates all three disadvantages ordinary single-layer reverse-acting disks have, namely: premature failure due to fatigue; pre-weakening of the dome by bringing in scores and grooves into the fragile burst membrane; and complicated mounting of the disk. The KUB-V is torque independent according to its eight-times thicker burst layer compared to scored designs, as the burst pressure is determined by the buckling pin formula and is independent of material thickness. — *Rembe GmbH Safety + Control, Brilon, Germany*
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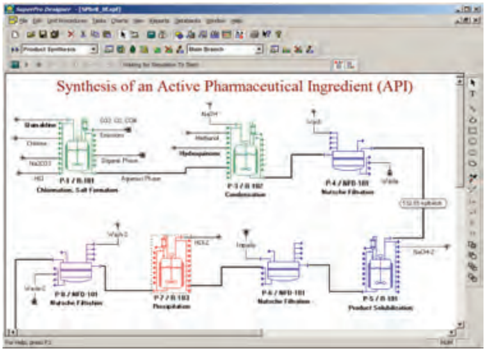
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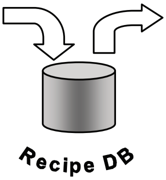
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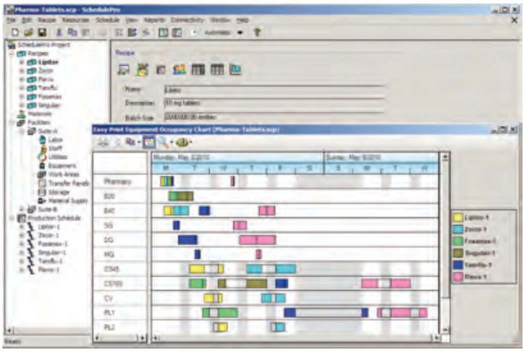

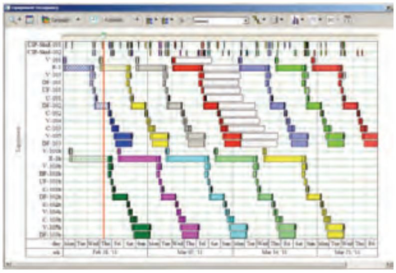

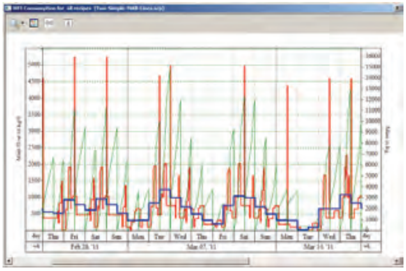

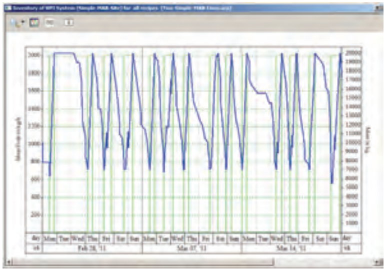

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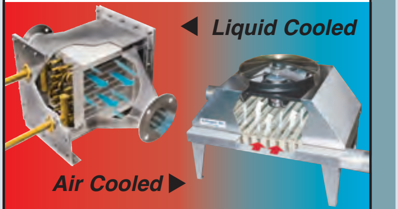

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See bottom of next page for advertising sales representatives' contact information

