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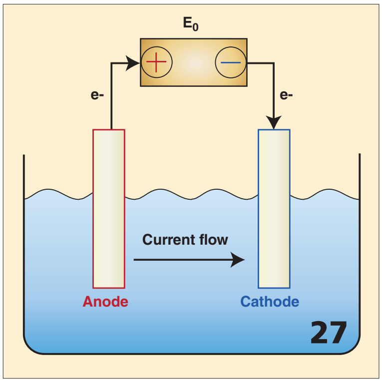

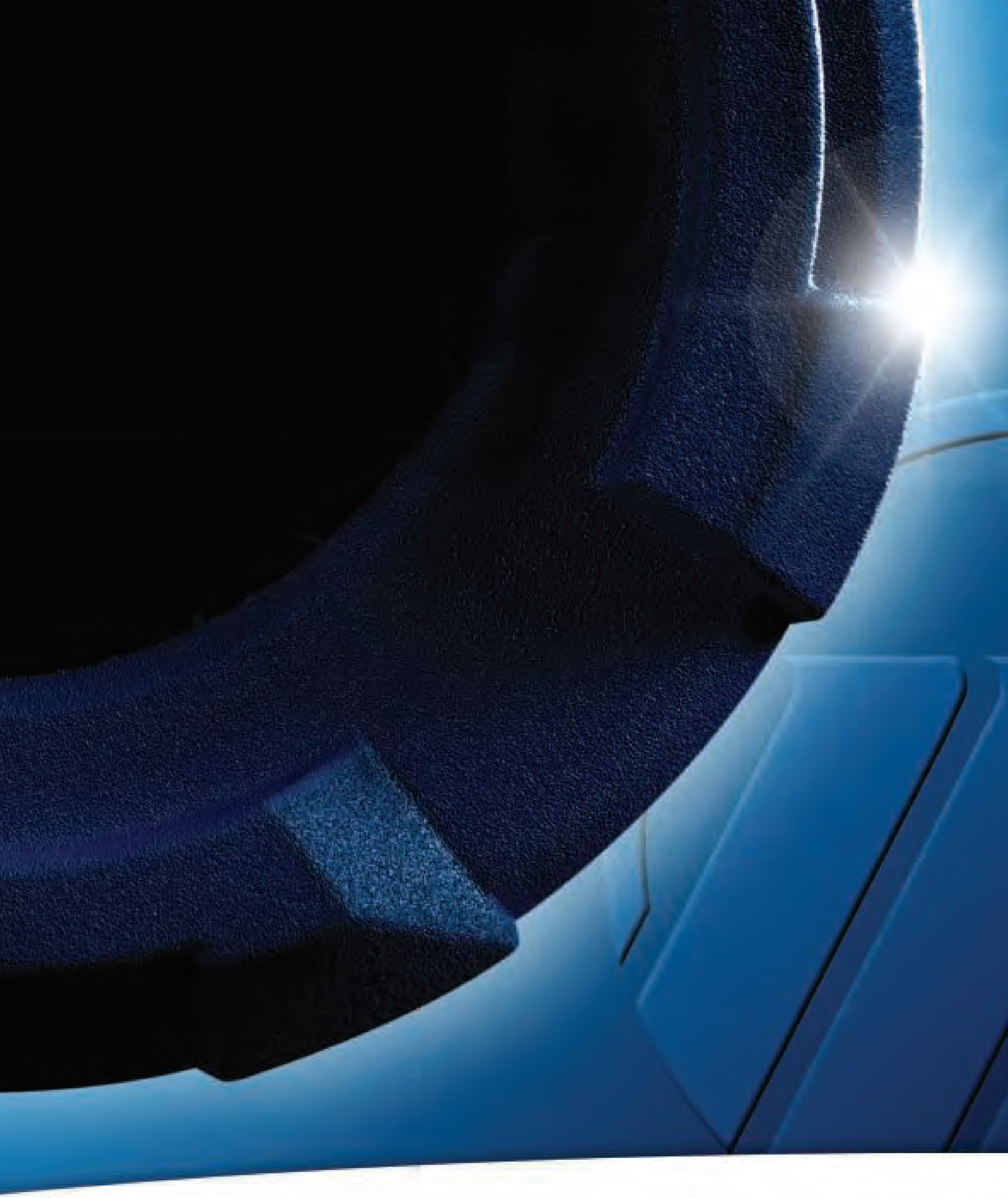

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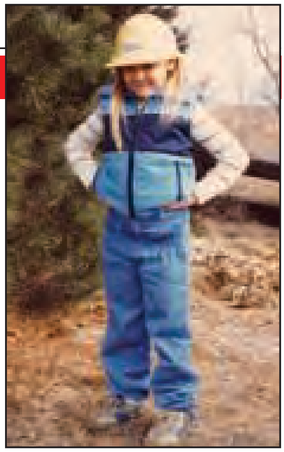
Editor's Page

Changes



Young Rebekkah Marshall with early career goals in mind

It always makes me nervous when people say "change is good." By now I've come to realize that statement is usually made after change has taken place, usually without planning, and we might as well make the best of it. Given an average situation, change is 50–50. Given a positive situation, there's more downside risk to change. The trick to successful change is managing that risk. We've had a few changes with *Chemical Engineering* over the past year and we've tried to manage the risk with research and planning.

In the spring we began running a higher quality, heavier, whiter paper. The change in paper quality makes the print easier to read and there's less ink bleed-through. Frankly speaking, my eyes aren't what they used to be and when it comes to reading, I need all the help I can get. Considering the average age within the industry, I may not be alone.

Early in 2012 we moved to a more consistent layout of our articles and departments. For some time we had sections of the magazine moving around to accommodate production; good for us, bad for the reader, so we made the change. Your time is valuable and by having consistency, we hope it is easier for you to find articles and sections quickly, month after month.

In this issue we have a new, two-page table of contents. Our former one-page version was crammed with information, making it difficult to find specific topics; much like trying to load everything on the home page of a website. We made the change to the two-page version to make it easier to read and to give our editors more room to explain the articles listed. Our intent is to make it easier for you to find the information you are looking for.

These are fairly innocuous changes and, if they do not work, we can change them back. That is not always the case; sometimes a decision is made or a change occurs and it is difficult or impossible to go back. Often that is the case with personnel changes, which leads me to our latest change. It is with mixed emotions that we bid farewell to Rebekkah Marshall, our Editor-in-Chief for the past six years. She has done a terrific job guiding our editorial team and filling the pages of the magazine, our website, our newsletters, and our bookstore with relevant information. She worked closely with the development of our ChemInnovations conference and she managed our Plant Cost Index and economic indicators. And over the total of 12 years with us, she has done much, much more. We will miss her day-to-day interaction, her outgoing and positive personality, and her great spirit. Rebekkah has done a tremendous job carrying on the legacy of past editors and preparing the path for our team and new editors to come, thus addressing the risk of our biggest change.

Fortunately, we will not lose Rebekkah completely. While she is starting a new chapter of her life on a family business with her husband, we have asked her to assist with our Editorial Advisory Board, the ChemInnovations Advisory Board, the Kirkpatrick award and the *Chemical Engineering* awards program. She may contribute editorially as she has time.

As of this publication, the *Chemical Engineering* editorial team, contributing editors, and support staff are filling the gaps as we search for a new editor to join the group. We wish Rebekkah great success with her new business and we look forward to working with her, at least periodically, for a long time to come.

Change is not always good but if you make plans, manage the risk, prepare contingencies, and keep an open mind, it can be. We hope you are pleased with *Chemical Engineering* and, as always, we welcome your input on how we can improve. ■

Brian Nessen, Publisher

Letters

Farewell to CE readers

Last month, after almost 12 years with *Chemical Engineering*, I resigned as this magazine's Editor in Chief. I have been given an opportunity to work in my husband's architectural design business, and the benefit of spending more time with my young children is simply too good to pass up.

For almost six years, I have had the honor of serving as this magazine's Editor in Chief, and I hope to be involved with it in an advisory capacity moving forward. Starting with this issue, however, the editorial leadership is now being handled by Dorothy Lozowski, in whom I have great confidence. She can be reached at dlozowski@che.com.

Professionally, I have essentially "grown up" here at *Chemical Engineering*. I started as an Assistant Editor in January of 2001. I later became an Associate Editor in 2003, Managing Editor in 2005 and Editor in Chief in 2007, following the passing of my friend and mentor, Nick Chopey. So, in a lot of ways, it feels like I am leaving home. It has been an honor and a privilege to serve with the *Chemical Engineering* team of editorial, production, circulation, marketing and sales staff — past and present — and observe the deep sense of ownership, responsibility and more than 110 years of tradition that they uphold. Meanwhile, I have thoroughly enjoyed the interactions I have had with readers, authors and technology providers. Working as an editor for this magazine has put me in a unique position to observe the very wide range of benefits that chemical engineers continue to bring to our society. That awareness will always be with me.

Sincerely,

Rebekkah Marshall
Editor in Chief (2007–2012)

Consider plastics for acid handing

I read with interest the "Acids Handling" cover story in the October issue of *Chemical Engineering*. I was a little surprised at the emphasis placed on metals as the solution for cladding and lining and also as the primary solution for specific equipment. Our company Micromold Products, Inc. makes a solid PTFE piping system, that is widely used for the handling of concentrated versions of each of the five acids discussed. We also make a number of other PTFE, PVDF and other plastic fluid handling components such as valves, strainers, solid and PTFE-lined dip pipes, spargers, thermowells and numerous other specialty items for difficult to handle acids. And we are not the only suppliers of such items. I think an article that discusses the application of plastics to handle such acids would be of interest to your readers.

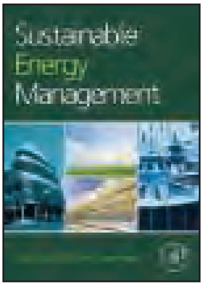
I enjoy reading your magazine. Keep up the good work.

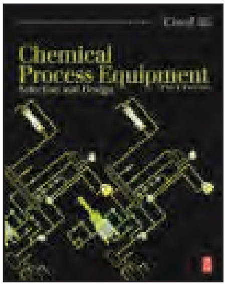
Justin Lukach, President
Micromold Products Inc., Yonkers, NY

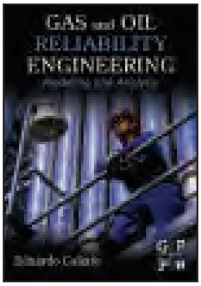
Postscripts, corrections*

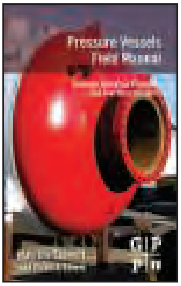
October, A Steamy Situation, pp. 20–22: The Website for Spirax Sarco was incorrect. Our apologies. The correct address is www.spiraxsarco.com. ■

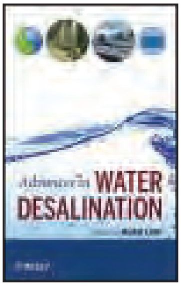
* The online version of these article have been amended and can be found at http://www.che.com/archives/extras/ps_and_corrections/











Sustainable Energy Management. By Mirjana Golusin, Stevan Popov and Sinasa Dodic. Elsevier Inc., 225 Wyman Street, Waltham, MA. 02451. Web: elsevier.com. 2013. 436 pages. $79.95.

Chemical Process Equipment: Selection and Design, 3rd ed. By James Couper, W. Roy Penney and James Fair. Elsevier Inc., 225 Wyman Street, Waltham, MA. 02451. Web: elsevier.com. 2012. 864 pages. $150.00.

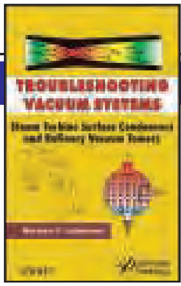
Gas and Oil Reliability Engineering: Modeling and Analysis. By Eduardo Calixto. Elsevier Inc., 225 Wyman Street, Waltham, MA. 02451. Web: elsevier.com. 2012. 544 pages. $99.95.

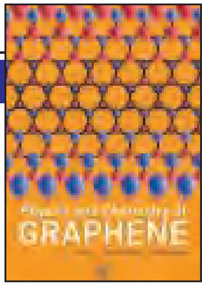
Pressure Vessels Field Manual: Common Operating Problems and Practical Solutions. By Maurice Stewart and Oran Lewis. Elsevier Inc., 225 Wyman Street, Waltham, MA. 02451. Web: elsevier.com. 2012. 498 pages. $79.95

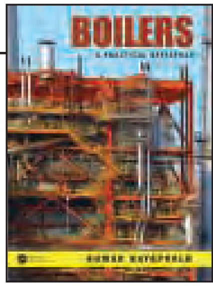
Testing Adhesive Joints. Edited by Lucas da Silva, David Dillard, Bamber Blackman and Robert Adams. John Wiley & Sons Inc., 111 River St., Hoboken, NJ 07030. Web: wiley.com. 2012. 468 pages. $140.00.

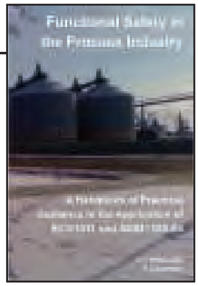
Advances in Water Desalination. Edited by Noam Lior. John Wiley & Sons Inc., 111 River St., Hoboken, NJ 07030. Web: wiley.com. 2012. 712 pages. $175.00.

Bookshelf









Troubleshooting Vacuum Systems: Steam Turbine Surface Condensers and Refinery Vacuum Towers. By Norman Lieberman. John Wiley & Sons Inc., 111 River St., Hoboken, NJ 07030. Web: wiley.com. 2012. 280 pages. $175.00.

Physics and Chemistry of Graphene: Graphene to Nanographene. Edited by Toshiaki Enoki. Pan Stanford Publishing, 8 Temasek Blvd., Tower three, Singapore, 038988. Web: panstanford.com. 2012. 476 pages. $149.95.

Boilers: A Practical Reference (Industrial Combustion). By Kumar Rayaprolu. CRC Press, Taylor and Francis Publishing Group, 6000 Broken Arrow Parkway, NW, Suite 300, Boca Raton, FL 33487. Web: crcpress.com. 2012. 649 pages. $249.95.

Fault-Tolerant Process Control: Methods and Applications. By Prashant Mhaskar, Jinfeng Liu and Panagiotis Christofides. Springer Publishing Co., 11 West 42nd Street, 15th floor, New York, NY 10036. Web: springerpub.com. 2013. 284 pages. $129.00.

Cleaner Combustion and Sustainable World. Edited by Haihing Qi and Bo Zhao. Springer Publishing Co., 11 West 42nd Street, 15th floor, New York, NY 10036. Web: springerpub.com. 2013. 1412 pages. $399.00.

Understanding Distillation Using Column Profile Maps. By Daniel Beneke, Mark Peters, David Glasser, Diane Hildebrandt. John Wiley & Sons Inc., 111 River St., Hoboken, NJ 07030. Web: wiley.com. 2012. 384 pages. $149.95.

Propylene Production via Propane Dehydrogenation. By Intratec Inc., Intratec, 5847 San Felipe Street, Suite 1752, Houston, TX 77057. Web. Intratec.us. 2012. 80 pages. $829.00.

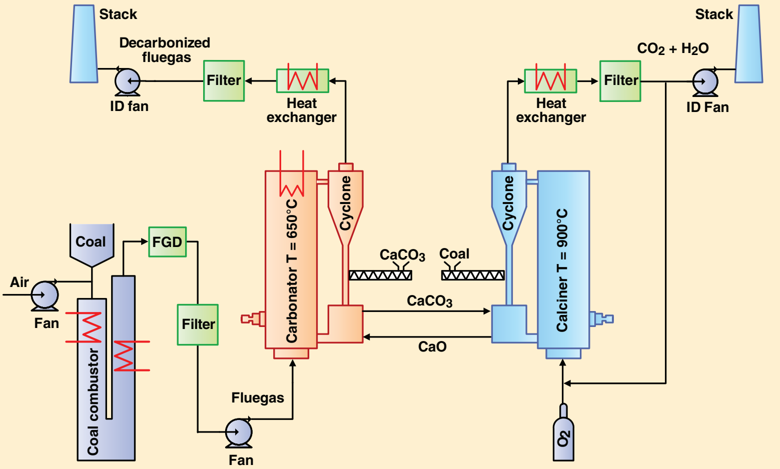
Functional Safety in the Process Industry: A Handbook of Practical Guidance in the Application of IEC61511 and ANSI/ISA-84. By K.J. Kirkcaldy and D. Chauhan. Self-published on lulu.com. 214 pages. $25.00. ■

Scott Jenkins

CHEMENTATOR

Edited by Gerald Ondrey January 2013

Scaleup planned for a new CO_2-capture process



Plans are underway to field-test a process that removes more than 90% of the carbon dioxide from power-plant fluegas, while reducing both the energy input and operating costs by 50% compared to conventional amine-based CO_2-scrubbing technology. The so-called carbonate-looping process has undergone four years of testing in a 1-MW_{th} pilot plant at the Technical University (TU) of Darmstadt (Germany; www.tu-darmstadt.de). Now, with support from the German Federal Economics Ministry and industrial partners, a new project has started to scale up the process 20-fold, and to demonstrate the technology in an existing (yet-to-be determined) coal-fired power plant in Germany.

