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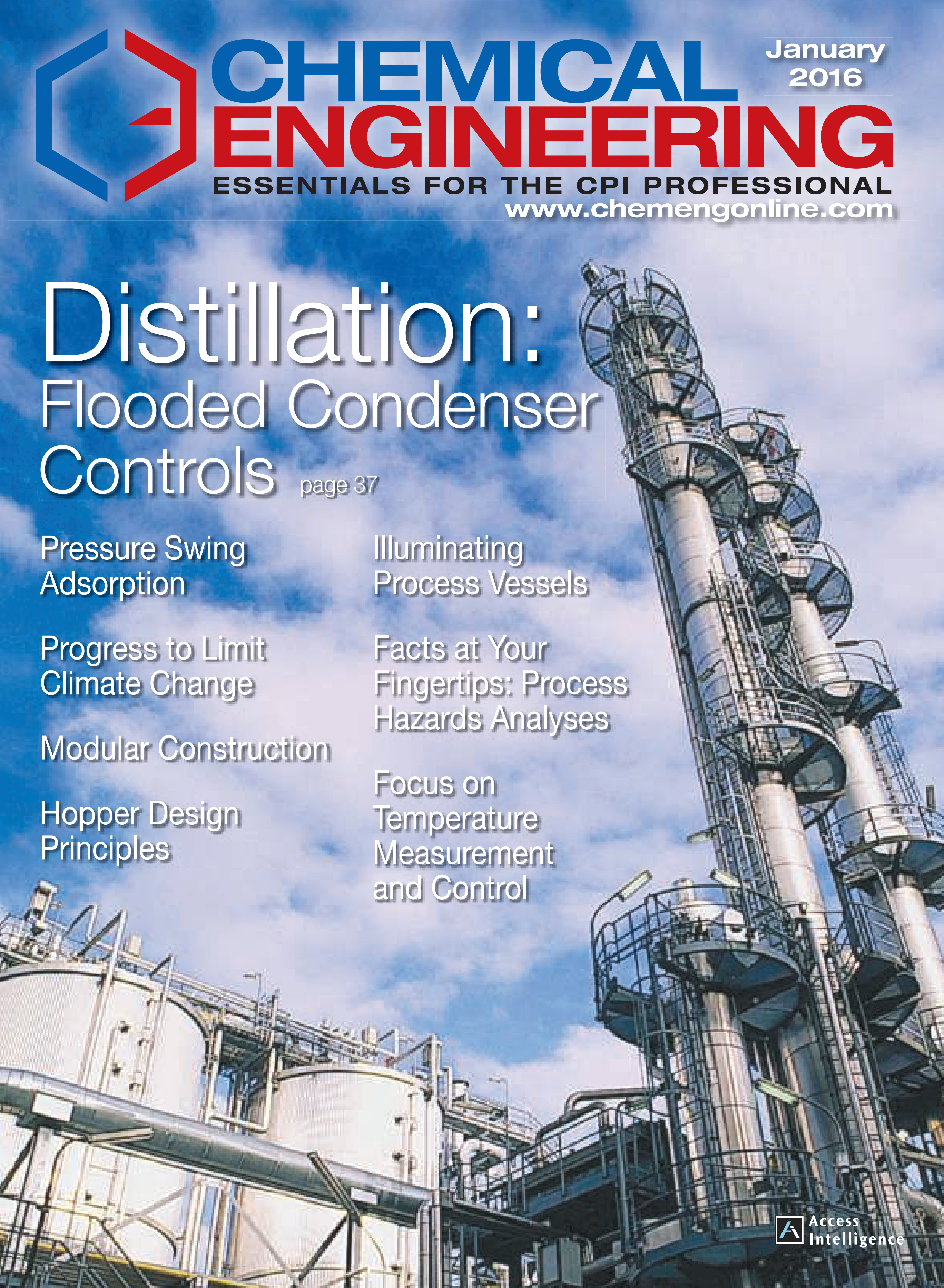

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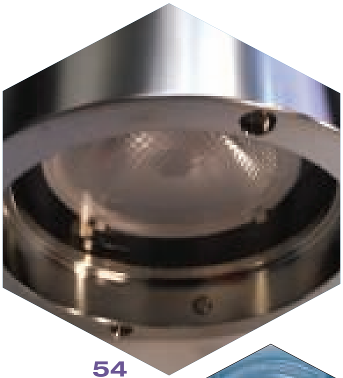

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Cover: Rob Hudgins; Project photograph provided courtesy of Fluor Corp.

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Editor's Page

Tackling environmental challenges

Last month marked the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21). World leaders gathered in Paris, France with the goal of working out an international agreement aimed at minimizing global warming and thereby avoiding potentially catastrophic climate-related events. The negotiations resulted in a landmark agreement, with 195 countries committing to lower greenhouse gas (GHG) emissions in order to limit the rise in global temperatures to less than 2°C above pre-industrial temperatures.

The historic global accord reached in Paris has wide-reaching implications for economics, government policies and the scientific community. The ongoing efforts by scientists and engineers to reduce GHG emissions will undoubtedly get a boost. Our Newsfront in this issue, Progress to Limit Climate Change (pp. 16–19), highlights some of the technological advances that have been made in this area to date.

Recycling gains momentum

In addition to reducing GHG emissions, much more is needed for environmental sustainability. Another area that has been gaining momentum is recycling. A recent report*, released jointly by the Association of Plastic Recyclers (APR) and the American Chemistry Council (ACC) states that for the twenty-fifth year in a row since surveying began in 1990, the number of pounds of plastic bottles collected for recycling in the U.S. has increased. In 2014, the increase was 97 million pounds over 2013, for a total surpassing 3 billion pounds of plastic bottles collected.

Plastic bottle resins are identified by their corresponding numbers: 1) polyethylene terephthalate (PET); 2) high-density polyethylene (HDPE); 3) polyvinyl chloride (PVC); 4) low-density polyethylene (LDPE); 5) polypropylene (PP); and 6) polystyrene (PS). According to the report, the bulk of the U.S. plastic bottle market is made up of PET and HDPE, which together comprise around 97% of that market. Recycled HDPE resin is used primarily in non-food-application bottles as well as pipe and lawn products. Recycled PET resin is used mainly for fiber and food bottles. More information about recycling can be found in the report for interested parties. Also, see PET Recycling on p. 7 of this issue. Recycling of much more than plastic is, of course, also needed. See, for example, our report on New Frontiers in Metals Recycling in the April 2015 issue.

In this issue

Our Cover Story on distillation takes an in-depth look at flooded condenser control (pp. 37–49). The Feature Report on pressure-swing adsorption shows that this versatile technology can be used for more than just hydrogen purification (pp. 50–53). Our Newsfront on modular construction points out the pros and cons to this widely growing trend (pp. 20–24). Important information about bulk solids handling is in this month's Solids Processing article (pp. 58–63), and there is much more in this issue. We hope you enjoy it. ■

Dorothy Lozowski, Editor in Chief

* 25th Annual National Post-Consumer Plastics Bottle Recycling Report, available on http://plastics.americanchemistry.com/Education-Resources/Publications/2014-National-Post-Consumer-Plastics-Bottle-Recycling-Report.pdf

Letters

On the subject of ethics

Thank you for writing this article [Engineering Ethics Survey: What's Your Opinion?, *Chem. Eng.* October 2015, pp. 50–55]. Many of us, as we proceed through our careers, are faced with some difficult choices, which can have quite an impact on our future. An ethical misstep can ruin a career and hurt any[one] dependent on an [that] individual. I am convinced that many of the younger [engineers] have no idea of the pressures that can fall upon them.

I liked your selection of cases, especially #7, as so often internal organization relationships really amplify the pressure on decisions.

Your fine article brought back memories of many discussions in the past with my fellow members of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). For a lot of years, I operated the ASHRAE Think Tank, an email group of about a hundred officers, ex-officers, directors and ex-directors of the society. We would discuss subjects that might directly or indirectly impact the membership. One of these was ethics.

I brought up the subject for discussion as I was alarmed at the membership of some technical committees and standards committees with obvious conflicts of interest. This reminded me of the ASME versus Hydrolevel case heard by the U.S. Supreme Court and decided in favor of Hydrolevel. You may find it interesting to search for this on the Internet. There are many references.

I realize this case concerned a non-profit organization's matter, but the fact that it went to the Supreme Court and that ASME lost certainly got the attention of the ASHRAE folks. Unfortunately, much time has passed; the problem is as bad or worse today.

I hope that your article is picked up by others and that your magazine will periodically run articles on ethics. By the way, you might do a search on "Ethicana." Perhaps you know about it.

Thanks, again, for the article.

Lawrence (Larry) Staples
Prairie Village, KS

Editor's note: The survey on ethics from our October 2015 issue is still open. If you would like to participate, you can find a link to the survey on our website at the end of the article at www.chemengonline.com/engineering-ethics-survey-whats-opinion/

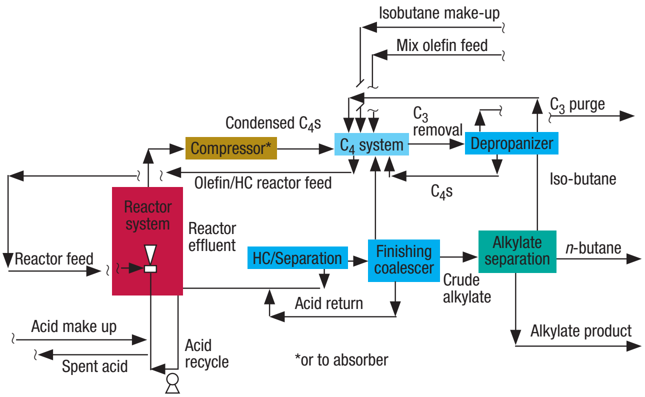
Postscripts, corrections

December 2015, "New catalyst removes cyanide from wastewater." On p. 8, the name Raveendran Shiju is missing the "n" at the end of Raveendran.

October 2015, "Pipe Insulation: Finding the Optimal Thickness." On p. 62, a sign in Equation (6) was inadvertently changed from plus to minus. Because this mistake was not part of the derivation, the error does not propagate through, so does not change anything that follows. The correct form of Equation (6) should contain the terms T_2+460 and T_a+460.

Slash costs with this advanced sulfuric-acid alkylation process

Edited by:
Gerald Ondrey



Alkylate — the main component in high-octane gasoline — is produced by catalytic reaction of C_3–C_5 olefins with isobutane in the presence of strong acid catalyst. Although there has been progress in the use of solid-acid catalysts (see, for example, *Chem. Eng.*, June 2013, p. 11), sulfuric-acid alkylation is becoming increasingly popular in recent years due to safety and environmental concerns with hydrofluoric-acid alkylation, says Amarjit Bakshi, president and CEO of Refining Hydrocarbon Technologies (RHT; Katy, Tex.; www.rhtgulfcoast.com).

RHT has completed pilot testing and is now ready to commercialize its advanced sulfuric-acid alkylation process. The RHT process (flowsheet) is based on classical sulfuric-acid alkylation chemistry that has been used since the 1940s. However, the RHT process uses a unique mixing device that requires less energy and maintenance than alternative processes, and works at lower temperatures at essentially isothermal conditions, explains Bakshi. Low-temperature operation favors the formation of the desired high-octane product (trimethylpentanes and dimethyl hexane), while minimizing side reactions, such as polymerization, disproportionation, cracking and the formation of unstable esters of H_2SO_4.

Other features of the RHT technology are a reduction in acid consumption to about 50% of the conventional processes and an advanced coalescer design and operating conditions for enhanced separation of the acid and hydrocarbons. As a result, a neutralization stage — required in conventional processes — is not needed, which results in a "dry process," with reduced corrosion issues, Bakshi says. In addition, RHT offers a third major improvement as an integral part of the technology, which absorbs the C_4s autorefrigeration vapors in heavier hydrocarbons/recycle alkylate, instead of the more costly compression stage. "These improvements reduce the capital expenditures (Capex) by about 33 to 40% compared to conventional technology," says Bakshi. Operating expenses are also reduced by about 40%, he says.

PET RECYCLING

Polyethylene terephthalate (PET) can be quickly depolymerized into virgin monomers using a patented process that was developed, and is being scaled up by Ioniqa Technologies BV (Eindhoven, the Netherlands; www.ioniqa.com). The company recently finalized a multi-million-euro funding round with Chemelot Ventures BV for scaling up Ioniqa's process 1,000-fold to the 100-L demonstration scale. This year, Ioniqa aims to reach the kiloton scale, to be later followed by a fully operational 10,000-m.t./yr plant in the Netherlands in 2017.

Although technology is available for recycling colorless PET, the bulk of PET products are colored, which has made recycling difficult. As a result, more than 50 million ton/yr of petroleum-based PET (from bottles, packaging, filling, clothing and carpets) is either incinerated, landfilled or ends up in the ocean, says the company. Ioniqa's Magnetic Smart Process is based on its proprietary Magnetic Fluid Catalyst (an iron-based ionic liquid).

(Continues on p. 8)

These robust organosilane-based membranes promise benefits

A new desalination membrane has been developed by an industry-academia collaboration team, led by professor Toshinori Tsuru at Hiroshima University (Japan; http://home.hiroshima-u.ac.jp/membrane/en/index.html). The work is the culmination of a five-year project that began in 2011 with support from the Japan Science and Technology Agency.

The research team fabricated organosilica membranes based on bis(triethoxysilyl)ethane (BTESE) for the separation layer. The stable organosilica structure enables the membrane to withstand exposure to high chloride concentrations of up to 35,000 parts per million (ppm) per hour — much higher than the 15,000-ppm limit of conventional membranes. The organosilica structure also withstands high concentrations (100–1,000 ppm) of NaClO, which is often used in reverse-osmosis (RO) plants to prevent fouling by biofilms; and can handle temperatures up to 90°C.

In laboratory immersion tests, the BTESE-derived membranes showed a NaCl rejection of higher than 99%, which is comparable or better than that of commercialized seawater-desalination membranes, as well as nearly the same water permeability (1×10^{-13} m^3/m^2 s Pa at 25°C).

In addition to RO applications, the membranes may also find use for dehydrating alcohols via pervaporation technology. The researchers demonstrated "excellent" stability of the BTESE-based membranes in long-term pervaporation trials with 50 wt.% aqueous solutions of isopropanol (IPA) at both 75 and 100°C.

Compared to conventional polyamide membrane technologies, the robustness of the new membrane promises to enhance RO processes, by eliminating pretreatment steps, as well as by allowing operation at higher temperatures and pressures for treating boiler feed water.

Note: For more information, circle the 56-digit number on p. 66, or use the website designation.

SEMICONDUCTORS

This month began a three-year project to reduce greenhouse gas emissions released by thin film tools used in the semiconductor industry during the production of semiconductors by using alternative fluorine gas mixtures. Called ecoFluor, the project is combining the technology and know-how of Solvay S.A.'s (Brussels, Belgium; www.solvay.com) Global Business Unit (GBU) Special Chem, Texas Instruments, Muegge and The Fraunhofer Institute for Microsystems and Solid State Technologies (EMFT). The project is partly funded by the German Federal Ministry of Research and Education (BMBF; Bonn).

The ecoFluor project focuses on new cleaning processes for chemical vapor deposition (CVD) chambers in the semiconductor industry and replaces the three major cleaning gases hexafluoroethane (C_2F_6), tetrafluoromethane (CF_4) and nitrogen trifluoride (NF_3) with gas mixtures based on F_2/N_2/Ar mixtures. These F_2 gas mixtures will be produced in GBU Special Chem's plants in Bad Wimpfen, Gemany and Onsan, Korea.

Such replacement can have a meaningful environmental impact considering that the most widely used cleaning gas, nitrogen trifluoride, has a global warming potential (GWP) of 17,200 times that of CO_2, while the proposed alternative has a GWP equal to CO_2.

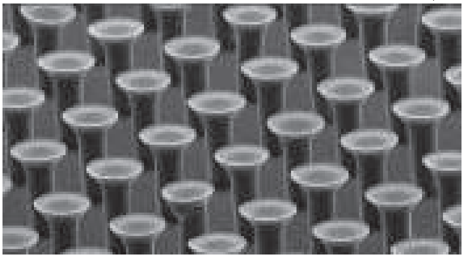
NEW RESIN

The combination of a specially designed catalyst with new process technology has given rise to a new type of plastic resin that can address current performance gaps in packaging applications, according to its developer, The Dow Chemical Co. (Midland, Mich.; www.dow.com). "The new resin eliminates the standard tradeoff between toughness and stiffness," explains David Parrillo, global R&D director for Dow Pack-

(Continues on p. 9)

Dry adhesive technology mimics gecko's feet

nanoGriptech



A dry adhesive technology inspired by the microscopic hairs on gecko's feet is said to be the first of its kind to be commercialized. Known as Setex, the technology was developed by nanoGriptech Inc. (Pittsburgh, Pa.; www.nanogriptech.com), a company spun out of Carnegie Mellon University, and uses no chemicals and leaves no residue.

The adhesive consists of a structured surface containing millions of nano-scale elements shaped like tiny hairs with widened tops (see micrograph). When the nano-hairs come into close contact with another surface, van der Waals interactions (dipole-dipole attractions) act to adhere the nanostructures to the surface. The nano-hairs work via the same principles observed in the adhesion of microscopic, hair-like structures called setae on the surface of a gecko's feet.

The company adapted processes initially developed for other industries to manufacture templates for the nanoscale surface structures in the adhesive, explains Paul Glass, nanoGriptech's vice president for engineering. Then the template is used to produce the nanostructured surface out of various polymers. The proprietary process modifies the nanostructures for improved adhesion, and a wide range of materials can be used to construct the surface structures and its substrate.

NanoGriptech offers films of its materials in one- and two-sided versions for use in a wide range of applications. Glass says the material can allow for new functionality in a number of areas, so many uses are still being explored. For example, Glass points out that Setex is being used to seal chemical and biological protective suits used by the U.S. Army, and is being investigated for use in industrial gripping applications for high-value glass, as well as in automotive seating and for various uses in the apparel industry.

A hybrid solar cell that utilizes waste heat to boost efficiency

Scientists from Yonsei University (Seoul, South Korea; www.yonsei.ac.kr) led by Prof Eunkyoung Kim, have developed a hybrid solar cell to enhance the photo-conversion efficiency of a solar cell with a thermoelectric device operated by photothermally generated heat. The efficiency was increased by more than 20% under sunlight irradiation using the transmitted light through the photovoltaic cell as a heat source.

The scientists achieved thermoelectric and pyroelectric conversion by pairing a dye-sensitized photovoltaic film with transparent conducting polymers poly(3,4-ethylenedioixythiophene)s (PEDOTs). The polymers are a suitable multi-energy harvester because their doping states are easily controlled to optimize transparency and photothermal conversion. Because the dye in a dye-sensitive solar cell typically absorbs only part of the ultraviolet (UV) and visible range of incident sunlight, the transmitted and wasted sunlight can be reused for photothermal (PT) and pyroelectric (PE) harvesting and, eventually, for photothermal conversion.

Compared with a bare thermoelectric (TE) system, the photothermal-pyro-thermoelectric device developed by the scientists showed more than six times higher thermoelectric output with the additional pyroelectric output. The photothermally driven pyroelectric harvesting film provided a very fast electric output with a high voltage output of 15 V. A high voltage output is crucial to enhance the conversion efficiency as well as to operate an organic electronic implement with a high working voltage.

The pyroelectric effect was said to be significant due to the transparent and high photothermal PEDOT film, which could also act as an electrode.

Taking advantage of the enhanced output energy from the hybrid energy harvester, a homemade circuitry was prepared to operate a light-emitting diode (LED) lamp and electrochromic display (ECD) device. The energy from the PE film was enough to turn the LED lamp on, but it was not possible to turn on an ECD. However, after only a few minutes of sunlight exposure, the ECD was operated and showed a color switching from blue to colorless and back to blue. The scientists claim the solar powering of ECD had never been achieved through hybrid energy cells with PT/PE before.

A step forward for bio-based butadiene

Increased use of ethane from shale deposits as a feedstock for ethylene production has focused attention on the growing need for on-purpose production of butadiene, which has traditionally been produced primarily as a byproduct of conventional ethylene production from naphtha. Among the areas of exploration has been a bio-based route to butadiene using renewable feedstock.

Now, a joint effort by Genomatica (San Diego, Calif.; www.genomatica.com) and Braskem (São Paulo, Brazil; www.braskem.com) has resulted in the continuous, direct production of butadiene from sugar using a fermentation-based process. The companies say that their technology platform is "running well" and they have been producing bio-based butadiene at laboratory scale since June 2015.

The Genomatica-Braskem program has developed a bacterial strain capable of consuming sugar and synthesizing butadiene in 2-L fermenters. Using computational tools, Genomatica identified 60 possible metabolic routes to butadiene and selected the five most promising — in terms of enzyme activity and specificity, as well as favorable free energies — for experimental validation. With genetic engineering, enzyme modification and directed-evolution on the relevant metabolic pathway, Genomatica was able to increase the enzyme performance by a factor of 60, says Nelson Barton, senior vice president for R&D at Genomatica.

The two companies took a "process-first" approach to the project, Barton explains, taking advantage of Braskem's expertise in butadiene processing to co-optimize the complete production process along with the microbial strain.

Genomatica and Braskem are currently working to scale up the process to produce sufficient volumes of butadiene to test downstream processing unit operations, Barton notes.

aging and Specialty Plastics. "So it has unique properties that allow for higher-performing packaging materials."

The polymer, known as Innate, is a linear low-density polyethylene (LLDPE) resin that is produced with a proprietary catalyst that arose from intensive high-throughput catalyst screening, Parrillo says. The catalyst is applied in a specially designed process system derived from Dow's solution-based polyethylene process technology.

Parrillo says Dow's new packaging polymer can be made into films with up to double the abuse resistance of current coextruded plastic films, without compromising on other properties. Innate packaging resin is available in pellet form, and can be processed using the same equipment already used for the production of polyethylene products, Parrillo notes. Innate is currently being produced in one U.S. and one European location, and is available commercially.

OIL-SPILL ABSORBANT

Materials scientists from Drexel University (www.drexel.edu) and Deakin

(Continues on p. 10)

University (Melbourne, Australia; www.deakin.edu.au) have developed a new material, called a boron nitride nanosheet, that can absorb up to 33 times its weight in oils and organic solvents. Developed over two years with support from the Australian Research Council, the material is now ready to be tested by industry. According to Alfred Deakin Professor Ying Chen, the lead author of a paper recently published in *Nature Communications*, the material is the most exciting advancement in oil-spill-remediation technology in decades. The boron nitride nanosheets are flame resistant, which means they could also be used as a heat or electricity insulator.

BIOFUELS FROM ALGAE

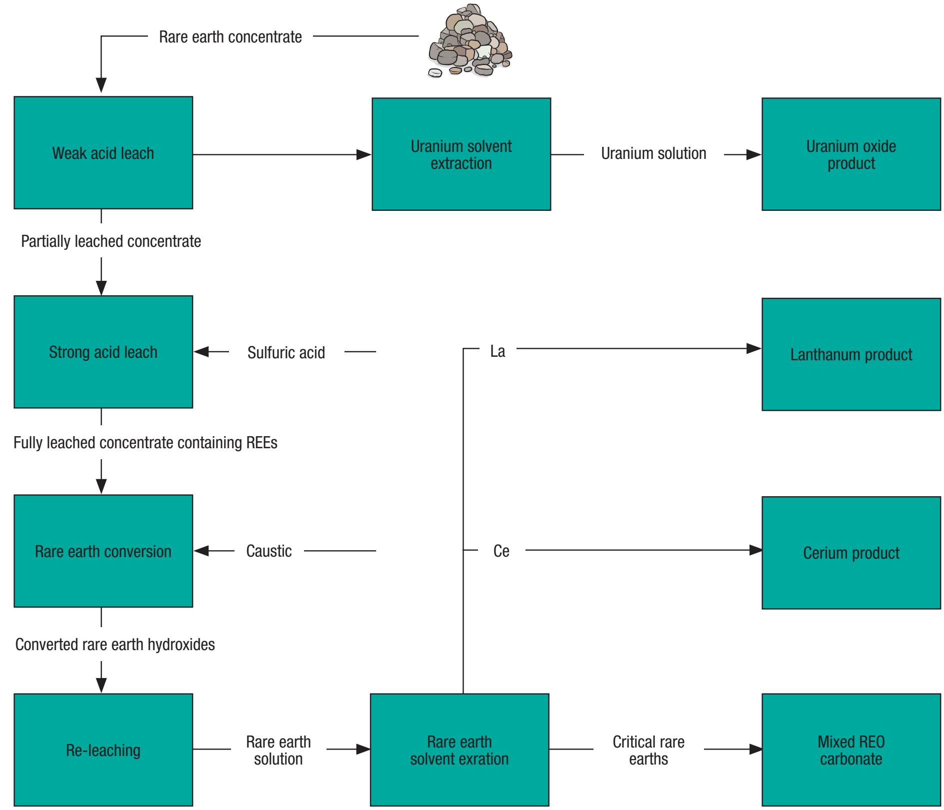
Last month, Chiyoda Corp. (Yokohama, Japan; www.chiyoda-corp.com) landed an engineering, procurement and construction (EPC) contract for building Japan's first demonstration plant for the production of biofuels (jet and diesel) from algae-based oil. The plant, which is scheduled to be operational by the first half of 2018, will produce 5 barrels per day (bbl/d; 125,000 L/yr) of ASTM-compliant biokerosene, next generation biodiesel and bionaphtha using domestically produced and procured feedstock, such as the microalgae *Euglena* and inedible plant oils.

The biotech company, euglena Co. (Tokyo; www.euglena.jp) will supply the microalgae feedstock, as well as investing in and operating the plant, which will be located in the city of Yokohama (also co-funding the project) at the Keihin site of Asahi Glass Co. Other members of this cooperative project are the energy-trading company, Itochu Enex; diesel-engine maker, Isuzu Motors Ltd.; and the airline company, All Nippon Airways Co. (ANA).

The partners aim to produce 125,000 L/yr in 2020, which is sufficient to sup-

(Continues on p. 11)

Progress on E.U. project to produce rare earth elements from Greenland



A refinery pilot test was successfully completed on the Kvanefjeld rare-earth (RE) project located in the southern tip of Greenland, about 10 km from Narsaq. The project is wholly owned by Greenland Minerals and Energy Ltd. (Perth, Western Australia; www.ggg.gl). The pilot test was carried out in Finland by Outotec (Espoo, Finland; www.outotec.com) at Outotec Pori Research Laboratories, as part of the EURARE program, which aims to safeguard the uninterrupted supply of RE raw materials and products to the E.U. economy. The pilot test followed a feasibility study and conceptual 3-D design of the plant carried out by Tetra Tech Proteus (Perth, Western Australia; www.proteuseng.com.au). The study indicated the project's long life of more than 100 years and its cost-competitive capability.