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1	16	31	46	61	76	91	106	121	136	151	166	181	196	211	226	241	256	271	286	301	316	331	346	361	376	391	406	421	436	451	466	481	496	511	526	541	556	571	586
2	17	32	47	62	77	92	107	122	137	152	167	182	197	212	227	242	257	272	287	302	317	332	347	362	377	392	407	422	437	452	467	482	497	512	527	542	557	572	587
3	18	33	48	63	78	93	108	123	138	153	168	183	198	213	228	243	258	273	288	303	318	333	348	363	378	393	408	423	438	453	468	483	498	513	528	543	558	573	588
4	19	34	49	64	79	94	109	124	139	154	169	184	199	214	229	244	259	274	289	304	319	334	349	364	379	394	409	424	439	454	469	484	499	514	529	544	559	574	589
5	20	35	50	65	80	95	110	125	140	155	170	185	200	215	230	245	260	275	290	305	320	335	350	365	380	395	410	425	440	455	470	485	500	515	530	545	560	575	590
6	21	36	51	66	81	96	111	126	141	156	171	186	201	216	231	246	261	276	291	306	321	336	351	366	381	396	411	426	441	456	471	486	501	516	531	546	561	576	591
7	22	37	52	67	82	97	112	127	142	157	172	187	202	217	232	247	262	277	292	307	322	337	352	367	382	397	412	427	442	457	472	487	502	517	532	547	562	577	592
8	23	38	53	68	83	98	113	128	143	158	173	188	203	218	233	248	263	278	293	308	323	338	353	368	383	398	413	428	443	458	473	488	503	518	533	548	563	578	593
9	24	39	54	69	84	99	114	129	144	159	174	189	204	219	234	249	264	279	294	309	324	339	354	369	384	399	414	429	444	459	474	489	504	519	534	549	564	579	594
10	25	40	55	70	85	100	115	130	145	160	175	190	205	220	235	250	265	280	295	310	325	340	355	370	385	400	415	430	445	460	475	490	505	520	535	550	565	580	595
11	26	41	56	71	86	101	116	131	146	161	176	191	206	221	236	251	266	281	296	311	326	341	356	371	386	401	416	431	446	461	476	491	506	521	536	551	566	581	596
12	27	42	57	72	87	102	117	132	147	162	177	192	207	222	237	252	267	282	297	312	327	342	357	372	387	402	417	432	447	462	477	492	507	522	537	552	567	582	597
13	28	43	58	73	88	103	118	133	148	163	178	193	208	223	238	253	268	283	298	313	328	343	358	373	388	403	418	433	448	463	478	493	508	523	538	553	568	583	598
14	29	44	59	74	89	104	119	134	149	164	179	194	209	224	239	254	269	284	299	314	329	344	359	374	389	404	419	434	449	464	479	494	509	524	539	554	569	584	599
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BUSINESS NEWS

PLANT WATCH

Outotec to deliver the world's largest iron-ore pelletizing plant in Brazil

June 30, 2011— Outotec Oyj (Espoo, Finland; www.outotec.com) has agreed to deliver an iron-ore pelletizing plant to Samarco Mineração S.A. The new plant will be installed at Samarco's iron ore port in Ponta de Ubú, EspÌrito Santo, Brazil. Once operational at the end of 2013, the plant will treat 9.25-million metric tons (m.t.) of iron ore per year.

Evonik to build plant in Marl for products used in adhesives and sealants

June 30, 2011 — Evonik Industries AG (Essen; www.evonik.com) will build a plant in Marl, Germany, for producing functionalized polybutadiene. The liquid polybutadiene is expected to go onstream in the fall of 2012.

AkzoNobel invests €140-million in Frankfurt chlorine plant

June 20, 2011 — AkzoNobel (Amsterdam, the Netherlands; www.akzonobel.com) is investing €140 million to convert its chlorine plant in Frankfurt am Main, Germany, to membrane electrolysis technology. The new facility, due to come onstream in the 4th Q of 2013, will increase current capacity by around 50% to an expected 250,000 tons, up from 165,000 tons.

Linde builds Indonesia's largest air separation unit

June 14, 2011 — The Linde Group (Munich, Germany; www.linde.com) has closed a longterm deal to supply the Indonesian steel corporation PT. Krakatau POSCO (PTKP) with industrial gases. PTKP is a joint venture (JV) between the South Korean steel corporation POSCO and Krakatau Steel. Linde will invest around €88 million to construct what is said to be the country's largest air separation unit (ASU) with a capacity of around 2,000 m.t./d of oxygen at Cilegon, where PTKP is constructing the first integrated steelworks in Southeast Asia. The ASU is scheduled to go onstream in October 2013.