In the carbonate-looping process (flow sheet), filtered fluegas enters a carbonator reactor — a fluidized-bed reactor — in which lime (CaO) reacts with the CO_2 from fluegas at 650°C to form calcium carbonate. The $CaCO_3$ is separated in a cyclone from the decarbonized fluegas, then calcined at 900°C in a second fluidized-bed reactor, the calciner, to release the CO_2 and regenerate CaO for reinjection into the carbonator. The captured CO_2 is then cooled (with heat recovery) and filtered to produce a pure CO_2 stream that can be utilized or stored.

Since less energy is required for CO_2 separation from the fluegas in comparison to alternative CO_2 post-combustion scrubbing technologies, the carbonate looping process is less expensive to operate. Furthermore, compared to amine-based adsorbents, which are corrosive and also undergo thermal degradation, a natural and cheap sorbent, limestone, can be used, says professor Bernd Epple, director of TU Darmstadt's Institute for Energy Systems and Technology. Also, because the looping process operates at higher temperatures, the heat of the fluegas from carbonator and calciner can be used to produce high-temperature steam for electricity generation. The carbonate-looping process can easily be retrofitted onto existing coal- and gas-fired power plants, says Epple.

Improved bioleaching for nickel recovery

An Indian team from the Institute of Minerals & Materials Technology (www.immt.res.in), and Utkal University (both Bhubaneswar, Orissa, India; www.utkal-university.org) has achieved significant improvement in the recovery of nickel from lateritic ore by using oxalic acid produced by the fungus *Aspergillus niger* supplemented with manganese.

Prior to leaching, thermal pre-treatment (at 600°C for 5 h) changes the mineral structure and brings the mineral phase transformation by dehydroxylation of the goethite matrix in raw chromite overburden. Pretreatment develops micropores and cracks and converts the overburden into a mesoporous structure, which in turn is more susceptible to leaching agents.

Oxalic acid acts as a metal chelating agent. It can be obtained synthetically, but the most convenient way is via metabolites secreted by several fungi under specific conditions. Fungal micelle grows on the surface of ore particles. Thus, in the case of a fungal bioleaching system, the concentration of oxalic acid at the interface of ore and fungal micelle is much higher than the total concentration of oxalic acid in the bulk medium, thus making it more efficient than chemical leaching.

Nickel recovery from pre-treated chromite overburden was a maximum of up to 38.6% by adding 80 ppm of manganese to the culture media, while 24.0 % of nickel was recovered without adding manganese.

The chromite overburden samples were

(*Continues on p. 15*)

Soy polyurethanes

Scientists at Battelle (Columbus, Ohio; www.battelle.org) have developed a water-based polyurethane (PU) that uses soy oil instead of petroleum to produce the polyol precursor. Whereas standard water-based PUs require adding N-methyl-2-pyrrolidone (NMP) to lower viscosity, Battelle's process eliminates the need for NMP, thereby reducing costs, handling, reporting regulations, vapors and pollution, says Battelle. The new PU has less odor than petroleum-based PUs and can be used in applications such as paints, inks, top coatings, seal coatings, as well as adhesives for the "peel-and-go" market.
Battelle has filed a patent, and will seek licensing partners to scale up the product to mass manufacturing.

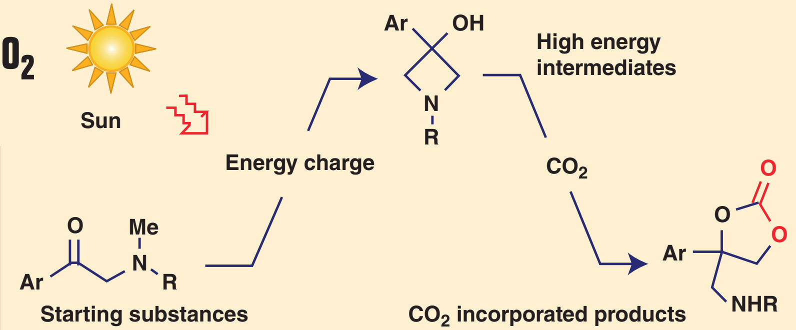
New MOFs

Researchers from the KIT Institute of Functional Interfaces (IFG; Karlsruhe, Germany; www.kit.edu), with collaboration from other institutions in Bremen, Mainz, Bielefeld and Thuwal (Saudi Arabia), have developed a new method to produce metal-organic frameworks (MOFs) with pore sizes

(*Continues on p. 12*)

Note: For more information, circle the 3-digit number on p. 60, or use the website designation.

Using sunlight to incorporate CO_2 into alpha-amino ketones



The research group of Masahiro Murakami at Kyoto University (Kyoto, Japan; www.sbchem.kyoto-u.ac.jp/murakami-lab) has synthesized a promising pharmaceutical precursor using only sunlight (as energy source) and CO_2 (as co-reagent). The solar-driven process involves two consecutive reactions (diagram): first, light transforms an α-methylamino ketone into an energized, cyclic intermediate through intramolecular rearrangement; then, CO_2 is incorporated into a highly strained (thus highly reactive) ring to form a cyclic amino-substituted carbonic acid diester, which could be a useful precursor for chemical syntheses.

The second step, which occurs in the dark, can be carried out in the same glass reaction vessel by simple addition of a base (cesium carbonate), and heating to 60°C. An 83% yield is achieved after 7-h sunlight irradiation and 10 h for CO_2 capture. Murakami says the technique is very simple to perform and that even diffuse sunlight on cloudy days is enough to drive the process. Also, the process is very adaptable because a wide variety of α-methylamino ketones could be used as starting materials, he says.

Although the Murakami consecutive process does not involve CO_2 reduction into carbohydrates, its mechanistic energy profile (diagram) resembles that of photosynthesis, and presents a simple model of the chemical utilization of solar energy for CO_2 incorporation. The group is now investigating the reaction using easily available starting materials.

Nanoscale particles help produce steam . . .

A research group at Rice University (Houston; www.rice.edu) has developed a method for vaporizing water into steam using sunlight-illuminated nanoparticles, with only a small fraction of the energy heating the fluid. Sub-wavelength metal or carbon particles are intense absorbers of optical radiation. When dispersed in a liquid, the light-absorbing nanoparticles can quickly reach temperatures well above water's boiling point, where the liquid becomes steam, and the particles remain in the liquid phase. A thermodynamic analysis conducted by the Rice team showed that 80% of the absorbed sunlight energy converted liquid to vapor, while 20% of absorbed light energy went toward heating the liquid surrounding the nanoparticles, say the researchers. The group applied the technique to ethanol-water distillation, and found that the distillate contained a higher percentage of ethanol than what would be predicted by the water-ethanol azeotrope. The research could advance compact solar-energy applications in distillation, desalination and sanitation, especially in resource-poor areas.

. . . and generate hydrogen

Meanwhile, another research team is using clusters of gold atoms at sub-nanometer sizes to enhance the photocatalytic production of hydrogen from water. Sustainable H_2 production from a non-fossil-fuel source could have significant environmental and energy-efficiency benefits. The scientists, from Stony Brook University (Stony Brook, N.Y.; www.stonybrook.edu) and Brookhaven National Laboratory (Upton, N.Y.; www.bnl.gov) modified the surface of a semiconductor catalyst — cadmium sulfide — with sub-nm gold particles, and found that the activity of the CdS for evolving H_2 gas photocatalytically under visible light increased by up to 35 times over that of the CdS alone. It appears that the activity enhancement of the photocatalyst is related to the sub-nanometer dimensions of the gold particles, say the researchers, because larger gold particles had much lower activity. The research team believes that surface modification with gold to increase H_2 production can be extended to other semiconductor photocatalysts.

(Continued from p. 11)

never reached before. MOFs are highly ordered molecular systems with metal atoms at nodes and organic components as rods. The pores in these frameworks are freely accessible. MOF powders are used to store smaller molecules, such as H_2, CO_2 or CH_4. For more complex applications, such as the storage and release of antibiotics, MOF coatings are required.

At IFG, the team uses a technique known as liquid-phase epitaxy to make a new class of MOFs called surface-mounted MOFs (SURMOFs 2). The process allows the size and shape of the pores, and their chemical functionality to be adjusted to the desired application. The pore sizes of these SURMOFs 2 are 3 nm × 3 nm, which is large enough for small proteins. Now the researchers are working to increase the length of the organic rods to be able to store larger proteins, and possiblly metallic nanoparticles for applications in optics and photonics.

HART + Foundation

Specifications for transfer blocks for HART and *Wireless*HART devices have been added to the latest Foundation fieldbus (FF) technical specifications, says the HART Communication Foundation (Austin, Tex.; www.hartcomm.org). This addition enables full integration of HART and *Wireless*HART device information, including device diagnostics, into a Foundation for ROM (re-

(Continues on p. 14)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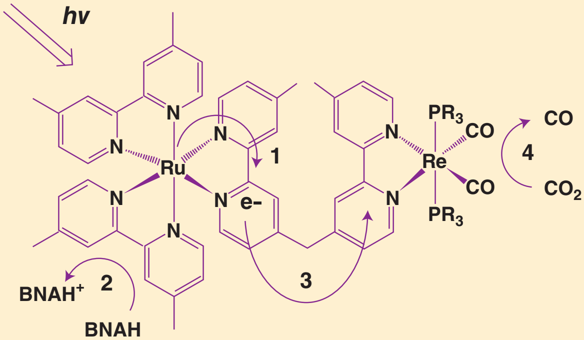
A step toward artificial photosynthesis

A photocatalyst that reduces CO_2 into carbon monoxide is being commercialized by Tokyo Chemical Industry Co. (Tokyo, Japan; www.tcichemicals.com/en/jp/index.html). Developed by Osamu Ishitani and his research group at Tokyo Institute of Technology (TiTech; Japan; www.chemistry.titech.ac.jp/~ishitani/index-jp.htm), the catalyst is a step towards artificial photosynthesis whereby CO_2 can be converted into useful chemicals using sunlight.



Ishitani's group combined a rhenium (I) biscarbonyl complex (which efficiently reduces CO_2, but has a low absorption coefficent for visible light) with a ruthenium (II) complex as photo sensitizer (a strong absorbance for visible light) to form a supramolecule dubbed Ru(II)-Re(I). This dual complex system shows a very high efficiency for reducing CO_2 into CO under irradiation with visible light. The catalyst was improved by optimizing the ligands on the Re site. Ru-Re(FPh), with two tri(*p*-fluorophenyl)phosphine ($P(p\text{-}FPh)_3$) ligands, was found to be a good photocatalyst with high selectivity for CO (quantum yield of 0.15), high efficiency (turnover frequency of TF_{CO} = 207 h^{-1}) while maintaining a high stability. The researchers also showed that even under irradiation with high-intensity light, the photocatalytic performance was maintained with a relatively high quantum yield and the highest-ever reported turnover frequency (TF_{CO} = 281 h^{-1}).

Ishitani's group also clarified the balance of transferred electrons in this photocatalytic reaction and found that the two electrons necessary for CO formation were provided by two sequential reductive-quenching processes of the excited Ru photo-sensitizer unit by the reductant 1-benzyl-1,4-dihydronicotinamide (BNAH; diagram).

A starch-based cationic polymer for oil recovery

Cationic polymers have been used in the petroleum industry as shale-control agents, demulsifiers, blocking agents, and filtrate reducers for drilling fluids, but process complexity and high cost have limited their application. Now researchers from Zhejiang Normal University (Jinhua; www.zjnu.edu.cn) and Shandong University (Jinhua, both China; www.sdu.edu.cn) have reported the preparation of a water-soluble cationic starch that significantly enhances oil recovery when injected after conventional water flooding.

The commonly used partially hydrolyzed polyacrylamide (HPAM) is not suitable for high-salinity reservoirs in the enhanced-oil-recovery technique. The researchers therefore prepared water-soluble quaternary ammonium cationic starch — which has a better salt tolerance — through the reaction of maize starch with 2-chloroethyltrimethyl ammonium chloride under mechanical stirring at 80°C in the presence of catalyst NaOH. HPAM (3530S, SNF) was used for comparison without further purification. Both the modified starch solution and HPAM solution were prepared using reservoir formation water (total salinity degree = 5,727 mg/L) as solvent.

Model oil used in laboratory simulations was made from degassed oil of Gudao oilfield and engine oil. Its viscosity at 70°C was 72 mPa-s. The researchers found that the starch has a better salt tolerance than HPAM.

Studies of the starch's adsorption characteristics showed that the starch's adsorption rate on oil sand surfaces and oil-water interfaces is relatively fast, and the adsorption capacity is pH-dependent. The researchers believe that the adsorption of the modified starch on oil sand plays an active role in the enhanced oil recovery of this cationic starch flooding. Furthermore, the researchers found that the cationic starch possesses better dynamic-adsorption capacity than HPAM.

(*Continued from p. 12*)

mote operations management) system. This revision to the Foundation fieldbus specification is significant because now suppliers can creat FF transducer blocks that enable HART and *Wireless*HART device measurement and diagnostics information to be integrated into the FF infrastructure.

Bio-based packaging

Researchers at the VTT Technical Research Center of Finland (www.vtt.fi) have developed a process to produce the PGA (polyglycolic acid polymer) monomer, glycolic acid, from bio-based materials more efficiently than before. Bio-based PGA plastic is said to have excellent barrier properties. Bio-based PGA plastic is 20–30% stronger than poly lactic acid — the most popular biodegradeable plastic on the market — and is able to withstand temperatures 20°C higher. PGA also breaks down more quickly than PLA, but its biodegrability can be regulated if necessary, says VTT.

Lignin-based plastic

Researchers from Oak Ridge National Laboratory (ORNL; Oak Ridge, Tenn.; www.ornl.gov) have developed a process to transform lignin byproduct into a thermoplastic — a polymer that becomes pliable above a specific temperature. Larger lignin molecules are reconstructed through either a chemical reaction with formaldehyde, or by washing with methanol. The resulting crosslinked rubber-like material can be processed like plastic. Potential applications of the new thermoplastic include lower-cost gaskets, window channels, irrigation hoses, dashboards and car seat foam, says ORNL.

OPVs on steel

ThyssenKrupp Steel Europe AG (Duisburg, Germany; www.thyssenkrupp-steel-europe.com) has joined the Solliance research program — a partnership of R&D organizations in the ELAT region (Eindhoven-Leuven-Aachen) — on organic pho-

(*Continues on p. 16*)

Membrane reactor may reduce wastage of natural gas . . .

A small-scale ceramic membrane reactor to convert natural gas to transportable liquids in a single step is being developed by Ceramatec, Inc. (Salt Lake City, Utah; www.ceramatec.com) under a $1.7-million grant from the U.S. Dept. of Energy's (DOE) Advanced Research Project Agency (ARPA, Washington, D.C.; www.doe.gov). The goal is to monetize the natural gas associated with oil production at remote locations. This gas — about 5-quadrillion Btu/yr worldwide — is currently flared or pumped back into the ground, says Elango Elangovan, project manager.

The company will develop a catalyst-membrane reactor to demonstrate the technical and economic feasibility of the process. Natural gas will be fed into the reactor and will be converted to a higher-hydrocarbon liquid by a catalyst that is coated on one side of the membrane. Co-produced hydrogen will permeate the membrane and will be recovered. The liquid could be transported and used for the production of chemicals and fuels, says Elangovan. He declines to give details on the catalyst, except to say that it is a proprietary metal catalyst.

Ceramatec's main focus is on improving the conversion efficiency, which so far has been low in laboratory tests, he says. The company is scheduled to deliver a small-scale reactor to ARPA within two years.

. . . and this reactor will produce methanol directly from methane

Under another ARPA contract (see previous item), the Gas Technology Institute (GTI, Des Plaines, Ill.; www.gastechnology.org) is developing a process to convert natural gas directly into methanol and hydrogen. The process is much simpler and more efficient than the conventional high-temperature and capital-intensive steam-reforming process, says Chinbay Fan, GTI's R&D director.

The reaction is carried out at room temperature and pressure, using inorganic metal-oxide cation intermediates as oxidation catalysts. Fan notes that the process is electrochemically charged to ensure continuous regeneration of the catalyst and to achieve high conversion efficiency and selectivity.

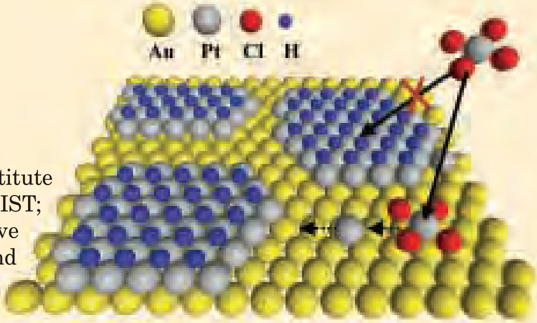
In preliminary laboratory tests, the process has achieved conversion of only a little more than 50%. However, Fan expects this will be improved to more than 90% before GTI delivers a 1-gal/day reactor to DOE in six months' time.

Bioleaching for nickel recovery

(*Continued from p. 11*)

collected from Sukinda Mines in the state of Orissa. The recovery of nickel in the goethite matrix of the chromite overburden needs to be achieved with minimal energy consumption and by an eco-friendly method. Hence, microbe-assisted bioleaching processes have emerged as alternatives to hydrometallurgical processes.