The size of Kvanefjeld places it at the top three RE deposits in the world for qualified resources. The deposit also contains sufficient levels of uranium and zinc in the orebody to produce commercially viable byproducts. The project is expected to produce 40,000 metric tons per year (m.t./yr) of rare earth oxides, including 5,000 m.t./yr of the valuable heavy rare element oxides. Uranium production capacity will be about 1.2 million kg/yr, ranking the project in the top 10 uranium producers in the world.

Greenland Minerals and Energy Ltd. (GMEL) metallurgy manager, Damien Krebs, says the company developed a completely novel refining process (diagram) to deal with the unique RE-bearing mineral steenstrupine, which only occurs in significant quantities in Kvanefjeld. (A more detailed flowsheet and process description can be found in the online version of this story at www.chemengonline.com).

After leaching, lanthanum and cerium will be removed from the rare-earth-chloride solution using solvent extraction to produce the four following RE products: lanthanum oxide 99% grade (4,500 m.t./yr), cerium hydroxide 99% grade (7,600 m.t./yr), mixed lanthanum and cerium oxide (3,700 m.t./yr) and mixed critical RE oxide (7,900 m.t./yr).

All products will be transported to Europe for sales apart from the mixed critical RE oxide, which will be transported to Non Ferrous China (Beijing; www.nfc.com.cn) for separation into 14 RE oxides at 99.95% purity.

Making hydrogen (and carbon) by cracking methane in molten metal

A process that converts methane into hydrogen and carbon black has been developed by researchers at the Institute for Advanced Sustainability Studies (IASS; Potsdam; www.iass-potsdam.de) and the Karlsruhe Institute of Technology (KIT; Karlsruhe, both Germany; www.kit.edu). In a joint project initiated by Nobel Laureate and former IASS scientific director, professor Carlo Rubbia, the proof-of-concept has now been demonstrated.

Based on a novel reactor design proposed by Rubbia, CH_4 cracking takes place in molten metal. CH_4 is introduced into the bottom of a column full of molten tin at temperatures above 750°C. As the bubbles rise, CH_4 is thermally cracked into H_2, with carbon black depositing on the bubble surface. The bubbles disintegrate at the top, releasing H_2 and leaving behind a powder film of carbon black, which can recovered and sold.

From 2012 to 2015, IASS and KIT have performed experimental campaigns in KIT's Karlsruhe Liquid Metal Laboratory (KALLA) in a 1.2-m tall reactor made of quartz and stainless steel. In a recent campaign, the reactor operated continuously for two weeks, producing H_2 with a 78% conversion rate at temperatures of 1,200°C.

A lifecycle assessment (LCA), performed by IASS and RWTH Aachen University, shows that CH_4 cracking is comparable to water electrolysis, and 50% "cleaner" than steam-methane reforming, with respect to CO_2 emissions per unit of H_2 produced

Preliminary economics calculations show that the technology could achieve costs of €1.9–3.3/kg of H_2 (using German natural gas prices, and without taking the market value of carbon into consideration).

IASS and KIT will next focus on optimizing some aspects of the reactor design, such as the carbon-removal process, and progressively scale it up to accommodate higher flowrates. ■

ply the weekly flight from Haneda to Itami with jet fuel containing 10 vol.% of the biokerosene.

Since 2014, euglena has been developing bio-jet fuel, and (in collaboration with Isuzu) biodiesel fuel. In June 2015, the company also entered a licensing agreement with Chevron Lummus Global LLC — a joint-venture between Chevron USA Inc. and CB&I Technology Venture, Inc. — and Applied Research Associates, for the Bio-fuels Isoconversion Process technology.

CEMENT OFFGASES

Last month, Joule Unlimited (Bedford, Mass.; www.jouleunlimited.com) and HeidelbergCement AG (Heidelberg, Germany; www.heidelbergcement.com) announced a partnership designed to explore application of Joule's technology to mitigate carbon emissions in cement manufacturing. As part of the agreement, emissions (or offtake gas) from various HeidelbergCement factories could provide Joule with the waste CO_2 required to feed its advanced Helioculture platform, which effectively recycles CO_2 back into liquid fuels (for more details, see *Chem. Eng.*, April 2015, p. 13). ❐

LINEUP

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Plant Watch

Dow to increase capacity for glycidyl methacrylate at Freeport site

December 10, 2015 — The Dow Chemical Co. (Dow; Midland, Mich.; www.dow.com) plans to complete a debottlenecking project at its Freeport, Tex. facility to increase capacity for glycidyl methacrylate (GMA) in the second quarter of 2016. GMA is used in coatings, waterborne resins, finishes, adhesives and plastic modifiers.

Axens selected as licensor for Socar petroleum refinery

December 3, 2015 — Axens (Rueil-Malmaison, France; www.axens.net) has been selected to provide technology for the modernization of Socar's (www.socar.az) Heydar Aliyev Oil Refinery, located in Baku, Azerbaijan. The project will increase the facility's processing capacity from 6 to 7.5 million metric tons per year (m.t./yr).

UOP to provide methanol-to-olefins technology to Chinese company LUXI

December 2, 2015 — LUXI Chemical Group Co. will use Honeywell UOP's (Des Plaines, Ill.; www.uop.com) methanol-to-olefins (MTO) process to convert methanol derived from gasified coal into 293,000 m.t./yr of ethylene and propylene at its facility in Liaocheng, China.

Linde to build liquid-producing ASU in Bangladesh

December 1, 2015 — The Linde Group (Munich, Germany; www.linde.com) announced an investment of €14.6 million in Rupganj, Bangladesh to build an air-separation unit (ASU) that will produce approximately 100 m.t./d of liquefied gases, making it the largest liquid-producing ASU in Bangladesh. The new ASU is due to come onstream by 2017.

Shell invests in alpha-olefins capacity expansion at Geismar site

December 1, 2015 — Shell Chemical LP (Houston; www.shell.com/chemicals) announced an investment to increase the alpha olefins (AO) production capacity at its manufacturing site in Geismar, La., making the site the largest AO producer in the world. Shell will build a fourth AO unit in Geismar, adding 425,000 m.t. of capacity, and bringing the total AO production at the site to more than 1.3 million m.t./yr. Construction of the new unit will begin in the first quarter of 2016.

BASF to expand compounding capacities for engineering plastics in Europe

November 28, 2015 — BASF SE (Ludwigshafen, Germany; www.basf.com) is expanding the compounding capacities for engineering plastics at the Schwarzheide, Germany site. The additional capacity will be available in 2017, and will include up to 70,000 m.t./yr of the engineering plastics Ultramid polyamide and Ultradur polybutylene terephthalate.

LyondellBasell to build world's largest PO/TBA plant on U.S. Gulf Coast

November 23, 2015 — LyondellBasell (Rotterdam, the Netherlands; www.lyondellbasell.com) is advancing plans to build what is said to be the world's largest propylene oxide (PO) and tertiary butyl alcohol (TBA) plant. The planned location for the plant is in the Houston area, and the new site's annual production capacities are anticipated to be around 450,000 m.t./yr of PO and 900,000 m.t./yr of TBA.

Chemours breaks ground on world-scale production plant for HFO-1336mzz

November 19, 2015 — The Chemours Co. (Wilmington, Del.; www.chemours.com), along with its partner Changshu 3F Zhonghao, has broken ground on the what is said to be the world's first full-scale production facility for the HFO-1336mzz foam-expansion agent in Changshu, China. This site, expected to begin production in mid-2017, will provide increased capacity of low global-warming-potential (GWP) foam expansion agents and refrigerants.

Mergers & Acquisitions

Ineos to acquire sulfuric acid producer in Spain

December 14, 2015 — Ineos (Rolle Switzerland; www.ineos.com) intends to acquire 100% of the shares of Befesa Valorización de Azufre, S.L.U. (BVA), a regional market leader for sulfuric acid and oleum located in Bilbao, Spain. BVA owns a plant with capacity to produce 340,000 m.t./yr of sulfuric acid and related products. The purchase price was not disclosed. This acquisition will effectively double the production capacity of Ineos' Sulphur Chemicals business.

Dow and DuPont to combine in massive merger, creating DowDuPont

December 11, 2015 — DuPont (Wilmington, Del.; www.dupont.com) and Dow have approved a definitive agreement under which the companies will combine. Upon closing of the merger transaction, which is expected in the second half of 2016, the new company will be named DowDuPont and will have a combined market capitalization of approximately $130 billion. The parties intend to then separate DowDuPont into three independent companies focused on agriculture, materials and specialty products, respectively.

Circle 13 on p. 66 or go to adlinks.chemengonline.com/61491-13

Kuraray dissolves battery materials joint venture KBMJ
December 10, 2015 — Kuraray Co. (Tokyo, Japan; www.kuraray.co.jp/en), along with Kureha Corp., Irochu Corp. and Innovations Network Corp. of Japan, have agreed to dissolve Kureha Battery Materials Japan Co. (KBMJ), a joint venture (JV) for lithium-ion-battery materials. While KBMJ will become a wholly owned subsidiary of Kureha, the JV's operations related to plant-based hard carbon-anode materials will be taken over by Kuraray on Jan. 1, 2016.

Celanese divests vinyls and acrylics emulsions unit in Spain
December 7, 2015 — Celanese Corp. (Irving, Tex.; www.celanese.com) has concluded the sale of its atmospheric (vinyl and acrylics) emulsions unit in La Canonja, Spain. IQOXE, a Tarragona-based petrochemical company, is acquiring the 25,000-m.t. operation from Celanese. Financial details of the transaction were not disclosed.

Fluor acquires Netherlands-based Stork Holding for $755 million
December 7, 2015 — Fluor Corp. (Irving, Tex.; www.fluor.com) has signed an agreement to acquire 100% of Netherlands-based Stork Holding B.V. for €695 million ($755 million). Stork is a provider of maintenance, modification and asset-integrity services for large existing industrial facilities in the oil-and-gas, chemicals, petrochemicals, industrial and power markets.

Wood Group to acquire industrial contractor Infinity for $150 million
December 3, 2015 — Wood Group (Houston; www.woodgroup.com) has agreed to acquire The Infinity Group (Clute, Tex.), an industrial construction and maintenance contractor serving the petrochemical, petroleum refining and gas-processing sectors, for an initial consideration of $150 million.

LyondellBasell to acquire PP compounding assets of Zylog
December 1, 2015 — LyondellBasell has entered into a definitive agreement to acquire the polypropylene (PP) compounding assets of India-based Zylog Plastalloys Ltd. Upon completion of the acquisition, LyondellBasell will become the third-largest producer of PP compounds in India, with a capacity of 44,000 m.t/yr.

Air Liquide to acquire Airgas for $13.4 billion
November 19, 2015 — Air Liquide (Paris, France; www.airliquide.com) has reached an agreement to acquire Airgas, Inc. (Radnor, Pa.; www.airgas.com), for a total enterprise value of $13.4 billion. In the transaction, Airgas will become a wholly owned subsidiary of Air Liquide.

Dow to purchase Beaumont aniline facility from Chemours
November 19, 2015 — The Chemours Co. has signed a definitive agreement to sell its aniline facility in Beaumont, Tex. to Dow for approximately $140 million in cash. As part of this transaction, Chemours has entered into an agreement to meet Dow's additional aniline requirements with supply from its Pascagoula, Miss. facility. ■

Mary Page Bailey

Progress to Limit Climate Change

As world leaders agree on the need to reduce greenhouse gas (GHG) emissions, major milestones and new technologies point toward potential solutions

Source: SaskPower

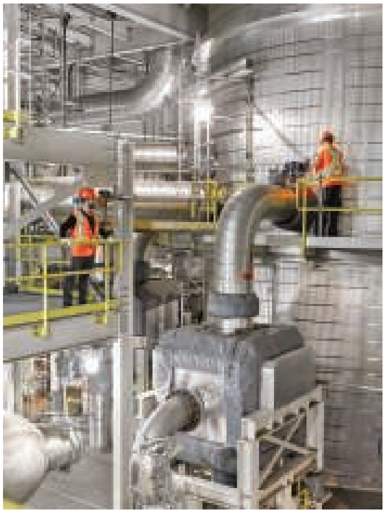


FIGURE 2. A view inside the CCS facility of SaskPower's Boundary Dam Unit 3 in Canada. This plant, with more than one year of operation, is the world's first coal-fired power plant to capture and store the CO_2 from the fluegas

Last month, delegates from 195 countries converged on Paris, France for the 21st Conference of the Parties (COP21; November 30 – December 12) to the United Nations Framework Convention on Climate Change (UNFCCC). The goal of COP21 was to reach an international agreement on how to limit global warming by reducing or eliminating the emissions of greenhouse gases (GHGs). After all-night deliberations, the UNFCCC agreement — to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels" — was adopted by all parties on December 12.

The buildup to COP21

Already by last October, 120 countries had submitted to the U.N. their Intended Nationally Determined Contributions (INDCs), which are their national targets for reducing GHGs. The U.S., for example, intends to achieve "an economy-wide target of reducing its GHG emissions by 26–28% below its 2005 level in 2025, and to make best efforts to reduce its emissions by 28%." The target covers all GHGs in the 2014 Inventory of the U.S. GHG Emissions and Sinks: CO_2, CH_4, N_2O, perfluorocarbons (PFCs), hydrofluorocarbons (HFCs) SF_6 and NF_3. Similar INDCs were issued by: Japan (26% reduction of GHGs by 2030 compared to 2013 (25.4% reduction compared to 2005); Canada (30% reduction of GHG emissions below 2005 levels by 2030); and Australia (26–28% below 2005 levels by 2030). China pledged to peak emissions by 2030 and increase its share of non-fossil fuels in primary energy consumption to around 20%. The E.U. aims for at least 40% domestic reduction in GHG emissions by 2030 compared to 1990.

Achieving such targets will require the efforts and expenditures across all sectors of the chemical process industries (CPI): oil-and-gas (CO_2 and CH_4), petroleum refining (CH_4 and CO_2), chemicals (CO_2, CH_4, N_2O), power generation and transmission (CO_2, PFCs), semiconductor fabrication (SF_6 and NF_3), as well as iron, steel and cement making (CO_2). Consumers, too, will ultimately feel the effects on their pocketbooks, with higher costs for electricity, more fuel-efficient transportation, and "greener" buildings. The priority areas listed by the parties submitting INDCs is shown in Figure 1.

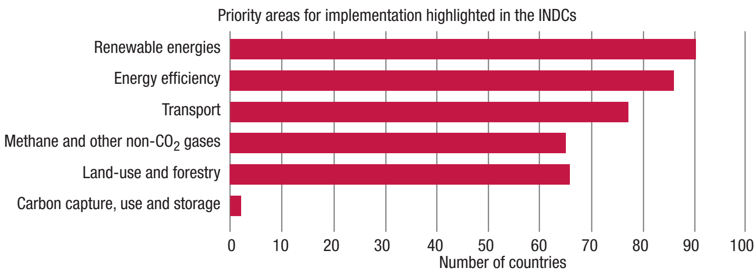


FIGURE 1. Renewable energies and energy efficiency were priorities for the majority of countries' Intended Nationally Determined Contributions (INDCs)

Source: http://unfccc.int/files/adaptation/application/pdf/all__parties_indc.pdf

In the buildup to COP21, The Institute of Chemical Engineers (IChemE; Rugby, U.K.; www.icheme.org) Energy Center Board issued a statement (December 2) that outlines five priority topics for the climate talks: energy efficiency; energy storage and grid management; carbon capture, storage (CCS) and utilization; nuclear energy; and sustainable bioenergy. "The technologies exist **now** to deliver massive energy savings and GHG emissions reductions in all five priority areas. Taken together, they represent a pathway to a decarbonized energy system that can be realized **now**, as long as the agreement made at COP21 recognizes that the time has come for deployment of such technologies" (emphasis IChemE's).

"Chemical engineers already understand the technology needed to limit atmospheric CO_2 levels. Now is the time to start using it, says professor Stefaan Simons, chair of IChemE's Energy Center. "World leaders can shift the focus from research and development (R&D) to demonstration and deployment. We can give policy makers the solutions needed to mitigate climate change," he says.

This position was supported by U.N. Secretary General, Ban Ki-

Moon during COP21, who said "The solutions to climate change are on the table. They are ours for the taking. Let us have the courage to grasp them."

Progress in CCS

Because fossil-fuel-based power generation represents the largest source of CO_2 emissions around the world, most experts and authorities agree that CCS will be required to prevent global temperatures from exceeding safe levels. However, two main challenges to widespread deployment of CCS technologies in the power sector are the need to bring down the cost to a level that sustains competition with low-carbon technologies and to establish plant sites where CO_2 storage is available and economic, according to the 2015 World Energy Outlook Special Report: Energy and Climate Change, published last October by the International Energy Agency (Paris, France; www.iea.org). Nevertheless, efforts are continuing to address these two challenges, as well as increasing the acceptance of the technology.

Last September, the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL; Morgantown, W. Va.; www.netl.doe.gov) released the fifth edition of its Carbon Storage Atlas (Atlas V), which shows prospective CO_2 storage resources — in saline formations, oil and natural gas reservoirs, and unmineable coal seams — of at least 2,600 billion m.t. — an increase over the 2,380 billion m.t. reported in the 2012 Atlas. This vast resource has the potential to store hundreds of years' worth of industrial GHG emissions, permanently preventing their release into the atmosphere, says NETL.

New CCS milestones

CCS achieved an important milestone in the fall of 2014, with the startup of SaskPower's Boundary Dam Unit 3 (120 MW) in Canada (Figure 2) — the world's first commercial power plant to come online with CO_2 capture (for more details, see "CO_2 Gets Grounded," *Chem. Eng.*, April 2014, pp. 21–23).

More recently (last November), Fluor Corp. (Irving, Tex.; www.fluor.com) completed the construction of Shell's (The Hague, the Netherlands; www.shell.com) Quest CCS project near Fort Saskatchewan, Alberta, Canada. The Quest CCS project is designed to capture more than 1 million m.t./yr of CO_2 from the Scotford Upgrader, which turns oil-sands bitumen into synthetic crude oil. The CO_2 from the upgrader's hydrogen-production plant is captured by an amine solution, and then released and liquefied so it can be pipelined 65 km north to be injected 2 km underground for permanent storage.

The governments of Alberta and Canada have invested significantly in Quest, contributing $740 million (Canadian) and $120 million, respectively. Effective government support and robust regulatory frameworks will continue to be critical to accelerating the momentum of CCS implementation worldwide, says Shell.

As part of the funding agreement,

Source: Air Liquide

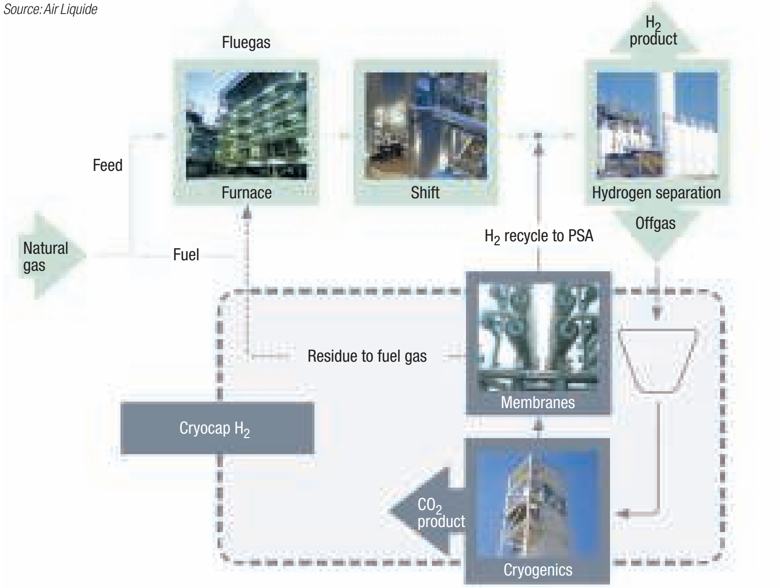


FIGURE 3. The Cryocap H_2 process marked its commercial debut at Air Liquide's steam-methane reformer (SMR), which generates H_2 for a nearby petroleum refinery. The captured CO_2 is purified and liquified for a number of applications

Shell is sharing information online (www.energy.alberta.ca/CCS/3848.asp) about Quest's design, processes and lessons learned to help make CCS technologies more accessible and drive down costs of future projects.

Meanwhile, Mitsubishi Heavy Industries, Ltd. (MHI; Tokyo, Japan; www.mhi-global.com), the Japan Research Institute, Ltd. (www.jri.co.jp) and Inpex Corp. (www.inpex.co.jp; all three Tokyo, Japan) submitted a proposal to the Mexican Ministry of Economy, Trade and Industry (METI) to study the feasibility of a CCS-EOR project in Southern Mexico. The study — expected to be completed in March — will be based on the KM CDR process, which uses the high-performance KS-1 solvent that MHI and Kansai Electronic Power Co. co-developed (*Chem. Eng.*, January 2004. p.13).

The KM CDR process is also featured in a number of CCS projects, including what is said to be the world's largest post-combustion CO_2 system for a coal-fired power plant in Texas. Scheduled for startup in early 2017, the system will have a CO_2-capture capacity of 1.4 million m.t./yr. The CO_2 that is captured from fluegas of Unit 8 of NRG Energy Inc.'s (Houston; www.nrg.com) WA Parish generation station — a coal-fired power plant located about 60 km southwest of Houston — will be transported through about 80 km of pipeline to be used for enhanced oil recovery (EOR) at the nearby West Ranch oil field to boost crude oil production. As of September 2015, the engineering, procurement and construction (EPC) activities are over 60% complete, and construction is on schedule, with over 50% of the pipe installed, according to the DOE.

Meanwhile, efforts continue to find more efficient solvents to capture CO_2, as regularly reported in the Chementator department of this magazine. Linde Group (Munich; www.linde.com), for example, is involved in a joint pilot-scale project with BASF SE (Ludwigshafen, both Germany; www.basf.com) to test solvent-based advanced technology for the improved economic capture of CO_2 from fluegas. This is taking place at the National Carbon Capture Centre (NCCC) in Wilsonville, Ala. The innovative technologies being tested integrate an advanced aqueous amine-based solvent and CO_2 capture process technology from Linde. The new solvent, OASE blue from BASF is an alternative to the standard monoethanolamine MEA), a benchmark solvent employed in fluegas CO_2-capture applications. The process-related innovations from Linde incorporated into the project include: gravity-driven instage absorption column cooler; high-capacity structured packing; advanced emission-control wash loop; placement of a reduced-size fluegas blower downstream of the absorption column; and higher pressure stripping of the captured CO_2.

According to Linde, operations and testing since January 2015 have already validated several performance targets set. A CO_2 capture rate exceeding 90% with a purity rate exceeding 99.8% is being achieved. The regenerator has also been operated at pressures up to 3.4 bars, which is a first for this technology. The higher pressures offer reduction of the downstream CO_2 compression energy as well as compressor capital costs. The testing has also validated the functional performance of all the process innovations, says Linde.

A 'cool' method to recycle CO_2

Last November, Air Liquide (Paris, France; www.airliquide.com) launched its Cryocap technology — a cryogenic process that captures CO_2 released during H_2 production. Connected to Air Liquide's largest H_2 production unit in France, located in Port-Jérôme, Notre-Dame-de-Gravenchon (Normandy), Cryocap represents an investment of around €30 million that was decided by the Air Liquide Group in 2012, with an €9-million support from Haute Normandie region, the community of Caux Vallée de Seine communes, and ADEME (French Environment and Energy Management Agency) through the Programme d'Investissement d'Avenir, a program for investment for the future.

Developed jointly by Air Liquide R&D and Engineering & Construction teams, Cryocap made its commercial debut on Air Liquide's steam methane reformer (SMR), which has been supplying approximately 50,000 Nm^3/h of H_2 to the neighboring petroleum refinery, Esso Raffinage SAF (ExxonMobil group). The Esso refinery uses the H_2 to remove the sulfur content of the automotive fuels.

As seen in Figure 3, the SMR produces synthesis gas (syngas; a mixture of H_2 and CO), which is then converted to a H_2-rich gas in a water-shift reactor. The H_2 is then purified in a pressure-swing-adsorption (PSA) unit. The Cryocap H_2 unit captures CO_2 from the (PSA) offgas. The offgas is filtered, compressed and dried in an adsorption unit, and sent to a cryogenic purification unit, where the CO_2 is separated from the other components by a combination of partial condensation and distillation. A pure and pressurized CO_2 stream is produced from the cold box. Noncondensed gases are recycled through a membrane system to recover H_2 and CO_2. Membrane residual gas is sent to the burners of the SMR, and H_2-rich gas is recycled to the PSA inlet, which increases the overall H_2 production.

Cryocap is said to be first CO_2-capture technology using a cryogenic process. After being purified, the captured CO_2 can be used to meet a variety of industrial needs for carbonic gas supply (carbonation of beverages, food preservation and freezing, and so on). At this site, the Cryocap unit has a capture capacity of 100,000 m.t./yr of CO_2.

The company also has two additional Cryocap processes for recovering CO_2 from the offgases of steel plants (Cryocap Steel) and thermal power plants (Cryocap Oxy). Although the cost of CO_2 capture depends on project specifics, Air Liquide says Cryocap delivers the lowest cost of CO_2 production among industrial sources, in particular, when compared to traditional technologies, such as amine-based absorption processes.

A ‘carbon-negative fuel’

At COP21, Carbon Wealth Scandinavia AB (Stockholm, Sweden; www.skymining.com) launched its so-called SkyMining technology, which the company has now demonstrated and is ready for commercialization and scaleup. In SkyMining, a fast-growing, special strain of Elephant grass is used to “extract” CO_2 from the atmosphere. The grass grows about 4 m per 100 days on marginal land, and can be harvested at least twice a year, explains the Carbon Wealth director Rory McMeekin. After harvesting, the biomass is then processed by a proprietary thermal-carbonization process into a solid fuel dubbed CNF (for carbon negative fuel). CNF has an energy content that is up to 30% higher than dry wood and brown coal, and costs about half that of heating oil, is cheaper than charcoal, and is competitive with coal, says the company. CNF also has the same grindability and shape as coal, making it suitable for co-firing, the company adds. Production of CNF has been demonstrated at the 1-m.t./h scale, and is ready for scaleup, says McMeekin.

What makes CNF earn its “carbon negative” title is the fact that about 20% of the CO_2 captured from the atmosphere remains stored underground in the root system of the grass, says McMeekin. Each hectare of grass planted on marginal land can sequester and store over 14 m.t./yr of CO_2. There are vast areas of unused land on which the grass could be grown, and after a number of seasons, the once-marginal land will be transformed into fertile cropland due to the carbon that is returned to the soil, says McMeekin. “This is a natural, holistic approach to producing a clean, sustainable fuel while reducing CO_2 in the atmosphere.” ■

Gerald Ondrey

Is Modular Right For Your Project?

Modular construction provides many benefits, but the decision to go modular should be thoroughly investigated

Modular construction, which includes projects from small- and large-scale process systems to pilot plants to entire modular facilities, is a growing trend in the chemical process industries (CPI). More than ever before, project owners are considering employing modular rather than traditional construction, because it often provides significant savings in schedule and labor costs. However, even though there are valuable benefits, modular construction is not suitable in every situation. This article discusses the advantages of modular projects, as well as provides advice on how to determine if a modular approach is the right the solution for your project needs.