Tecnimont wins contract for polyolefin plants in India

June 13, 2011 — Maire Tecnimont S.p.A.'s (Rome, Italy; www.mairetecnimont.it) main operating company, Tecnimont S.p.A. (Milan, Italy) and its fully owned subsidiary Tecnimont ICB Pvt. Ltd. (TICB) of India have been awarded two contracts by ONGC Petro additions Ltd. (OPaL) for the realization of polyethylene (PE) and polypropylene (PP) plants in Dahej, Gujarat State, India. With a total value of about $440 million, the two contracts include a PP plant of 340,000 ton/yr and two high-density/linear-low-density swing PE plants of 360,000 ton/yr each. The Ineos Innovene PP process will be used for the PP plant and the Ineos Innovene G process will be used for the two PE plants.

AkzoNobel forms partnership in China to secure TiO_2 supply

June 6, 2011 — AkzoNobel has entered into a partnership with Quangxi CAVA Titanium Industry Co. in China for the production and supply of titanium dioxide. The collaboration includes the construction of a new TiO_2 plant in Qinzhou. Quangxi CAVA Titanium Industry Co. is currently in the process of designing and constructing a 100,000-ton TiO_2 plant at an industrial site in Qinzhou. Production is expected to start in early 2014.

Toyo wins contract for Indonesia's first butadiene plant

June 6, 2011 — Toyo Engineering Corp. (Toyo; Chiba, Japan; www.toyo-eng.co.jp) has been awarded a contract for a 100,000-ton/yr butadiene plant for PT Petrokimia Butadiene Indonesia. The plant, located at Cilegon, is slated to start up in 2013. The approximately $110-million lump-sum project will be executed by Toyo Engineering Korea Ltd. The butadiene will be produced using licensed Lummus/BASF technology.

A new PET production plant is planned for SKC in Korea

June 6, 2011 — SKC Co. (Seoul, Korea) and Uhde Inventa-Fischer GmbH (Berlin, Germany; www.uhde-inventa-fischer.com) have signed a contract for a plant to produce high-quality polyethylene terephthalate (PET) for the manufacture of films in Jincheon, Republic of Korea. The plant will have two lines with production capacities of 144,000 and 54,000 m.t./yr of resin. The commissioning is scheduled for the 2nd Q of 2012. The plant will use Uhde Inventa-Fischer's 2R technology.

Praxair expands its Gulf Coast hydrogen supply

June 6, 2011 — Praxair, Inc. (Danbury, Conn.; www.praxair.com) is expanding its hydrogen capacity under longterm supply agreements with Valero Energy Corp. for 270-million standard cubic feet per day (scfd). In Louisiana, Praxair is installing a new, 135-million scfd H_2 plant at Valero's St. Charles refinery. Startup is expected in the 4th Q of 2012. A new 135-million scfd H_2 plant is being installed at Valero's Port Arthur, Tex., refinery. Plant startup is scheduled for the 1st Q of 2013. Hydrogen is used by petroleum refiners to produce ultra-low-sulfur diesel fuels.

MERGERS AND ACQUISITIONS

GEA acquires the powder specialist Nu-Con

July 11, 2011 — GEA Group AG (Düsseldorf, Germany; www.geagroup.com) has acquired Nu-Con Ltd. (Auckland, New Zealand), a global supplier of powder handling equipment. The company will be integrated into the segment GEA Process Engineering. The transaction will be financed entirely through GEA Group's existing credit facilities. It remains subject to approval by the anti-trust authorities and is expected to be consummated in September 2011.

Shell and Paques form JV to push bio-desulfurization technology for oil & gas

July 6, 2011 —Shell Global Solutions (Amsterdam; www.shell.com/globalsolutions) and Paques Holding B.V. (Balk, both the Netherlands; www.paques.nl) have agreed to form a 50–50 JV, Paqell B.V., to focus their efforts on the marketing of biological desulfurization in the oil-and-gas sector for high-pressure gas applications using Thiopaq O&G (oil & gas) technology. Once an R&D program is concluded by the end of next year, Paqell will operate from the Watercampus in Leeuwarden. For now, Paqell operates from Leeuwarden, Amsterdam and Balk; all in the Netherlands.