A low-cost route to ultrathin Pt films



Gokcen/NIST

Researchers at the U.S. National Institute of Standards and Technology (NIST; Gaithersburg, Md.; www.nist.gov) have developed a relatively simple, fast and effective method of depositing uniform, ultrathin layers of platinum atoms onto a surface. The technique may lead to a reduction in the amount of precious metal needed for catalyst applications, such as catalytic converters in automobiles and hydrogen fuel cells.

Electroplating of Pt on gold was used as the model study. Normally, electro-deposition leads to a patchy and rough surface because the Pt atoms tend to first attach to any defects on the Au surface, and then the Pt deposit builds up on the Pt layer.

The NIST team found that when the voltage — the driving force of the reaction — is increased to much higher levels than required, water molecules start to break down and form hydrogen ions. The hydrogen quickly forms a layer covering the freshly deposited Pt, thereby preventing further deposition of Pt.

Furthermore, the team discovered that by pulsing the applied voltage, it is possible to selectively remove the hydrogen layer. This enables the electroplating process to be repeated to form multiple layers.

The electroplating process occurs in a single plating bath and is said to be 1,000 times faster than making comparable films using, for instance, molecular beam epitaxy.

The results of the study were reported in the December 7 issue of *Science*. Now the researchers are looking to see if the technique also works with a number of other metal and alloy combinations. ■

(*Continued from p. 14*)

tovoltaics (OPVs). OPVs are flexible solar cells made of light-active plastics and can be manufactured by cost-effective processes suitable for large-scale production. Although less efficient than conventional Si-based PVs, they offer the potential to be made at low cost and offer advantages when used on large surfaces, such as roofs and facades of buildings. New processes will be investigated to incorporate OPVs into flat steel products.

Tailored iron oxide

Lanxess AG (Leverkusen, Germany; www.lanxess.com) has added a new specialty iron oxide for the production of cathodes for lithium-ion batteries. The engineered iron oxide — tradenamed Bayoxide E B 90 — has good morphological properties and high reactivity, making it suitable for use in the E-mobility field, says the company. ❏

Newsfront

KIRKPATRICK CHEMICAL ENGINEERING ACHIEVEMENT AWARD

Nominations for the 2013 round are now open

Many of you know of a company — perhaps your own employer — that has recently commercialized an innovative process, product, or other chemical-engineering development. If so, we would like to hear from you. Nominations are open for this magazine's 2013 Kirkpatrick Chemical Engineering Achievement Award. We aim to honor the most-noteworthy chemical engineering technology commercialized anywhere in the world during 2011 or 2012.

Chemical Engineering has awarded this biennial prize continuously since 1933. The 2013 winner will join a long and distinguished roster, studded with such milestones as Lucite International for its Alpha process for making methyl methacrylate (2009); Cargill Dow LLC: For its production of thermoplastic resin from corn (2003); Union Carbide low-pressure low-density polyethylene (1979); M.W. Kellogg single-train ammonia plants (1967); the U.S. synthetic rubber industry (1943) and Carbide & Carbon Chemical's petrochemical syntheses (1933). The most-recent achievements appear in the table.

THE MOST-RECENT WINNERS

2011 — ***Veolcys Inc. and Oxford Catalyst Group.*** For their small scale, modular synthetic fuel technology

2009 — ***Lucite International UK Ltd.*** For its Alpha process for making methyl methacrylate (MMA)

2007 — ***Axens.*** For its Esterfip-H process for making biodiesel fuel

2005 — ***Chevron Phillips Chemical***. For advances in alpha-olefins technology

2003— ***Cargill Dow LLC***. For producing a thermoplastic resin based on corn as the starting material

2001— ***BOC Group, Inc***. For low-temperature NOx absorption out of fluegases

1999 — ***CK Witco Inc***. For a streamlined organofunctional alkoxysilanes process

1997— ***Membrane Technology & Research, Inc***. For a system to recover monomer from polyolefin purge streams

For a full list of winners, see www.che.com/kirkpatrick.

How to nominate

Nominations may be submitted by any person or company, worldwide. The procedure consists simply of sending, by March 15, an unillustrated nominating brief of up to 500 words to:

Gerald Ondrey, Secretary
Kirkpatrick Award Committee
c/o Chemical Engineering
11000 Richmond Ave, Suite 500
Houston, TX 77042
Email: awards@che.com

The nomination should summarize the achievement and point out its novelty, as well as the difficulty of the chemical-engineering problems solved. It must specify how, where and when the development first became commercial in 2011 or 2012.

If you know of an achievement but do not have information to write a brief, contact the firm involved, either to get the information or to propose that the company itself submit a nomination. Firms are also welcome to nominate achievements of their own.

The path to the winner

After March 15, the Secretary will review the nominations to make sure they are valid — for instance, that the first commercialization did in fact take place during 2011–2012. Then he will submit copies to more than 100 senior professors who head accredited university chemical engineering departments and, accordingly, constitute the Committee of Award. Working independently of each other, each professor will vote for what he or she considers to be the five best achievements, without trying to rank them.

The five entries that collectively receive the most votes become the finalists in the competition. Each finalist company will then be asked to submit more-detailed information — for instance, a fuller description of the technology, performance data, exhibits of press coverage, and/or a description of the teamwork that generated the achievement.

The Secretary will send copies of these more-detailed packages to a Board of Judges, which, meanwhile, will have been chosen from within, and by, the Committee of Award. In late summer, the Board will inform the Secretary as to which one of the five finalist achievements it has judged the most noteworthy. The company that developed that achievement will be named the winner of the 2013 Kirkpatrick Chemical Engineering Achievement Award. The four other finalist companies will be designated to receive Honor Awards. Sculptures saluting the five achievements will be bestowed with appropriate ceremony at ChemInnovations, which takes place in Galveston, Tex. this September (www.cpievent.com). ■

Rebekkah Marshall

WANTED: REPEATABILITY AND CONSISTENCY

Using powder-flow-measurement test equipment that provides repeatable, consistent results is key to a successful process

In the processing environment, powders often appear to exhibit variable flow behavior, which can be the cause of significant inefficiency in the form of unplanned shut downs or compromised product quality. However, the reality is that powder flow properties are influenced by a diverse array of parameters from air and moisture content to particle size, shape and surface charge.

This complexity often makes it difficult to predict behavior from the physical properties that are routinely measured, such as particle size or composition. As a result, materials that appear to meet a specification may go on to perform poorly in the process, simply because the specification is not defined in terms of parameters that correlate with process performance, says Tim Freeman, managing director, Freeman Technology (Tewkesbury, U.K.; http://www.freemantech.co.uk).

Vinnie Hebert, product manager for powder flow testers with Brookfield Engineering Laboratories, Inc. (Middleboro, Mass.; www.brookfieldengineering.com), agrees. "The biggest challenge is characterizing powder products efficiently and definitively," he says. "Especially in the food and pharmaceutical industries, there is a lot of mixing and blending of product that comes into play or testing of raw material as it comes in the door. The challenge is to make sure the product is consistent and will flow properly all the time."

Brookfield Engineering

FIGURE 1. The new Brookfield PFT Powder Flow Tester delivers quick and easy analysis of powder flow behavior in industrial processing equipment. It is suitable for manufacturers who process powders daily and want to minimize or eliminate both downtime and expense that can occur when hoppers discharge erratically or fail to discharge altogether

Specifically, there is the issue of how to characterize flow in a way that relates to how the powder will behave in the process. Also, there is a need to ensure that powder measurement techniques effectively address that same potential for variability that is observed in processing. Therefore, achieving high reproducibility in testing, which equates to accuracy and high sensitivity, relies on controlling all of the variables that may have an impact on flow properties, says Freeman.

Test methods

Because the measurement of powder flow has been challenging processors for years, different test methods have been developed. Traditional techniques range from the simple, such as angle of repose, to the more sophisticated, as exemplified by shear testing. "Unfortunately many techniques or instruments suffer from poor reproducibility and, by trying to capture the complexity of powder behavior with just a single figure, a large number fail to provide data that correlates with processing performance," says Freeman. "Both of these issues are increasingly limiting at a time when manufacturers are targeting the very highest levels of process efficiency."

Freeman Technology

FIGURE 2. The Freeman Technology FT4 Powder Rheometer, a universal powder tester, offers three instruments in one. It combines a patented blade methodology for measuring flow energy with a range of shear cells, wall friction modules and other accessories for measuring bulk properties

Hebert agrees. "No company can have downtime," he says. "Downtime costs money and trying to fix a problem due to a jam in a hopper or clog caused by poor flow characteristics can't be tolerated. So, to have an instrument that can measure all the important powder flow characterizations accurately and consistently, and stop those things from happening before they come to fruition, is a challenge for industry."

One of the biggest roadblocks has

Jenike & Johanson

FIGURE 3. The Schulze Ring Shear Tester (RST) provides the benefits of the fully automated, full scale RST in a compact package. This tester for fine chemical applications requires only 3.5 mL of sample

always been the lack of reproducible results in standard tests, such as the angle of repose, Hausner ratio and the Carr index. "These flow-measurement tests have been around a long time, but the methods involved can be subjective," says Hebert. "It has always astounded me that chemical processors spend hundreds of thousands of dollars on R&D and product formulation, but then use simple tests with variables that can be as subjective as how lightly or heavily someone taps a beaker of material on a table to get a bulk density calculation."

What processors should be looking for, notes Hebert, is a method that is comparable to the old-standbys that processors are accustomed to and comfortable with, but uses a more defined type of test with a defined consolidation stream — so it's repeatable all the time. So, to overcome challenges related to repeatability, reliability and consistency, equipment providers are turning to automated testers that have well-defined methodologies since these enhance reproducibility. In addition to consistency, the newer instruments, says Hebert, are simple to set up and run and easily provide a significant amount of data in a short period of time.

"Enshrining closely defined measurement methods in automated protocols deskills the analytical process, reducing reliance on operator expertise and enhancing reproducibility," says Freeman. "Such advances have therefore been instrumental in, for example, increasing the reproducibility associated with shear testing, thereby ensuring its ongoing usefulness."

Dynamic testing

Dynamic powder testing is another helpful addition in the powder testing arsenal, according to Freeman. He explains that dynamic powder testing

MEASURING FLOW PROPERTIES: 101

When chemical processors need to measure powder flow, the first question should be, "What powder flow properties are needed?" The answer depends on the application, says John W. Carson, president of Jenike & Johanson, Inc. (Tyngsborough, Mass.; www.jenike.com). If the issue is flow from a bin, silo or hopper, the most important flow properties are cohesive strength, internal and wall friction, compressibility and, if the material is a fine powder, its permeability. If the issue is flow through a pneumatic conveying system, important flow properties include pickup velocity, abrasiveness and friability. If it's flow through a chute, wall friction and chute angles are needed. If the issue is performance in a fluidized bed, minimum fluidization velocity is important, explains Carson.

After determining which properties are needed, the next question is, "What test equipment will provide the required properties?" An important consideration is whether relative flow properties are sufficient (such as for quality control), or if design parameters are needed for troubleshooting or equipment design, he says.

The next consideration should be how to obtain a representative sample of the bulk solid. This is not a trivial matter, notes Carson, since no matter how good the test equipment and technician, determining the flow properties of a non-representative sample will likely lead to erroneous conclusions.

Test conditions must next be considered, he advises. What temperature does the material enter the process? Does it remain at that temperature or change? Is the atmosphere surrounding the particles just air or some specialized gas (for example, for inerting)? What about its moisture content – is it controlled or variable? How long does the material remain at rest in the equipment before it is discharged?

The next decision is whether to measure the flow properties in-house or in a contract lab. A range of flow-property test equipment is available on the market. However, Carson warns, "One should be cautious of purchasing equipment solely on the basis of price only to find out later that it doesn't provide all the information that is needed. Most engineers do not have much of an understanding of the nuances of powder flow and the requirements of testers. Frequently, simple quality control testers are assumed to be more than they are."

If a company decides to set up their own laboratory to measure flow properties, Carson suggests considering the following factors:

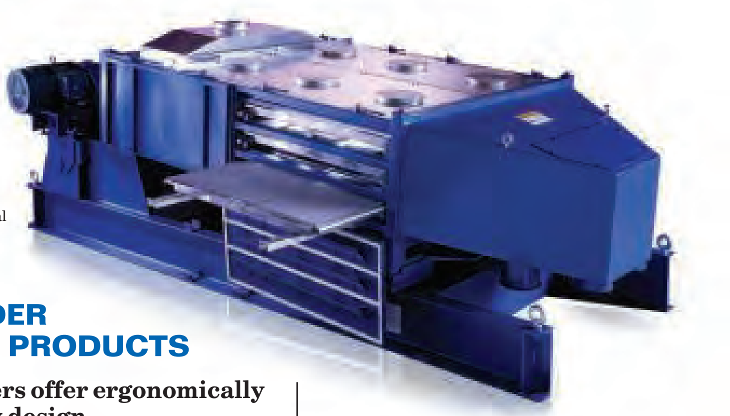
- What is the cost of maintaining highly trained, qualified technicians for powder flow testing that is only required once in awhile?
- Are all the support equipment and systems required to properly and fully characterize the flow properties available? "I often find that a company obtains just one or two testers that give only some of the necessary flow property information," he says
- Is there a long-term need for the equipment? Equipment that is initially purchased on a single purpose basis, assuming that it will meet long-term requirements, often gets set aside within a few years
- What to do with the data? If the issue is only quality control, the answer is relatively simple: compare to a known standard — although you still need to be sure you are measuring the appropriate property, and you need to know what differences from the standard are significant. However, if reliable data are needed for troubleshooting or equipment design, this requires highly trained and experienced engineers who know how to interpret and use the data

The alternative to purchasing test equipment is to use a specialized laboratory where samples can be sent for testing. Some of these laboratories can run tests onsite if the situation demands — for example, if the material's flow properties are transient in nature, requiring testing of fresh material, or if the material is hazardous. ❑

generates values of flow energy from measurements of the rotational and axial forces, acting on a blade as it rotates through the sample in a defined way. Flow energy values are some of the most sensitive powder parameters, they and have a proven track record when it comes to the correlation with processing performance that is critical for plant optimization.

By combining dynamic testing strategies with other techniques, such as modern shear- and bulk-property measurement techniques, processors can secure a database of robust, reproducible powder properties. "Experience suggests that for the majority of applications, these properties hold the key to understanding how best to process any specific powder," says Freeman. "By focusing on those few that most closely correlate with process performance, it is possible to build a specification for any given process that will reliably and efficiently detect powders that are unsuitable, prior to their introduction into the plant. In this way, it is possible to eliminate problems with batch-to-batch variability in either a feed or intermediate, and also, to robustly assess new feeds for an existing unit." ❑

Joy LePree



Rotex Global

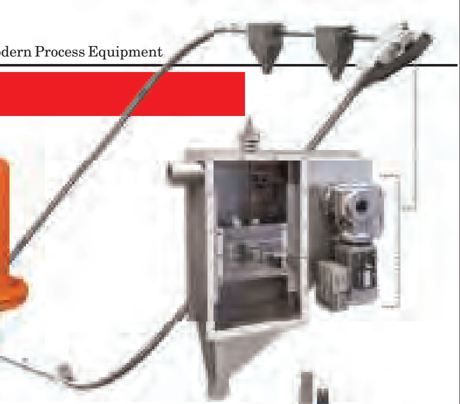
POWDER FLOW PRODUCTS

Screeners offer ergonomically friendly design

APEX Screeners (photo) offer the standard screening performance of a classic Rotex unit, but with an ergonomically friendly design that enables installation in low-overhead environments and operation and maintenance by a single operator. Side access doors were added to allow a single individual to inspect and change screens in a matter of minutes. The patented lift cam system provides easy access to the ball trays and screens. The screeners employ a Gyratorial Reciprocating motion and near-horizontal screen surface to ensure the material has maximum contact with the screening surface for the most efficient screening possible. Yields may improve as the material stratifies quickly at the inlet end of the machine for maximum contact time as it is conveyed down the screen surface. — *Rotex Global, LLC, Cincinnati, Ohio*
www.rotex.com

Rotary vibrators address specific applications

Electric Rotary Vibrators (ERVs; photo, p. 21) provide an effective driving force for vibratory screeners, feeders and conveyors. The units are flow-aid devices that move material



Modern Process Equipment

Eriez Manufacturing

Powder Technologies

efficiently from small hoppers to large bunkers. They are designed for quiet, trouble-free operation. The elliptical action of the ERVs helps settle material in bags, boxes or other materials for shipping or storage. Standard models are constructed for wet or dusty environments. These vibrators feature a durable powder-coat finish, tropicalized windings and adjustable eccentric weights to set force output. They offer continuous operation at 100% force output. — *Eriez Manufacturing Co., Erie, Pa.*
www.eriez.com

An integrated drive makes this conveyor flexible

The design of the Chain-Vey tubular drag conveyor (photo) incorporates an integrated drive unit to provide flexibility. The new drive feature uses one pipe (instead of two), making it suitable for transport in tight spaces. It offers gentle conveying capabilities, low maintenance and energy efficiency, a loop-style layout for multiple pickup and discharge point configurations and an explosion-proof rating. — *Modern Process Equipment, Inc., Chicago, Ill.*
www.mpechicago.com