Modular construction

Modular construction features complete units, prefabricated in a shop away from the plant site. The modules are typically built indoors in a controlled, assembly-line fashion and contain all the necessary components — including columns, reactors, heat exchangers, pumps and other process equipment, as well as instrumentation, piping, electrical wiring, lighting, control systems, safety showers and fire protection systems — all mounted within structural steel frames. Upon completion of the module or modules, testing of all components is performed at the shop and the modules are then transported, fully assembled, to the site, via truck or barge, depending upon the individual project size and location. The modules are lifted and set onto a pre-laid foundation and connected to each other, as well as to the plant utility piping and control systems (Figure 1).

Modular benefits

"Modular projects are becoming the norm and are considered a standard delivery option for construction projects," says James Flake, director of operations, modular consulting, with Jacobs (Pasadena, Calif.; www.jacobs.com). "Just eight to ten years ago, we were one of only a few engineering, procurement and construction (EPC) firms bringing modular construction into the discussion. Now, our clients are modular-savvy and ask us to talk about them. We have a client who says their philosophy used to be, 'Help me understand why we should use modules,' but now jokes and says our job is to help them understand where they shouldn't use modules."

The reason for the shift in thinking is because modules, done correctly and for the right reasons, can provide several significant benefits (Figure 2).

The most compelling reason to go modular, according to the experts, is the shorter schedule. According to Brian Loftus, vice president of business development with Koch Modular Process Systems (Paramus, N.J.; www.modularprocess.com), building a process module in a shop, with a well-

Koch Modular Process Systems

FIGURE 1. A lead crane lifts and sets one of approximately 20 modules comprising a reaction and distillation process to produce high purity chemicals for the electronics industry

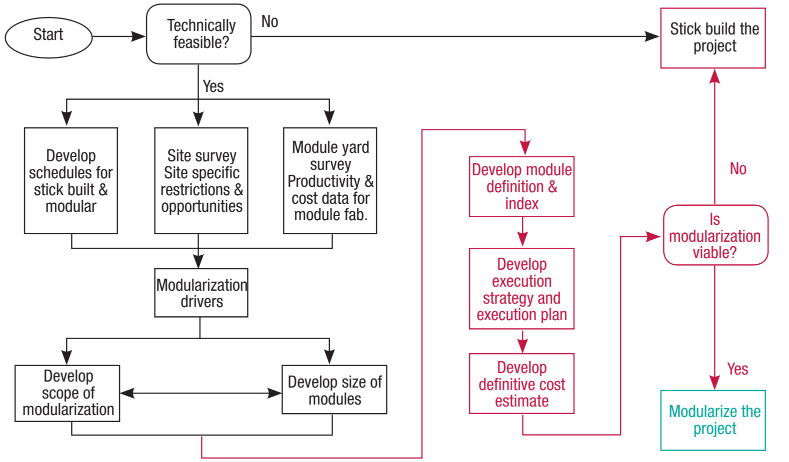
Fluor

FIGURE 2. On the Shell Quest Carbon Capture and Storage Project in Canada (see also Newsfront on pp. 16–19), Fluor used its 3rd Gen Modular Execution approach to reduce the project's plot space requirements, optimizing process block layouts and consolidating equipment into modules

controlled fabrication sequence, can save months when compared to traditional stick building methods outdoors onsite, where work is subject to weather-related delays, work permits, work stoppages or waiting for cranes and construction equipment. He says a typical schedule for delivery of a complete modular process unit, fabricated in stainless- or carbon-steel, is eight to nine months from the receipt of a purchase order, including all engineering and design activities.

Spencer Everitt, engineering manager with Xytel (Spartanburg, S.C.; www.xytelcorp.com), which builds modular pilot plants and commercial-scale units, adds that the compressed schedule provided by modular construction performed in a controlled-environment shop allows the project owner to bring product to market faster, which may also have major financial perks.

Building the modules offsite also results in minimal plant site interruption. In the case where a new process unit is being built alongside an existing operating unit, there may be hazards and safety risks associated with field construction activities, says Loftus. "It may not be safe to have contractors and construction workers walking around in a chemical plant, so often it makes sense to move construction off site to minimize the potential hazards and production interruptions," he explains.



Fluor

FIGURE 3. Using a flow chart such as this can help determine whether it's economically feasible to modularize a project

Everitt agrees that the modular model can significantly reduce plant shutdowns. "Because we are able to use really good three-dimensional technology and create very detailed laser drawings of where the module will be placed in a facility, we are able to build accordingly, then simply drop our modules in, plug them in and be out of the facility in four to five days, compared to the four to five months it would take to install the same project using traditional stick build. Again, there are financial benefits due to the reduced downtime."

Another major benefit, according to Paul Hochi, director of project development, modular consulting, with Jacobs, is the predictability of modular projects. "The cost and schedule with a modular project tends to be less variable than with stick-built. I believe this is the most underestimated benefit in modular evaluations," he says. The predictability of project cost and schedule is possible because of the nature of modular construction — there are no work stoppages due to permitting, labor or weather issues when work is performed in a controlled shop with skilled workers, notes Hochi. And, project quotes are usually done on a lump-sum pricing basis, so there are no surprises, says Loftus.

Loftus adds that single-source responsibility is another modular advantage. "The ability of one firm to provide all services from process design to pilot testing to construction enables our customers to benefit from a single-source supplier who can take responsibility for the overall process design, construction, integration, startup, commissioning and de-bottlenecking of the process," he says. "This de-risks the project for the customer, while also reducing

Linde

FIGURE 4. Modular gas plants, such as this Ecovar plant, are installed around the world for the dedicated production of oxygen, nitrogen, hydrogen or other industrial gases. Linde owns and operates the plants, monitoring and controlling production remotely. They deliver reliable, low-cost supply with no upfront investment cost, no overhead costs for labor, and no operating risk

costs. With each layer of interface on a stick-built project comes more risk and more cost because each firm takes a profit along the way."

Is modular the right choice?

While there are many advantages associated with modular projects, the experts will agree that modular is not always the right solution, and the decision to take the modular route should be business-based. "Before moving forward with a modular project, you need to be sure you can execute a modular job well and that the business case for executing as a modular project meets the project's objectives," says William Meyer, vice president, construction-modularization, with Fluor Corp. (Dallas, Texas; www.fluor.com). "In simplest terms, that means we are looking to determine if a modular project will be beneficial and, if so, the proportion of manhours we need to move offsite for the maximum amount of value," Meyer explains. "This will vary from project to project, location to location and from one timeframe to another. You can have an identical project in a different location or during a different timeframe and the feasibility study could yield a very different result," he says.

"When determining whether a modular solution is the wise choice, you need to come up with a balance," Meyer continues. "If you're looking at economics alone, you're looking at a balance between moving manhours offsite into a more productive, more cost-effective location. On the downside, there will be additional costs associated with more detailed engineering work, more quantities of structural steel required, plus the cost of transporting the modules to the site and installing them onsite, to name the primary cost drivers for many projects. There comes a point in the equation where increasing the materials or the engineering hours or factoring the cost of transportation to move additional manhours offsite causes you to reach a plateau where the marginal benefit you achieve by moving manhours to the fabrication shop will be offset by the additional costs incurred to do so. You have to find the sweet spot for your project, meaning the appropriate proportion of work to include in your modular scope. Sometimes, the business case benefit may be dependent upon other factors, such as compressed schedule, reduced footprint or reduced loss of downtime."

For this reason, Jacobs' Hochi says it is important to take a "holistic" approach when considering a modular project. "Many of the benefits are direct to the project but some are advantageous to the business, as well, so we tell clients to also consider their business drivers when contemplating a modular project," he says. "Perhaps they want the project up and running as quickly as possible so they can get product to market faster. Perhaps there's a labor shortage in the area and they want to mitigate the risk of work stoppages by going modular. Increased safety related to taking the elevated work closer to grade in a fabrication shop may be another factor to consider."

That said, there are certain challenges associated with some construction projects that typically make certain projects "good candidates" for modular construction, says Meyer. Situations that fall into this category include multiple large-scale projects in one region, which often results in a higher demand for construction resources in that area; a major project being built in a remote location where skilled labor productivity is a challenge and manpower is difficult to obtain; projects in areas that are subject to weather extremes such as a lot of snow, high winds or hurricanes; and projects that do not have a large "lay down" area where materials or construction crews and equipment can be placed and stored during a long-term project.

Because there are so many variables associated with the decision making process, Meyer has created a flow chart, shown in Figure 3.

"*You have to find the sweet spot for your project, meaning the appropriate proportion of work to include in your modular scope.*"

William Meyer, Fluor

Special situations

While modularization provides benefits for many projects, there are a few unique situations in which modular projects are especially attractive.

Onsite gas supply solutions. While modularization provides benefits for many projects, there are a few unique situations in which modular projects are especially attractive. For example, some CPI applications require continuous amounts of high-quality gases, which include O_2, N_2 and H_2. However, since this is not their core business, many of these processors look for a supplier to manage the availability of these gases. The supplier will often install a modular solution onsite, which potentially eliminates delivery interruption, removes the cost of delivery and assures the processor of the reliability of supply. Linde LLC (Murray Hill, N.J.; www.lindeus.com) is one such company that offers onsite supply solutions.

Ecovar onsite gas supply solutions are modular supply systems built around standardized components to ensure maximum cost efficiencies and to assure quality of fabrication (Figure 4). Standardized design and dimensions help keep fabrication and installation costs low. These cost savings enable competitive gas prices to be offered to customers.

Through the combination of standard modular onsite plants and backup liquid tanks, the Ecovar facilities offer solutions with minimal capital expenditure, low operating costs and low consumption of utilities, such as energy and water. Systems and system modules can be combined as required to create tailored solutions that suit local requirements, and the systems can be designed for indoor or outdoor installation to fit available space and utilities (energy, water and compressed air).

"There are several things that are attractive about this modular gas-plant scenario," says Nick Onelli, conceptual engineering manager, with Linde. "A large H_2-generating plant, for example, can take three to four months to install onsite via traditional stick-build, but these smaller, modular and compact plants can be installed in about a month. The overall time from release of plan to having an operating plant is reduced from 18 months to three years in a stick built project, to 6 to 15 months in modular construction. That's a significant reduction in time and on-site risk.

"The other benefit is that the customer can concentrate on his core business because we offer a model where we build, own and operate the gas plant," says Michael Barrasso, senior business development manager with Linde. "There isn't a large investment in a gas plant, they don't have to hire labor or maintain the gas plant and they receive a reliable supply of gas, much in the same way they would receive electricity from the utility."

Developing technologies. Many developing technology companies are interested in working with modular process designers, says Loftus. "Often we start with these firms during the process development and help them evolve their technology from that stage into pilot testing. From there they want to deploy their technology to the marketplace and one of the options many now consider is to sell a complete packaged system to their customer rather than just selling a bundle of technology on paper. In these cases, we can help them design and construct modules so they can sell their technology as a modular process system to their end user."

He says this business model benefits both the technology company and the end user. "The technology company can more easily leverage their IP [intellectual property] management because, if they sold the technology in paper format, it is easily disseminated and they lose control over how the technology is executed, but if the technology is sold as a complete package, it keeps the IP at home and they have more control over detailed engineering, which increases the quality control of the technology they are selling. In addition, the revenue proposition is often better," Loftus explains. "The end user also benefits for the reasons anyone undergoing a modular project benefits — the construction schedule is compressed and the labor costs are reduced due to the efficiencies of modularization.

"This is really a unique application for modularization because there's benefits for both customers." ■

Joy LePree

Temperature measurement

United Electric Controls

Omega Engineering

HART-compatible transmitter eases temperature monitoring

Industrial sensors monitor temperature or pressure abnormalities by comparing the process conditions with pre-programmed setpoints in a PLC or DCS controller. The HART-compatible One Series 1XTXSW transmitter line (photo) is said to be the first to integrate 4–20-mA output and two solid-state programmable relays (compatible with HART 7) for monitoring temperature or pressure in safety, alarm and emergency-shutdown applications. Typical electromechanical switches are blind and cannot alert workers that something is amiss with the device, says the company. With this device, however, users deploying a HART communications networks can add switches to the field assets used in their predictive-maintenance strategy and reduce routine inspections and unplanned shutdowns. Combining HART and smart diagnostics in one device, workers can manage all of their instrumentation assets, including switches, using a centralized asset-management solution. A large, back-lit display provides process values and setpoint programming. The One Series 1XTXSW hybrid transmitter switch effectively replaces a gage, switch and transmitter, requiring only one connection to the process. This helps to improve reliability while reducing lifecycle costs, and allows for health and switch-status notifications at about half the cost of a traditional process-control transmitter, says the manufacturer. The new One Series iX line has worldwide hazardous location approvals for Class I, Divisions 1 and 2 (Zones 0, 1 and 2). — *United Electric Controls, Watertown, Mass.*
www.ueonline.com

PID control simulator supports temperature tracking

The Platinum Series controller demonstration and training kit provides a PID control simulator (photo) that is a fully integrated temperature-control system. It is suitable for use in both closed-loop (PID) and simple on-off temperature control, in both heating and cooling applications. This unit has a thermoelectric heating and cooling element that is capable of 5–50°C setpoint, and a Type K thermocouple for temperature readings. The unit comes with panel-mounted USB and Ethernet connectivity, an alarm indicator, a 4–20-mA remote setpoint potentiometer, a push-button digital input, and more. Its 32-bit, 120-MHz ARM processor provides full PID control process with auto-tuning and a fuzzy-logic-based, adaptive control algorithm. According to the company, the unit automatically adjusts and optimizes the control-loop parameters based on external environmental or control-system deviations. A comprehensive set of alarm functions may be used to trigger output signals, or modify the display colors for conditions that are above or below a threshold value, or in or out of the acceptable range. Setup is easy, says the company, thanks to an integrated four-button keypad and a structured menu system that eases navigation to only those parameters applicable to the selected configuration step. — *Omega Engineering, Inc., Stamford, Conn.*
www.omega.com

Measure temperature reliably in high-voltage systems

To ensure optimal operational safety for power plants and grids, critical factors, such as hot spots inside high-voltage transformers, power-factor-correction capacitors and alternators are monitored. Similarly, temperature is routinely measured on high-voltage distribution power lines, and in gas-isolated power breakers and power-factor-adjusted capacitors. The FotempTrafo is a fiber-optic thermometer that is available with one to eight measurement channels. Its compact design and height-adjustable DIN-rail clip allow for easy installation in a cabinet. A wide selection of interfaces (RS-232, RS-485,

Note: For more information, circle the 3-digit number on p. 66, or use the website designation.

Profibus and Modbus) makes communication easy. A fast measurement speed of 250 ms per channel allows the direct detection of overloads. Its measurement range is from –200 to 300°C, with an accuracy of ±0.2K, says the company, which notes that its use of gallium arsenide (GaAs) in the sensor tip eliminates the need for recalibration throughout the product life. The probe sensor is completely non-conductive, and the fiber-optic sensors offer complete immunity against radio-frequency interference (RFI), electromagnetic interference (EMI), nuclear magnetic resonance (NMR) and microwave radiation— *Optocon AG, Dresden, Germany*
www.optocon.de

Compact thermal imager provides sharp images

The M12 7.8KP Thermal Imager (photo) is said to have the highest pixel density in its class, and its exclusive Dual Sense pixel technology provides sharp definition of hot and cold details within any given image. It is designed to support troubleshooting and predictive maintenance activities. It is particularly useful for determining thermal conditions associated with hard-to-access systems. Its Dual Sense technology allows the imager to individually optimize pixels, which helps to reduce or eliminate the blurring of hot and cold details in complex scenes, says the manufacturer. When the device is integrated with the company's Thermal Imager Report Software, users can analyze images and generate reports quickly and easily. Users can download images from the thermal imager with its included 8-GB SD card or micro-USB connection port. Every image capture also generates an image with the .png file format, allowing images to be emailed for convenience. — *Milwaukee Tool, Milwaukee, Wisc.*
www.milwaukeetool.com

This temperature transmitter is accurate and EMC-resistant

The Model T15 is a new digital transmitter (photo) with analog output. Designed to process signals from resistance sensors and potentiometers, it is ready for operation in less than three seconds, according to the company, and offers a high basic accuracy of 0.1% of span, at a measuring rate of up to 20 measured values per second. At the same time, the T15 fulfills high standards of safety, for example, in accordance with NAMUR recommendations for EMC protection, signalling and sensor-break monitoring. It is said to be the first transmitter to be certified to the new EMC protection standard, DIN EN 61326-2-3:2013. The T15 also has ATEX and IECEx approvals for use in hazardous areas. When used with the WIKA-soft-TT software, the transmitter can be programmed intuitively. Both head-mounted and rail-mounted versions are available. — *WIKA Alexander Wiegand SE & Co. KG, Klingenberg, Germany*
www.wika.com

Distributed temperature sensor keeps a watchful eye

The DTSX 3000 Distributed Temperature Sensor is a single device that is capable of detecting minute temperature changes, and monitoring the temperature distribution over a long distance or across a wide area. It can measure the temperature along fiber-optic cables up to 50 km in length (eight times the distance possible with the company's previous model), with a spatial resolution of one meter. It is well suited for plant and infrastructure maintenance applications that require the monitoring of temperatures over long distances or wide areas. Specific applications include temperature monitoring of the outer walls of high-temperature industrial furnaces, the detection of gas and liquid leaks in tanks and other large production facilities, and the detection of abnormal heat levels in power lines and natural-gas-recovery processes. — *Yokogawa Corp. of America, Newnan, Ga.*
www.yokogawa.com

Thermocouple wire resists oxidation at high temperatures

This company's Type N thermocouple wire provides excellent repeatability and resistance to oxidation at high temperatures (1,500°F and above) and in applications where sulfur is present. The nickel-based thermocouple alloy resists oxidation at higher temperatures, and is designed for applications with temperatures from 200 to 2,000°F, such as high-temperature heat-treating applica-

Milwaukee Tool

WIKA Alexander Wiegand SE

Quintex GmbH

Signal Fire Wireless Telemetry

Measurement Computing

Saelig

tions. — *Watlow Electric Manufacturing Co., St. Louis, Mo.*
www.watlow.com

This electronic thermostat has a flameproof enclosure

A common challenge for many electronic controllers located in hazardous areas is setting the temperature and alarm setpoints. Adjustments normally require the power supply to be switched off before opening the flameproof enclosure housing, which makes accurate, onsite setting challenging, says the company. By contrast, the EXTC 100 (photo) is a fully adjustable, remote-controlled, electronic controller that is housed in a flameproof (Ex-d type) enclosure. It can be fully controlled by means of an intrinsically safe, remote-control infrared beam — without having to open or turn off the unit. All settings are stored and accessed securely, using a four-digit password. This hazardous-area thermostat is available for electric trace heating circuits and other processes. — *Quintex GmbH, Lauda-Königshofen, Germany*
www.quintex.eu

Device supports wireless monitoring of field assets

The Sentinal-RTD (photo) is the latest interface option that can be added to this company's Wireless Remote Sensing System, to support two-, three- or four-wire RTD sensors. As part of the company's Class 1, Division 1 Sentinel node family, the Sentinel-RTD provides a direct connection to P100 2-, 3- or 4-wire RTD sensors (and other types are available upon request). The device has a long life with an intrinsically safe battery pack, making it especially well-suited to function reliably in demanding outdoor industrial environments (such as oil-and-gas operations). The Signal Fire Remote Sensing System (SFRSS) uses long-range, mesh-networking technology, and uses Sentinal (and other types of) battery-powered wireless notes to interface with the sensors. The nodes extract and then communicate data to control devices via a gateway. The system has an open architecture, which allows users to integrate many types of sensors, including RTDs, to monitor remote assets. In this way, the SFRSS can be used to build a full wireless network using the best sensors for each sensing application point. — *Signal Fire Wireless Telemetry, Hudson, Mass.*
www.signal-fire.com

Device manages high-precision thermocouple measurements

The TC-32 high-precision, thermocouple-measurement device (photo) offers 32 thermocouple channels plus 8 digital inputs and 32 digital outputs/alarms. For larger systems, users can add the TC-32-ESP module to double the number of TC inputs (to 64), digital inputs (to 16), and digital outputs/alarms (to 64). The TC-32 and TE-32-EXP are 19-in.-rack-mountable and feature easy-to-connect, mini-jack connectors for all thermocouple channels. The device features USB and Ethernet interfaces, 24-bit resolution for high-accuracy measurements, and includes a wide range of software support. It can provide digital alarm notifications when a temperature exceeds programmed limits. — *Measurement Computing Corp., Norton, Mass.*
www.mccdaq.com

Multi-function loop calibrator uncovers hidden problems

The portable PIE 850 Multifunction Calibrator (photo) is a handheld instrument that combines eight single-function calibrators (including a milliamp current calibrator, a voltage calibrator, a thermocouple calibrator, and more), legacy 10–50-mA capabilities, and advanced troubleshooting tools. The PIE 850 is capable of diagnosing common loop-control problems that are hard to find, says the company. Loop-diagnostic technology and the LoopScope feature show key loop parameters — such as current, voltage and resistance — at a glance. It is compatible with all common instruments, smart transmitters and PLCs with 14 types of thermocouples and 9 types of RTD tempearature sensors, says the company. This lightweight tool includes a backlit display for use in dark environments, a protective rubber boot and built-in stand, a hands-free carrying case and all test leads.— *Saelig Co., Fairport, N.Y.*
www.saelig.com ■

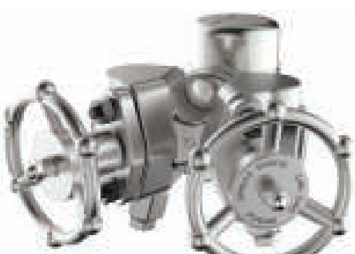
Suzanne Shelley

New Products

Sierra Instruments

Siemens

Union Instruments



Spirax Sarco

Measure energy flow with these smart meters

InnovaMass 240i and 241i vortex mass flowmeters (photo) are specifically designed for precise energy management in steam, compressed-air, natural-gas and water applications. The meters are equipped with the Raptor II operating system, which allows for fast processing and enables the use of robust software applications, including FloPro, which improves point-velocity accuracy. The patented sensor technology extends the measurement range for fluids with Reynolds numbers well below 5,000. The onboard Smart Interface Portal (SIP) software provides quick access to field validation and meter configuration. Users can also access diagnostics through the SIP or the meter's LCD display to automatically check firmware and hardware, and report faults to the factory for immediate repair. Tuning from the SIP or local display allows field adjustments for the low-flow cutoff and vortex coefficient. Through the SIP, firmware can also be updated or repaired in-situ. — *Sierra Instruments, Monterey, Calif.*
www.sierrainstruments.com

Operator control and monitoring in special environments

The new stainless-steel Simatic Inox Pro monitors and panel PCs (photo) are suitable for use in hygienic production areas, while also meeting the requirements of the chemical and oil-and-gas industries. The devices have a high, IP66K degree of protection, and are suitable for use in the food and tobacco, pharmaceutical, cosmetics, and fine chemical industries. The devices have an analog-resistive 19-in. touch display covered by a contiguous, chemically resistant decorative foil, and also have food-grade seals and splinter protection for the display. The stainless-steel enclosure is ground with a 240-grain size, which produces a surface that is smooth enough to protect against contamination. The Inox Pro devices are available either as the IPC277D Inox Pro industrial PC or as the IFP1900 Inox Pro Ethernet monitor. — *Siemens AG, Munich, Germany*
www.siemens.com

Monitoring pipelines for integrity of coatings

Pipelines have to be protected from corrosion by a pore-free coating. To ensure that the factory coating and the coating applied at the work site are free of pores, they are tested by applying high voltage between the steel pipe and a test electrode. If a spark-over occurs here, this indicates a defect in the coating. This coating must be touched up and then must undergo another test. The mobile UIP insulation tester (photo) delivers reliable testing of pipe coatings for defects. With adjustable test voltages of 5 to 30 kV and a comprehensive assortment of corresponding test electrodes, coated pipes and system components can be quickly and reliably tested. Typical applications of the device are pipeline construction and liquid gas tanks. — *Union Instruments GmbH, Karlsruhe, Germany*
www.union-instruments.com

Next-generation connectors for steam-trap installations

Traditional steam-trapping assemblies often require the plant to be shut down for new traps to be installed, taking significant time and reducing production output. The new PC3000 & PC4000 pipeline connectors (photo), with single or double isolation, allow for steam traps to be installed without shutting down the process. These pipeline connectors are appropriate for the petroleum, petrochemical and specialty chemical industries. They are suitable for manifold applications where steam traps are used on tracing and main-line drainage. Some of the features and benefits include: a forged body rated for ASME 600 that is suitable up to 800°F; a fully shrouded piston valve stem, which reduces the potential for corrosion; and a standard fitted strainer, which protects the steam trap from debris entrained in the condensate. — *Spirax Sarco, Inc., Blythewood, S.C.*
www.spiraxsarco.com

Improved connectivity with tablet-based shaft alignment

After introducing tab@lign — the first-ever laser-shaft-alignment app — in 2013, this company now adds new

features and the latest OS3 sensor technology into the package (photo). New features include advanced graphical PDF reporting, showing the alignment condition as found and as left. Photos of the machine or application may also be included, as well as additional asset-related data. The report may be sent immediately via email, which drastically reduces the alignment cycle time. Another improvement is the addition of tolerances whereby the alignment status is evaluated automatically and displayed in the results screen. The tab@lign package also now comes with the latest OS3 sensors for the best precision of its class, says the manufacturer. — *Prüftechnik Dieter Busch AG, Ismaning, Germany*
www.pruftechnik.com

These flowmeters are equipped with high-temperature sensors

For flowmeters, sensors limit the maximum operating temperature while the flow volume and direction of flow are registered by means of spindle rotation. In addition to the available standard model for temperatures of up to 125°C, the economically priced OMP series is now also available with high-temperature sensors for operating at temperatures up to 200°C. The so-called Volumeter (photo) delivers a precision of ±0.1% of the measuring value. — *Kral AG, Lustenau, Austria*
www.kral.at

TDL analyzer series is expanded for refining applications

Four additions have been added to this company's portfolio of tunable-diode-laser (TDL) spectrometers (photo). The GPro 500 has been available for O_2, CO and moisture measurement. Now, models for O_2 plus temperature, CO%, CO_2%, and a combined CO_2% plus CO% make the full GPro 500 portfolio suitable for many petroleum-refinery processes, where paramagnetic and extractive non-dispersive infrared (NDIR) analyzers are normally used. These applications include catalyst regeneration in fluidized catalytic cracking (FCC) units, and ethylene oxide and purified terephthalic acid production. For processes where accurate, low-range extractive measurement is required, the company has also introduced a white cell adaptation that provides an effective path length of 10 m and boosts measurement resolution by a factor of 10. — *Mettler Toledo AG, Udorf, Switzerland*
www.mt.com/tdl