Dow and Ube form JV to manufacture electrolytes for Li-ion batteries

July 6, 2011 —The Dow Chemical Co. (Midland, Mich.; www.dow.com) and Ube Industries, Ltd. (Ube; Tokyo, Japan; www.ube-ind.co.jp) have agreed to form a JV to manufacture and market formulated electrolytes for lithium-ion batteries. The 50–50 JV, named Advanced Electrolyte Technologies LLC, is expected to be finalized later this year, pending regulatory approval. The JV's first manufacturing facility is expected to be built at Dow's Michigan Operations' site in Midland for startup in 2012.

Elevance acquires Delta Biofuels facility

June 7, 2011 — Elevance Renewable Sciences Inc. (Bolingbrook, Ill.; www.elevance.com) has acquired the Delta BioFuels facility in Adams County, Miss. The company intends to convert the facility to a biorefinery and derivatives operation in a multi-phase project that will involve an investment of more than $225 million. ■

Dorothy Lozowski

FOR ADDITIONAL NEWS AS IT DEVELOPS, PLEASE VISIT WWW.CHE.COM

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Economic Indicators

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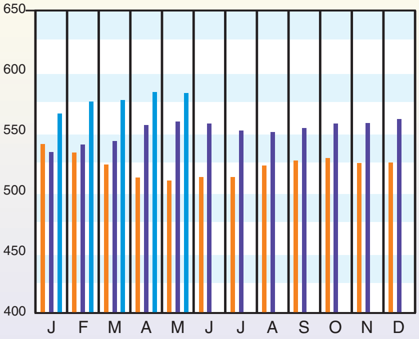
CHEMICAL ENGINEERING PLANT COST INDEX (CEPCI)

(1957-59 = 100)	May.'11 Prelim.	Apr.'11 Final	May.'10 Final
***CE* Index**	581.7	582.3	558.2
Equipment	707.3	708.0	670.2
Heat exchangers & tanks	673.0	671.4	629.9
Process machinery	663.7	665.3	631.8
Pipe, valves & fittings	861.8	867.9	828.3
Process instruments	440.1	443.7	424.8
Pumps & compressors	904.4	904.7	903.1
Electrical equipment	503.0	502.6	473.2
Structural supports & misc	755.7	752.8	697.5
Construction labor	325.0	325.8	327.8
Buildings	518.2	517.1	513.9
Engineering & supervision	332.9	333.6	339.7

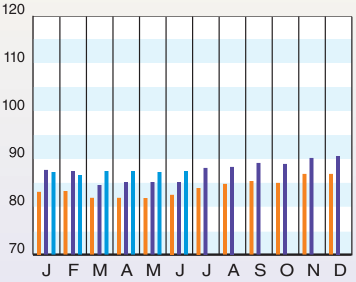
Annual Index:
2003 = 402.0
2004 = 444.2
2005 = 468.2
2006 = 499.6
2007 = 525.4
2008 = 575.4
2009 = 521.9
2010 = 550.8