Mixing and dispersing for smaller, lab-scale applications

The multi-functional Ystral PiloTec processing system (photo) for induction, mixing and dispersing offers dust and loss-free powder induction and wetting under vacuum and dispersing in one package. An exchange of mixing tools also allows inline dispersing with multi-stage shear ring systems. Modular capabilities of the PiloTec allow problem-free upgrades to a PiloTec plant processing system including Ystral mixing system, powder and liquid handling systems, incorporating measuring and weighing technology, lifting devices and other modular components. — *Powder Technologies, Inc., Hainesport, N.J.*
www.powdertechusa.com

Weighing system accurately weighs product in transfer

The Conweigh weighing system can accurately weigh powders, granules, food particles, pellets, capsules, tablets and other bulk materials being transferred into and out of production processes via Volkmann conveyors. Conweigh registers weight within ±1% or better, allowing adjustments to be made to avoid weight gains or losses during transfer and to improve production outcomes. — *Volkmann, Inc., Hainesport, N.J.*
www.volkmannusa.com ■

FOCUS ON

Pressure Measurement & Control

Omega Engineering


American Sensor Technologies


Endress+Hauser

A compact pressure transmitter for easy reading

Rangeable industrial pressure transmitters in the PX5100 Series (photo) are compact and feature a backlit display for easy reading that rotates for its location. Wetted parts are made of stainless steel, and the device features a program lock function, as well as rapid ranging with internal push-buttons, and thin-film sensor technology. The PX5100 can monitor a wide variety of wet or dry media in applications such as pump control, hydraulic control systems, compressor controls, process automation and tank level. — *Omega Engineering Inc., Stamford, Conn.* **www.omega.com**

These regulators handle high-pressure gases

Types 1301F and 1301G high-pressure regulators are designed for situations where high-pressure gas must be reduced for use as pilot supply pressure in pilot-operated regulators, or as loading pressure in pressure-loaded regulators. With a durable stainless-steel diaphragm, both types are also suitable for a wide range of other applications involving high-pressure reduction of various gases. Type 1301F provides an outlet to 225 psig in three spring ranges, while the Type 1301G provides outlet pressures to 500 psig in one spring range. — *Emerson Process Management, Chanhassan, Minn.* **www.emerson.com**

Use these pressure transmitters when hygiene is key

The Cerabar M PMC51 and PMP51 pressure transmitters (photo) are specifically designed for use in the food-and-beverage and biotechnology industries. The units are suitable for accurate measurements of absolute and gage pressure in gases, steams or liquids, as well as for level, volume or mass measurements in liquids. Standard accuracy is 0.15%, the company says, but models with accuracy of 0.075% are available as an option. The Cerabar M transmitters are available with ceramic or metal process-isolating diaphragm seals, which allow the sensors to work at temperatures of up to 752°F and pressures up to 6,000 psi. A Cerabar M transmitter can be programmed to calculate level, volume and mass in any tank shape by means of a programmable characteristic curve that accounts for level, pressure, density of the medium and gravitation constant. The PMP51 has a piezoresistive measuring cell, while the PMC 51 has a capacitive measuring cell. — *Endress+Hauser Inc., Greenwood, Ind.* **www.endress.com**

Get pressure and temperature data from a single process point

Models AST46PT and AST20PT (photo) are innovative pressure and temperature sensors and transmitters that are designed to provide outputs for both measurements from a single process point. The dual-output configuration reduces process penetration points and leaks that are important considerations in critical systems, such as hydrogen, oxygen, heavy-oil processing, hydraulics, analyzers, pipelines and ammonia systems, the company says. AST20PT is a stainless-steel, media-isolated pressure and temperature sensor, while the AST46PT is explosion-proof. Both are ideal for low-power systems, since both readings are generated with the power consumption of one sensor. — *American Sensor Technologies, Mt. Olive, N.J.* **www.astsensors.com**

This pressure transmitter has efficiency-enhancing features

This company has added energy-enhancing features to its SmartLine industrial pressure transmitters that make it easier to support field devices and promote plant reliability. For ex-

Note: For more information, circle the 3-digit number on p. 60, or use the website designation.

Supercritical Fluid Technologies

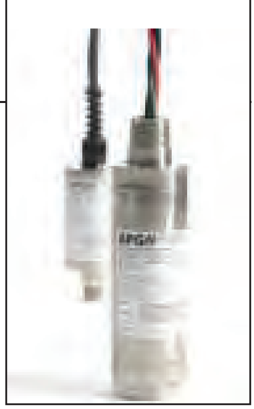
ample, the transmitters have a display that allows users to show process data in graphical formats and to communicate messages from the control room. The display shows easy-to-read trend lines and bar graphs, and a unique platform for operator messages. SmartLine transmitters also feature modular components to simplify field repairs and reduce the inventory needed for those repairs. — *Honeywell Corp., Morristown, N.J.*
www.honeywell.com

Determine solubility in high-pressure fluids with this device
The Phase Monitor II (photo) measures the solubility of various compounds and mixtures in supercritical and other high-pressure fluids. The device provides direct visual observation of materials under researcher-controlled conditions. The Phase Monitor permits experiments in liquid, supercritical carbon dioxide or liquefied gases, and can help investigate the effects of co-solvents on the solubility of compounds of interest. The device allows direct observation of dissolution, precipitation and crystallization of compounds over a wide range of pressures and temperatures. The Phase Monitor II can also be used for studies of melting point depression and polymer swelling in supercritical carbon dioxide. Experiments can be performed at pressures up to 10,000 psi, and at temperatures from ambient to 150°C. — *Supercritical Fluid Technologies Inc., Newark, Del.*
www.supercriticalfluids.com

This pressure indicator has a high-performing data logger
The IPI Mk II pressure indicator combines the ease of an analog gage with the easy-to-read display of a digital calibrator, this company says. Available in ten different pressure ranges from 1 to 700 bars, the portable IPI Mk II is a true field indicator that has full temperature compensation and data logging software. The indicator is suitable for potentially explosive environments, and is available either as a stand-alone indicator or in one of six test-ready systems equipped for pressure measurement. — *Ametek Test and Calibration Instruments, Allerod, Denmark*
www.ametek.com

Make blanketing operations more efficient with this regulator
The BD4-LP low-pressure valve (photo; p. 24) is designed for tank blanketing applications, and can reduce inlet pressure as high as 100 psi down to only inches of water column in one stage with constant flow. The basic principle of the BD4-LP tank blanketing valve is to maintain positive pressure within the storage tank by introducing an inert gas at a specific low pressure, the

Burling Valve



Automation Products Group

company says. Once the desired pressure is established, the pressure regulator closes and maintains the desired pressure. According to the company, the major advantages of the BD4-LP are simple design, low cost and ease of operation, which can enable a more efficient blanketing operation. — *Burling Valve Co., Port Arthur, Tex.*
www.burlingvalves.com

Use these pressure transducers in hazardous locations
PT-400 heavy duty pressure transducers (photo) have received ATEX and IECEx certification for use in hazardous locations throughout the world. With all stainless-steel laser-welded construction, these pressure transducers deliver reliable high-pressure sensing in harsh environments that are prone to shock, vibration and pressure spikes over a range of operating temperatures. This company also now offers a larger-sized pressure transducer for oil and gas applications. The PT-400 transmitters provide a minimum of 10 million operating cycles with high accuracy in temperatures from –40 to 180°F. The product is designed for applications in oil drilling, water and wastewater industries. — *Automation Products Group Inc., Logan, Utah*
www.apgsensors.com

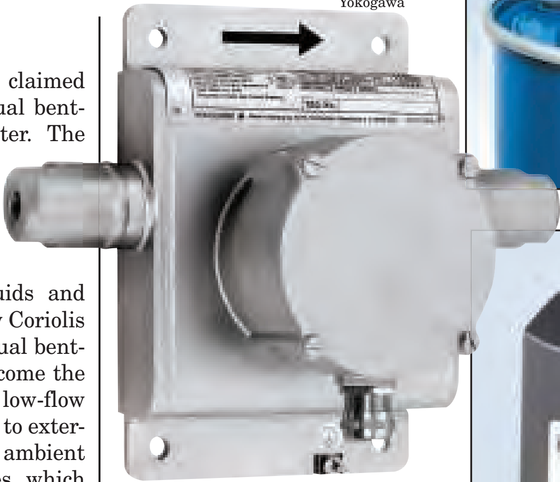
These pressure sensors are designed for plastics processing
The Echo Series of melt pressure sensors offers quality performance and value for plastic processing, utilizing standard configurations and pressure ranges. Echo sensors are designed to meet customer requirements by providing a combination of economic value and performance for general extrusion applications, while providing a ±0.2% repeatability when measuring process pressures. Echo Series sensors should be used when the application requires a quality measurement for optimized control, but not the costs of all the extra features, says the company. Echo sensor diaphragms are coated with titanium aluminum nitride as a standard offering, providing superior performance over less effective coatings. — *Dynisco LLC, Franklin, Mass.*
www.dynisco.com ■

Scott Jenkins

Vanton Pump and Equipment

JANUARY New Products

Yokogawa



This Coriolis flowmeter is the smallest of its kind

The RotaMass LR (photo) is claimed to be the world's smallest dual bent-tube Coriolis mass flowmeter. The unit is designed to be self-draining and to measure both liquids and gases, with a mass flow measurement span from 0 to 40 kg/h. The accuracy is ±0.15% for liquids and ±0.5% for gases. This low-flow Coriolis meter is based on a proven dual bent-tube design designed to overcome the shortcomings of single-tube low-flow meters, such as susceptibility to external vibrations and changes in ambient or process fluid temperatures, which lead to less accurate and stable measurements. The RotaMass LR uses an inline temperature sensor, ensuring exact and fast measurements in process temperatures ranging from –50 to 150°C. — *Yokogawa Corp. of America, Newnan, Ga.*
www.yokogawa.com/us

Siemens

Bürkert

A weighing module for monitoring silo and bin levels

The Siwarex WP231 (photo) is the first weighing module for the Simatic S7-1200 control system. The module is suitable for monitoring filling levels in silos and bins and for products being weighed on platform scales. It is intended for industries that require a high level of accuracy, such as food and beverage, pharmaceutical and chemical industries. The device is suitable for use in explosive atmospheres, Ethernet connections and an RS485 RTU interface with Modbus protocol enable it to be operated from a Modbus HMI panel without being connected to the Simatic S7-1200 control. — *Siemens Industry Automation Division, Nuremberg, Germany*
www.siemens.com/wp231

A dosing unit for microliter volumes

The new micro dosing unit Type 7615 (photo) is a high-precision diaphragm pump for exact dosing in the microliter range. Comprised of three valves, the dosing unit doses 5 µL in one stroke with an accuracy of ±2%. The maximum flowrate is 8 mL in both directions. The flowrate can be changed by the frequency, operating at 5 Hz standard, with options for 10, 25 and 40 Hz. The micro dosing unit is an alternative to syringe pumps, for applications in analytical laboratories, water analysis and the dosing of lubricants. — *Bürkert GmbH & Co. KG, Ingelfingen, Germany*
www.buerkert.de

Handle acids and caustics with this non-metallic drum pump

The portable, non-metallic Flex-I-Liner rotary peristaltic pump (photo) evacuates drums and totes containing acids, caustics, salts, chlorides and reagent-grade chemicals without corrosion of the pump or contamination of the fluid. The self-priming design of the Flex-I-Liner has no seals to leak or valves to clog, and allows the pump to run dry for extended periods of time without damage. Compact in size, with an integral handle, the Flex-I-Liner fits on drum lids without protruding, and has sufficient lift characteristics to operate from the floor, skid or stand. Only two non-metallic parts contact the fluid: a thermoplastic body block, and an elastomeric flexible liner that can be replaced in the field without special tools. The rigid body block of the Flex-I-Liner is made from polypropylene, ultra-high molecular weight polyethylene or polytetrafluoroethylene (PTFE), and the flexible liner is made from either natural rubber, Neoprene, Buna-N or other elastomers. — *Vanton Pump and Equipment Corp., Hillside, N.J.*
www.vanton.com

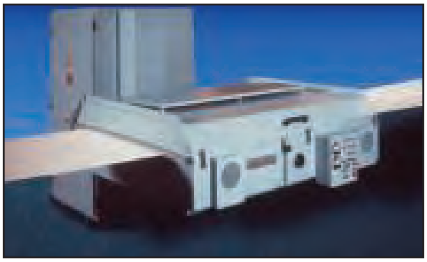
Note: For more information, circle the 3-digit number on p. 60, or use the website designation.

New Products

Metso

WIKA Alexander Wiegand

TLV



Radio Frequency

Analyze pulp online with this instrument

The new Metso Pulp Analyzer (photo) provides the first online measurement of micro-scale details of fiber properties, thereby giving pulp and papermakers a tool to help predict how fiber properties will affect final sheet-strength properties. The pulp analyzer features a new high-definition fiber-imaging module, which measures fibrillation, vessel segments, flocs and other particles. Fibrillation measurements, combined with other fiber properties measured by the analyzer, can be processed in a modeling tool for predicting final sheet strength. The analyzer samples from up to 20 process fiber streams. — *Metso Corp., Helsinki, Finland*
www.metso.com/analyzers

This steam trap has scale removal capability

The LEX3N-TZ (photo) is a high-performance, temperature-control trap for steam service that has a built-in scale-removal function. An auger is built into the steam trap to remove scale and solids buildup from the valve seat during operation, preventing steam leakage and loss of temperature control. The versatile design of the LEX3N-TZ enables adjustment of the temperature setting between 120 and 390°F, which allows its use as an automatic, non-freeze valve, or as a high-temperature air vent. The durable, stainless-steel construction with over-expansion protection prevents damage to the bimetal element and ensures a long service life. The in-line-repairable LEX3N-TZ is available in 0.5-, 0.75- and 1.0-in. NPT (national pipe thread) connection sizes. — *TLV Corp., Charlotte, N.C.*
www.tlv.com

A pressure probe for level measurements with media contact

The new LH-20 submersible pressure transmitter (photo) has a diameter of only 22 mm, and has an accuracy of up to 0.1%, even in harsh operating conditions. This probe is suited to almost all applications in level measurement with full media contact. The probe is available with a parallel temperature output signal, HART communication and a scaleable measuring range. For resistance against the media, the probe can be supplied in a stainless-steel or titanium version with PUR, PE or FEP cable. — *WIKA Alexander Wiegand SE & Co. KG, Klingenberg, Germany*
www.wika.com

Save space and energy with this radio frequency dryer

The Macrowave RF Drying System (photo) provides greater efficiency that conventional convection and infrared systems for the high-speed drying of water-based patterned glue and coatings in the converting and textile industries. This RF drying system selectively heats only the patterned coatings (wetted sections) on the web and leaves the bound moisture in the substrate intact, thus preventing over drying, distortion and shrinking, says the manufacturer. Capable of operating at speeds up to 2,000 ft/min, this system needs one-third to one fifth of the floor space required for hot-air and IR dryers, permits lower web temperatures and provides up to 80% energy savings says the company. — *Radio Frequency Co., Inc., Millis, Mass.*
www.radiofrequency.com

Monitor changing particle characteristics with this probe

The FBRM (Focused Beam Reflectance Measurement) is used for tracking the rate and degree of change to particle structures and droplets at full process concentration. FBRM G600L (photo) quickly captures particle-change information for fast optimization of crystallization and particle and droplet processes. With a pneumatic probe suitable for classified hoods, FBRM G600L can be used in vessels from 500 mL to 10 L, or inserted into a continuous pipeline. In standard design, the probe can be used at temperatures from –10 to 150°C, and an option is available for temperatures down to –80°C. — *Mettler-Toledo, Greifensee, Switzerland*
www.mt.com/fbrmg600l ■

Gerald Ondrey and Scott Jenkins

CHEMICAL ENGINEERING
FACTS AT YOUR FINGERTIPS
Department Editor: Scott Jenkins

Non-chemical Water Treatment

Non-chemical water treatment methods generally utilize electricity to prevent scale formation, mitigate corrosion and control microbial growth. When properly applied, non-chemical water-treatment technologies help plants reduce chemical consumption, minimize waste and possibly save water and energy. The following descriptions outline several types of non-chemical water-treatment methods.

Magnetic fields

When wrapped around a length of pipe, metal induction coils (solenoids) can form a reaction chamber in which an electromagnetic field can be produced (Figure 1). The strength of the magnetic field is proportional to the current flowing through the coil and the number of wire loops.

Magnetic fields are said to control scale in heat exchangers by modifying the surface charge on particulate matter in the water. This allows scale-forming ions, such as calcium and carbonate, to react on the surface of the particulate or colloidal matter, resulting in the formation of calcium carbonate powder that preferentially settles out in the tower basin, or is removed by a sidestream separator instead of forming hard, calcite scale in the heat exchanger. However, research on its effectiveness is equivocal, with some reporting favorable results and others showing no ability on the part of the magnetic field to alter scale formation.