Membrane filtration with built-in advantages

This company's polypropylene (PP) spiral membranes (photo) are said to be more compact than alternatives, and thus provide a larger filtration area for a better performance and the possibility to produce a wider product range. These membranes deliver sustainable benefits, such as reduced water and chemical consumption, as well as longer service life, which means less maintenance and downtime. The PP spiral membranes are even more hygienic than conventional membranes, as they withstand high numbers of cleaning-in-place (CIP) cycles, hot cleaning temperatures and high pH levels. — *Alfa Laval AB, Lund, Sweden*
www.alfalaval.com

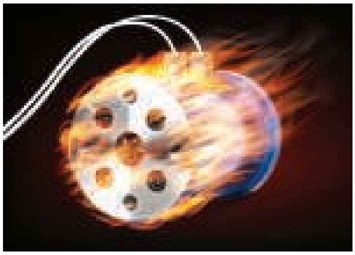
New compact gear pumps fit into tight spaces

The UP2 family of self-priming, compact electric gear pumps (photo) are available in 12- and 24-V d.c. versions and with flowrates up to 2.6 gal/min for water (52.9 gal/h for oil). The UP2 Series is designed for applications with an operating temperature range of –10 to 60°C. Self-priming to 1.5 m, UP2 gear pumps measure 3 in. × 5 in. × 4-3/8 in., enabling them to be placed in very tight enclosures. The Model UP2/Oil gear pumps feature bronze gear construction and are designed for the transfer of engine oils, fresh water or other non-corrosive viscous liquids. Model UP2/P gear pumps, featuring PTFE gears, are designed for transfer of fresh and salt water, as well as for diesel fuel. — *Clark Solutions, Hudson, Mass.*
www.clarksol.com

An acrylic binder designed for use with low-VOC paints

Rhoplex 800h acrylic binder was created to allow for early hardness development in low-VOC (volatile organic compound) paints. The controlled polymer-morphology technology employs

Prüftechnik Dieter Busch



Kral

Mettler Toledo

Alfa Laval

Clark Solutions

BinMaster

Asahi/America

PRAB

Aqua-Aerobic Systems

hard, soft and functional monomers in a single waterborne acrylic binder to help improve hardness and block resistance in high-gloss and deep-tone architectural paints. According to the company, coatings formulated with Rhoplex 800h binder, when compared to those formulated with competitive binders, show improved tack resistance and demonstrate excellent scrape and print resistance — important qualities for trim surfaces, windows and door frames. — *Dow Coating Materials, Midland, Mich.*
www.dowcoatingmaterials.com

Use this probe for level detection with heavy materials

This company's stainless-steel HD probe (photo) can be attached to either the Procap I or Procap II capacitance probes. This rugged probe comes in a standard 8-in. length and features a shield that guards against false readings from material buildup on the probe. The wide diameter of the probe increases the surface area for maximum sensitivity and performance. It is suitable for use with temperatures up to 500°F, making it appropriate for challenging applications. Because the probe is solid and 1-in. in diameter, it is resistant to bending and extremely durable, says the manufacturer. It can be used for level detection in heavy materials, such as coal, aggregates, grains or other materials with a high bulk density. — *BinMaster, Lincoln, Neb.*
www.binmaster.com

These enclosures are now available in 316 stainless steel

The TS 8 enclosure cabinet is now available in 316 stainless-steel construction for use in harsh environments, providing resistance to corrosion, high temperatures, common chlorides (such as salt present in seawater), as well as chemicals, including sulfuric acid, bromides, iodides and fatty acids. The addition of the 316 stainless-steel iteration of the TS 8 extends the cabinet's applications to oil-and-gas, water-supply and wastewater-management installations. The modular enclosure systems can be connected for further flexibility. The new TS 8 models have lower weight, while adding 30% more mounting space within, along with easier assembly, according to the manufacturer. — *Rittal Corp., Schaumburg, Ill.*
www.rittalenclosures.com

Achieve faster actuation for butterfly valves

The Speed Handle kit for butterfly valves (photo) consists of this company's PlasGear handwheel and an attached grip, and allows for smoother and faster single-handed revolutions for quicker valve actuation. The Speed Handle grip is constructed of black Nylon 6 with a stainless-steel 400, chromate-treated M10 bolt and stainless-steel M10 hex nut. Designed for use with this company's butterfly valves in sizes 1.5 through 16 in., the Speed Handle can be installed in the field to in-service valves, or at the factory for new valves. — *Asahi/America, Inc., Malden, Mass.*
www.asahi-america.com

Reduce waste fluids with this coolant-recycling system

The Guardian coolant recycling system (photo) is a management tool for fluid reclamation for operations with industrial coolant or washwater reservoirs. The Guardian system can reduce new fluid purchases by up to 75% and reduces waste fluids up to 90% by recycling used coolants, says the company. Free-floating and mechanically dispersed tramp oils are reduced to 0.1% or less at process rates of 90 to 1,500 gal/h. Guardian systems operate with a continuous-overflow process that provides multiple passes to prevent rancidity. — *PRAB, Kalamazoo, Mich.*
www.prab.com

Optimize chemical addition in cloth-media filters

The IntelliPro filtration optimization system (photo) is a PC-based control system for this company's cloth-media filters that uses realtime data to optimize chemical addition to meet phosphorus-removal objectives. The system features automatic, optimal-dose selection for metal salts, polymer and pH-adjusting chemicals. The IntelliPro system is can be used to assist treatment plants in achieving

low-level phosphorus objectives while reducing expenses. Advantages of the IntelliPro system include: chemical savings through load-based control; automated multi-point analysis; automatic chemical-dose response curves that replace jar testing; and automatic composite sampling. — *Aqua-Aerobic Systems, Inc., Loves Park, Ill.*
www.aqua-aerobic.com

Use this power-distribution system for plant maintenance

The MGS-DC-30KVA-480-220-110 power distribution system enables operators in industrial settings to utilize power sources independently of the work area. The 30-kVA system converts three-phase or single-phase 480 V a.c. to single-phase 120 and 240 V a.c. Designed to withstand demanding conditions, the transformer is mounted to a 3/16-in. carbon-steel mounting platform, and the distribution assembly is mounted on a rugged square steel tubing frame with rectangular carbon-steel skid pockets and a top-mounted eyelet to allow for ease of transport. This unit is suitable for use in many applications, including plant maintenance and welding stations. — *Larson Electronics, Kemp, Tex.*
www.larsonelectronics.com

Vibrating hoppers for handling fibrous and flaky materials

The Live Bin is a self-contained vibrating hopper that is designed to provide positive discharge of a wide range of materials, including those in the micron size range, as well as fibrous and flaky media, on a first-in, first-out basis, assuring mass flow and eliminating material segregation. The bins may be used to discharge to any feeder or process line, or wherever a surge bin is required. Because the Live Bin's design does not require a flexible seal, it is especially suited for sanitary applications. Live Bins may be operated on their own support legs, or can be hung from overhead steel, making them readily adaptable for scale mounting. Capacities range from 3 to 100 ft^3 of storage. — *VibraScrew Inc., Totowa, N.J.*
www.vibrascrew.com ■

Mary Page Bailey and Gerald Ondrey

Process Hazards Analysis Methods

Department Editor: Scott Jenkins

Different methodologies are available for conducting the structured reviews known as process hazards analyses (PHAs) for new processes. PHAs are often conducted or moderated by specialists, with participation by the design team, representatives of the facility owner, and experienced process operators.

Each different PHA method is better-suited to a specific purpose and should be applied at different stages of the project development. The table includes brief descriptions of some of the most widely used PHA methods in the chemical process industries (CPI).

When to use different methods

Different types of PHA studies have varying impact, depending on the design phase in which they are applied. For example, if a consequence analysis is not performed in a conceptual or pre-FEED (front-end engineering and design) phase, important plot-plan considerations can be missed, such as the need to own more land to avoid effects on public spaces; or the fact that the location might have a different elevation with respect to sea level than surrounding public places impacted by a flare plume.

Some other studies, like HAZOP, cannot be developed without a control philosophy or piping and instrumentation diagrams (P&IDs), and are performed at the end of the FEED stage or at the end of the detailed engineering phase (or for improved results, at the end of both) to define and validate the location of pressure safety valves (PSVs) as well as to validate other process controls and instrument safety requirements.

QRA or LOPA evaluations (or both) are undertaken after the HAZOP study to validate siting and define safety integrity levels (SIL), to finally meet the level required by the plant. ■

Editor's note: The definitions in the table, and associated comments, were adapted from the following article: Giardinella, S., Baumeister, A. and Marchetti, M. Engineering for Plant Safety. *Chem. Eng.*, August 2015, pp. 50–58. An additional reference is the following article: Wong, A., Guillard, P. and Hyatt, N. Getting the Most Out of HAZOP Analysis, *Chem. Eng.*, August 1, 2004, pp. 55–58.

TABLE: DIFFERENT PHA METHODS AND APPROACHES

Method	Description
Consequence analysis	This method quantitatively assesses the consequences of hazardous material releases. Release rates are calculated for the worst case and also for alternative scenarios. Toxicological endpoints are defined, and possible release duration is determined
Hazard identification analysis (HAZID)	HAZID is a preliminary study that is performed in early project stages when potentially hazardous materials, general process information, initial flow diagram and plant location are known. HAZID is also generally used later on to perform other hazard studies and to design the preliminary piping and instrumentation diagrams (P&IDs)
What-if method	The what-if method is a brainstorming technique that uses questions starting with "What if...," such as "What if the pump stops running" or "What if the operator opens or closes a certain valve?" For best results, these analyses should be held by experienced staff to be able to foresee possible failures and identify design alternatives to avoid them
Hazard and operability study (HAZOP)	The HAZOP technique has been a standard since the 1960s in the chemical, petroleum refining and oil-and-gas industries. It is based on the assumption that there will be no hazard if the plant is operated within the design parameters, and analyzes deviations of the design variables that might lead to undesirable consequences for people, equipment, environment, plant operations or company image. If a deviation is plausible, its consequences and probability of occurrence are then studied by the HAZOP team. Usually an external company is hired to interact with the operator company and the engineering company to perform this study. There are at least two methods using matrices to evaluate the risk *(R):* one evaluates consequence level *(C)* times frequency *(F)* of occurrence; and the other incorporates exposition (*E*) as a time value and probability *(P)* ranging from practically impossible to almost sure to happen. In this method, the risk is found by the following equation: $R = E \times P \times C$
Layer-of-protection analysis (LOPA).	The LOPA method analyzes the probability of failure of independent protection layers (IPLs) in the event of a scenario previously studied in a quantitative hazard evaluation like a HAZOP. LOPA is used when a plant uses instrumentation independent from operation, safety instrumented systems (SIS) to assure a certain safety integrity level (SIL). The study uses a fault tree to study the probability of failure on demand (PFD) and assigns a required SIL to a specific instrumentation node. For example, in petroleum refineries, most companies will maintain a SIL equal to or less than 2 (average probability of failure on demand $\geq 10^{-3}$ to $<10^{-2}$), and a nuclear plant will tolerate a SIL 4 (average probability of failure on demand $\geq 10^{-5}$ to $<10^{-4}$)
Fault-tree analysis	Fault-tree analysis is a deductive technique that uses Boolean logic symbols (that is, AND or OR gates) to break down the causes of a top event into basic equipment failures or human errors. The immediate causes of the top event are called "fault causes." The resulting fault-tree model displays the logical relationship between the basic events and the selected top event
Quantitative risk assessment (QRA)	QRA is the systematic development of numerical estimates of the expected frequency and consequence of potential accidents based on engineering evaluation and mathematical techniques. The numerical estimates can vary from simple values of probability or frequency of an event occurring based on relevant historical data of the industry or other available data, to very detailed frequency modeling techniques. The events studied are the release of a hazardous or toxic material, explosions or boiling-liquid expanded-vapor explosion (BLEVE). The results of this study are usually shown on top of the plot plan
Failure mode and effects analysis (FMEA)	This method evaluates the ways in which equipment fails and the system's response to the failure. The focus of the FMEA is on single equipment failures and system failures

L-lysine HCl Production from Glucose

By Intratec Solutions

Amino acids are the basis for all proteins and are considered building blocks of life. Among them, lysine (biologically active in its L-stereoisomer form) is one of the essential amino acids not synthesized biologically in the body. In this context, lysine is typically used as a supplement in human food and animal feed.

L-lysine is commonly commercially produced as L-lysine monohydrochloride (L-lysine HCl), with purity higher than 98.5 wt.%, which corresponds to 78.8 wt.% of free lysine.

The process

The following paragraphs, along with Figure 1, describe a conventional fermentation process for L-lysine HCl production. The process can be divided into three main parts: fermentation; product recovery; and product concentration, drying and packaging.

Fermentation. The culture media used in the batch and fed-batch phases of fermentation are prepared by mixing process water, glucose and nutrients. The fermentation step is performed in fed-batch mode and under aerobic conditions. In the batch phase, the microorganism seed is fed into the fermenters, which have been filled previously with the fermentation batch medium. After glucose exhaustion, the batch phase is finished and the fed-batch phase is started. During the fed-batch phase, glucose and nutrients are continuously supplied until the desired L-lysine concentration is achieved. At the end of the fermentation, the broth is sent to a buffer tank to provide a continuous flow to the downstream process steps.

Product recovery. The fermentation broth is sent to an ultrafiltration system for the removal of cell debris and other suspended solids. Subsequently, the liquor from ultrafiltration is fed to ion-exchange columns, where L-lysine is selectively adsorbed. The adsorbed L-lysine is eluted from the ion-exchange resins by washing with an aqueous ammonia solution.

Product concentration, drying and packaging. The L-lysine eluted from the ion-exchange columns is mixed with mother liquor from the product-filtration step and concentrated by evaporation. The concentrated lysine solution is acidified with hydrochloric acid, and free L-lysine is converted to L-lysine HCl.

The L-lysine HCl solution is then sent to the crystallizer, and lysine salt is filtered. The mother liquor is recycled to the evaporator and the wet cake is conveyed to dryers. Final dry L-lysine-HCl (98.5 wt.%) is obtained and sent to a packaging line before being stored in bags.

Economic performance

The total capital investment estimated for construction of a plant producing 100,000 metric tons per year of L-lysine HCl in the U.S. is about $350 million. The capital investment includes total fixed capital, working capital and additional capital requirements. Other assumptions considered are:

- Period of the analysis is second quarter of 2015.
- The plant includes installations required to provide a total storage capacity of 20 days for raw materials consumed and product generated.

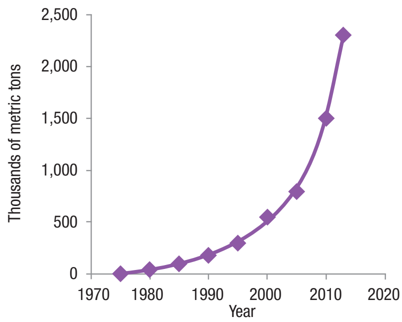


FIGURE 2. There has been significant growth recently in the global production of L-lysine

Global perspective

Worldwide production of white meat (for example, poultry and pork) has significantly increased over the past forty years. The growth has led to a much higher demand for L-lysine. Figure 2 illustrates the growth in L-lysine production over the past several decades. ■

Edited by Scott Jenkins

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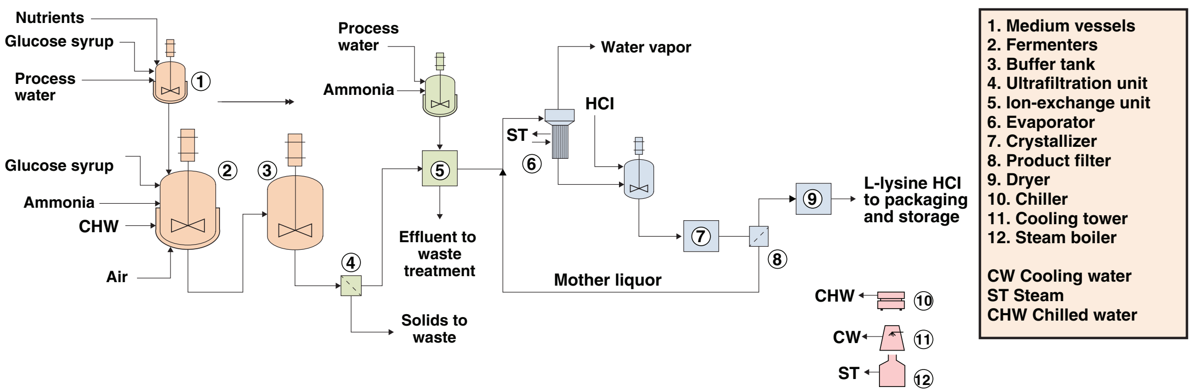


FIGURE 1. The diagram shows the production of L-lysine HCl via a conventional fermentation process

Flooded Condenser Controls: Principles and Troubleshooting

Flooded condensers are the prime tower pressure-control methods for total condensers that generate only liquid products, and although these control methods can be troublesome, a good understanding of their principles will help achieve improved, trouble-free operations

Henry Z. Kister
Fluor Corp.

FIGURE 1. Distillation columns are crucial in many facilities, and pressure control within the tower is of the utmost importance in ensuring steady operations

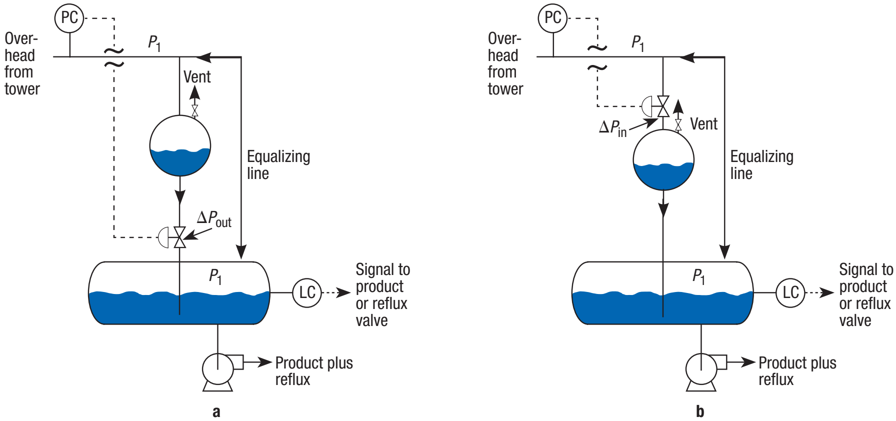
IN BRIEF

Pressure is the most important variable for controlling distillation columns (Figure 1) because pressure affects every aspect of a distillation system: vaporization, condensation, temperature, volatility and so on. An unsteady pressure typically results in an unsteady column.

There are several ways to control tower pressure, depending on how the tower is configured. If a tower has an overhead vapor product, manipulating the vapor flowrate usually controls pressure. If the tower has no vapor product (it has a total condenser and produces only liquid), tower pressure can be controlled by partially flooding the condenser and manipulating the liquid level in the condenser. Another alternative for either vapor or liquid products is to manipulate the coolant flowrate (or temperature) to control the tower pressure. Coolant manipulation is popular in refrigerated towers, but is usually avoided in cooling-water condensers, as it can cause accelerated fouling and corrosion.

Flooded condenser control is by far the preferred pressure-control method used with water-cooled total condensers (those generating liquid products only). It is also common with air-cooled total condensers. In this control method, the condenser area is partially flooded by condensate. The flooded tubes do not contact the vapor and perform little condensation. The column pressure is controlled by manipulating the flooded area.

FIGURE 2. These common flooded-condenser control arrangements show two different control-valve configurations. In Figure 2a, the control valve is located in the condensate liquid line, and in Figure 2b, the control valve is placed in the vapor line



Raising the liquid level in the condenser floods additional tubes, which reduces condensation area, thereby raising tower pressure. Conversely, lowering the liquid level in the condenser exposes more tubes, which increases the condensation area, and subsequently lowers the column pressure.

The principles of flooded condenser controls were described in literature more than 60 years ago. Chin's classic paper on distillation pressure-control describes many of the principles and good practices [*1*]. Yet, these methods continue to be among the most troublesome distillation controls. A good understanding of the principles, as well as learnings from past experiences, are key for avoiding many of the potential problems [*2*]. This article provides an updated and detailed description of the principles of flooded condenser control, and applies them to address many of the most common traps that can cause operational issues.

Common control arrangements

Although the flooded area performs little condensation, it serves the vital purpose of subcooling the condensate. Subcooling is beneficial when pumping volatile liquids [*3*]. Although the subcooling consumes some heat-transfer area, this area is not always added in the exchanger design. Some designers are comfortable to assume that the subcooling area can come from the overage included in the exchanger design [*3*]. Conversely, others prefer to oversize the condensers by as much as 25% to ensure subcooling, especially when the subcooling is critical, as in hot-vapor-bypass schemes [*4*].

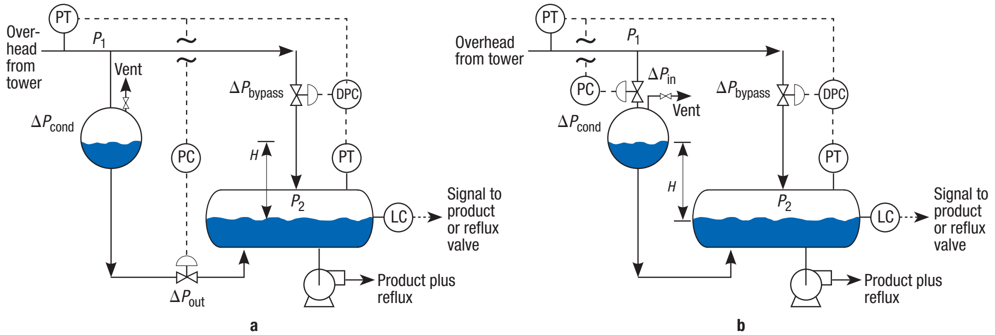
Figure 2 shows two common flooded-condenser control arrangements, both with the condenser mounted above the reflux drum. Figure 2a has the control valve in the condenser liquid outlet. The required control valve is small, and should be located as close to the reflux drum as possible to maximize static head when the condensate enters at the top of the drum [*1*]. For condensate entrance at the bottom of the reflux drum (as seen in Figure 3a), the valve should be located at the lowest horizontal leg. This method is simple and linear, and maintains the same pressure in the column and in the drum. It is therefore often favored [*1*, *5*].

This control method requires that a pressure-equalizing line is included [*1, 5, 6, 7*]. Without this line, the pressure in the reflux accumulator will be unsteady. A smaller equalizing line is required when the subcooled liquid is introduced near the bottom of the drum, as shown in Figure 2a.

Figure 2b shows a flooded condenser scheme similar to that in Figure 2a, but with the control valve located at the condenser vapor inlet. Similar to the method in Figure 2a, the condenser liquid outlet line must enter near the bottom of the reflux drum, and a pressure-equalizing line is required.

Placing the control valve in the vapor inlet (Figure 2b) renders the condensation pressure lower than when the valve is in the condensate outlet (Figure 2a), resulting in the requirement of additional condenser surface area. If no additional area is provided, tower pressure must be raised, which increases energy consumption. The required vapor-control valve is large and may be expensive with large overhead lines.

Figure 3 shows three additional flooded-condenser control schemes, all containing a control valve in the condenser vapor bypass. Figures 3a and 3b are analogous to Figures 2a and 2b; the only difference being the addition of the bypass control valve. This control valve helps overcome the pres-



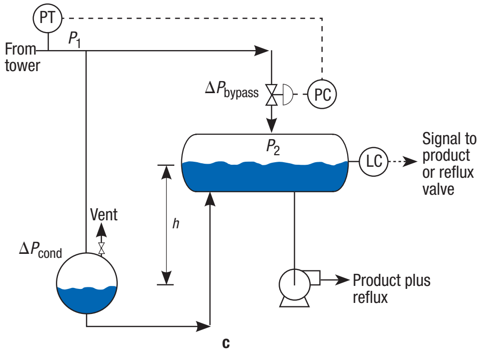


FIGURE 3. Three flooded-condenser control schemes with valves in the vapor bypass are shown: Figure 3a places the pressure-control valve in the condensate liquid line; Figure 3b places the pressure-control valve in the vapor line; and in Figure 3c, the pressure-control valve is in the hot-vapor bypass

sure drop in the condenser, especially when the liquid head is small.

Figure 3c shows the hot-vapor-bypass pressure-control method. Here, the location of the pressure-control valve is switched from the condenser route in Figures 2, 3a and 3b to the hot-vapor bypass. The condenser is at ground level, typically 10–20 ft below the reflux drum (which may be horizontal or vertical). The condensate must be subcooled so that the liquid surface in the drum is colder than in the condenser. While the pressure in the condenser is equal to the vapor pressure of the condensing vapor, the drum pressure is the vapor pressure of the cooler liquid surface in the drum. The difference in vapor pressures lifts condensate from the condenser into the drum. To reduce column pressure, the valve is throttled, reducing the hot vapor supply to the drum, and the drum's liquid surface cools. The colder surface has less vapor pressure. This increases the pressure difference between the condenser and the drum, which in turn sucks liquid from the condenser into the drum. This exposes additional tubes in the condenser, and increases the condensation rate, which lowers column pressure.

The hot-vapor-bypass arrangement permits the condensers to be mounted at ground level instead of on a platform above the reflux drum. Locating large cooling-water condensers at ground level eliminates the requirement for a massive condenser-support structure, and there is also no need to pipe cooling water to high elevations. This provides easy access for maintenance, the piping is simple, the control valve is small, and the response is fast [*3, 8*]. These advantages can translate into considerable savings in steelwork, platforms, trolleys and maintenance. These savings can be major in large installations, especially where a battery of condensers rather than a single exchanger is used. However, this method suffers from many potential issues, which are described in detail in Ref. 9.