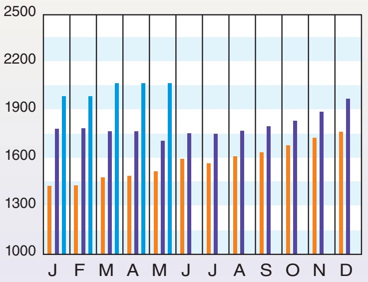
CURRENT BUSINESS INDICATORS

	LATEST	PREVIOUS		YEAR AGO
CPI output index (2007 = 100)	Jun.'11 = 87.4	May.'11 = 87.2	Apr.'11 = 87.4	Jun.'10 = 85.1
CPI value of output, $ billions	May.'11 = 2,072.3	Apr.'11 = 2,072.8	Mar.'11 = 2,072.8	May.'10 = 1,711.0
CPI operating rate, %	Jun.'11 = 75.4	May.'11 = 75.1	Apr.'11 = 75.3	Jun.'10 = 72.8
Producer prices, industrial chemicals (1982 = 100)	Jun.'11 = 342.6	May.'11 = 336.0	Apr.'11 = 322.7	Jun.'10 = 264.1
Industrial Production in Manufacturing (2007=100)	Jun.'11 = 89.8	May.'11 = 89.7	Apr.'11 = 89.7	Jun.'10 = 86.6
Hourly earnings index, chemical & allied products (1992 = 100)	Jun.'11 = 157.4	May.'11 = 157.0	Apr.'11 = 155.4	Jun.'10 = 153.6
Productivity index, chemicals & allied products (1992 = 100)	Jun.'11 = 112.1	May.'11 = 110.9	Apr.'11 = 111.1	Jun.'10 = 112.2

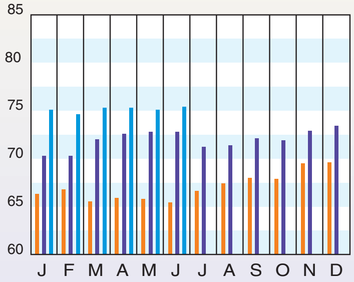
CPI OUTPUT INDEX (2007 = 100)



CPI OUTPUT VALUE ($ BILLIONS)



CPI OPERATING RATE (%)

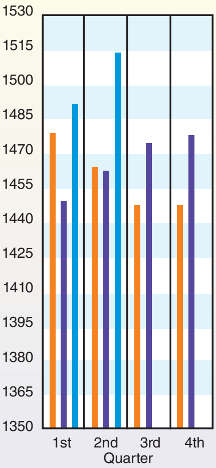


Current Business Indicators provided by Global Insight, Inc., Lexington, Mass.

MARSHALL & SWIFT EQUIPMENT COST INDEX

(1926 = 100)	2nd Q 2011	1st Q 2011	4th Q 2010	3rd Q 2010	2nd Q 2010
M & S INDEX	1,512.5	1,490.2	1,476.7	1,473.3	1,461.3
Process industries, average	1,569.0	1,549.8	1,537.0	1,534.4	1,522.1
Cement	1,568.0	1,546.6	1,532.5	1,530.0	1,519.2
Chemicals	1,537.4	1,519.8	1,507.3	1,505.2	1,493.5
Clay products	1,557.5	1,534.9	1,521.4	1,518.3	1,505.6
Glass	1,469.2	1,447.2	1,432.7	1,428.5	1,416.4
Paint	1,584.1	1,560.7	1,545.8	1,542.1	1,527.6
Paper	1,480.7	1,459.4	1,447.6	1,444.5	1,430.1
Petroleum products	1,672.0	1,652.5	1,640.4	1,637.0	1,625.9
Rubber	1,617.4	1,596.2	1,581.5	1,579.3	1,564.2
Related industries					
Electrical power	1,494.9	1,461.2	1,434.9	1,419.2	1,414.0
Mining, milling	1,623.5	1,599.7	1,579.4	1,576.7	1,569.1
Refrigeration	1,856.4	1,827.8	1,809.3	1,804.8	1,786.9
Steam power	1,546.5	1,523.0	1,506.4	1,502.3	1,488.0

Annual Index:
2003 = 1,123.6 **2004 = 1,178.5** **2005 = 1,244.5** **2006 = 1,302.3**
2007 = 1,373.3 **2008 = 1,449.3** **2009 = 1,468.6** **2010 = 1,457.4**



CURRENT TRENDS

Capital equipment prices, as reflected in the *CE* Plant Cost Index (CEPCI), decreased approximately 0.10% on average from April to May, after increasing approximately 1.14% from March to April.

Meanwhile, according to the American Chemistry Council's (Washington, D.C.; www.americanchemistry.com) mid-year economic report, total output for the global chemical industry is expected to grow by 4.8% in 2011, 5.3% in 2012, and 4.7% in 2013.

Visit www.che.com/pci for more information and other tips on capital cost trends and methodology. ■