Electrostatic devices

Water conditioning can also be achieved by passing water through an electrostatic charge. This equipment is designed with a positively charged, insulated electrode that is inserted into the center of a grounded cylindrical casing, which serves as the negative electrode. The application of high voltage on the central electrode produces an electrostatic charge across the annular space between the electrodes. The water is conditioned as it flows rapidly through the electrostatic field. These devices are said to work by virtue of the water molecules being rearranged into an orderly array between the electrodes. This causes the scale-forming ions, such as calcium and magnesium, to be surrounded by a "cloud of water molecules," thus preventing scale formation. Beyond testimonials, little independent evidence exists in the U.S. to support the effectiveness of this equipment.

Ultrasonic water treatment

Ultrasonic water treatment is primarily targeted at preventing or controlling bacterial growth. Sound waves outside the range of human hearing are produced by a low-power, high-frequency generator inside a reaction chamber. Microorganisms are destroyed by the wave energy. The medical literature indicates that high-energy ultrasonic generators can be effective in killing bacteria and viruses, albeit at high power and prolonged contact time. Sizing a unit for a typical industrial cooling tower that is capable of providing sufficient power (kilowatts) at the design flowrate is a challenge. Further, the antimicrobial properties of the device are limited to free-floating organisms. Ultrasonic waves are incapable of limiting the growth of biofilms and algae.

Electrochemical methods

Several classes of water treatment equipment are designed around fundamental electrochemistry principles (Figure 2). Corrosion is considered to be an electrochemical process whereby current flows from the anode to the cathode. Oxidation occurs at the anode, causing metal to be dissolved into the water (corrosion occurs at the anode, and reduction occurs at the cathode). No corrosion occurs at the cathode, because it is "protected" by the current that flows onto the metal surface from the anode. If two dissimilar metals are coupled in an anode/cathode cell, the less noble or less stable metal will become the anode. The anode is sacrificed, thereby protecting the more noble metal, which functions as the cathode. The higher the corrosion current, the faster the anode will be consumed.

In electrolysis, direct current (d.c.) electricity is used to produce oxidation/reduction reactions in a variety of chemical processes. Chlorine, caustic soda, aluminum, magnesium and copper are made or refined industrially in large electrochemical cells.

Electrodeposition removes scale-forming impurities by the electrochemical deposition of calcium and magnesium (and other) salts at the cathode of an electrochemical cell. Direct current is applied to the cell at a rate sufficient to drive the precipitation reactions at the cathode.

Microbiological control

Ozone functions as a strong oxidizing biocide in cooling towers and drinking water systems. It is produced in a corona discharge generator by passing a stream of dry air through an electric arc to yield O_3. Typically, 0.5 to 1.0 lb of ozone per 100 tons of air treatment is employed. The power consumption is about 15 kWh per pound of ozone produced. Most experts agree that ozone is effective in controlling microbiological growth in cooling towers. However, additional claims by ozone proponents that it conserves water, prevents scale deposition and mitigates corrosion are in dispute.

When bacteria are exposed to ultraviolet (UV) radiation, the organisms are rendered unable to reproduce. This process is most effective in water that is relatively clean and pure to minimize the absorption of light by suspended solids and other debris. The UV dosage required to destroy microorganisms is measured in microwatt-seconds per centimeter squared ($\mu Ws/cm^2$). Depending on the organism, this can vary from 2,500 to over 26,000 $\mu Ws/cm^2$. Ultraviolet light is only lethal during the time that the organism is exposed directly to the light.

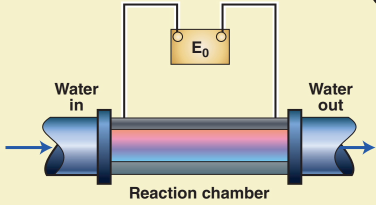


FIGURE 1. The efficacy of magnetic fields for reducing scaling, such as those produced by passing current through coils wrapped around a pipe, has been controversial for many years

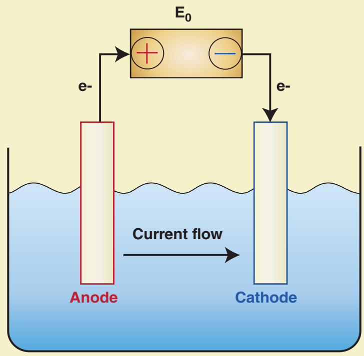


FIGURE 2. Electrochemical cells can be used to generate small quantities of chlorine or bromine for water treatment

Membrane separation

Another class of non-chemical water treatment methods is reverse osmosis (RO) and electro-deionization (EDI). These processes remove over 99% of the dissolved solids present in the raw feedwater to produce a purified water stream. RO utilizes a pressure differential across a semipermeable membrane to reject dissolved salts at the membrane surface, while allowing the purified water to permeate through the pores of the membrane. The RO process produces a concentrated brine stream that is typically 25% of the feedwater flow.

Electro-deionization separates feedwater into a purified water stream and a concentrated brine stream, but instead of pressure differential, this is done in conjunction with an electric field produced by the potential difference between an anode (+) and cathode (–). The potential difference between the electrodes creates the driving force across the membrane. Positively charged ions selectively pass through the membrane and are attracted to the cathode. Negatively charged ions are separated by the membrane and move toward the anode.

Editor's note: This edition of "Facts at Your Fingertips was adapted from the article "Non-chemical water treatment" by William Harfst (*Chem. Eng.*, April 2010, pp. 66–69).

Waste Heat Recovery Methods And Technologies

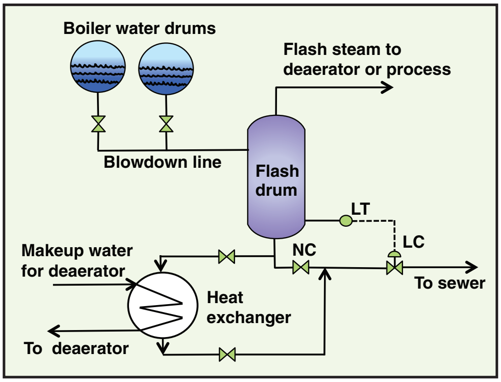


FIGURE 1. This schematic shows a flash tank system for condensate heat recovery

There is significant potential for recovering some of the wasted heat in the CPI. Key requirements, benefits and drawbacks for numerous techniques are reviewed

C.C.S. Reddy and **S.V. Naidu**, Andhra University
G.P. Rangaiah, National University of Singapore

Waste heat recovery (WHR) is essential for increasing energy efficiency in the chemical process industries (CPI). Presently, there are many WHR methods and technologies at various stages of implementation in petroleum refineries, petrochemical, chemical and other industry sectors. Increasing energy costs and environmental concerns provide strong motivation for implementing more and newer methods and technologies for WHR.

Most of the literature on this topic is based on individual methods and techniques, but there is a need for an integrated approach. The main objective of this article is to provide a review of promising methods and technologies for WHR (up to 400°C) as a ready resource that can be used for better understanding and preliminary selection of suitable WHR techniques. To this end, various WHR practices in industry and in the literature are compiled and analyzed for their implementation benefits and constraints. Accordingly, the scope of this study includes a comprehensive review of various applicable WHR methods and technologies for the CPI (especially petroleum refineries), and guidelines for implementing the selected method or technology.

BACKGROUND

Waste heat is energy that is rejected to the environment. It arises from equipment and operating inefficiencies, as well as from thermodynamic limitations on equipment and processes. Often, part of waste heat could potentially be used for some useful purpose. At present, about 20 to 50% of energy used in industry is rejected as waste heat [*8*]. A significant part of this wasted energy is low-temperature heat that is sent to the atmosphere mainly from cooling water, fin-fan coolers and fluegases. Usually, distillation column overhead streams at temperatures of 100–200°C reject heat by fin-fan coolers, and streams at a temperature less than 100°C reject heat to the cooling water system. WHR can be defined as the process of capturing some portion of the heat that normally would be wasted, and delivering it to a device or process where it can be used as an effective, economical and environmentally friendly way to save energy.

Large investments are presently incurred to exhaust waste heat to the atmosphere in the form of cooling towers, fin-fan coolers and very tall stacks for the disposal of fluegases. WHR has the potential to minimize these costs, and to reduce environmental impact along with several other benefits. Development of an optimum WHR system depends on the following factors:

- *Quantity and temperature of waste heat*: The quantity of waste heat should be large enough to make WHR economical. Costs of WHR systems are lower with increased availability of waste heat. Usually, waste heat at high temperatures can be utilized with a higher efficiency and with better economics. Also, more technology options are available for converting waste heat at high temperatures into other useful energy forms than waste heat at low temperatures
- *Uses of recovered waste heat*: The end use of recovered heat has a large influence on the implementation of WHR. For example, if the WHR project generates low-pressure steam that is already available in excess supply, then there will be little or no payout
- *Cost of energy:* This will be greatly influenced by the presence or absence of a cogeneration facility in the company
- *Availability of space*: In operating plants, space availability can be the biggest constraint. It is beneficial to place WHR equipment close to the heat sink to minimize piping and operating costs
- *Minimum allowable temperature of waste heat fluid*: For the case of fluegas heat recovery using carbon-steel equipment and ducting, the fluegas temperature should not be lower than the fluegas acid dew point
- *Minimum and maximum temperature of the process fluid*: If WHR generates steam and exports it to a steam header in a petroleum refinery, then WHR and steam tem-

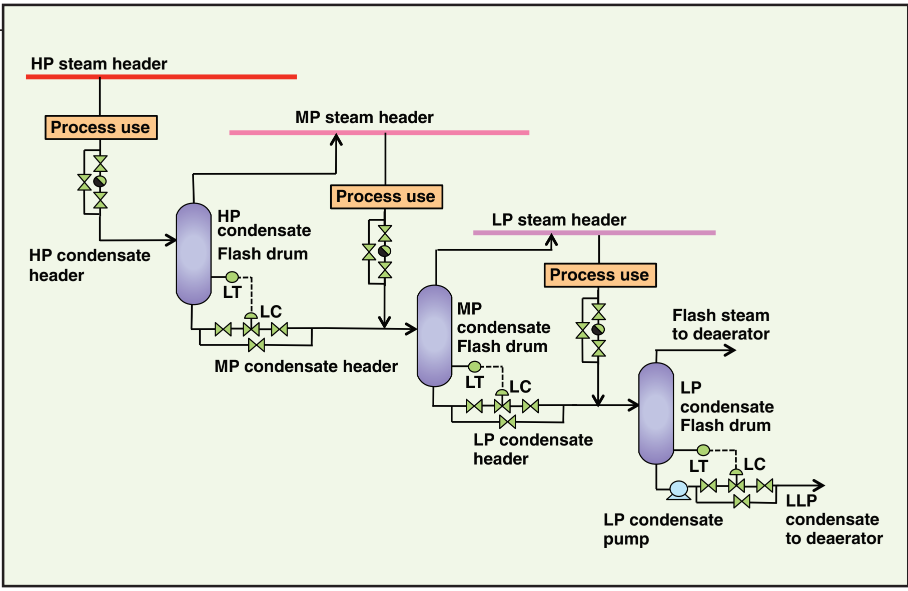


FIGURE 2. This is an example of an efficient steam-condensate recovery system

perature are dictated by the steam header pressure, since petroleum refineries generally operate steam headers at fixed pressures. Low-temperature steam generation will result in more WHR compared to high-temperature steam generation

- *Chemical compositions of waste heat process fluids*: These will dictate the materials of construction for the WHR system, and consequently affect the costs
- *Facility's heat-to-power ratio*: If the heat-to-power ratio in the facility is higher than that for the cogeneration plant, the excess steam demand is usually met by utility boilers. Any saving in steam demand (by better heat recovery) saves fuel in the utility boilers and leaves the operation of the cogeneration plant unchanged. However, if the cogeneration plant meets the entire site's heat load, the value of savings from better heat recovery can be considerably reduced. Saving a ton of steam not only saves the fuel required to raise it, but also eliminates the associated power output that is produced at 80–90% marginal efficiency [*25*]

Additional factors include: management's payback criteria for energy recovery projects; impact of WHR on some equipment, such as burner turndown [*38*]; operating and maintenance schedules for the equipment that is generating and receiving waste heat; and reliability and availability of WHR equipment.

The potential benefits of WHR include the following:

- Improvement in energy efficiency of the process, reduction in fuel costs, reduction in emissions of SOx, NOx, CO, CO_2 and unburned hydrocarbons (UHCs). Energy consumption can typically be reduced by 5 to 30% in most cases
- Reduction or elimination of cooling-water and fin-fan air coolers
- Lower stack heights due to lower fluegas temperatures (if dispersion of pollutants is within the accepted limits). For new projects, this will lead to lower capital expenditure
- Higher flame temperatures since combustion air preheating heats furnaces better and faster
- Increased productivity since waste heat used for preheating the feed can increase throughput
- Reduction in equipment sizes because WHR reduces fuel consumption, which leads to a reduction in fluegas production. This results in size reduction of fluegas handling equipment such as fans, stacks, ducts, burners and more
- Reduction in auxiliary energy consumption due to reduced equipment sizes, which leads to reduced power requirements of auxiliary equipment, such as fans
- Power generation by Rankine cycle, organic Rankine cycle, Kalina cycle and others
- Chilled water can be produced economically using heat pumps

The best strategy for WHR is to minimize its generation and maximize its recovery. Waste heat minimization can be best addressed at the process design stage using existing and new innovative techniques.

MAXIMIZING WHR

For new projects, as well as existing plant revamps, the following design strategies and techniques will be useful for maximizing WHR. First, the following three strategies for direct use of waste heat should be considered and evaluated:

1. The first option is to reuse the waste heat within the process or equipment itself. This is the most economical and effective method of using waste heat. The most common area of heat reuse in the originating process is the boiler or fired heater. The principal advantages of using waste heat in this manner are that the source and sink are generally close together, and there are no problems in matching heat availability with demand
2. The second option is to use waste heat in other equipment within the process unit itself. This means generation of plant utilities, such as hot oil systems, or use of heat in other processes. This will help to reduce capital expenditure for piping and will also aid operational and maintenance issues, such as shutdown of different units at different times
3. The third option is to consider waste heat to generate steam, hot oil or power that can be utilized in other units within the facility. This option may arise because the waste heat is at an insufficiently high temperature for reuse in the originating process unit or because of process requirements, such as when precise control of heat input is needed

After these three strategies are considered, direct reuse (heat recovery) should then be considered prior to WHR for power generation (WHTP). An example is the use of an air pre-

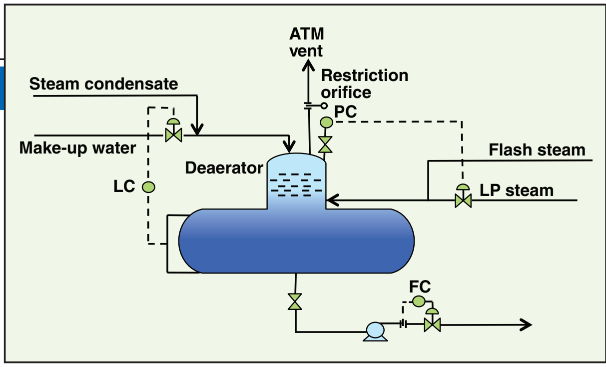


FIGURE 3. A schematic for typical steam deaerator is shown here

heater to recover waste heat from fluegases instead of generating steam or installing a hot oil circuit. Whenever possible, waste heat streams having similar temperatures should be combined to improve the economics. One such example is combining fluegases in the same unit to install a common air preheater.

Wherever possible, maximize WHR by combining various WHR techniques and methods. One example is the organic Rankine cycle (for more on organic Rankine cycles, see Recover Waste Heat From Fluegas, *Chem. Eng*., September, 2010, pp. 37–40) followed by a heat pump for WHR from fluegases of high temperatures (such as 400°C). Another example is thermal or mechanical compression of atmospheric flash steam for direct heating of water in a deaerator.

Once a strategy for improving WHR is selected, a detailed study of the strategy is required. The next two sections discuss several WHR opportunities applicable to the CPI, for example in petroleum refining, and strategies for minimizing waste heat generation.

WHR OPPORTUNITIES

Recovery of low-pressure steam

When high-pressure boiler-blowdown water or steam condensate is depressurized to lower pressure, part of it flashes into steam due to the enthalpy difference between high- and low-pressure condensate. The enthalpy of flash steam is almost as high as the enthalpy of high pressure steam. Hence, there is a good potential to save energy by recovering and reusing the flash steam.

WHR from boiler blowdown water. A simple boiler-blowdown heat-recovery system consists of a blowdown drum to separate flash steam and condensate. It is used for small blowdown flowrates (typically < 1 ton/h). Separated flash steam can be used in deaerators directly, or can be upgraded to higher pressure using thermal vapor recompression (TVR) or mechanical vapor recompression (MVR).

If the amount of blowdown water is significant, then in addition to flash steam recovery, sensible heat recovery from blowdown water will also be economical. Such a system consists of a flash tank and a heat exchanger to preheat deaerator makeup water as shown in Figure 1. It saves steam requirements in the deaerator, and also eliminates capital expenditure for cooling or quenching the blowdown water, or for cooling ponds. A predictive tool to estimate heat recovery from blowdown water was presented by Bahadori and Vuthaluru [*5*]; this requires boiler-water drum pressure, flash drum pressure and deaerator makeup water temperature.