Hydraulics of flooded condensers

Figure 3a shows a very common arrangement. The condenser is elevated above the drum, with the condensate descending into the drum due to gravity. The column pressure-control valve is in the condensate line from the condenser to the drum, which enters the drum below the liquid level. Up to this point, this scheme is the same as Figure 2a. The difference is that in Figure 3a, there is also a control valve in the condenser bypass. The presence of this control valve renders the pressure in the drum lower than at the condenser, which introduces a vapor-pressure effect. Assuming negligible line pressure losses, a pressure balance on the condenser gives Equation (1) below.

$$P_1 - P_2 = -H + \Delta P_{cond} + \Delta P_{out} \quad \textbf{(1)}$$

The variables in Equation (1) are defined as follows:

- P_1 is the pressure at the junction between the vapor line to the condenser and the condenser bypass in psia
- P_2 is the pressure at the vapor space inside the reflux drum in psia
- H is the head differential between the condenser liquid level and the reflux-drum liquid level in psi
- ΔP_{cond} is the condenser pressure drop in psi
- ΔP_{out} is the pressure drop across the condensate outlet control valve in psi

The density used to calculate the head differential H is the difference between the liquid and vapor densities, due to the presence of a static leg of vapor in the bypass line. The vapor density is based on the drum pressure and the drum vapor-space temperature. The liquid density is best approximated as the density of the subcooled liquid leaving the condenser. Without a control valve in the bypass (Figure 2a), then $P_1 = P_2$, and Equation (1) becomes Equation (2).

$$H = \Delta P_{cond} + \Delta P_{out} \quad (2)$$

Equation (2) states that for the Figure 2a configuration, the head required to drain the condenser must be high enough to overcome the condenser pressure drop plus the pressure drop of the condenser outlet valve. This condition may not be satisfied when the condenser pressure drop (ΔP_{cond}) is high, or the available liquid head H is low. Adding the valve in the bypass (converting the Figure 2a scheme to Figure 3a) changes the difference between P_1 and P_2 to ΔP_{bypass}, giving Equation (3).

$$P_1 - P_2 = \Delta P_{bypass} \quad (3)$$

Combining Equations (1) and (3) gives the scheme shown in Figure 3a, represented by Equation (4).

$$H + \Delta P_{bypass} = \Delta P_{cond} + \Delta P_{out} \quad (4)$$

Therefore, the pressure drop across the bypass valve helps the gravity head push the liquid from the condenser into the drum. For the arrangement in Figure 3b, the pressure drop at the condenser inlet ΔP_{in} (psi) replaces the pressure drop at the condenser outlet ΔP_{out}, and Equation (4) becomes Equation (5) below.

$$H + \Delta P_{bypass} = \Delta P_{cond} + \Delta P_{in} \quad (5)$$

For the arrangement in Figure 3c, there are no control valves at the condenser inlet or outlet, and the liquid head h (psi) is the difference between the reflux-drum liquid level and the liquid level in the condenser, meaning that $h = -H$. The value of H in Equation (4) is negative, as the liquid level in the reflux drum is at a higher elevation than that of the condenser. Equation (4) then becomes Equation (6).

$$\Delta P_{bypass} = \Delta P_{cond} + h \quad (6)$$

Vapor pressure differentials

As long as there is no hydraulic restriction in the condenser bypass line (Figure 2a), and the pressure drop of the condenser inlet line and at the condenser entry is low, the pressure is the same at the condenser as at the reflux drum. In this case, the vapor-pressure differential between the condenser surface and the drum's liquid surface is zero. In all other situations, the vapor-pressure differential plays a role, often a major one.

The pressure differences between the condenser and the drum in Figures 3a, 3b and 3c introduce vapor-pressure effects. In Figures 3a and 3c, $P_1 - \Delta P_{cond}$ is the vapor pressure of the liquid surface in the condenser, assuming most of the condenser pressure drop is near the condenser inlet — usually a reasonable assumption for total condensers. In Figures 2b and 3b, the vapor pressure of the liquid surface in the condenser is $P_1 - \Delta P_{in} - \Delta P_{cond}$. In all the schemes in Figures 2 and 3, P_2 is the vapor pressure at the reflux-drum surface.

In the schemes in Figures 2 and 3, the hot vapor provided by the bypass condenses onto the drum liquid surface, which keeps the surface hot. At steady state, the hot bypass introduces sufficient vapor to maintain the temperature of the drum's liquid surface at the value corresponding to the desired vapor pressure P_2. Heat flows from the hot liquid surface to the subcooled liquid underneath, and there are also atmospheric heat losses from the vapor space of the drum. These heat flows must be matched by condensing the hot vapor from the bypass.

As long as the drum surface remains steady, most of the heat flow from the surface to the subcooled bulk liquid is by conduction. Since process liquids are good thermal insulators, the conduction heat transfer from the hot surface to the subcooled liquid is small. In reality, convection and some bulk movement raise the heat transfer from the surface to the subcooled bulk liquid, but even accounting for these, the bypass vapor flowrate can easily match the heat demand at the drum liquid surface.

Ref. 9 details the heat balance for the drum in relation to the scheme in Figure 3c. The heat-balance discussion presented there also fully applies to other flooded-condenser control schemes (Figures 2a, 2b, 3a and 3b).

The vapor-pressure effects become of utmost importance in the hot-vapor-bypass scheme with submerged condensers (Figure 3c). In this scheme, the vapor-pressure differences directly determine the flooded height in the condenser. In the elevated-condenser schemes (Figures 3a and 3b), the condenser inlet or outlet valve directly determines the flooded height, with the bypass mainly used to provide sufficient pressure drop, per Equations (4) and (5).

With the hot-vapor-bypass scheme (Figure 3c), the vapor-pressure difference provides the driving head that pumps the condensate liquid from the condenser into the reflux drum as described in Equation (6). Equation (3) can be combined with Equation (6) to give Equation (7):

$$P_1 - P_2 - \Delta P_{cond} = h \quad (7)$$

Equation (7) shows that the vapor-pressure difference is balanced by the liquid head lift. If higher pressure is required in the tower, there is a need to flood more area in the condenser. This requires reducing the liquid head lift h. To achieve this, the vapor-pressure differential $P_1 - P_2 - \Delta P_{cond}$ must be reduced. With P_1 and ΔP_{cond} constant, this is achieved by opening the hot-vapor bypass to raise P_2. Opening the hot-vapor bypass heats up the liquid surface in the drum, which raises the vapor pressure P_2. Conversely, to reduce column pressure, there is a need to lower the liquid level in the condenser, which raises the liquid head lift. This is achieved by closing the bypass valve. This cools the surface in the drum and lowers P_2. The larger $P_1 - P_2$ difference sucks liquid from the condenser into the drum, thus exposing more condenser area for condensation. These mechanisms are described in detail in Ref. 9.

OVERCOMING CHALLENGES

Correct configuration is mandatory for the success of all flooded condenser schemes, due to their challenging nature.

Vapor to vapor and liquid to liquid lines

Bypass vapor must enter the vapor space of the reflux drum. The bypass should be free of pockets where liquid can accumulate, and any horizontal runs should drain into the reflux drum. The author is familiar with cases where a pocket of liquid in the hot-vapor-bypass line in Figure 3c led to severe oscillations and column pressure swings. Most importantly, liquid from the condenser must enter the reflux drum near the bottom of the drum, well below the liquid surface. This is imperative with the Figure 3c configuration, and also highly recommended with the other schemes. The rule is "vapor to vapor, liquid to liquid."

If the liquid enters at the bottom of the drum with an upward momentum (as shown in Figures 3a, 3b and 3c), a horizontal baffle should be added above the inlet to spread the momentum of the incoming liquid jet. As reported in Refs. 9 and 10, liquid jets at velocities of a few feet per second can easily penetrate through several feet of drum liquid, bringing a variable amount of subcooled liquid to the drum liquid surface, disturbing the surface. In some cases, such disturbances have caused a massive amount of liquid to be suddenly sucked from the condenser into the drum [*9*, *10*].

Figure 4a depicts a case in which violation of this practice led to severe pressure fluctuations, an inability to maintain column pressure and a capacity bottleneck [*9*, *11*]. In this scheme, subcooled liquid mixed with vapor at its dewpoint, and vapor collapse occurred at the site of mixing. The rate of vapor collapse varied with changes in subcooling, overhead temperature and condensation rate. Variation of this collapse rate induced pressure fluctuations and hammering.

The green piping in Figure 4b shows the piping modification that eliminated the problem. The liquid and vapor lines were separated, and the vapor line was altered so that it introduced vapor into the top of the reflux drum. After these changes were made, the tower pressure no longer fluctuated, and the problem was completely solved.

This case is one example of a violation of the "vapor to vapor, liquid to liquid" rule described above, and is the most common cause of poor performance with hot-vapor-bypass schemes. A number of these cases have been reported in literature [*5*, *6*, *11*, *12*].

Most importantly, liquid from the condenser must enter the reflux drum near the bottom of the drum, well below the liquid surface

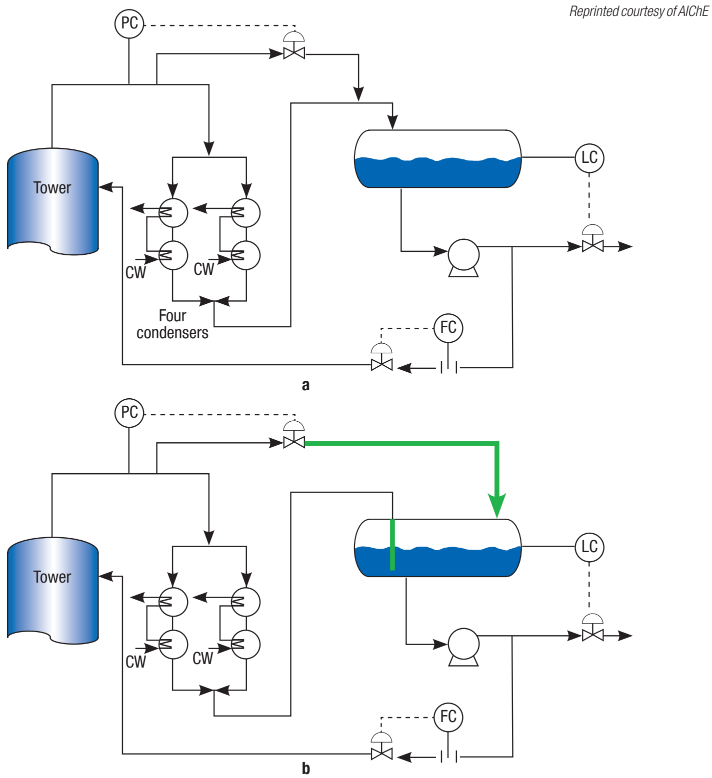


FIGURE 4. These diagrams show correct and incorrect hot-vapor-bypass hookups. Figure 4a illustrates a common mistake that leads to pressure fluctuations. Figure 4b shows modifications (in green) that correct the issues in Figure 4a, and provide sound pressure control [*9*]

Any subcooled liquid streams entering the drum must also enter at or near the bottom of the drum. In one case, subcooled liquid entered the drum vapor space (presumably due to unflooding of the liquid inlet) [*6*]. The vapor space was 100°F hotter, and rapid condensation sucked the liquid leg between the drum and condenser into the drum in seconds.

With the systems in Figures 2a, 3a and 3b, there is some debate in the literature whether the liquid should be introduced into the vapor space or into the liquid at (or at least near) the bottom of the drum. Ref. 1 recommends liquid entry above the liquid level so that drum level does not affect the condenser level.

The author and others strongly prefer that the subcooled liquid enters at the bottom of the drum [*8*, *13*]. Introducing subcooled liquid above the liquid level is likely to cause vapor collapse onto the cold liquid. This in turn may result in pressure fluctuations and possible hammering. Further, introducing the subcooled liquid onto the drum liquid surface drops the vapor pressure in the drum by a large amount, raising the demand of hot vapor from the bypass tremendously, and often overwhelming the capacity of the bypass. Unless a much larger bypass is available, the pressure inside the drum can decrease to as low as the vapor pressure of the liquid at the subcooled temperature. The author is familiar with situations where this pressure loss pulled vacuum inside the reflux drum. In other cases, drum pressure fluctuated, sometimes wildly. In some other situations where the bypass was large, the liquid almost entirely lost its subcooling, causing cavitation of the reflux pump. Splashing subcooled liquid onto the drum surface can also lead to the generation of static electricity. The higher the difference between the bubble point and the subcooled temperature, the more aggravated these issues become. Configurations where the liquid line enters the drum liquid also have the advantage of providing a better seal to the condenser and preventing vapor from blowing through the condenser [*3*].

A common design practice is to introduce the liquid from the top of the drum via a slotted or perforated pipe, so that most of the liquid is introduced below the drum liquid level, but some is splashed onto the liquid surface. This method is better than introducing all the liquid into the vapor space, but is not as good as introducing all the liquid near the bottom of the drum, and has been troublesome. The larger the opening that discharges liquid into the vapor space, the more troublesome this method is likely to be, especially in situations with a high degree of subcooling, such as during cold winter nights or low-rate operation. The issues are identical to those described in the previous paragraph. In the author's experience, severe hammering has occurred when highly subcooled liquid was introduced from the top of the drum with perforated or slotted dip pipes. The hammering ceased after the slots in the vapor space were blocked.

Surface agitation

Operation may be troublesome if the drum's liquid surface is agitated. Surface agitation is a particular concern with the hot-vapor-bypass scheme (Figure 3c), but the other schemes are not immune. Such agitation stirs up subcooled liquid and brings it to the hot liquid surface in the drum, causing fluctuations in the drum pressure. The source of agitation may be from impingement of a high-velocity hot vapor jet on the liquid surface, due to upward-directed subcooled liquid jets reaching the liquid surface, as well as other causes. Control instability has been reported when surface agitation occurred due to strong external vibrations on the reflux drum platform [*14*]. Agitation of the liquid surface can often be avoided by judicious baffling [*9*].

Inert padding

Instability due to surface disturbances or agitation may be alleviated, even mitigated, by padding the drum with non-condensable inert gases. A source of inerts, such as nitrogen or fuel gas, is connected to the vapor space of the drum. The drum pressure is controlled by adding or venting the inerts. The drum pressure is no longer the vapor pressure of the liquid, but now equals the sum of the vapor pressure (*VP*) of the drum liquid and the inerts partial pressure, as shown in Equation (8). The box on p. 44 presents a practical calculation example of the effects of inerts in a tower.

$$P_2 = VP_{\text{drum liquid}} + P_{\text{inerts}} \quad (8)$$

With total condensers, inert padding is usually implemented during operation as a temporary solution to alleviate instability, especially since the inerts can be quite expensive. The vented inerts contain vaporized product. In the calculation example on p. 44, assuming ideality and equilibrium, 10% (3.1 psia/30 psia) of the vent gas at 80°F on a molar basis will be hexane. On a weight basis, the hexane fraction of the vent gas is even higher due to the low molecular weight of the inerts — 26% hexane on a weight basis for nitrogen padding. This vented product is likely to be lost, and may increase flaring or emissions. The inerts, even nitrogen and fuel gas, can be absorbed into the product, and can later increase pressure in downstream equipment, resulting in more product loss and flaring downstream. To avoid inconsistent transitions from the inert-addition mode to the venting mode, there is often a pressure range in which inerts are added simultaneously with venting, which compounds the previously described issues [*15*]. In order to maximize product recovery and minimize emissions and flaring, some experts recommend against using inert padding with total condensers, other than as a temporary solution [*15*]. Diagnosing the cause of, and eliminating the surface instability, is usually a preferred longterm solution, especially with volatile products.

Decanting water

If the reflux drum is used to decant small quantities of free water from condensed hydrocarbons or other water-insoluble organics, the entry point of the condensate liquid (and other subcooled liquid streams that may contain free water) should be located within the drum opposite to the end at which the liquid product and reflux are withdrawn. The water-removal boot should be just upstream of the point where the reflux and product streams are withdrawn [*16*], as illustrated in Figure 5 for the control system from Figure 2a. In many cases, a short standpipe (about 6 to 12 in. tall) or judicious baffling are used as additional measures to keep water out of the reflux and product draw [*16*], but these additional measures may lead to water accumulation in the drum. Also, corrosion is possible when the interface level controller in the boot malfunctions, and potentially acidic water is not adequately removed from the drum. Ref. 17 describes a related experience.

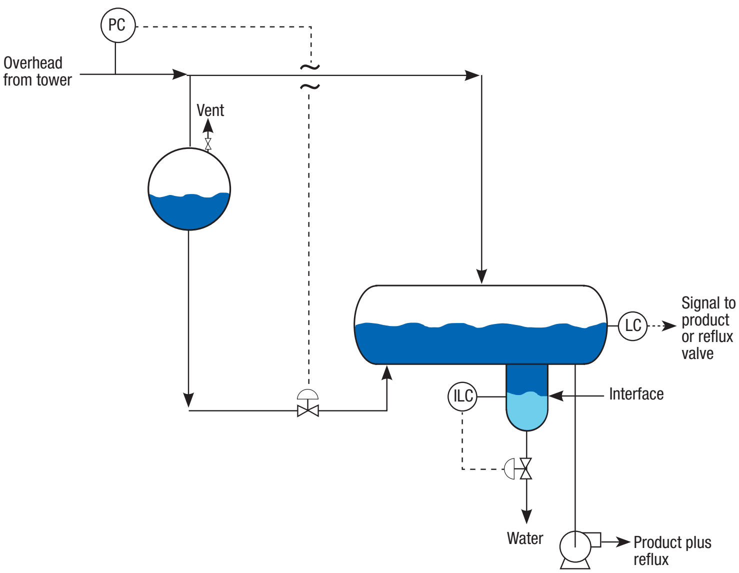


FIGURE 5. The flooded-condenser control scheme from Figure 2a is illustrated here with a water decanting configuration

Non-condensable gases

Flooded condenser schemes are suitable only for total condensers, although some less satisfactory variations are also available for partial condensers [*5*]. The schemes in Figures 2 and 3 can handle small amounts non-condensable gases, such as those introduced during startups or upstream upsets. To handle these non-condensables, vents are required on the condenser and the drum. The condenser vents can be directed to the vapor space of the drum, to an upstream unit or elsewhere. The drum vents should be board-operated, and if frequent venting is anticipated, the condenser vents should also be board-operated. In one case, a debutanizer flooded-condenser system experienced frequent high pressure, instability and flaring due to the breakthrough of non-condensables from an upstream tower that had control issues [*18*]. The problem

THE IMPACT OF INERT PADDING

Consider a tower making hexane top product at 35 psia and 210ºF. The overhead vapor is totally condensed, and is subcooled to 80ºF before entering the reflux accumulator at 30 psia. With no inerts, the drum liquid surface will be at about 200ºF to match the vapor pressure of hexane at 30 psia. A disturbance that lifts 5% of the subcooled liquid to the surface will cool the surface to 194ºF (0.05 × 80ºF + 0.95 × 200ºF), which will in turn drop the drum pressure by 3 psi — quite a large pressure swing. In contrast, with inerts filling the drum vapor space, the drum surface can be as cool as the subcooled temperature of 80ºF. At this temperature, the vapor pressure of hexane is 3.1 psia, with the partial pressure of the inerrts making up the remaining drum pressure. A 6ºF drop in surface temperature will lower the hexane vapor pressure to 2.7 psia, causing only a small change of 0.4 psia to the drum pressure. ❏

was mitigated by adding a manual board-operated condenser vent that was opened upon high pressure and vented to an upstream system.

Insufficient subcooling

Flooded-condenser control methods produce subcooled reflux and product. This subcooling is beneficial in avoiding net positive suction head (NPSH) issues in the pump or flashing problems in the reflux or product line. Such flashing can lead to instability, poor reflux distribution at the tower inlet, slug flow and even hammering [*19*]. The instability may be particularly severe with the flooded drum method (discussed below), due to its potential interaction with the column pressure control. However, other flooded condenser methods can also exhibit such issues.

Subcooling is diminished when the condenser nears its maximum capacity. This may be the natural maximum limit, or can be caused by fouling, non-condensable accumulation, condenser drainage or other issues. Subcooling is also diminished when liquid is splashed onto the surface of the drum, as discussed earlier. Finally, many advanced controls use pressure minimization strategies, such as Shinskey's floating pressure control [*19*, *20*]. These strategies reduce tower pressure during periods of favorable ambient temperatures to conserve energy, and in high-pressure towers (greater than 150 psia), can also maximize capacity. The pressure reduction brings the condenser closer to its limit, and by doing so, minimizes subcooling.

Issues with insufficient subcooling can be avoided, as long as the condenser is not near its capacity limit. The keys are to avoid splashing the condensate liquid onto the drum surface, minimize condenser fouling, properly vent non-condensables from the condenser and adequately monitor the subcooling. Some override control, or simply an operator advisory to limit the pressure minimization upon low subcooling, may also be beneficial.

Air condensers

Air condensers are elevated above the reflux drum, so the only compatible flooded condenser schemes are those for condensers mounted above the drum (as seen in Figures 2, 3a and 3b, as well as Figure 7, discussed further below). The hot-vapor-bypass scheme (Figure 3c) requires mounting the condenser below the drum, and is incompatible with air condensers. In one tower, overhead vapor was condensed in an elevated air condenser followed by a ground-level cooling water condenser. The Figure 3c scheme worked well when the liquid level was in the water condenser, but became unstable on cold days when the air condenser supplied the total condensation duty and the liquid level climbed into the air condenser. The solution was to reduce the air condenser duty by shutting off fans and closing louvers so the liquid level remained in the water condenser [*9*].

An air condenser has a small ratio of height to width. Any change in liquid level, even as small as 1 in., may result in an entire tube row being covered or uncovered. Typically, an air condenser will have very few rows (well below 10), so covering or uncovering one results in a bump in heat transfer. It is common to slightly slope several bottom tube rows, or all rows, towards the outlet so that the movement of liquid level up or down the tubes is smoother [*4*].

Valve configurations

There are unique issues associated with the various valve configurations shown in Figures 2 and 3. The following sections detail these issues and provide some guidance for avoiding them.

Valve in the condenser vapor inlet line (Figure 2b and 3b). As mentioned earlier, this method places a backpressure valve in the overhead vapor line, thereby reducing condenser temperature difference and capacity.

To minimize pressure drop, the overhead valve is often designed for a small pressure drop when fully open. This often leads to valve oversizing. When oversized, the valve operates barely open during winter and cold spells. In this situation, very small valve movements cause large fluctuations in tower pressure. In one case, it was necessary to throttle a manual valve upstream in the line to force the control valve to operate close to its half-open position [16].

This method is prone to liquid hammering if the valve closes excessively. In one case, the valve closed fully under some startup conditions [21]. Vapor downstream of the valve rapidly condensed, causing liquid to be rapidly drawn from the reflux drum, which in turn generated a liquid hammer that shook the whole unit. The problem was solved by changing the valve so that it would not fully close [21].

Valves in both the condenser and bypass lines (Figures 3a and 3b). The addition of the second valve generates potential interaction between the loops controlling pressure and differential pressure. There is also the question of which variable should be used to control the bypass. Friedman's work in Ref. 22 specifically addresses these questions.

Friedman advocates controlling the bypass using a separate drum-pressure controller (Figure 6a), rather than the differential pressure controller in Figures 3a and 3b. Ref. 1 reports one successful case with the system shown in Figure 6a where the liquid head was small and the valve in the bypass line was needed.

The Figure 6a scheme is uncommon, but the author is familiar with troublesome interaction between the pressure controllers in this scheme. This interaction is discussed in Refs. 8 and 22. Ref. 22 states that in this interaction, the two control loops help each other. Both references also state that the key for success with this scheme is to tune the drum pressure fast and the column pressure slow, much like a level controller. However, as previously stated, tower pressure is the most important column-control variable. It therefore needs to be tuned fast so it does not wander. Unlike pressure, level does not affect many variables, and as long as it stays within limits, it can move slower and be allowed to drift. Therefore, the Figure 6a scheme is not recommended by the author.

Another issue with using a separate drum pressure controller is that every time the setpoint is changed on the tower pressure controller, the same change must be made on the reflux-drum pressure controller [8]. The reflux-drum pressure setpoint needs to be lower than the tower pressure setpoint, making the scheme prone to major upsets if operator error occurs. To overcome this issue, Ref. 8 proposes an advanced control that subtracts an appropriate bias from the tower setpoint to provide the setpoint for the reflux-drum pressure controller.

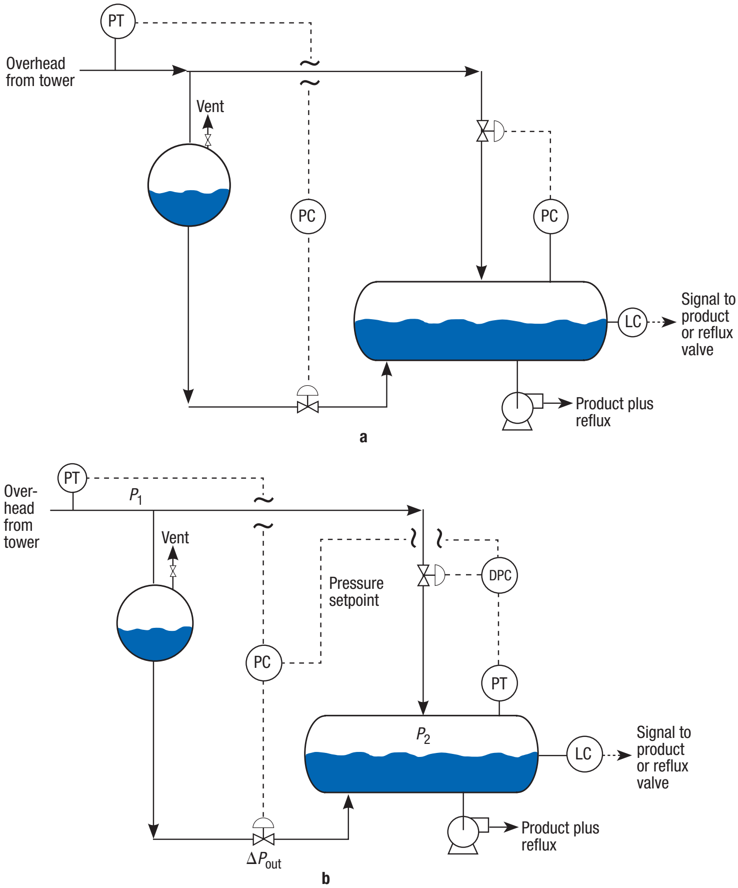


FIGURE 6. These schemes present alternatives to differential pressure control on the vapor bypass. Figure 6a shows a separate pressure controller on the reflux drum, which is not favored by the author. Figure 6b uses the pressure setpoint in the differential pressure controller, and alleviates concerns regarding negative controller interactions

A widely preferred alternative to the dual pressure-controller scheme in Figure 6a is the differential-pressure (dP) control scheme in Figure 3a and 3b. Friedman notes that with this scheme, the two controllers tend to fight each other. Upon an increase in column pressure, the condenser outlet valve (Figure 3a) opens, lowering the liquid level in the condenser, while the dP controller opens the bypass valve, which raises the liquid level in the condenser. While there is some debate in industry about the operability of this control scheme, it is accepted that if both controllers are tuned fast, there may be an unfavorable interaction.

A simple solution, practiced by many of those that reported the scheme to be troublesome, is to tune the dP valve slow or to place the dP valve in manual mode. These solutions have been implemented successfully to overcome the controller interactions. It is important to keep in mind that the main objective of the dP valve is to provide a restriction that will overcome the pressure drops on the righthand sides of Equations (4) and (5), so there is no need for tight control of the bypass pressure drop. One must simply ensure that adequate resistance is present.

In Figure 6b, Friedman presents a more elegant, albeit less widely practiced, solution. Instead of controlling the actual dP, the dP is set as the difference between the setpoint on the pressure controller and the drum actual pressure. This scheme has the strength of Figure 3a, which maintains a set dP, without getting into the negative interactions. Also, this configuration permits fast tuning of the pressure controller, which is essential. As in the Figures 3a and 3b schemes, the pressure should be tuned fast and the dP slower. Remember that the dP's only purpose is to provide sufficient pressure drop across the condensate valve.