For blowdown operations from 45 to 2.5 barg, typical estimated payback periods are shown in Table 1. The basis used includes: flash steam cost of $31/ton; condensate outlet temperature at the cooler is 40°C; condensate-cooler overall heat-transfer coefficient, U = 1,136W/m^{2}K, demineralized (DM) water (makeup water to deaerator) inlet and outlet temperatures are 30°C and 50°C respectively.

TABLE 1. TYPICAL PAYBACK FOR A BLOWDOWN-WATER HEAT-RECOVERY SYSTEM

High-pressure condensate flowrate, ton/h	Typical flash separator (without demister) dimensions: diameter X height, m	Condensate cooler area, m^2	Payback, months
16	2 X 4.07	33.16	1.4
12	1.74 X 3.8	24.87	1.5
8	1.42 X 3.48	16.58	1.9
4	1 X 3.06	8.29	3.2

Steam condensate recovery. Reusing the hot condensate in the deaerator saves energy and reduces the need for treated boiler feedwater. The substantial savings in energy and purchased chemicals costs make building a complete condensate-return piping system very attractive. An additional benefit of condensate recovery is the reduction in the blowdown flowrate due to better boiler feedwater quality.

Due to the pressure and energy involved, high-pressure (HP) steam condensate should be recovered to the medium-pressure (MP) steam-condensate header; MP steam condensate should be recovered to the low-pressure (LP) steam-condensate header, and LP steam condensate should be recovered to the low-low pressure (LLP) steam condensate header (with a pressure close to that of the deaerator) using flash drums. Flash steam generation can be estimated with 0.6 to 4.3% accuracy, using the following equation and steam property spreadsheet, (freely available at www.x-eng.com; accessed in January 2012):

Flash steam, % = (sensible heat at high pressure – sensible heat at low pressure) × 100 ÷ latent heat at low pressure **(1)**

Recovered MP and LP flash steam can be used efficiently by mixing it in respective steam headers with sufficient superheat. LP flash steam can be directly used in the deaerator or can be upgraded using TVR or MVR for process use. This will also minimize the piping cost for the condensate header. Such a design is shown in Figure 2. A very detailed steam-condensate system-design review is available in Fleming [*18*].

Steam traps are mainly used to remove condensed steam from the system. If they are not properly maintained, they can malfunction, resulting in the loss of valuable steam to the condensate recovery network. Proper selection of steam traps and their maintenance is key to minimizing waste heat generation and steam loss. For a site without proper steam-trap

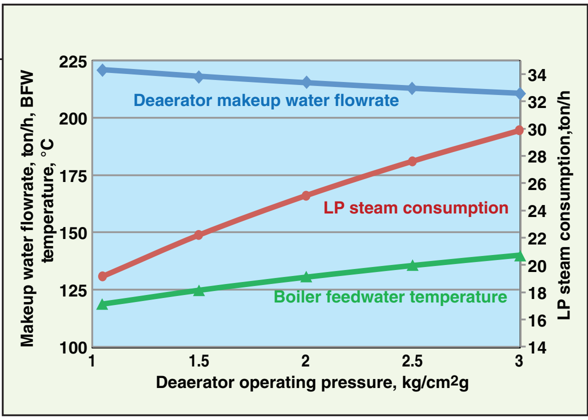


FIGURE 4. Increasing the operating pressure of a steam deaerator can make more use of low-pressure (LP) steam

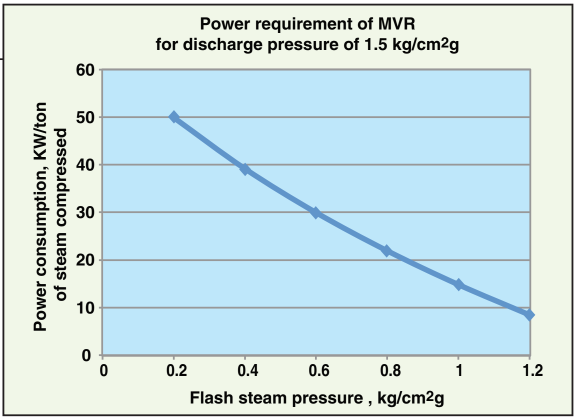


FIGURE 5. This plot shows the energy requirement for steam compression for a discharge pressure of 1.5 kg/cm^2g (assuming compressor polytropic efficiency of 75% and saturated steam condition at the inlet)

monitoring and maintenance planning, it is not uncommon for about 25% of steam traps to leak [*39*]. Since a typical petroleum refinery can have a few thousand steam traps, the malfunction of 25% of these steam traps could result in huge energy losses if the traps blow to the atmosphere. And, if the steam traps blow to closed-loop condensate recovery, this can result in water hammering in the condensate recovery header.

Typical steam losses through blowing steam traps can be easily estimated based on the *Cv* (flow coefficient) method presented by Branan [*11*]. If the rated capacity of a steam trap is not available, then steam losses due to leaks or failures can be roughly estimated (assuming leakage size as a circular hole) using Grashof's formula [*12*]:

$$\text{Steam leak, lb/h} = 0.70 \times 0.0165 \times 3{,}600 \times A \times P^{0.97} \quad (2)$$

Where 0.70 is the coefficient of discharge for the hole, 0.0165 is a constant in Grashof's formula, *A* is the area of leaking hole in square inches and *P* is the pressure inside the steam line in psia.

Many efficient steam-trap monitoring systems are available from vendors. Use of suitable steam-trap monitoring systems can be very beneficial for minimizing waste-heat generation and also maintenance costs. Radle [*37*] highlighted the importance of intensive steam-trap management. McKay and Holland [*31*] presented methods to estimate energy savings from steam system losses. These methods can be used to estimate energy savings, and thus cost savings to justify improvements in steam trap systems.

Maximizing use of LP steam

Petroleum refineries usually have the capability to generate excess LP steam (< 5 kg/cm^2g), mainly from steam turbine operations and also due to low temperature WHR. Any LP steam generation in excess of the demand may need to be released to the atmosphere. This will result in wasted energy. Petroleum refineries typically address this issue by switching some of the process steam-turbine drivers (generating LP steam) to electric motors, or by reducing the generation of LP steam from WHR.

The first method may reduce cogeneration benefits. Flash steam (near atmospheric pressure) is generally not recovered. This results in loss of recoverable energy. Sometimes flash steam is condensed using cooling water or air cooling. This will lead to a waste of latent heat of flash steam. Some attractive ways to use additional LP steam and atmospheric flash steam are outlined below.

Optimization of the deaerator pressure. Generally, deaerators are designed to operate at very low pressures (~1.05 kg/cm^2g) mainly to maximize cogeneration benefits. They use very low pressure steam (using pressure reduction of LP steam) and flash steam as the heating media. However, they are generally designed for relatively higher pressures (mechanical design pressures), such as 3.5 kg/cm^2g. If makeup-water, flash-steam and condensate-recovery header pressures have safe operating margins for high pressure operation of the deaerator, one can increase the deaerator operating pressure to enable more usage of LP steam (Figure 3).

A higher operating pressure of the deaerator can result in the following benefits:

- Increased use of LP steam with minimum modification costs
- Potential to either totally eliminate or reduce the size of boiler feedwater (BFW) preheaters (used to prevent condensation of acid gases at the cold end side of economizers) at the inlet of economizers
- Elimination or minimization of the use of HP or MP steam used at these BFW preheaters, which can instead be used in a steam turbine to generate power
- If the boiler is not installed with an economizer, then there is no requirement for a BFW preheater. In this case, boiler fuel requirements will reduce in relation to additional heat absorption at the deaerator

To further illustrate this concept, consider the following example. A deaerator (design pressure of 3.5 kg/cm^2g) produces 240 ton/h of BFW, using makeup water at 80°C, LP steam from steam turbines at 177°C and 3.5 kg/cm^2g. It can be seen from Figure 4 that as the operating pressure of the deaerator is increased, more LP steam is consumed and the BFW temperature increases.

Heating of combustion air with LP steam. LP steam can be used to preheat combustion air at boilers and fired heaters. This will reduce fuel consumption at the boiler or fired heater. In some cases, it also helps to prevent cold end corrosion in air-to-air pre-heaters. The typical payback period depends on available space in combustion air ducting, the cost of LP steam, and the proximity of steam and condensate headers.

Upgrading LP or flash steam with

MVR or TVR. LP steam or flash steam is generated by boiler steam-condensate flashing or leaks from steam turbines. It can be upgraded for process use via mechanical or thermal vapor recompression. Vapor recompression requires a mechanical compressor (in MVR) or steam jet ejector (in TVR) to increase the temperature of steam to make it usable for process duties. LP steam can be compressed to higher pressures using MVR. Figure 5 shows typical energy requirements for MVR. The coefficient of performance (COP; for a heat pump, this is the ratio of heat rejected at high temperature at the condenser to the energy input by the compressor) of MVR is very high — around 10–30 depending on the compression ratio. MVR is limited to applications where the compressor inlet pressure is above atmospheric and the compression ratio is less than 2.1 per stage (maximum value for single-stage centrifugal compressors used in the petrochemical industry [*22*], due to cost considerations).

In TVR, motive steam at comparatively higher pressure is used to compress the LP flash steam using a steam ejector, and then delivered at an intermediate pressure. The following equation can be used to quickly estimate the approximate quantity of motive steam required for upgrading a given quantity of very low pressure steam [*32*].

$$Rm = 0.4 \times e^{[4.6 \times \ln(PD/PL)/\ln(PM/PL)]} \quad (3)$$

Where *Rm* is the ratio of mass flowrate of motive steam to mass flowrate of load steam, *PM* is the absolute pressure of motive steam, *PL* is the absolute pressure of LP steam and *PD* is the target absolute pressure of discharge steam. This equation is empirical, applicable to motive saturated steam below 300 psig, and should be used for an *Rm* between 0.5 and 6.

Typical motive steam requirements of TVR for a discharge steam pressure of 1.5 kg/cm^{2}g at various load steam pressures are shown in Figure 6. Steam recompression requires only 5–10% of the energy needed to raise an equivalent amount of steam in a boiler (OIT Tip sheet #11, January 2006, www1.eere.energy.gov/industry/bestpractices/pdfs/steam11_waste_steam.pdf).

Desalination. If sea water is readily available, LP or flash steam can be used to produce fresh water from sea water using various desalination technologies. Ophir and Gendel [*34*] discussed desalination by multi-effect flash vaporization to minimize energy consumption using 1.5–4.5 barg steam, generated from back-pressure steam turbines. They concluded that the technology using steam turbines (operating using 1.5–4.5 barg steam) and compressors (driven by steam turbine, for compressing flashed steam) reduced desalination costs by 13% compared to ejector technology. A thermal- and economic-performance study for low-temperature multi-effect evaporation desalination systems (LT-MEE), integrated with a steam-driven single-effect LiBr-H_2O absorption heat pump, was presented by Wang and Lior [*43*]. A 60–78% water production gain was reported due to this integration as compared to stand-alone LT-MEE.

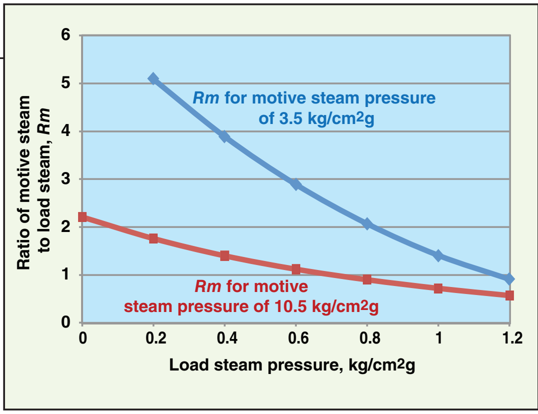


FIGURE 6. Typical steam requirements are shown for thermal vapor recompression at a discharge pressure of 1.5 kg/cm^{2}g

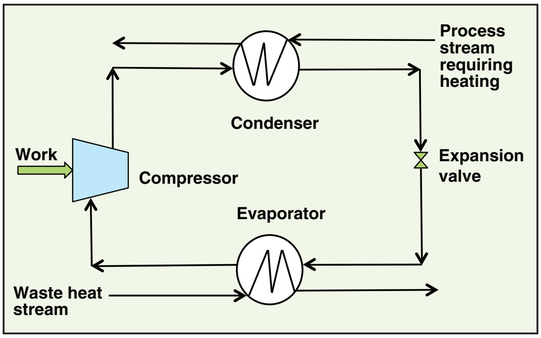


FIGURE 7. Mechanical vapor compression is depicted here

APPLYING HEAT PUMPS

Heat pumps to raise temperature

Heat pumps consume energy (external mechanical or thermal energy) to increase the temperature of waste heat and ultimately reduce the use of fuel. With low temperature lifts (difference between the evaporator and condenser temperatures) less than 100°F, heat pumps can deliver heat for lower cost than the cost of fuel (U.S. Dept. of Energy, Industrial heat pumps for steam and fuel savings, http:// www1.eere.energy.gov/industry/bestpractices/pdfs/heatpump.pdf, Accessed in January 2012).

Mechanical heat pumps. Closed-cycle mechanical (vapor compression) heat pumps are generally applicable for waste heat temperatures less than 100°C. A working fluid (typically ammonia, a hydrocarbon-based or another refrigerant) takes in waste heat and evaporates. The fluid is compressed and then condensed to give out heat at a higher temperature than the waste heat stream, and is finally returned to the evaporator via an expansion valve (Figure 7). Typical COP values for mechanical heat pumps are in the range of 3–8.

Absorption heat pumps. There are two types of vapor-absorption heat pumps. The first type (Type 1) is applicable for waste heat temperatures between about 100 and 200°C. They transfer heat from a high-temperature heat source (waste heat) to bring a low-temperature process stream to an intermediate temperature. LiBr heat pumps can generate a temperature output of ~100°C. Typical COP values for these heat pumps are 1.2–1.4.

New-generation heat pumps are under development to generate temperatures up to 250°C for steam generation (HPC; www.heatpumpcentre.org/en/aboutheatpumps/heatpumpsinindustry, Accessed in January 2012). The absorption heat transformers (AHT) or temperature amplifier are Type 2 pumps, and operate in a

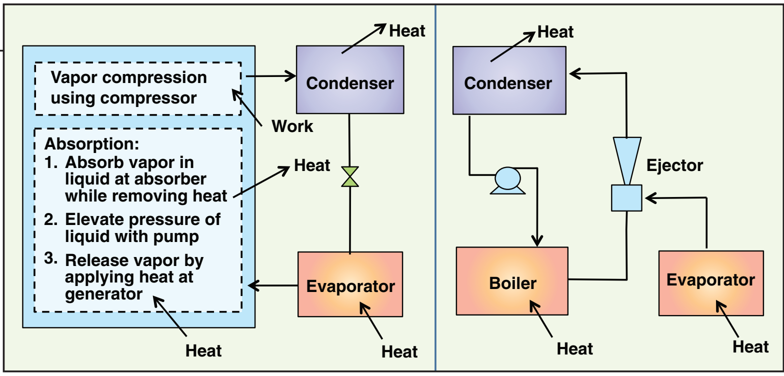


FIGURE 8. These schematics show absorption and mechanical refrigeration (left) and steam-jet refrigeration using an ejector (right) [22]

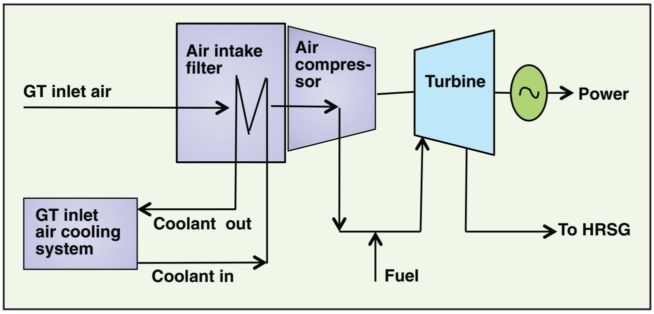


FIGURE 9. This gas turbine includes a compressor, turbine and air-intake filter with inlet-air cooling

cycle opposite to that of absorption heat pumps (Type 1). They take in waste heat at an intermediate temperature that is too low to be useable and upgrade some of it to a useful, higher temperature and cool the rest, thus acting as "heat splitters". Up to about half the heat of the waste heat source can be upgraded. LiBr-based units can achieve temperature lifts up to 50°C from waste heat sources at temperatures of 80 to 100°C. Heat transformers can have output temperatures up to about 150°C. Typical COP values for heat transformers are 0.3–0.5. An industrial application of the AHT system to obtain hot water was recently presented by Horuz and Kurt [*24*].

Applications. Both types of heat pumps (mechanical and absorption) can be used in distillation columns to save substantial energy (~33% reduction) for separating compounds with very close boiling points, such as propane/propylene and *i*-butane/*n*-butane [*14*]. A low temperature lift gives a high COP and a large amount of heat upgraded per unit power. Open-loop mechanical (vapor compression) and thermal-compression heat pumps are used for flash steam recovery and desalination. An excellent review on advances in heat pump systems was recently presented by Chua and others [*13*]. Operating parameters and installation costs for various heat pumps are available in Ref. 8.

Heat pumps as chillers

Absorption heat pumps can also be used as chillers, which use thermal rather than mechanical energy for operation. Absorption chillers generally employ either LiBr or ammonia absorption in water. LiBr-water systems are limited to evaporation temperatures above freezing, because water is used as the refrigerant.

Advantages of the LiBr-water systems are that less equipment is needed, and operation can be at lower pressures. But this is also a drawback because pressures are below atmospheric, causing air infiltration into the system, which must be purged periodically. Due to corrosion problems, special inhibitors must be used in the LiBr-water system. NH_3 absorption systems require high pressure distillation for regeneration of NH_3, as water is also volatile. Refrigerant NH_3 requires much higher pressures — about 1,100–2,100 kPa (absolute) in the condenser. The NH_3-water system is capable of achieving evaporating temperatures below 0°C.

The COP for absorption refrigeration (COP_{abs}) is the ratio of refrigeration rate to heat input at the generator. Various chillers are compared in Table 2. More-detailed performance characteristics of refrigeration chillers are given in "ASHRAE Handbook-Refrigeration" [*3*]. NH_3-H_2O and LiBr-H_2O chiller systems operate with comparable COPs.

The capital cost of absorption refrigerators rises sharply as the temperature of the heat source falls, making WHR uneconomical. Compared to mechanical chillers, absorption chillers have a low COP. Nonetheless, they can substantially reduce operating costs because they are energized by low-grade waste heat, while vapor compression chillers must be motor or engine driven. Absorption chillers are also more economical than steam jet refrigeration, which requires steam supply at relatively higher pressures of 7 kg/cm^{2}g, makeup water and more cooling water. The waste heat source for an absorption chiller can be LP steam, or a hot gaseous or liquid stream. General operating principles of various chillers are shown in Figure 8. Typical operating requirements of various chillers are summarized in Table 2.

A typical application of absorption chillers is for heat recovery from fluegases (HRSG; heat recovery steam generator) to produce chilled water. HRSG recovers heat from gas-turbine (GT) exhaust gases. GTs consist mainly of one air compressor, one turbine and an air intake filter, as illustrated in Figure 9. Chilled water can be used to reduce the air inlet temperature at the air compressor of the GT. Air density at the air compressor inlet thereby increases, and hence mass flow increases through the air compressor. This is the most cost-effective method for increasing gross power output of the GT. It increases net incremental power output faster than incremental fuel consumption, resulting in improved overall fuel efficiency (reduced heat rate).

GT intake air through the air compressor can also be cooled by WHR using an ejector refrigeration system (EWRS). Application of an EWRS, utilizing about 30% of the total exhaust gas heat to pre-cool the air compressor intake air by 25°C, increases GT power output by 15–20% and the thermal efficiency by 2.0–3.5% [*36*]. The effect of an air compressor's inlet-temperature

TABLE 2. TYPICAL OPERATING REQUIREMENTS OF ABSORPTION AND MECHANICAL CHILLERS				
Type of Chiller	Main Driver	Typical Steam and Electrical Power Requirements	Typical Cooling Requirements [16]	Typical COP
Single stage absorption (LiBr system)	Very low pressure steam (~100 kPag) or hot water or hot stream > 93°C	Steam: 2.36–2.41 kg per kWh of refrigeration. Electrical power: 0.0028 –0.0114 kW/kWh of refrigeration [3]	2.5 kW per kW of refrigeration	0.6 -0.75
Double stage absorption (LiBr system)	Relatively higher pressure steam (~800 kPag or more) or hot stream > 143°C	Steam: 1.25–1.29 kg per kWh of refrigeration. Electrical power: 0.0028–0.0114 kW/kWh of refrigeration [3]	2.0 kW per kW of refrigeration	1.19 -1.35
Mechanical compression (propane)	Motor or engine driven compressor	Electrical power: 4.5 kW/kW of refrigeration [4]	1.283–1.125 kW per kW of refrigeration	4.5

reduction on power output of a typical GT is shown in Figure 10.

Use of chilled water (generated by using waste heat in a single-stage absorption chiller) at pre-condensers, can substantially reduce the fixed and operating costs of multi-stage steam ejector systems by condensing most of the suction vapor before entering the vacuum system.

Another application of absorption chillers is the recovery of the propane fraction of flare gas. Flaring in petroleum refineries occurs when waste refinery gas cannot be used in boilers or fired heater systems and has to be burned. The propane fraction of this waste stream represents a valuable coproduct that could be salvaged. One U.S. Dept. of Energy (DOE) sponsored project is on the development of an NH_3 absorption unit running on waste heat to chill the gaseous waste stream from the reformer to about –30°C to recover 200 barrels per day (bbl/d) of propane at a Denver refinery. This technology boosted profit by $900,000/yr, and paid for the unit in less than two years (http://www1.eere.energy.gov/industry/petroleum_refining/pdfs/ultramar.pdf, accessed in May 2011).

FLUEGAS HEAT RECOVERY

High-temperature stack gases represent the major area of energy loss in combustion processes. The temperature of a fluegas depends on the temperature of fluid inside the tubes of the convection section of fired equipment, and the WHR method. Fluegas acid dew-point temperatures limit the possible heat recovery due to corrosion. For combustion of fuels with sulfur, it is widely accepted that 1–5% of SO_2 generated in a combustion process will be converted into SO_3 [19]. Based on SO_3 content and H_2O partial pressure, the sulfuric acid dew point can be easily calculated using the following equation [22]:

$$T_{dew}\,(SO_3) = 1{,}000/\,[2.276 - 0.0294 \ln(P_{H2O}) - 0.0858 \ln(P_{SO3}) + 0.0062 \ln(P_{H2O}\,P_{SO3})] \quad (4)$$

Where T_{dew} (SO_3) is the sulfuric acid dew point in Kelvin, P_{H2O} and P_{SO3} are partial pressures in mm Hg. A simple-to-use predictive tool for estimating the acid dew point, which accounts for fuel type, sulfur fraction in fuel and excess air, was recently presented by Bahadori [6]. So, for greater heat recovery from fluegas, changing the stack and its material of construction may also be required.

Heat reuse in the same process

Economizers for boilers. An economizer recovers waste heat from fluegases by heating BFW, and hence reduces boiler fuel requirements. Fluegases are often rejected to the stack at 30 to 70°C higher than the temperature of the generated steam. Generally, boiler efficiency can be increased by ~ 1% for every 22°C reduction in fluegas temperature. By recovering waste heat, an economizer can often reduce fuel requirements by 5 to 10% and usually pay for itself in less than two years. Air preheat also reduces excess air. Economizers can be classified as condensing and non-condensing types for fluegas streams.

Non-condensing type: Their implementation requires a gas-to-liquid exchanger to be installed in the exhaust stack. They recover a major part of sensible heat from the fluegases as the heat is removed above the acid dew point. These economizers are applicable for boilers using fuel oil or gaseous fuel. They can be installed with bare tubes of carbon-steel construction or with glass coating, or finned tubes depending on the composition of fluegases and heat recovery targets.

Condensing type: They recover latent heat as well as sensible heat from fluegases and hence are able to increase boiler efficiency by up to 10%. They can be indirect- or direct-contact types. In an indirect-contact economizer, cold deaerator makeup water flows through a heat exchanger to recover fluegas sensible and latent heats. Condensed water from the fluegas will become acidic and need to be disposed of with proper treatment.

In direct-contact economizers, raw water is sprayed directly into the fluegas, to cool it below its acid dew point. These economizers typically use a packed bed for better contact of water with fluegases. The sprayed water and condensed water from the fluegas become hot and acidic, and the heat is recovered by another heat exchanger using cold deaerator makeup water. The economizer requires a pump to circulate hot water in a closed loop. A small stream of this water needs to be continuously disposed of (with proper treatment), and raw water needs to be added to compensate for the lost water. The temperature of fluegases can be reduced to 43–60°C, depending on the amount of hydrogen, water in

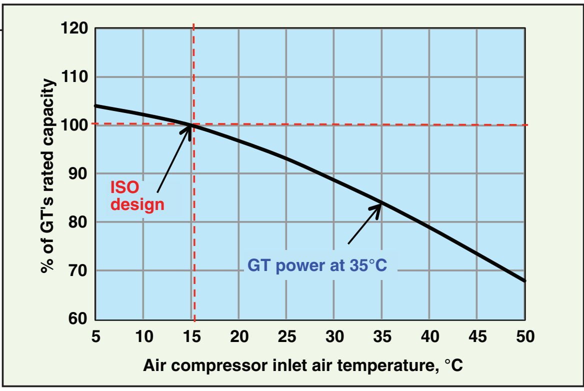


FIGURE 10. The effect of inlet air temperature on the power output of a typical gas turbine is shown [22]

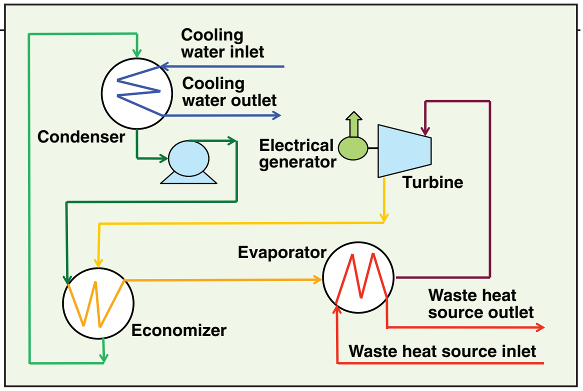


FIGURE 11. This diagram depict an organic Rankine cycle (ORC) with an economizer (internal heat exchanger)

the fuel, amount of excess combustion air used and humidity of air.

An indirect-contact condensing type of economizer can heat deaerator feedwater to a higher temperature compared to the direct-contact condensing type. The possibility of corrosion from the acidic condensate is prevented by using more expensive materials like stainless steel and glass fiber for ducts and stacks, or by coating exposed metal surfaces with a resistant material, such as Teflon.

Condensation systems generally reduce particulate and SOx emissions. The penalty for firing with excess air decreases with reduction in fluegas temperature. Condensing economizers are difficult to implement (due to corrosion issues), if the boiler is sharing a flue stack with other fired equipment. Condensing economizers are applicable only if there is a requirement for hot water.

Economizers for fired heaters. If fluegas temperatures are very high (~700°C), then adding a new coil to the convection section can increase furnace capacity and reduce fuel consumption by bringing the fluegas temperature to within 50–100°C of the process-fluid inlet temperature at the inlet of the convection section [*20*].

Combustion air heating for boilers and fired heaters. An air pre-heater (APH) is a heat exchanger placed in the exhaust stack or ductwork that extracts a large portion of thermal energy in the fluegases and transfers it to the incoming combustion air. WHR from stack gases through air preheating proves to be more advantageous than other methods [*15*]. This practice also reduces required capacities of forced- and induced-draft fans because the combustion air quantity is reduced. The amount of energy saved through APH can be very large since stack temperatures can be reduced to below 180°C (depending on the fluegas acid dew point). APHs require space, but energy savings can be as much as 20–30%, for the case of fired heaters. There are two types of air preheaters: recuperator and regenerator.

A *recuperator* is a fixed air-to-fluegas heat exchanger (without moving parts) placed in the furnace stack to preheat incoming air with hot fluegas. A *regenerator* is an insulated container filled with metal or ceramic shapes that can absorb and store relatively large amounts of thermal energy and then release that energy subsequently. Another design of a regenerator for continuous operation uses a continuously rotating wheel containing a metal or ceramic matrix. The fluegases and inlet stream (such as combustion air) pass through different parts of the wheel during its rotation to receive heat from the fluegases and release heat to the cold, inlet stream.

Installing APHs for smaller heaters (with absorbed duties of 7,000 to 10,000 kW and less) may not meet payback period requirements for most petroleum refineries. The payback period for installation of an economizer or APH depends mainly on the fluegas flowrate, stack temperature, annual operating hours and the need for hot water. An economizer or APH for water-tube boilers is typically not attractive for units operating under 10 kg/cm^{2}g or below 20 ton/h of steam production, nor any size boiler that will normally run at reduced capacity. For industrial boilers, dual installation using both an economizer and an APH is rarely economical or installed.

Heat recovery using a heat-pipe. A heat pipe is a heat transfer element that can quickly transfer heat from one point to another with merits of high efficiency and compact size. Its heat transfer coefficient in the evaporator and condenser zones is 1,000–100,000 W/m^{2}K, and its thermal resistance is 0.01–0.03 K/W, thus leading to a smaller area and mass of a given heat exchanger [*42*]. The mechanism of heat pipes is to employ evaporative heat transport to transfer thermal energy from one point to another by evaporation and condensation of a working fluid or coolant.

Because a heat pipe cannot function below the freezing point nor above the critical temperature of its working fluid, the selected working fluid must be within this range. In addition, vapor pressure, surface tension, contact angle and viscosity in the heat pipe must be considered in the selection of a working fluid [*26*]. Working fluids that can be used in low-temperature heat recovery include methanol (10–130°C), flutec PP2 (10–160°C), ethanol (0–130°C), water (30–200°C) and toluene (50–200°C). Heat-pipes can be used as APHs in steam boilers, but their installations are limited, largely due to higher costs. Another major limitation of heat pipes is that they must be tuned to particular cooling conditions. The choice of pipe material, size and coolant all have an effect on the optimal temperatures in which heat-pipes work.

Gas turbine (GT) inlet air heater. GT inlet air (after air compression) can be heated with fluegases. Also, BFW can be preheated by installing an economizer in a heat recovery steam generator).

Heat reuse in other equipment

Fired heaters. Fluegas heat can be used for steam generation in the economizer, steam superheater and hot oil

TABLE 3. COMPARISON OF TYPICAL CAPITAL COSTS FOR VARIOUS POWER CYCLES

Conversion Technology	Typical Sources of Waste Heat	Capital Cost
Traditional steam cycle	Exhaust from gas turbines, reciprocating engines, incinerators and furnaces	$1,100–1,400/kW
Kalina cycle	Gas turbine exhaust and boiler exhaust	$1,100–1,500/kW
Organic Rankine cycle	Gas turbine exhaust, boiler exhaust and heated water	$1,500–3,500/kW

system. The pressure of steam generated will depend on the fluegas (hot stream) temperature. Steam pressure levels can be optimized with the available fluegas temperatures and based on the plant's steam balance. Steam generation has the advantage that piping costs may be less due to proximity of steam headers in the plant; its disadvantage is that steam header pressures at a petroleum refinery, for example, are usually fixed, and hence, cannot maximize the amount of possible heat recovery. Generation of high pressure steam is preferred as it can be used for power generation. However, HP steam generation will lead to lower heat recovery from fluegas or another hot stream. A more costly and efficient system will use steam generation followed by air preheating.

In addition to steam generation, economizer coils can be added to heat water or intermediate heat transfer fluids. Saturated steam generated in the steam generators can be super heated by recovering heat from fluegases or hot streams. A hot oil circuit can be installed to supply heat to multiple locations in the process unit. A hot oil system can maximize the heat recovery, but requires additional capital investment.

Gas turbine. The exhaust gases from a GT (with and without duct firing) can be used for steam generation in HRSG at multiple pressure levels; or, it can be used to heat process streams. In some instances, the hot turbine exhaust is used as combustion air for a fired heater in the plant where a GT is located. Waste heat of HRSG exhaust can be used to produce chilled water using an absorption chiller or jet refrigeration to cool GT inlet air, and hence increase power output of the GT. It can also be used for organic Rankine or Kalina cycles (discussed in the next section) to produce power. The optimum choice of heat recovery method will depend on many factors, such as process heating requirements, available space, fluegas quantity, quality, refinery steam balance and payback criteria.

Heat recovery for power

All forms of energy, including work, can be fully converted into heat, but the converse is not generally true. As per the second law of thermodynamics, only a portion of the heat from a heat-work cycle — such as a steam power plant — can be converted to work. The remaining heat must be rejected as heat to a sink of lower temperature (atmosphere, for instance). For any process converting heat energy to mechanical energy, the Carnot efficiency is the theoretical maximum.

Organic Rankine cycle (ORC). This can work with waste heat streams in the lower-temperature range of 80 to 400°C [*35*] to generate electricity. An ORC engine is similar to a steam Rankine engine, except that it uses a lower-boiling-point organic fluid, instead of steam, as the working fluid. The working fluid is vaporized in the evaporator using waste heat, and the resulting high pressure vapor is expanded in a turbine to generate power. Low pressure vapor from the turbine is condensed in the condenser using cooling water or air. Finally, condensed working fluid is pumped to high pressure to the evaporator, to complete the cycle.

An economizer is generally added to reduce condenser cooling load and improve ORC efficiency, as illustrated in Figure 11. This cycle has the highest temperature at the evaporator and the lowest temperature at the condenser. In ORC, working fluids having higher vapor pressure than water are used. So, operating pressures and temperatures of ORC are lower than those of the Rankine cycle.

For working fluids with lower boiling points, the turbine inlet pressure can be higher and the circulating mass flow is lower (minimization of operating costs), thereby requiring a smaller size turbine. This results in no condensation during expansion in the turbines, which ensures longer life spans for turbine blades, and therefore super heating of the fluid is not required before expansion in the turbine.