- There is a potential for interaction between the drum and the condenser liquid levels [*5*, 9, *10*, *20*, *24*, *25*]. To mitigate the interaction, the pressure controller should be tuned much tighter than the drum level controller [*20*, *24*]. This can be an issue if the reflux drum is small, and the level controller needs to be tuned fast to avoid overflow or loss of level. Although this scenario is quite uncommon, the author has experienced it, and Ref. 26 reports an additional case where this occurred
- Because of the liquid leg between the condenser and the drum, non-condensables accumulate in the condenser and need venting from their accumulation points. If a vent line is absent, instability and capacity bottlenecks may result [*27*]
- Leakage of vapor through the bypass valve at the closed position can substantially reduce condenser capacity. In one case, closing a manual valve in the hot-vapor bypass increased condenser capacity by 50% [*28*]
- Undersizing the bypass control valve may lead to an inability to maintain the tower pressure during cold winter days when the drum is not insulated. In one situation, poor pressure control due to undersizing was improved by installing a throttling valve in the liquid line from the condenser to the drum [*29*]
- In some cases, the hot-vapor-bypass control valve is manipulated by the drum pressure instead of the tower pressure [*29*]. Dynamically, this control scheme is inferior because the vapor volume in the drum is much smaller than in the tower and more variable in response to ambient changes
- The reflux-drum vapor space may require insulation to minimize interference from rain and snow [*1*, *5*, *6*, *9*]. This issue is reported to be more pronounced with narrow boiling-range mixtures [*1*, *6*], and at high pressure [*6*], where small temperature changes have a large effect on the split of overhead flow between the condenser and the bypass. At the

To mitigate potential interactions between the drum and the condenser liquid levels, the pressure controller should be tuned much tighter than the drum level controller

Hot-vapor-bypass controls (Figure 3c). In the hot-vapor-bypass configuration with submerged condensers, there are numerous issues, which are covered in great detail in Ref. 9. The following are the key issues to keep in mind with this scheme:

- Correct piping is mandatory for the success of the hot-vapor-bypass control method. As described earlier, the bypass vapor must enter the vapor space of the reflux drum (Figure 3c or Figure 4b). The bypass should be free of pockets where liquid can accumulate, and any horizontal runs should drain into the reflux drum. Most importantly, liquid from the condenser, as well as any other subcooled liquid streams, such as the reflux-pump minimum-flow recycle stream, must enter near the bottom of the reflux drum. Many experiences have been reported in which incorrect piping led to instability, poor control and hammering [*4–6*, *11*, *12*, *23*]
- As previously described, operation may be troublesome and unstable if the drum's liquid surface is agitated [*1*, *6*, *9*, *10*]
- A sudden reduction in drum pressure can rapidly suck the liquid out of the condenser, causing a major upset [*9*,*10*]. There is also the possibility of U-tube oscillations [*5*, *24*, *25*]. Both issues can be mitigated by adding a throttling valve in the liquid leg between the condenser and the drum

other extreme, the incidence of Rayleigh fractionation with wide-boiling mixtures (where heavy components condense out without combining with the remaining mixture), can also interfere with this control system [*3*]

- The amount of subcooling and vapor bypass rates can only be determined empirically. Simplified sizing procedures are available [*6*, *30*], but these are based on heating all of the subcooled liquid to its bubble point, and therefore are grossly conservative. More reasonable sizing criteria can be inferred from the principles discussed in Ref. 9

Flooded drum scheme

Figure 7 illustrates the flooded reflux-drum method. Here, the drum runs full of liquid, and the level control of the reflux drum is eliminated. Sometimes, especially in gravity systems that have no reflux pump, the reflux drum itself can be omitted. The pressure controller directly controls distillate flow. Due to the absence of vapor space, the flooded drum is smaller than a drum with a vapor space, the piping is simpler, and together with the elimination of the level control, this method can offer significant capital-cost savings.

Due to the tight pressure control that is usually required, distillate flowrate controlled by this method is likely to fluctuate. These fluctuations may destabilize downstream units. This method should therefore only be used when the product goes to storage [*1*, *5*, *20*, *24*], and should be avoided when the product goes directly to another unit.

This method has sometimes been used to control reflux flow, but this practice is not recommended [*5*]. Here, reflux flow, rather than product flow, is likely to fluctuate, and this can destabilize the tower.

Besides the condenser venting issue above, the flooded-drum method has an additional venting issue. Accumulation of non-condensables in the drum may unflood the drum and interrupt the control action. These non-condensables must be vented from near the top of a liquid-full drum, so they need to be vented to a facility that can handle liquids, such as a knock-out drum. If accumulation of non-condensables is infrequent, manual venting from the top of the drum is often sufficient to maintain satisfactory operation. If non-condensables accumulate frequently, or the column is run unattended, automatic venting is required.

Figure 8 illustrates an automatic vent system that has worked well in practice [*5*, *12*, *31*]. A second pressure controller (PC 2), a level controller and a control valve in the vent line are added. The setpoint of PC 2 is lower than that of the normal pressure controller (PC 1). When the drum is full, the level controller keeps PC 2 tripped off, and the vent valve is closed. Drum unflooding (due to non-condensable accumulation) is sensed by a drop in drum level. The lower level activates PC 2. Since the setpoint of PC 2 is lower than PC 1, it opens the vent valve. As the drum pressure falls, PC 1 closes, helping to build up the drum level. As soon as the drum refills, the level controller trips PC 2, and the vent valve closes.

Since the venting required above is from a liquid-full drum, leaks from the vent line are likely to be liquid, giving a product loss much greater than a leaking vapor valve. Flashing of liquid across the valve can chill the vent line, sometimes resulting in icing or "weeping" on the outside of the pipe due to atmospheric moisture condensation, with possible overchilling or corrosion of the vent pipe. Ref. 16 describes one case of icing due to such a leak from a flooded drum in a debutanizer unit.

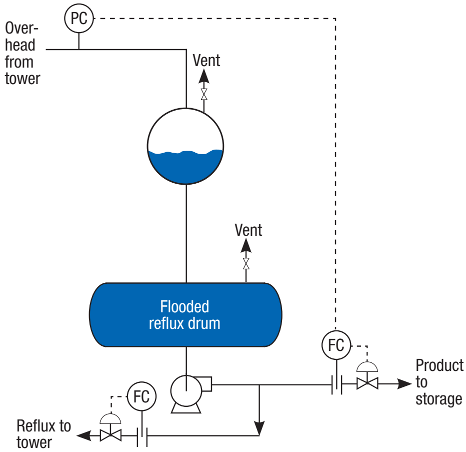


FIGURE 7. The flooded-drum control method can offer cost savings in some applications, but also introduces some unique issues

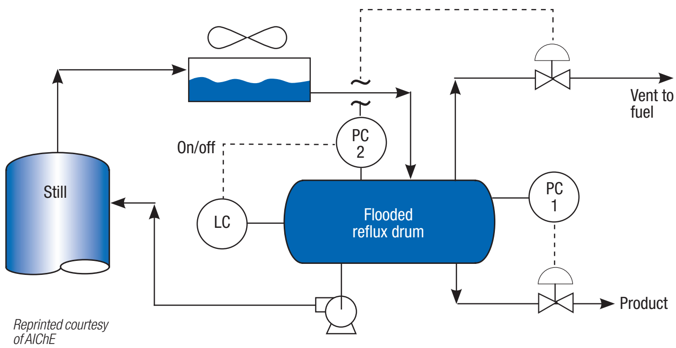


FIGURE 8. This flooded-drum automatic-vent system with dual pressure control has operated well in practice [*31*]

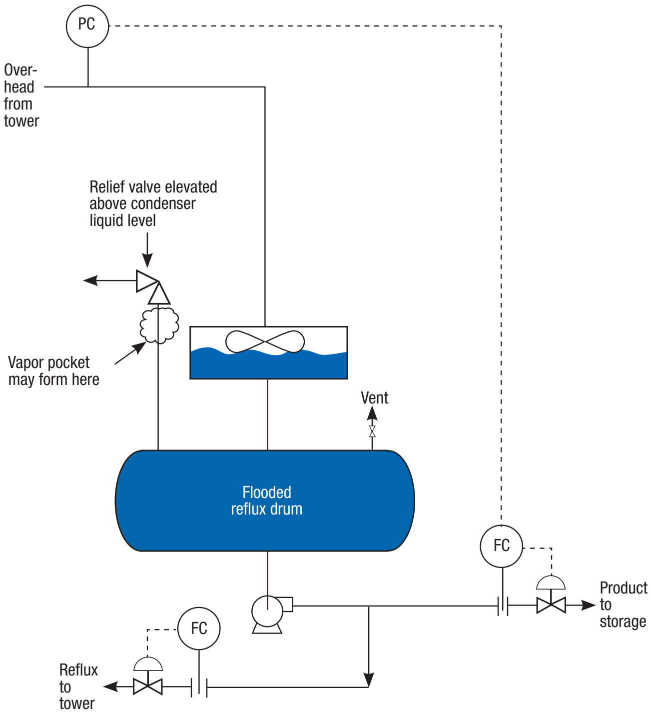


FIGURE 9. This configuration illustrates a relief valve mounted on a flooded drum

Unless the product is subcooled and at a significantly higher pressure than the storage facility, it is best to take the product to storage from downstream of the reflux pump (as shown in Figure 7). If the product is taken directly from the drum, flashing may occur downstream of the control valve, or it may be difficult to get the product into storage when the storage pressure is high. Either may cause instability or back excessive liquid into the condenser, thereby reducing its capacity and possibly leading to a relief situation. In one depropanizer process, pressure variations in elevated propane storage bullets downstream induced intermittent flashing and slug flow in the product line even though the product was pumped [*19*]. Collapse of vapor due to elevation and pressure changes is believed to have caused transient shockwaves and hammering, as well as chattering of the relief valves, in the pump-discharge circuit. The chattering was eliminated by adding a backpressure controller that prevented the flashing.

With the flooded drum method, a failure of the reflux pump often produces a relief situation. The condensate has nowhere to go, and quickly floods the condenser, ceasing condensation, causing the tower pressure to rise until the relief valve lifts. In other flooded condenser schemes (for instance, Figure 2a) where the reflux drum is not flooded, the vapor space in the drum provides operators with a few minutes to take action before the liquid fills the condenser. The author is familiar with one plant that replaced a flooded drum with a new non-flooded drum that was over twice the volume (to accommodate a vapor space) just to prevent recurrence of such a relief scenario.

Any relief valve mounted on the flooded drum (Figure 9) is most likely to discharge liquid, which may not provide adequate relief and may cause problems in the flare system. Furthermore, when the drum relief valve is elevated above the liquid level in the condenser, a vapor pocket may form in the valve inlet line during warm weather. Upon cooling (for instance, at night), the vapor pressure of the liquid in the small pocket falls. The vapor pocket may collapse, forcing a liquid rush that will hit the relief valve and cause chattering, as reported in two cases in Ref. 19. The need for a relief valve on the drum should be critically reviewed, as the relief valve on the tower should usually be able to relieve the drum.

Final remarks

Despite their importance in tower pressure control, flooded condenser controls have been some of the most challenging distillation-control techniques. However, operating experience indicates that they can be quite trouble-free when correctly designed and applied. It is hoped that the principles and experiences described in this article will pave the way for flooded-condenser controls' successful application for tower pressure control. ■

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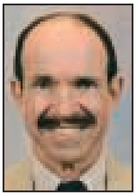
References

1. Chin, T.G., Guide to Distillation Pressure Control Methods, *Hydrocarbon Processing*, 58(10), p. 145, 1979.
2. Kister, H.Z., What Caused Tower Malfunctions in the Last 50 Years?, *Trans. Inst. Chem. Eng.*, Vol. 81, Part A, p. 5, January 2003.
3. Whistler, A.M., Locate Condensers at Ground Level, *Pet. Refiner*, 33(3), p. 173, 1954.
4. Schneider, D.F., and Hoover, M.C., Practical Process Hydraulic Considerations, *Hydrocarbon Processing*, p. 47, August 1999.
5. Kister, H.Z., "Distillation Operation," McGraw-Hill, New York, N.Y., 1990.
6. Hollander, L., Pressure Control of Light-Ends Fractionators, *ISA J.* 4(5), p. 185,1957.
7. Sloley, A.W., Effectively Control Column Pressure, *Chem. Eng. Prog.*, p. 38, January 2001.
8. Smith, C.L., "Distillation Control – An Engineering Perspective," Wiley, Hoboken, N.J., 2012.
9. Kister, H.Z., and Hanson, D.W., Control Column Pressure via Hot-Vapor Bypass, *Chem. Eng. Prog.*, p. 35, February 2015.
10. Kister, H.Z., and Hanson, D. W., Troubleshooting a Hot Vapor Bypass Control Instability, 10th International Conference on Distillation and Absorption, Friedrichshafen, Germany, September 14–17, 2014.
11. Kister, H.Z., and Litchfield, J.F., Distillation: Diagnosing Instabilities in

the Column Overhead, *Chem. Eng.*, p. 56, September 2004.

12. Kister, H.Z. "Distillation Troubleshooting," Wiley – Interscience, Hoboken, N.J., 2006.
13. Buckley, P.S., Luyben, W.L., and Shunta, J.P., "Design of Distillation Column Control Systems," Instrument Society of America, Research Triangle Park, N.C., 1985.
14. Hollowell, R.W., Private communication, May 2015.
15. Lieberman, N.P., "Troubleshooting Process Plant Controls", Wiley, Hoboken, N.J., 2009.
16. Lieberman, N.P., "Process Equipment Malfunctions", McGraw-Hill, New York, N.Y., 2011.
17. Cardoso, R., and Kister, H.Z., Refinery Tower Inspections: Discovering Problems and Preventing Malfunctions, Proceedings of the Distillation Topical Conference presentation, AIChE Spring Meeting, San Antonio, Tex., April, 2013.
18. Parsons, K., Private communication, March, 2015.
19. Mani, G., Avoid Condensation-Induced Transient Pressure Waves, *Hydrocarbon Processing*, p. 41, January 2011.
20. Shinskey, F. G., "Distillation Control for Productivity and Energy Conservation", 2d ed., McGraw-Hill, New York, N.Y., 1984.
21. Steinmeyer, D.E., and Mueller, A.C., Why Condensers Don't Operate as They Are Supposed To, Panel Discussion, *Chem. Eng. Prog.* 70(7), p. 78, 1974.
22. Friedman, Y.Z., Condenser Hot Vapor Bypass Control, *Hydrocarbon Processing*, p.150, June 2008.
23. Duguid, I., Take this Safety Database to Heart, Case MS16, *Chem. Eng.*, p. 80, July 2001.
24. Nisenfeld, A.E., and R.C. Seemann, "Distillation Columns", Instrument Society of America, Research Triangle Park, N.C., 1981.
25. Lupfer, D.E., Distillation Control for Utility Economy, Proceedings of the 53rd Annual Convention, Gas Processors Association, March 25–27, Denver, Colo., p. 159, 1974.
26. Laird, D., and Cornelisen, J., Control-System Improvements Expand Refinery Processes, *Oil & Gas J.*, p. 71, September 25, 2000.
27. Sloley, A.W., Simple Methods Solve Exchanger Problems, *Oil & Gas J.*, p. 85, April 20, 1998.
28. Lieberman, N.P., "Troubleshooting Process Operations," 4th Ed., PennWell Books, Tulsa, Okla., 2009
29. Hartman, E.L., and Barletta, T., Reboiler and Condenser Operating Problems, *PTQ*, p. 47, Summer 2003.
30. Durand, A.A., Sizing Hot Vapor Bypass Valves, *Chem. Eng.*, August 25, p. 111, 1980.
31. Kister, H.Z., and Hower, T.C., Unusual Case Histories of Gas Processing and Olefins Plant Columns, *Plant/Operations Prog.*,6(3), p. 151, 1987.

Author



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PSA Technology: Beyond Hydrogen Purification

Pressure swing adsorption technology is well known for H_2 purification applications, but the technique can also be used for other gas-separation processes in petroleum refining facilities

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IN BRIEF

Pressure swing adsorption (PSA) is a well-established process for the separation and purification of a wide range of industrial gases. PSA is generally safe, reliable and cost effective. In the petroleum refining industry, PSA systems are used to produce hydrogen from synthesis gas that is produced by steam-methane reforming (SMR), partial oxidation (POX) or gasification.

Although well known for H_2 purification, PSA technology can also be used for other gas-separation tasks. PSA systems can be used to recover H_2 from refinery offgases, to capture CO_2, and to generate O_2 and N_2 gases. This article provides an overview of PSA technology, including the scientific principles that dictate how it works, along with design considerations of PSA systems. In addition, the article summarizes how PSA technology can be used in several other petroleum-refinery applications beyond H_2 purification and the potential economic benefits that can be realized with this approach.

Selecting the best technology for a given gas-separation problem requires a thorough understanding of the available production technologies, including SMR, POX and gasification, as well as available separation technologies, such as membrane, cryogenic, absorption and adsorption. Identifying the optimal solution, and whether PSA technology could be a benefit, also requires a detailed knowledge of the capital and operating costs for the relevant process.

PSA principles

PSA technology is based on a physical binding of gas molecules to a solid adsorbent material. The adsorbent material can be a combination of activated carbon, silica gel, carbon molecular sieves and zeolites. The attractive forces between the gas molecules and the adsorbent material depend on the gas component, the type of adsorbent material, the partial pressure of the gas component and the operating temperature. Highly volatile compounds with low polarity, such as H_2 or He, are essentially not adsorbed at all compared to molecules such as CO_2, CO, N_2 and hydrocarbons. The relative attractive force of various gas molecules with a typical adsorbent material is shown in Figure 1.

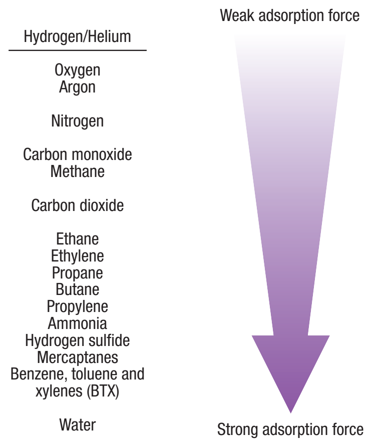

FIGURE 1. Highly volatile compounds with low polarity are not adsorbed onto the adsorbent material in a PSA system

The PSA process works at basically constant temperature and uses the effect of alternating pressure and partial pressure to perform adsorption and desorption. Since heating or cooling is not required, cycle time can be short — in the range of minutes. Furthermore, heat is not required for the regeneration of the adsorbent. Changes in temperature are caused only by the heat of adsorption and desorption and by depressurization. This results in an extremely long lifetime of the adsorbent material.

The PSA process works between two pressure levels. Adsorption of impurities is carried out at high pressure to increase the partial pressure of the undesired gases and, therefore, to increase the loading of the impurities onto the adsorbent material. Desorption, or regeneration, takes place at low pressure to reduce the residual loading of the impurities as much as possible.

Most PSA systems are based on equilibrium considerations. A typical equilibrium isotherm is shown in Figure 2. Adsorption isotherms show the relationship between partial pressure of a gas molecule and its equilibrium loading on the adsorbent material at a given temperature.

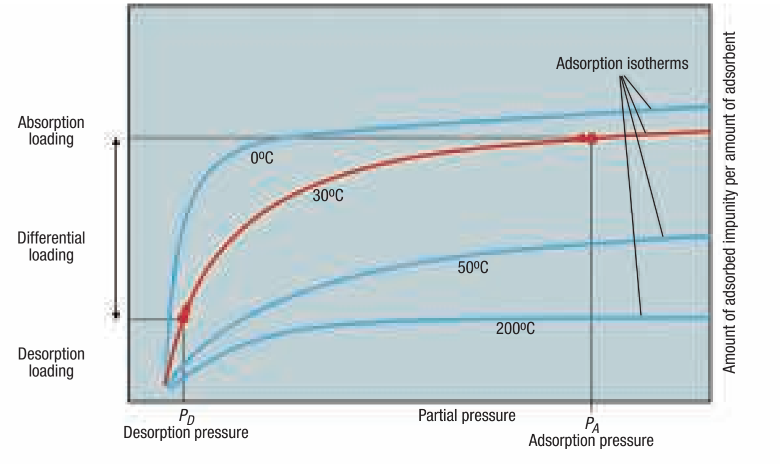

FIGURE 2. Adsorption isotherms show the relationship between partial pressure of a gas molecule and its equilibrium loading on the adsorbent material at a given temperature

Adsorption is carried out at high pressure — typically in the range of 10 to 40 bars — until equilibrium loading is reached. At this point, the adsorbent material must be regenerated in order to avoid impurity breakthrough to the product. This regeneration is done by lowering the pressure to slightly above atmospheric pressure, resulting in a corresponding decrease in equilibrium loading. As a consequence, the impurities on the adsorbent material are desorbed and the adsorbent material is regenerated. The amount of impurities removed from a gas stream in one cycle corresponds to the difference in the adsorption-to-desorption loading.

PSA system operation

A simplified schematic diagram of a H_2 PSA system is shown in Figure 3. An actual PSA operation is shown in Figure 4. The main process steps in a PSA operation, including adsorption, desorption and pressure equalization, are described below.

Adsorption. The feed gas is fed upward through the adsorber vessels. The impurities, including water, heavy hydrocarbons, light hydrocarbons, CO and N_2, are selectively adsorbed in the vessel from the bottom to the top. High-purity H_2 flows to the product line.

In the adsorption cycle, the adsorber vessels are placed on staggered cycles, resulting in a highly flexible purification unit that is not influenced by fluctuations in the composition, temperature and pressure of the feed gas stream.

The PSA system allows high performance by ensuring maximum utilization of the H_2 stored in an adsorber at the end of the adsorption cycle. The stored H_2 can be used for pressure equalization, repressurization and purging of other adsorbers.

Regeneration. Once the adsorption step is completed, the adsorber vessel is regenerated by the following four steps:

- Depressurization to a low-pressure level co-current to the feed flow. The co-current depressurization uses the hydrogen stored in the adsorber to repressurize and purge other adsorber vessels
- Depressurization in the counter-current direction to tailgas pressure (blowdown step) to remove the impurities from the adsorbent
- Purge is carried out at tailgas pressure with pure hydrogen to desorb the residual impurities from the adsorbent
- Repressurization adsorption pressure with pure H_2 coming from adsorbers

Pressure equalization. In order to recover most of the H_2 stored in an adsorber at the end of the adsorption step, several pressure equalizations are performed before starting regeneration of the gas.

After termination of the regeneration step, the pressure is increased back to the adsorption pressure level, and the process starts again from the beginning.

A typical PSA unit includes the following major components:

- Prefabricated valve skid
- Adsorber vessels
- Specially selected adsorbent material
- Tailgas drum
- Process control system

The scope of the PSA system can be altered to suit specific needs. For example, a feed-gas compressor or tailgas compressor can be included as an integrated solution.

One of the important requirements of a PSA system is the process control system. The key recommended features are listed below:

- High-purity H_2 at constant flow and pressure
- Automatic adjustments to pressure and flow fluctuations of the feed gas
- High H_2 recovery by optimizing equalization and purge steps
- Low sound emissions

Sophisticated software programs can safely control all switching, and control valves can provide a very efficient process cycle.

Refinery applications

The following section summarizes several applications for PSA systems at petroleum refineries, including H_2 separation, and several others that are not as widely used.

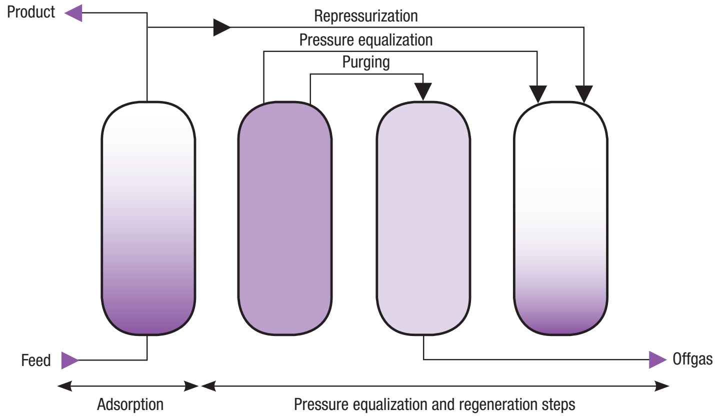

FIGURE 3. The main process steps of a typical PSA system, including adsorption, desorption and pressure equalization, are shown here

Hydrogen separation. The main application for PSA in a refinery is the recovery and purification of H_2 from gas streams, such as synthesis gases from steam reforming, POX or gasification, as well as from refinery offgases. The H_2 product can be obtained at high purity — up to 99.9999% — and high recovery rates of up to 90%.

CO_2 separation. PSA systems and vacuum-regenerated pressure swing adsorption systems (VPSA) can be employed for the bulk removal of CO_2. PSA/VPSA plants can also be used for the recovery and purification of CO_2 for liquefaction. A recent example of a PSA system used to recover CO_2 from the tailgas of an H_2 PSA system is shown in Figure 5. The H_2 PSA is a ten-bed system, and the CO_2 PSA is a five-bed system. The plant shown has a capacity of 48,000 Nm^3/h (normal cubic meters per hour) of H_2 and 8,000 Nm^3/h of CO_2.

FIGURE 4. Most PSA systems, such as the one shown here, are used for separating hydrogen from a gas mixture

C2+ separation. Refinery offgas (ROG) streams containing H_2, C1, C2 and heavier (C2+) hydrocarbons are usually available in refineries. These streams are often used as fuel. It is possible to process these gas streams and recover C2+ by PSA or VPSA as a way to capture greater value of C2+, which can then be used as a chemical feedstock. In this case, the C2+ fraction is recovered on low pressure, while H_2 and methane will stay on the high-pressure side. Several units have been placed into commercial operation and have been effective.

O_2 and N_2 generation. In a petroleum refinery, low-purity O_2 can be used to enrich the combustion air in fluid catalytic cracking (FCC) and sulfur recovery unit (SRU) operations. The production of gaseous oxygen at capacities of up to 10,000 Nm^3/h and purities of 90–94% can be most effectively achieved by VPSA processes. This method offers low specific-energy consumptions and operational simplicity, including simple startup and turndown capability.

Nitrogen is used in a refinery for inerting and blanketing. PSA systems can also be used to generate N_2 at capacities up to 5,000 Nm^3/h and purities of 98–99.9% (and higher).

Unlike H_2 PSA, CO_2 PSA and O_2 VPSA systems, the N_2 PSA system is based on the difference in the kinetics of adsorption of O_2 onto carbon molecular sieves.

Economic benefits

In the field of CO_2 removal and recovery, or purification, and for C2+ recovery, the technologies currently best known in the market are absorption units and cryogenic units. However, recent developments have made the recovery of CO_2 or C2+ technically feasible and economically viable with PSA technology. Respective reference plants have already been put into commercial operation and have proven the concept on an industrial scale.

The advantages of using PSA for these tasks, compared to other technologies, are low energy consumption, high purity levels, huge flexibility and comparatively low in-

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FIGURE 5. The plant scene depicted here shows a system for recovering CO_2 from the tailgas of a H_2 PSA system

vestment and maintenance costs. Selecting the most appropriate PSA technology can improve the overall profitability of a petroleum refinery by reducing costs and providing improved reliability, flexibility and environmental performance.

The key requirements and potential benefits of PSA systems are listed here:

Quality. The high switching cycles of PSA units require special equipment distinguished by a high degree of durability. It is essential to use only qualified components, which meet these demands perfectly and which have been proven over many years of experience.

Reliability. The use of suitable components, especially high-performance switching valves, provides high reliability.

Availability. High H_2 availability is essential for most refinery applications. With special features, such as the ability to operate with a reduced number of adsorbers, as well as adsorber group isolation and a redundant control system, PSA units can achieve virtually 100% on-stream performance and availability.

Flexibility. Excellent flexibility to cope with changing feed gas conditions and varying H_2 demand.

Modular design and prefabricated equipment. PSA systems are generally prefabricated to the maximum extent. The valve skids containing switching and control valves, instrumentation and interconnecting piping are completely prefabricated, preassembled and tested prior to delivery. This design philosophy reduces the time and costs needed for construction and commissioning onsite, keeping them to a minimum.

Easy maintenance. Maintenance is limited to easy and quick routine actions that can be carried out by the operators onsite. Attention is given to a proper accessibility of all valves and instruments inside the valve skid.

Concluding remarks

PSA technology can be used for much more than just recovering H_2. In some applications, such as the recovery of CO_2 or C2+ streams, PSA technology has certain distinct advantages compared to the more commonly used cryogenic or washing processes.

The advantages of PSA compared to other technologies are the low energy consumption, high purity levels, huge flexibility and comparatively low investment and maintenance cost. Selecting the most appropriate PSA technology can improve the overall profitability of a refinery by reducing cost and providing improved reliability, flexibility and environmental performance. Specialists can help to select the optimum PSA system for a specific purification task, in terms of the optimum ratio between plant performance and investment cost. ■

Edited by Scott Jenkins

Further reading

1. Shahani, G.H. and Kandziora, C., CO_2 Emissions from Hydrogen Plants: Understanding the Options. Lecture presented at the 2014 AFPM Annual Meeting, Orlando, Fla., March 23–25, 2014.
2. Adsorption Plants, Linde Engineering, Webpage found at www.linde-engineering.com, accessed November 2015.

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Illuminating Process Vessels: Advantages of Diffused Light

Don't panic — What appear to be scratches on a vessel may be an illusion caused by improperly applied LED lighting

David Star, Aarash Navabi and Mathew Hildner
L.J. Star

Imagine looking into a sight glass for a routine tank inspection, and seeing for the first time numerous scratches and potential points of contamination. What could have happened?

As more operators switch to light-emitting diode (LED) lighting to illuminate the interior surfaces of process vessels, many are often alarmed by the sudden appearance of scratches that appear on the vessel walls. In most cases, these are "false positives" caused by improper application of LED lighting. This article discusses the science behind this phenomenon, and provides guidance on how to properly apply LED lighting to gain a more accurate view of your processes.

Lighting choices

Many pharmaceutical and biotech companies are switching to LED lighting in their process operations, either as part of a company's environmentally friendly initiatives, or because of other advantages of LED lighting technology. In general, LED lights bring a variety of advantages. For instance, they have a far longer service life than traditional halogen bulbs, which reduces labor costs. LED lights can also be brighter, and their "color temperature" can be selected for optimal illumination of the process.

Unlike incandescent lights, LEDs emit very little heat compared to infrared light, which means they do not add heat to a process or environment. Finally, LED lights can be computer-controlled, which allows for dimming control.

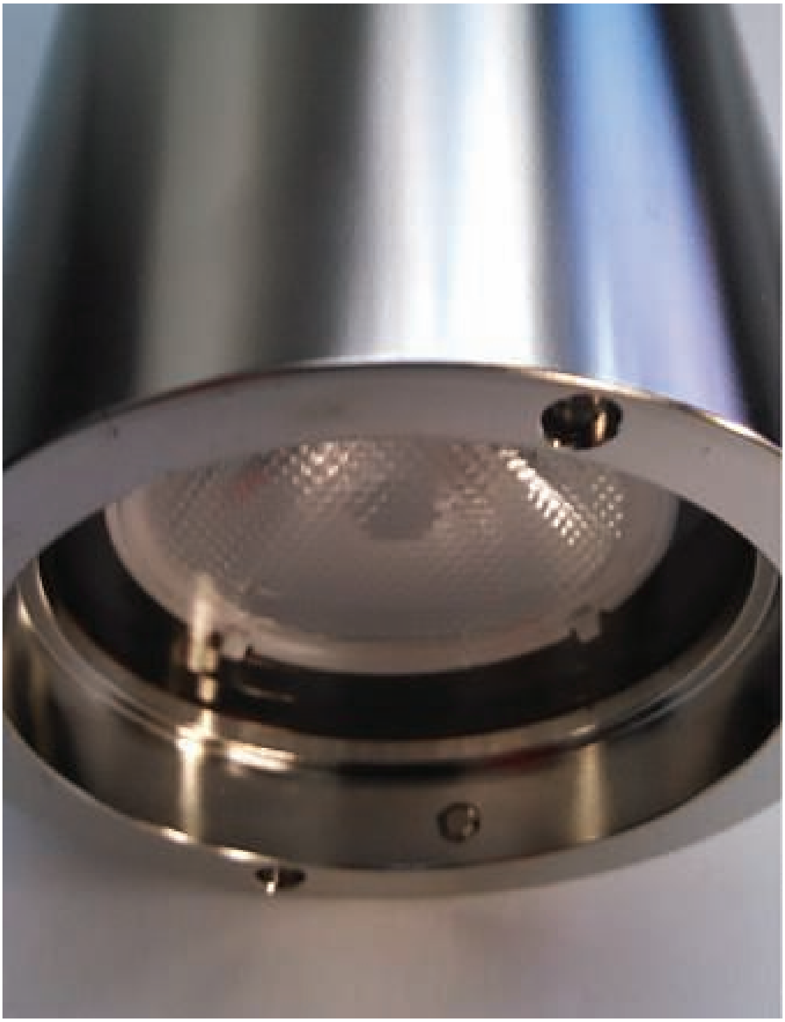

FIGURE 1. A light diffuser may be incorporated into the lens of a sight glass light (Source: L.J. Star)

However, LED lights will not be successful in an application unless they can provide an accurate view of the process. In order to prevent the appearance of insignificantly small scratches and surface features, LED lights used to illuminate process vessels should incorporate a diffuser in the lens.

A diffuser is a device that scatters light. They are commonly made out of translucent objects such as ground glass, Teflon or opal. Diffusers are a simple, affordable solution that can be specified at the time of sight-glass light selection (Figure 1).

For many pharmaceutical pro-

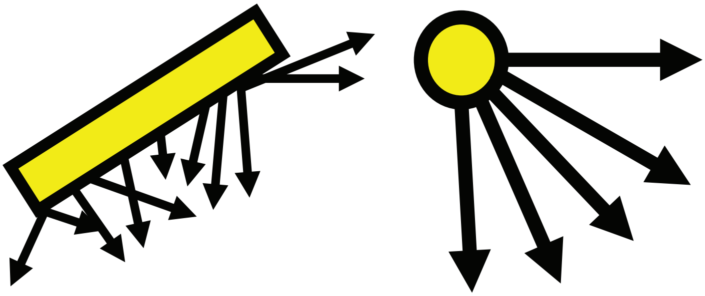

FIGURE 2. Halogen lights (left) emit light over a wide area from a diffused source. By contrast, LEDs (right) emit light directionally, from a point source, creating an undiffused light source that tends to illuminate surfaces more uniformly.

FIGURE 3. Figure 3a (left): A stainless steel surface viewed under diffused light appears pristine. Figure 3b (right): By contrast, the same stainless steel surface, viewed under undiffused light, reveals surface imperfections that may or may not be significant

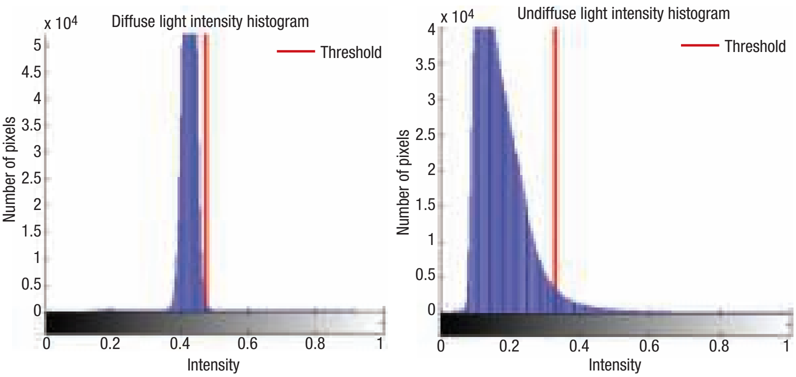

FIGURE 4. Figure 4a (left): The intensity distribution of diffused light on stainless steel is relatively narrow. Figure 4b (right): By contrast, the intensity distribution of undiffused light on stainless steel is wider

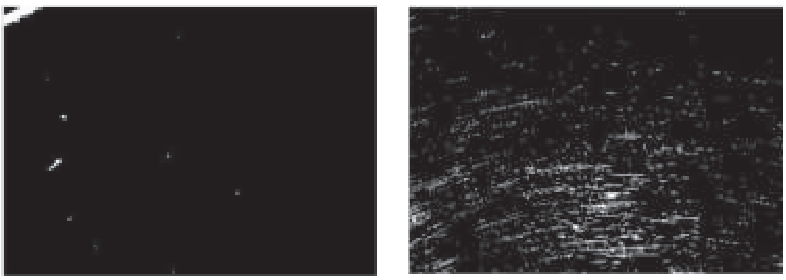

FIGURE 5. The binary image (left) was generated by shining diffused light on stainless steel. The binary image shown on the right was generated from shining undiffused light on stainless steel.

cesses, some food-and-beverage processes and specialized chemical-process operations, visual inspection is often used to observe the characteristics of the process medium and to verify certain process steps, such as a clean-in-place efforts. Such visual inspections should show smooth, crevice-free surfaces that cannot harbor bacteria or other contaminants.

Halogen lighting — the traditional, filament-based lighting option — has a natural tendency to produce light over a wide area and spread that light in all directions (because filaments illuminate in all directions). Under such diffused light, a highly polished stainless steel vessel has a mirror-like finish.

By contrast, LED lighting emits light from a small area, making the light emit radially outward as if it came from a single point. This radially emitted light is mostly undiffused light, so it reflects off objects more uniformly. Undiffused light will reveal tiny imperfections in the steel surface that are in most cases inconsequential. Figure 2 shows the difference between diffused and undiffused light sources.

To illustrate the different effects of diffused versus undiffused light, Figure 3 shows photos of the same steel surface under diffused and undiffused light. The stainless steel is polished to a pharmaceutical-industry common surface finish Ra (roughness) of less than 20 microinches (µin; roughly equivalent to 0.5 micrometers).

Viewed under diffused light (Figure 3a), the stainless steel appears bright and has a mirror-like finish (which presents the impression of a flawless reflection). However, when viewed under undiffused light (Figure 3b), the same steel appears dark and has many apparent scratches.To analyze these results, the color photos can be transformed into grayscale, and then the intensity distribution of the reflected light can be graphed on a histogram (Figure 4). The intensity distribution for the undiffused light is wide, has a long tail, and a lower mean than the intensity distribution for the diffused light. This shows that polished stainless steel reflects diffused light more consistently than undiffused light.

When the images are transformed into a high-contrast (binary) image (Figure 5), the reason for the wide spread in the histogram of the undiffused intensity distribution is related to all of the scratches present in the photograph in Figure 5b. By contrast, the diffused light image (Figure 5a) does not show as much variation (almost none of the binary image is white).

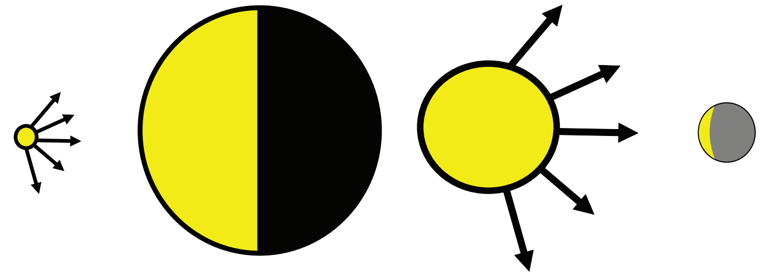

FIGURE 6. When the source of light is small compared to the illuminated object, the light produced is hard. When the source of light is large compared to the illuminated object, the light produced is soft [*4*]. Note the differences in the shadow patterns on the subjects

Phong Reflection Model

When an optic reflection model — called the Phong Reflection Model (box, p. 56) — is applied, then the mechanism for how undiffused light and diffused light behaves becomes more clear. The Phong Reflection Model is an empirical model for light reflection, which calculates the intensity of light using a number of inputs (see sidebar, below, for details). It is commonly used in reflection calculations for computer rendering [*1*].

Because no surface is perfectly smooth — even highly polished stainless steel has tiny hills and valleys on its surface — these imperfections affect the angle at which the light reflects [*2*]. The smaller the angle between the vectors, the more intense the reflection. The model predicts that the intensity of the diffused light will be constant for any viewer angle, and that undiffused light will reflect light more intensely in some areas when viewed at certain angles.

PHONG REFLECTION MODEL

The Phong Reflection Model (Equation 1) calculates the intensity of light at any point (I_p) using the material's specular reflection constant (k_s), diffused reflection constant (k_d), ambient reflection constant (k_a), and shininess constant (α), along with the direction vector of the light source ($\hat{L}_m$), the normal vector of reflection ($\hat{N}$), the ideal reflection vector ($\hat{R}_m$), and the viewer vector ($\hat{V}$). The inputs to the Phong Reflection Model are the ambient lighting intensity (i_a), the specular intensity (i_s), and the diffused intensity (i_d) [*1*].

$$I_p = k_a i_a + \sum_{m \in lights} \left(k_d \left(\hat{L}_m \cdot \hat{N} \right) i_{m,d} + k_s \left(\hat{R}_m \cdot \hat{V} \right)^{\alpha} i_{m,s} \right) \quad (11)$$

In the Phong Reflection Model, the light from an undiffused LED light source can be assumed to be only specular light (light that reflects at a consistent angle), while the light from a diffused LED can be assumed to be entirely diffused light [*2*]. Assuming that the intensity of the light source is the same for both LEDs, the intensity of light reflected for the undiffused light is dependent on the dot product of $\hat{R}_m$ and $\hat{V}$, while the intensity of diffused light is dependent on the dot product [Note: A dot product is an algebraic operation used to describe the resulting magnitude of two different vectors. When the vectors are perpendicular to each other, the dot product is 0; when the vectors are parallel to each other, the dot product is equal to A*B].]

For undiffused light, the dot product of $\hat{R}_m$ and $\hat{V}$ creates a large variation of intensities that a surface is capable of producing. Since no surface is perfectly smooth, there are hills and valleys present that will affect the angle that the light will reflect [*3*] (Figure 8). The smaller the angle between the vectors, the more intense the light. However, due to the way light deflects off of surfaces, only a small range of surface angles will result in the difference between the vectors being small. While most of an object's surface will have a lower intensity, areas with the proper angle will be noticeably more intense. And importantly, the intensity of the light will also change based on how the user orients his or her view, so features on the surface can appear and disappear based on the angle at which they are viewed [*5*].

For diffused light, the dot product of $\hat{L}_m$ and $\hat{N}$ will result in less variable light compared with the undiffused dot product. While the natural roughness of an object will result in a wide variation in $\hat{N}$, $\hat{N}$ will not change unless the surface is modified (Figure 9). This means that the only way to affect the intensity of diffused light is to change $\hat{L}_m$.

This is in contrast to the undiffused light source, where the intensity of the reflected spectral light will be affected by changes in both $\hat{L}_m$ and $\hat{V}$. This makes the intensity of the diffused light constant for any viewer angle. Additionally the $\hat{N}$ of a flat surface will average out to be perpendicular to the surface, unlike the $\hat{R}_m$ which can vary widely based on many factors of the surface roughness.

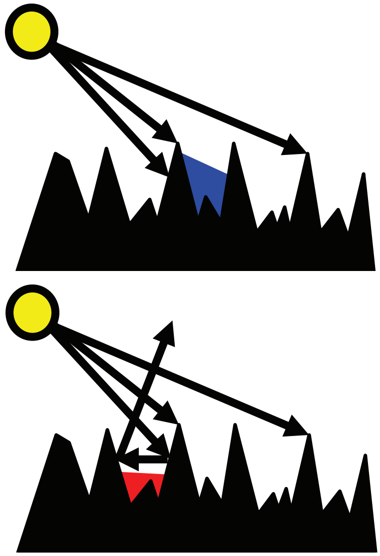

FIGURE 7. Figure 7a (left): Shadowing occurs on a rough surface. The light is unable to reach certain areas of the surface. Figure 7b (right): Masking occurs on a rough surface. The light is reflected off the geometry of the surface in such a way that the region will gain increased intensity

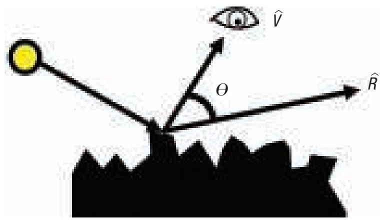

FIGURE 8. When spectral light reflects off of an uneven surface the difference between the reflection vector and the viewer vector affects the intensity of the reflected light

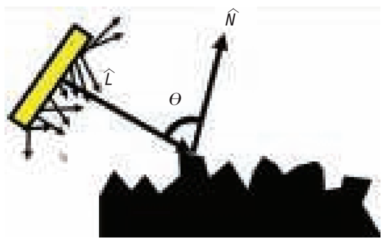

FIGURE 9. When diffused light reflects off of an uneven surface, the difference between the light vector and the normal vector affects the intensity of the reflected light

Hard and soft light

The difference between undiffused and diffused light on stainless steel does not end with how the light reflects off the steel. The geometry of the light source also affects the appearance of the steel surface. When the light source does not have an area much greater than the object it is illuminating, then hard light is produced [*3*] (Figure 6). The light-producing region of a typical LED is on the order of a square millimeter or less, which is relatively small.

When hard light hits an object, shadowing and masking occur [*4*] (Figure 7). Both of these phenomena occur because the geometry of the surface being illuminated blocks light from reaching certain areas of the surface (a phenomenon called shadowing; see Figure 7a), or reflects light in such a way that certain regions receive extra ligh, covering certain areas of the surface; this is called masking (see Figure 7b).

By contrast, soft light does not produce shadowing and masking, because the light hits the steel at a variety of angles.

Diffusers have a surface area that is measured in square centimeters, much greater than the imperfections on the surface of the steel, and therefore the light is soft. Soft, diffused light reduces the prominence of surface imperfections of steel through the reduction of both shadowing. ■

Edited by Suzanne Shelley

References

1. Lyon, Phong, Richard F., Shading Reformulation for Hardware Renderer Simplification, Apple Computer, Inc., accessed on the Web. 29 Sept. 2014 (http://dicklyon.com/tech/Graphics/Phong_TR-Lyon.pdf).
2. Jensen, Henrik W., Marschner, Stephen R., Levoy, Marc, and Hanrahan, Pat. A Practical Model for Subsurface Light Transport. Stanford, accessed on the Web. 29 Sept. 2014 (http://www.cs.berkeley.edu/~ravir/6998/papers/p511-jensen.pdf).
3. Curtin, Dennis P., Understanding Hard and Soft Light Short Courses. Short Courses, 2011, accessed on the Web. 29 Sept. 2014 (http://www.shortcourses.com/tabletop/lighting2-8.html>.
4. He, Xiao D., Torrance, Kenneth E., Sillion, François X., and Greenberg, Donald P., A Comprehensive Physical Model for Light Reflection, ACM SIGGRAPH Computer Graphics, Vol.25.4, pp.175–86, 1991.
5. Phong, Bui Tuong. Illumination for Computer Generated Pictures, Communications of the ACM, Vol. 18.6 (1975): 311–17, 1975.

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Hopper Design Principles

When hoppers are designed without consideration of the actual materials being handled, problems inevitably arise. Follow this guidance to avoid common solids-handling issues, such as erratic flow and no flow

Greg Mehos and Dave Morgan
Jenike & Johanson

Pivotal work on the development of the theory of bulk solids flow began in earnest in the early 1950s, when Andrew Jenike applied a solids-mechanics-continuum concept to develop a logical, theoretical approach for understanding and managing solids flow. He developed testing methods, equipment, and design techniques and conducted experiments to confirm and refine his groundbreaking analysis [*1*].

Prior to Jenike's work, bins and hoppers were typically designed primarily from an architectural or fabrication standpoint (for instance, hopper walls were sloped 30 deg from vertical to reduce the waste of wall materials, or 45 deg to minimize headroom requirements and simplify design calculations). However, extensive experience has shown that designing equipment without regard to the actual bulk materials being handled often leads to flow problems, such as arching, ratholing, erratic flow and even no flow. By measuring the flow properties of a bulk solid, the flow behavior of the material can be predicted, and more reliable hoppers and bins can then be designed.

Competing flow patterns

Two primary flow patterns can occur in a bin or a silo: mass flow and funnel flow (Figure 1). In mass flow, the entire bed of solids is in motion when material is discharged from the outlet. This behavior eliminates the formation of stagnant regions in the vessel, and affords a "first-in, first-out" flow sequence, which provides a more uniform velocity profile during operation. A uniform velocity profile also helps to reduce the effects of sifting segregation.

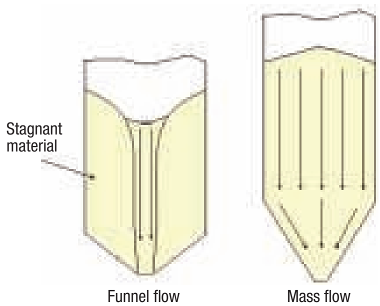

FIGURE 1. Two types of flow patterns can occur when a bulk solid is discharged from a hopper, bin or silo: A typical funnel flow pattern is shown on the left, and a mass flow pattern is shown on the right

By contrast, in funnel flow, an active flow channel forms above the outlet, but stagnant material remains (called ratholes) at the periphery of the vessel. Funnel flow can cause erratic flow, exacerbate segregation, reduce the live capacity of a vessel, allow particle degradation (leading to caking and spoilage) in stagnant regions. Depending on the vessel size, funnel flow can also induce high loads on the structure and downstream equipment, due to collapsing ratholes and the formation of eccentric flow channels.

For many materials, flow problems can be eliminated by ensuring that a mass flow pattern exists in the vessel. The first step to achieving mass flow is to ensure that the converging walls are steep enough, and have friction low enough, to allow the bulk materials to slide along them. This is accomplished by first testing the material to measure wall friction, and then calculating the minimum hopper angle that will allow mass flow.

Hopper angle for mass flow

Once the wall friction results are known, the recommended hopper angle to ensure mass flow can be readily calculated. The angle of wall friction (ϕ') is obtained by following the method described in ASTM D-6128 [*2*]. The test is performed using an instrument (shown in Figure 2) that involves placing a sample of powder inside a retaining ring on a flat coupon of wall material. Various normal loads are then applied to the powder, and the powder inside the ring is forced to slide along the stationary wall material. The resulting shear stress is measured as a function of the applied normal stress.

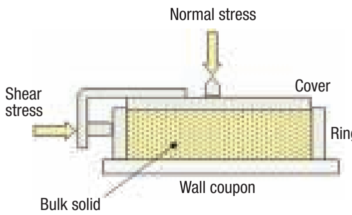

FIGURE 2. By measuring the force required to slide a sample of powder along a wall coupon, the angle of wall friction can be determined

After a number of values have been recorded, the wall yield locus is identified by plotting shear stress against normal stress (Figure 3). The angle of wall friction (ϕ') is the angle that is formed when a line is drawn from the origin of that graph to a point on the wall yield locus.

Jenike [*1*] found that the hopper angle required to allow flow along the walls depends on the friction between the powder and the walls, the friction between powder particles, and the geometry of the hopper. Design charts originally developed by Jenike [*1*] provide allowable hopper angles for mass flow, given values of the wall friction angle and the effective angle of internal friction (δ, which is determined by shear cell testing).

The charts mentioned above [*1*] are summarized in Figures 4 and 5 for conical and planar hoppers (for example, wedge-shaped hoppers and transition hoppers), respectively.

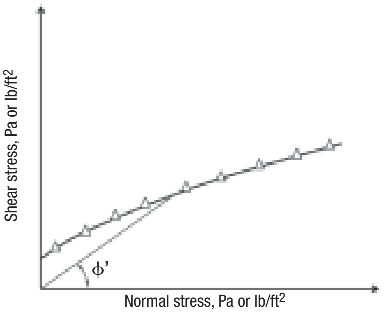

FIGURE 3. The angle of wall friction (ϕ') is determined by drawing a line between the wall yield locus (which is constructed by plotting shear stress against normal stress), and the origin, as shown here

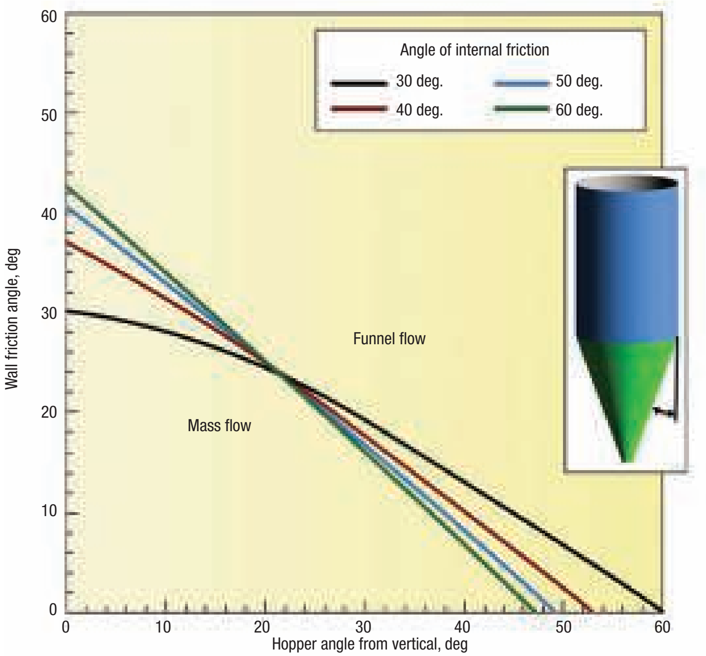

FIGURE 4. This plot shows the theoretical mass-flow hopper angles for hoppers with round or square outlets. Note: a minimum safety factor of 3 deg should be used

Note that the outlet of a wedge-shaped hopper must have a length that is at least three times its width for the relationship shown in Figure 5 to apply.

Values of the allowable hopper angle Θ' (measured from vertical) are on the *x*-axis, and values of the wall friction angle ϕ' are on the *y*-axis. Any combination of ϕ' and Θ' that falls within the limiting mass flow region of the chart will provide mass flow.

Hoppers with round or square outlets should not be designed at the theoretical mass-flow hopper-angle value. Otherwise, a small change in powder properties may cause the flow pattern inside the hopper to change from mass flow to funnel flow — bringing its associated risk of flow problems. A 3-deg margin of safety (with respect to the mass-flow hopper angle given in Figure 4) is recommended.

Sloping walls required for mass flow in wedge-shaped hoppers can be 10–12-deg less steep than those required to ensure mass flow in conical hoppers. Wedge-shaped and transition hoppers are therefore frequently used for materials that have high wall friction.

Minimum outlet dimension

The outlet of the hopper section must be large enough to prevent cohesive arches or stable ratholes from developing. The required outlet size depends on the cohesive strength and the bulk density of the powder. The cohesive strength is measured by shear-cell testing, as described in ASTM D-1628 [*2*] and D-6773 [*3*].

Figure 6 shows schematic diagrams for two common shear-cell testers. A sample of powder is placed in a cell and then pre-sheared — that is, the sample is consolidated by exerting a normal stress, and then sheared until the measured shear stress is steady. (This is shown in Figure 7, by the point (σ_{SS}, τ_{SS})).

Next, the shear step is conducted. During this step, the vertical compacting load is replaced with a smaller load, and the sample is again sheared until it fails. These pre-shear and shear steps are repeated at the same consolidation level for a number of reduced normal stresses, and

NOMENCLATURE

B	Outlet diameter or width, m or ft
B_{min}	Minimum outlet diameter or width to prevent arching, m or ft
D_f	Critical rathole diameter, m or ft
dP/dz	Pressure gradient, Pa/m or lb/ft^3
FF	Flow Function
f_c	Cohesive strength
ff	Flow factor
$G(\phi)$	Function defined by Jenike [*1*]; as shown in Figure 11
g	Acceleration due to gravity, m/s^2 or ft/s^2
$H(\Theta')$	Function defined by Jenike [*1*]; as shown in Figure 11
h	Bed depth, m or ft
k	Janssen coefficient
m	Parameter equal to 0 for slotted outlets, and equal to 1 for round outlets
R_H	Hydraulic radius, m or ft
u_o	Velocity of solids at outlet, m/s or ft/s
δ	Effective angle of internal friction, deg
ϕ	Static angle of internal friction, deg
ϕ'	Wall friction angle, deg
ρ_b	Bulk density, kg/m^3 or lb/ft^3
ρ_{bo}	Bulk density at outlet, kg/m^3 or lb/ft^3
σ_1	Major consolidation stress, Pa or lb/ft^2
σ_{crit}	Critical stress, Pa or lb/ft^2
σ_{SS}	Steady-state normal stress, Pa or lb/ft^2
$\bar{\sigma}$	Stress on the abutment of an arch, Pa or lb/ft^2
Θ'	Hopper angle from vertical, deg
τ_{SS}	Steady-state shear stress, Pa or lb/ft^2

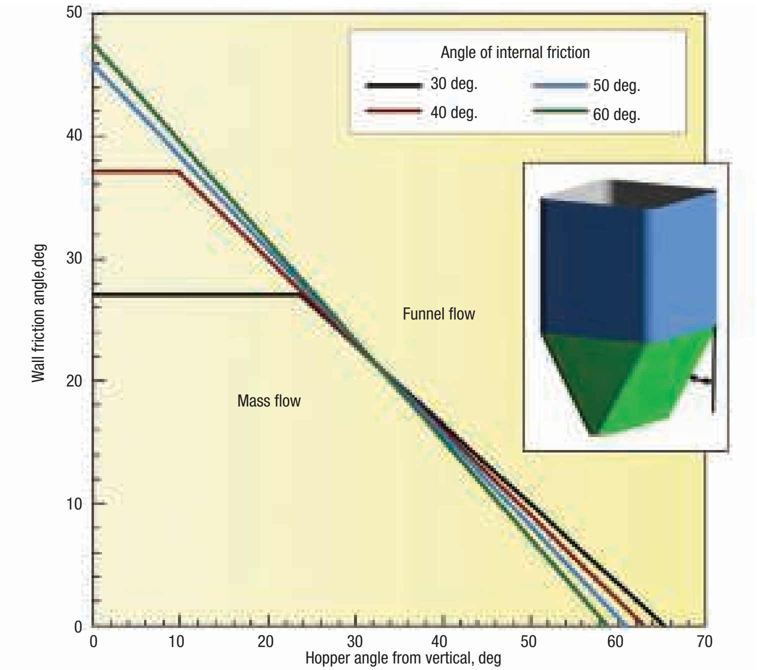

FIGURE 5. This plot shows the recommended wall angles to ensure mass flow in a hopper with flat walls and a slotted outlet

the yield locus is then determined by plotting the failure shear stress against the normal stress (Figure 7).

From the yield locus, the major consolidation stress (σ_1) and the cohesive strength (f_c) are determined. Because bulk solids are anisotropic, the stress on the sample varies with direction. The maximum value of the stress, which is called the major consolidation stress, depends on the material's internal friction and the magnitudes of the normal and shear

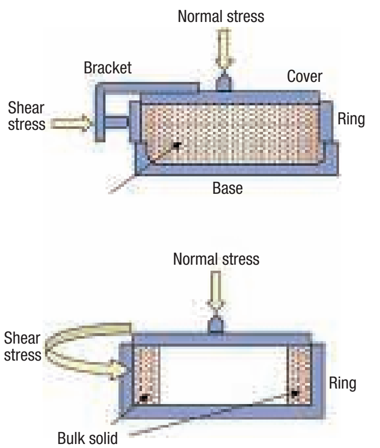

FIGURE 6. Two versions of the shear cell tester — the direct shear cell tester (top) and the ring shear cell tester (bottom) — are used to measure the cohesive strength of bulk solids

stresses imparted on the sample during the test.

Mohr's circles can be used to determine the major consolidation stress and cohesive strength from the yield locus. The major consolidation stress is the value of the intersection of the horizontal axis and a Mohr's circle, drawn through the steady-state point and tangent to the yield locus. The cohesive strength is related to the state of stress where a free boundary exists. Hence, the cohesive strength is the intersection of the horizontal axis and a Mohr's circle that passes through the origin (where stress equals zero) and is tangent to the yield locus. The kinematic angle of internal friction (ϕ) and

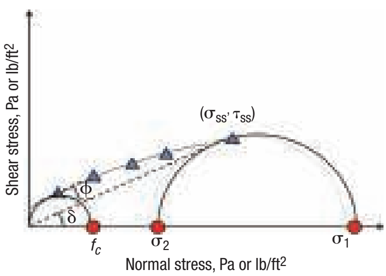

FIGURE 7. A Mohr's circle drawn through the steady-state point and tangent to the yield locus gives the major consolidation stress. A Mohr's circle tangent to the yield locus that passes through the origin gives the cohesive strength

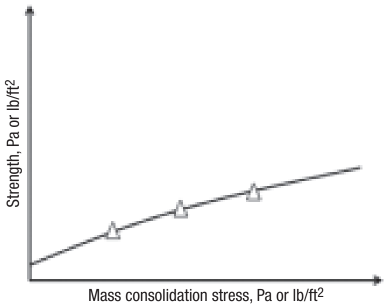

FIGURE 8. The relationship between the major consolidation stress and the cohesive strength is called the Flow Function

effective angle of internal friction (δ) can also be determined, as shown in Figure 7.

By conducting the test over a range of consolidation states, the relationship between consolidation pressure and the cohesive strength of the bulk material can be established, following a procedure established and described by Jenike [*1*]. This relationship is commonly called the material's Flow Function. An example of a powder's Flow Function is given in Figure 8.

Once a material's Flow Function has been determined, the minimum outlet width or diameter that will prevent cohesive arching can be calculated, using the hopper's flow factor (*ff*). Jenike defined the flow factor using Equation (1):

$$ff = \frac{\sigma_1}{\bar{\sigma}_1} \quad (1)$$

The flow factor is a function of the powder's effective angle of internal friction, the hopper angle, and the wall friction angle. Charts that provide flow factors for conical and wedge-shaped hoppers are given in Jenike [*1*]; Examples are shown in Figures 9a and 9b. Typical values of the flow factor range between 1.1 and 1.7.

Superimposing the material's Flow Function and flow factor on the same graph allows the cohesive strength and arch stress to be compared. The flow factor is constructed by drawing a line having a slope equal to 1/*ff* through the origin.

There are three possibilities:

- *The Flow Function lies below the flow factor, and the two curves do not intersect.* When this is the case, the stress imparted on the

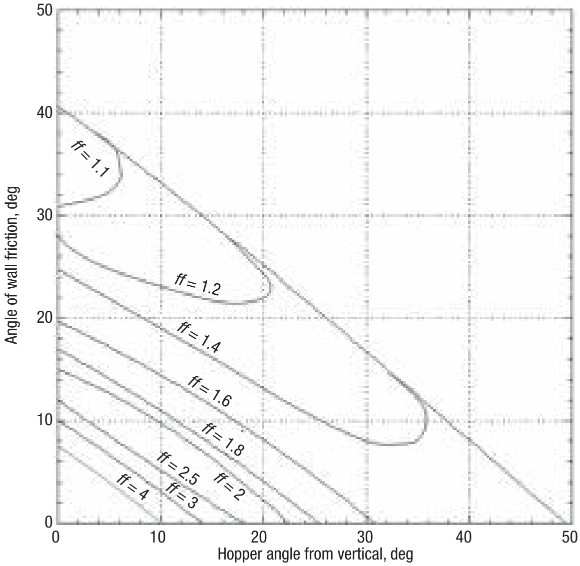

FIGURE 9A. The flow factor (ff) is the ratio of the arch stress to the major consolidation stress and depends on the effective angle of internal friction, the hopper geometry, the hopper angle, and the wall friction angle. The above diagram gives flow factors for conical hoppers, δ = 50 deg

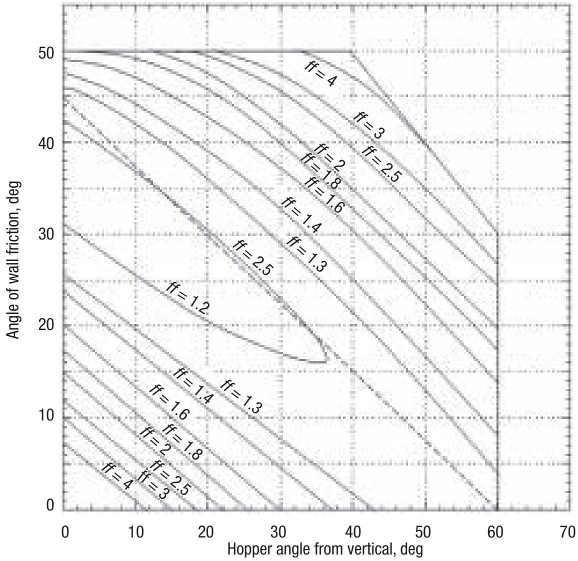

FIGURE 9B. The diagram shown here gives flow factors for hoppers with flat walls and slotted outlets, δ = 50 deg

arch is always greater than the material's cohesive strength, and there is no minimum outlet dimension requirement to prevent cohesive arching

- *The Flow Function lies above the flow factor and the curves do not intersect.* The bulk solid will not flow due to gravity alone, and another means of discharging the powder must be employed
- *The Flow Function and flow factor intersect, as shown in Figure 10.* At the point where the two lines intersect, the arch stress and the cohesive strength of the bulk solid are the same and equal to the critical stress (σ_{crit})

The minimum outlet diameter or width to prevent a cohesive arch from developing, B_{min}, can then be calculated from Equation (2):

$$B_{\min} = \frac{H(\theta')\sigma_{crit}}{\rho_b g} \quad (2)$$

The function $H(\theta')$ is shown in Figure 11. For funnel flow hoppers, the outlet must be large enough to prevent a cohesive arch and stable rathole from developing. To prevent the formation of a stable rathole, the hopper outlet diagonal should equal or exceed the critical rathole diameter, D_F. The critical rathole diameter is calculated by first determining the major consolidating pressure, σ_1, on the powder. In some cases, the consolidating load can be estimated by the Janssen equation (Equation (3)):

$$\sigma_1 = \frac{\rho_b g R_H}{k \tan\phi'}\left[1 - \exp\left(\frac{-k\tan\phi' h}{R_H}\right)\right] \quad (3)$$

The critical rathole dimension is then calculated using Equation (4):

$$D_f = \frac{G(\phi) f_C}{\rho_b g} \quad (4)$$

In Equation (4), f_C is the cohesive strength of the powder at the calculated consolidation pressure.

For wedge-shaped and pyramidal hoppers, stable ratholes will not form if the diagonal of the outlet is equal to D_F or greater. The diameter of the outlet of a conical funnel-flow hopper should not be less than the critical rathole dimension.

If a hopper with a circular outlet is designed with an opening large enough to prevent the development of a stable rathole, cohesive arching will not occur. For wedge-shaped hoppers, the width of the slotted outlet must be large enough to prevent a cohesive arch from developing. The same procedure that is used to determine the minimum outlet width to prevent arching in a wedge-shaped mass--flow hopper is followed, except that a flow factor of 1.7 is used.

Note that these analyses assume continuous handling of the powder. If the powder is to be stored at rest for a period of time, time tests should be conducted. Time tests are described in ASTM D-6128 and D-6773 [*2, 3*].

Feeder considerations

Feeders can also be a source of hopper flow problems if the incorrect devices are used or if they are improperly designed. This is especially true for hoppers with slotted outlets, where feeders should be designed to draw uniformly along the entire cross-section of the outlet in order for mass flow to occur. However, even hoppers with round outlets can have uneven flow if a proper interface is not utilized.

Rotary valves are often used beneath hoppers with round outlets. They are particularly useful for applications where a seal must be provided to prevent air from flowing out of or into the hopper outlet. If a rotary valve is used, a short vertical spool section should be installed between the hopper outlet and valve inlet. Otherwise, material may flow preferentially from the upside of the valve and affect the flow pattern inside the vessel. This is shown in Figure 12.

Screw feeders are primarily used

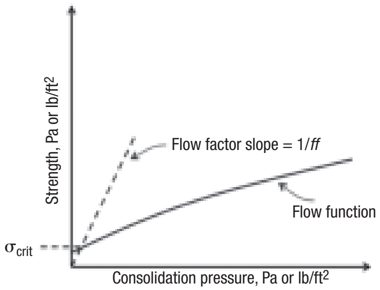

FIGURE 10. The critical stress σ_{crit} is determined from the intersection of the Flow Function and flow factor. At the point where the two lines intersect, the arch stress and the cohesive strength of the bulk solid are the same, and equal to the critical stress

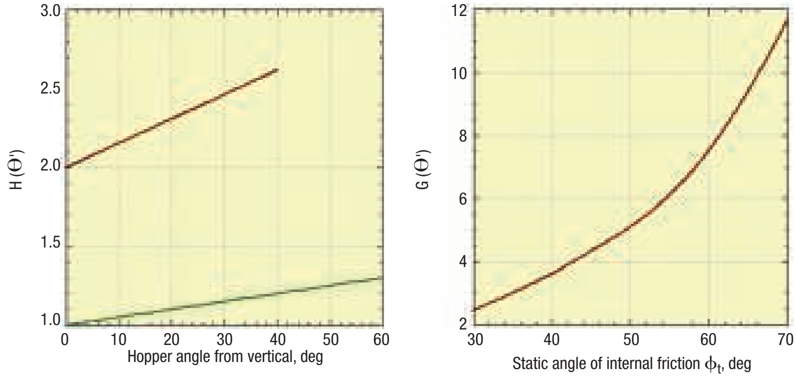

FIGURE 11. Functions $H(\Theta')$ and $G(\phi)$. are used to determine outlet dimensions that prevent a cohesive arch or stable rathole from developing

to control the discharge of powders from hoppers with slotted outlets. A screw is comprised of a series of flights wound around one or more shafts. A screw that has a constant pitch and diameter (and a constant shaft diameter) will give rise to the formation of a flow channel at the back of the hopper over the first flight of the screw. As shown in Figure 13, this channel will draw material from the top surface into the flow channel until a stable rathole forms and the channel empties. The rathole will then periodically fail as the base of the material falls above the screw. This will continue to broaden the flow channel, and this cyclic fail-flow-empty cycle will continue until the hopper empties.

A mass flow screw feeder, comprised of a tapered section followed by a section with increasing pitch, ensures that the capacity of the feeder increases in the direction of flow (see Figure 13). The length of the cone and the pitch schedule are chosen such that the capacity of the screw increases linearly along the hopper length. The length of the screw must be between three and six times the width of the hopper to meet fabrication tolerances, and the screw diameter is equal to the hopper width.

Discharge rate

For coarse powders, the maximum discharge rate from a mass flow hopper can be calculated using Equation (5):

$$u_o = \sqrt{\frac{Bg}{2(1+m)\tan(\theta')}} \qquad (5)$$

The parameter *m* is equal to 0 for slotted outlets, and is equal to 1 for round or square outlets. The mass discharge rate is equal to the product of the velocity, outlet cross-sectional area, and the material's bulk density at the outlet.

The maximum flowrate of a fine powder can be several orders-of-magnitude lower than that of coarser materials, due to an adverse gas-pressure gradient that forms. Because of vacuum that naturally develops above a hopper outlet when the voids in fine powders expand as the material discharges, the resulting counter flow of gas will hinder the solids flow. A limiting condition occurs when the compaction in the cylinder section forces too much gas out through the material's top surface.

At a critical solids-discharge rate, the solids-contact pressure drops to zero, and efforts to exceed this limiting discharge rate will result in erratic flow. Permeability testing is required to determine the outlet size required to achieve a desired discharge rate for fine powders. The limiting discharge rate from a mass-flow hopper for fine powders can be calculated using Equation (6):

$$u_o = \sqrt{\frac{Bg}{2(1+m)\tan(\theta')}\left(1+\frac{1}{\rho_{bo}\,g}\left.\frac{dP}{dz}\right|_{0}\right)} \qquad (6)$$

The magnitude of the pressure gradient depends on the bulk density and the permeability of the powder. Note that because of the vacuum that develops above the hopper outlet, the pressure gradient, *dP/dz,* is negative. See Schulze [*4*] for a discussion of the challenges of accurately predicting the pressure gradient.

Final remarks

Compared to liquids and gases, chemical engineers' training in bulk-solids handling is often lacking. By understanding the fundamental prin-

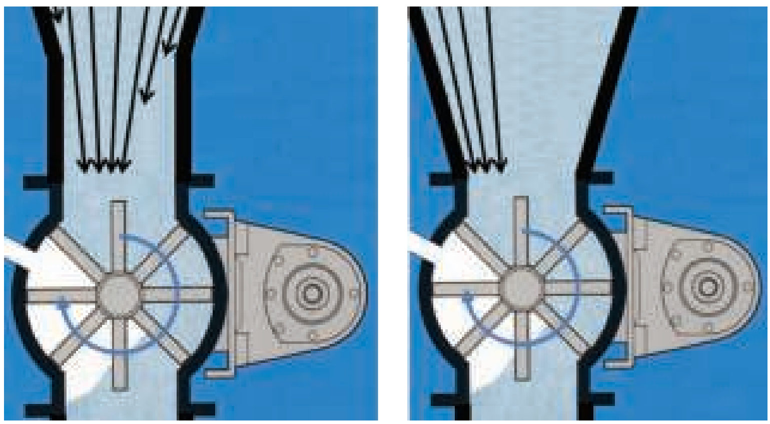

FIGURE 12. A hopper with a rotary valve should have a spool section above the valve inlet (left); otherwise, preferential flow may occur on one side of the hopper (right)

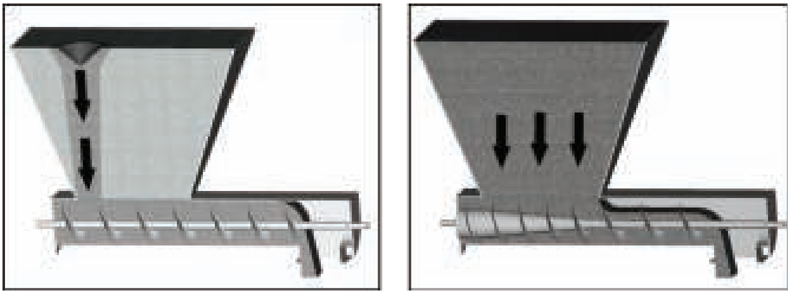

FIGURE 13. A screw feeder with a constant diameter and a constant pitch screw results in funnel flow. A mass-flow screw feeder where the screw has a tapered shaft and increasing pitch sections ensures that all material will flow when discharged

ciples and conducting proper flow properties tests, a chemical engineer can design reliable systems for storing and handling bulk solids. Knowing the relationship between a material's cohesive strength and consolidation stress allows the engineer to calculate hopper-outlet dimensions that will prevent flow obstructions from developing. Similarly, wall-friction test results allow engineers to determine hopper geometries that are required to promote mass flow. Permeability tests are required to calculate limiting mass-flow discharge rates. ■

Edited by Suzanne Shelley

References

1. Jenike, A.W., Storage and Flow of Solids, Bulletin 123, University of Utah Engineering Station, 1964 (revised, 1976).
2. ASTM D-6128, Standard Test Method for Shear Testing of Bulk Solids Using the Jenike Shear Cell, ASTM International, 2006.
3. ASTM D-6773, Standard Shear Test Method for Bulk Solids Using the Schulze Ring Shear Tester, ASTM International, 2008.
4. Schulze, D., "Powders and Bulk Solids – Behavior, Characterization, Storage, and Flow," Springer, New York, 2007.

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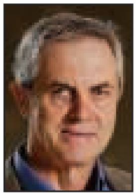

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Economic Indicators

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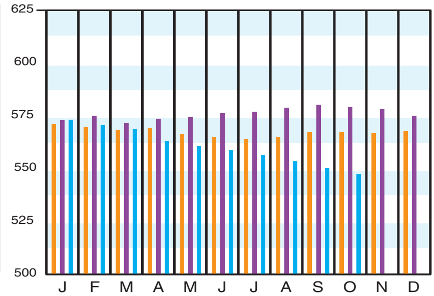
(1957-59 = 100)	Oct. '15 Prelim.	Sept. '15 Final	Oct.'14 Final
CE Index	547.4	550.3	579.7
Equipment	654.9	661.3	704.1
Heat exchangers & tanks	575.4	586.2	652.3
Process machinery	654.3	656.4	666.9
Pipe, valves & fittings	808.6	817.0	876.4
Process instruments	390.2	390.4	411.8
Pumps & compressors	956.4	956.4	941.1
Electrical equipment	508.2	510.3	516.0
Structural supports & misc	723.6	728.0	769.1
Construction labor	326.4	320.4	324.4
Buildings	540.6	539.1	547.1
Engineering & supervision	318.8	318.0	319.8

Starting with the April 2007 Final numbers, several of the data series for labor and compressors have been converted to accommodate series IDs that were discontinued by the U.S. Bureau of Labor Statistics

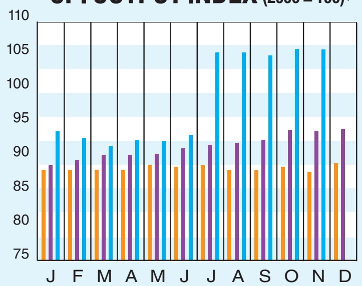
Annual Index:
2007 = 525.4
2008 = 575.4
2009 = 521.9
2010 = 550.8
2011 = 585.7
2012 = 584.6
2013 = 567.3
2014 = 576.1



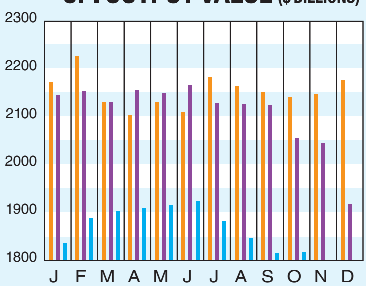
CURRENT BUSINESS INDICATORS

	LATEST		PREVIOUS				YEAR AGO
CPI output index (2012 = 100)	Nov. '15 = 105.9		Oct. '15 = 105.8		Sept. '15 = 105.0		Nov. '14 = 104.6
CPI value of output, $ billions	Oct. '15 = 1,817.7		Sept. '15 = 1,818.9		Aug.'15 = 1,841.6		Oct. '14 = 2,082.3
CPI operating rate, %	Nov. '15 = 76.3		Oct. '15 = 76.3		Sept. '15 = 75.8		Nov. '14 = 76.2
Producer prices, industrial chemicals (1982 = 100)	Nov. '15 = 234.6		Oct. '15 = 237.3		Sept. '15 = 238.1		Nov. '14 = 275.1
Industrial Production in Manufacturing (2012=100)*	Nov. '15 = 106.2		Oct. '15 = 106.2		Sept. '15 = 105.9		Nov. '14 = 105.2
Hourly earnings index, chemical & allied products (1992 = 100)	Nov. '15 = 160.4		Oct. '15 = 159.3		Sept. '15 = 160.9		Nov. '14 = 157.5
Productivity index, chemicals & allied products (1992 = 100)	Nov. '15 = 106.4		Oct. '15 = 105.7		Sept. '15 = 106.9		Nov. '14 = 105.7

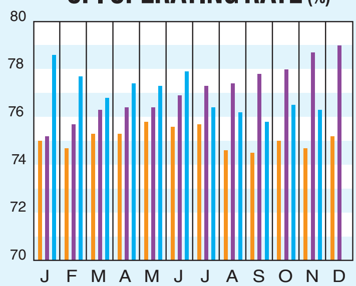
CPI OUTPUT INDEX (2000 = 100)†



CPI OUTPUT VALUE ($ BILLIONS)



CPI OPERATING RATE (%)



*Due to discontinuance, the Index of Industrial Activity has been replaced by the Industrial Production in Manufacturing index from the U.S. Federal Reserve Board.
†For the current month's CPI output index values, the base year was changed from 2000 to 2012
Current business indicators provided by Global Insight, Inc., Lexington, Mass.

CURRENT TRENDS

The preliminary value for the October 2015 *CE* Plant Cost Index (CEPCI; top; the most recent available) continued a string of monthly declines that has been observed in recent months. For October, the drop is driven by a decline in the Equipment subindex. The Buildings, Construction Labor and Engineering and Supervision subindices all increased in October. The preliminary CEPCI value for October is 5.6% lower than the corresponding value from a year ago at the same time. This represents continued growth of the year-to-year differential over the past several months. Meanwhile, the latest Current Business Indicators (CBI; middle) numbers showed a continued climb in the CPI output index and a decrease in producer prices.

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–Speed Kills, Klaver, Ali. 2012 Project Manager Magazine.

40 percent of projects in the oil and gas industry are subject to budget and schedule overruns.

–Capital Project Execution in the Oil and Gas Industry. M. McKenna, H. Wilczynski, D. VanderSchee. 2006 Booz Allen Hamilton survey from 2006 of 20 companies (super-majors, independents and EPC firms).

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–Deloitte. Effective Operational Readiness of Large Mining Capital Projects - Avoiding value leakage in the transition from project execution into operations. Article, 2012.

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–Construction Industry Institute: Adding Value Through Front End Planning. CII Special Publication 268-3.

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–Society of Petroleum Engineers, "The Great Crew Change: A Challenge for Oil Company Profitability", April 16, 2011.

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–2010 SBC Oil & Gas HR Benchmark, Schlumberger Business Consulting Energy Institute, March 2011.

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