Thermodynamic properties of working fluids affect the system efficiencies. An ORC working fluid should have a mainly positive or isentropic saturation vapor curve, high vapor density, high critical temperature and high heat stability. Liu and others [*30*] presented the effect of working fluids on ORC performance for WHR. Fluids used in ORC include propane, butanes, CFCs, freon, *n*-pentane, *iso*-pentane, hexane, ammonia, R245fa, octamethylcyclotetrasiloxane (D4) and many other proprietary fluids. Saleh and others [*40*] presented the performance of ORC for various working fluids for a maximum evaporator temperature of 100°C. A screening study of several working fluids based on power production capability and equipment size requirements was presented by Lakew and Bolland [*28*]. It shows that R227ea gives the highest power for a heat-source temperature range of 80–160°C and R245fa produces the highest in the range of 160–200°C. Wei and others [*44*] studied the performance and optimization of ORC for WHR.

The extent of heat recovery can be calculated from exergy (available energy) of the waste heat stream. For estimating the electric power recovered, the following formula can be used:

$$\text{Electrical power, kW} = \eta_e \times \eta_{carnot} \times WH = \eta_o \times WH \quad (5)$$

Where η_e is exergy efficiency; η_{carnot}= Carnot efficiency = 1 – (cold source temperature, K / waste heat stream temperature, K, η_o = ORC efficiency and *WH* is the waste heat in kW. For a quick estimation of power, one ORC supplier, Cryostar (www.cryostar.com/web/heat-conversion.php, accessed in January 2012) indicates a value of 0.5 for η_e. Labrecque and Boulama [*27*] stated that, for waste heat to useful work conversion, exergy efficiency as high as 70% is conceivable. Bourji and others [*10*] proposed a correlation for approximately estimating ORC power generation from fluegas temperatures between 350 and 500°F with ambient temperatures varying between 50 and 100°F. They also es-

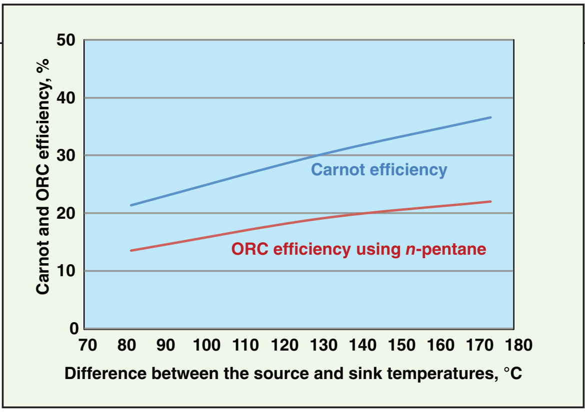


FIGURE 12. The efficiencies of Carnot and ORC are compared using *n*-pentane

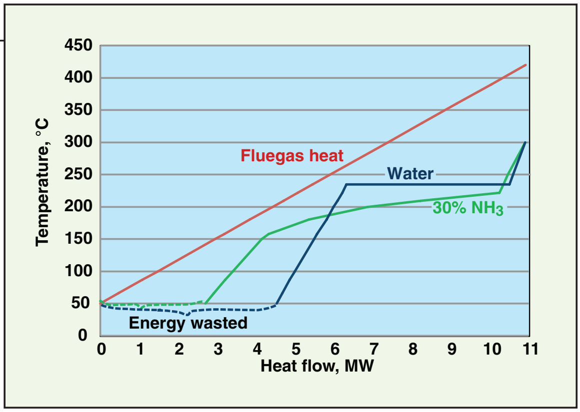


FIGURE 13. This comparison shows typical heat recovery from fluegases using H_2O or 30% NH_3 in H_2O mixtures, at 30 bar

timated ORC power-generation potential for various refinery capacities and breakdown for various refinery units, using fluegas WHR.

Using WHR, the efficiency of an ORC system ranges from 10% at 110°C to more than 22% at 270°C, depending on the temperature of the waste heat and working fluid (Freepower; www.freepower.co.uk/tech-overview.htm, accessed in January 2012). Drescher and others [*17*] reported ORC efficiencies as high as 28%, at a high waste-heat temperature of 350°C. The highest thermal efficiency is achieved when the hot stream temperature is as high as possible, and the sink temperature is as low as possible. A typical comparison of Carnot and ORC efficiency is shown in Figure 12.

Exhaust heat of an ORC can be further utilized to drive absorption chillers. Quoilin and Lemart [*35*] presented a compilation of various ORC manufacturers and market evolution for various waste-heat source-temperature ranges.

Typical applications of ORC in petroleum refineries include recovery of waste heat from HRSG fluegases (known as organic bottoming cycle), distillation overhead streams and some hot product streams. Most fluegas treatment methods, such as those involving fluegas scrubbing, carbon capture and sequestration, require the fluegas stream to be cooled prior to its introduction into the treatment train. Thus, the addition of an ORC system can be of great benefit when used in combination with a downstream fluegas treatment system, and can help to improve the overall economics of fluegas treatment by generating additional power from waste heat in the fluegas stream.

Kalina cycle. The Kalina cycle is a modified form of ORC using binary, mixed fluids instead of a single fluid. When a mixture of NH_3 and water (typically 70% NH_3) is used as the working fluid, the cycle is called "Kalina cycle". This particular cycle works with waste-heat-stream inlet temperatures in the range of 250 to 1,000°F and has the potential of efficiency gain over the ORCs. The main reason for improvement is that the boiling of the NH_3-water mixture occurs over a range of temperatures, unlike steam (conventional Rankine cycle) or ORCs at a constant temperature. Hence, the amount of energy recovered from the hot stream is higher, as illustrated in Figure 13. Integration of a Kalina cycle in a combined heat and power plant for efficiency improvement was presented by Ogriseck [*33*]. ORC and Kalina cycles are similar when the heat source is condensing steam.

Other improvements to ORC and Kalina cycles. There are a few improvements to ORC under different stages of development and implementation. A cascading closed-loop ORC (CCLC; www.chpcenternw.org/NwChpDocs/stinger%20presentation.pdf, accessed in January 2012), patented by WOW Energy Inc., claims to recover waste heat over a wide temperature range with better efficiency. Biasi [*9*] reviewed the application of CCLC to increase gas turbine power and efficiency.

The Neogen cycle (www.sti.nasa.gov/tto/Spinoff2005/er_7.html, accessed in January 2012) is a variation of Kalina cycle, developed by NASA and Unitel Technologies to achieve higher efficiencies. A capital cost comparison of Rankine cycle, ORC and Kalina cycle [*8*] is given in Table 3.

Plate and spiral heat exchangers

Compact-plate heat exchangers (CPHE) with their improved turbulence and counter-current flow, can achieve much higher heat-transfer efficiencies than traditional shell-and-tube heat exchangers, thereby increasing heat recovery and reducing the required heat-transfer area. Furthermore, the highly turbulent flow through the heat exchanger channels ensures the heat exchanger is kept clean, resulting in longer service time.

Case studies illustrating benefits of using CPHE in crude preheating, BFW preheating and steam generation are presented by Andersson [*1*]. CPHEs are generally applicable up to 450°C and 40 barg. Such units can be designed to work with crossing temperatures (for example, the cold-side outlet temperature is higher than the hot-side outlet temperature) and with temperature approaches as close as 3°C [*23*]. Packinox is an example of a welded-type CPHE that is suitable for very high pressures and temperatures, such as 120 barg and 650°C.

Plate heat exchangers with gaskets are used mainly for non-toxic and non-flammable substances at low temperatures and pressures. They can also be installed with fins.

Spiral heat exchangers exhibit better fouling resistance and higher heat transfer rates compared to shell-and-tube heat exchangers [*2*].

Final remarks

This paper provides a comprehensive review of several WHR methods and techniques applicable for process industries, especially petroleum refineries. It can be concluded from the review that considerable potential exists for recovering some of the wasted energy in the process industry, especially the petroleum refining industry, which can be used to improve energy efficiency. Economics of WHR vary from one unit to another and from site to site. A detailed economic study is required to decide the best WHR system(s) for a particular plant by considering many factors such as energy cost, plot size, capital cost, company payback criterion, operational, reliability, maintenance and process safety issues. ■

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Editor's Note

There are two additional sections to this article on Minimizing Waste Heat Generation, and a Summary of Waste Heat Recovery Methods, which are available online at www.che.com.

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Design and Specification of A Compressed Air System

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A practical overview of what to look out for when specifying a compressor and its associated components

An industrial compressed-air system is expected to supply air of defined quality, required pressure and desired quantity to all the plant air and instrument air consumers. With air being one of the most critical utilities of a chemical plant, a compressed air system should function efficiently and cost effectively. Therefore, designers should consider parameters such as air quality, air consumption and supply, storage and distribution and control management in their designs.

Most equipment manufacturers supply air compression and drying systems as packages comprised of many units put together. However, the purchaser of the system has the option of buying this complete package system or requesting only a portion of it. It is commonly observed that most compressed-air users design and install the air storage and distribution system themselves. For instance, in most FEED (front-end engineering and design) and basic engineering jobs the process licensors or the engineering contractors clearly demark the scope of work on a piping and instrumentation diagram (P&ID). Thus on a P&ID of a compressed air system, the compressor and dryer along with associated instrumentation and piping will be shown simply as a dotted block indicating the equipment manufacturers' scope. The downstream piping, storage receiver, distribution and instrumentation will be shown in much more detail indicating that the engineering responsibility lies with the owner or his or her detail-engineering contractor. Due to this predetermined work-scope split, process and mechanical engineers are entrusted with preparation-of-enquiry specifications of compressed air systems that will serve as input for the supplier of the compressor and dryer.

TABLE 1. TYPICAL PROCESS CONDITIONS AND QUALITY REQUIREMENTS OF INSTRUMENT AND PLANT AIR

Fluid	Compressed Air
Service	Instrument and plant air
Requirements:	
Process and design conditions	
Operating pressure, barg	8 – 8.5
Design pressure, barg	12.5
Operating temperature, °C	Ambient
Design temperature, °C	70 down to lowest ambient site temperature[2]
Quality	
Dew point at operating pressure at air dryer outlet[1], °C	At least 10°C below the lowest ambient site temperature
Maximum solid particle size, µm	< 3
Maximum quality of contaminants (oil, liquid and gas)	0.1 mg/m^3 or 0.08 ppm (w/w)

Notes:
1) Plant air does not need to be dried.
2) Typically –25°C at operating pressure or –40°C at atmospheric conditions in cold climate.

This article is intended for readers who want to gain a basic understanding of the components of a compressed air system. It also presents best practices that will prove helpful to a process engineer writing specifications for such a system.

Requirements

The main components of a conventional air-compression and drying system are shown in Figure 1. Air supplied by the compressor is split after the primary air receiver into two streams. A major part of the air stream is dried and utilized in the plant as instrument air. The other stream is not treated further and serves as plant air. If pressure in the instrument air header falls below a certain pre-set value, then a low-pressure switch (PSL) will close the shutoff valve and temporarily shut down the supply of plant air.

Before initiating the specification, the following points need to be considered for installing a proper air-system configuration:

1) Who are the end-users or air consumers of compressed air in the plant?
2) What is the expected quality of the compressed air in the plant?
3) How much total compressed air is required in the plant?
4) At what pressure is the air to be supplied to the consumers of compressed air in the plant?
5) What is the trend of air demand — intermittent or continuous?

Consumers or end users. As a first step, it is necessary to identify all equipment, machinery, instruments and tools that require compressed air in order to function. A list should be

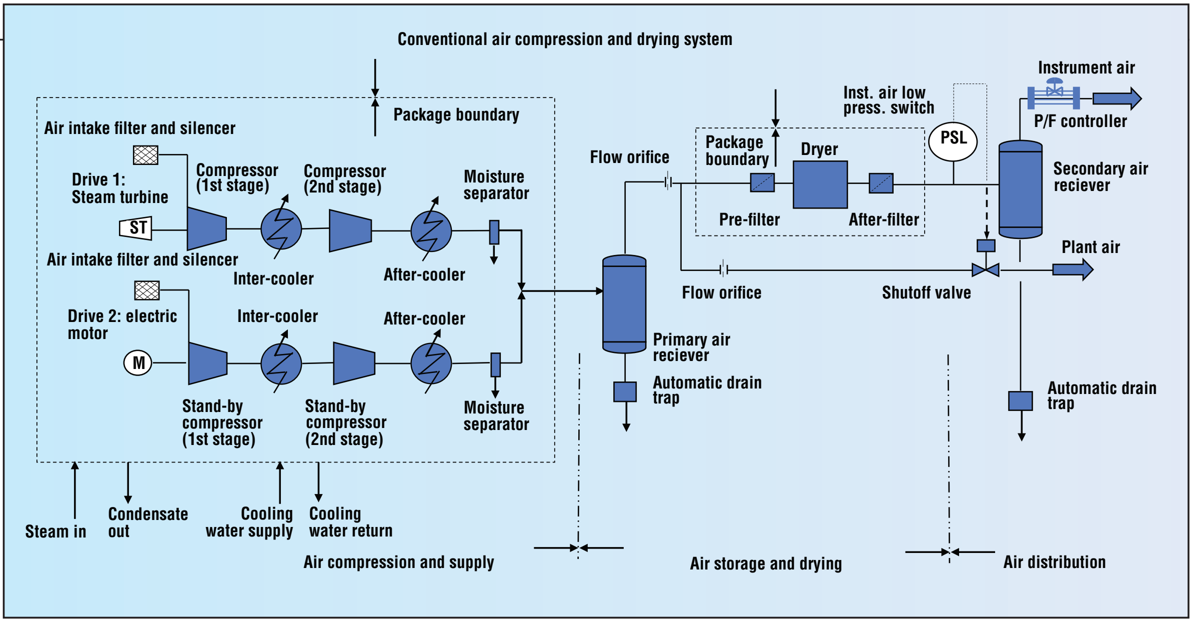

FIGURE 1. Shown here are the main components of a compressed air system

prepared that contains data, including number and type of consumers, minimum and maximum air-pressure requirements of each user, air flow required by each user, utilization factor and so on.

Compressed air has a number of industrial uses based on its service. A major application of compressed air, when used as instrument air, is valve actuator control. Other common applications of instrument air include use in laboratories, rotating equipment seals, paint spraying and powder coating, climate control and so on. Industrial workshops have consumer tools, such as pneumatic hammers, drills, grinders and such. Utility stations are often installed in a plant for general purposes and require plant air. Breathing air stations are provided in most chemical plants. Food, pharmaceutical and electronic industries require mostly process air. All of these users must be carefully identified and listed.

Quality. The air quality depends on the levels of contaminants that the end users can tolerate without affecting the smooth function of process (Table 1). Typical contaminants commonly encountered in compressed air systems include solids (dirt, dust, pipe scales, and particles from compressor wear), liquids (water and oil) and gases (water vapor, oil, chemical vapors). Based on the services catered to, the quality of compressed air ranges from plant air (least critical), process air and instrument air (critical) to breathing air (most critical).

The cost of producing compressed air goes up with each quality level. Each increased quality level requires installing additional purification equipment and leads to a higher initial capital investment. The future operating cost will also rise due to increased energy consumption and maintenance. Therefore, the air quality level should be determined as the first step.

The quality class of compressed air can be assigned as listed in detail in the international standard ISO 8573-1, which bases the classes on particle size, moisture and oil content in the air. For example, the air quality specification for instrument air is written as ISO 8573-1 Class 2.2.1, which means 1 micron particulate filtration, –40°F (–40°C) dew point and 0.08 ppm w/w (0.1 mg/m^3) oil filtration. The air class may also change from client-to-client based on the purity requirement of air for the particular service.

The most stringent quality class in this regard is Class 0. It does not mean that the contaminant level will be zero, but rather that the levels of particulate matter, dew point and oil content of the air supplied will be as per any values (typically lowest) specified by the user. Based on its equipment capabilities, the manufacturer must agree in writing that it can provide air of such a class.

Some points to be considered when talking about air quality are given below:

1. Minimizing or eliminating sources of contamination. Contaminants can enter the system at the compressor intake or could be introduced in the air stream by the system itself. Though equipment, such as separators, filters, dryers and condensate drains are used to improve the air quality, we can still try to reduce the load and thus the quality level expected from them by eliminating or minimizing sources of contamination. This can be done in a number of ways.

For example, locate the compressor's air-intake filters in a safe non-hazardous area in open air outside the plant building away from sources of dirt; dust; moisture; toxic, corrosive and flammable gases; and also at sufficient height (about 3 to 5 m) from ground level to avoid dust, debris, insects and so on. As the air intake is subject to extreme conditions with various contaminants causing fouling, corrosion and other problems, the material of intake filters should be selected with great care. Typically, the air intake filter and piping is made of stainless steel.

Also, one should avoid using lubricated air compressors in applications where high quality is desired.

2. Grouping of consumers. Consumers with similar air quality and pressure level can be grouped along with air-treatment equipment in close proximity. If different air quality requirements exist in the same plant then the plant can be divided into different units. The air treatment equipment can be kept dedicated to the end users with high-quality requirements.

For example, if only one consumer requires lubricant-free air, only air being supplied to it needs to be treated, thereby reducing costs. Alternatively (based on economic and operational analysis), high-quality air may be supplied with a dedicated, lubricant-free compressor. However, if there is a sufficiently high requirement of higher air quality (say 70% or more), then the entire plant can be supplied with this quality level.

Quantity — Estimating system capacity and margins. Before installing a compressor, the quantity of air flow required by the plant should be known. The required compressed-air capacity is the sum of air requirements of instruments, tools and process operations assuming normal plant operation at full load (taking into account the operational load factor of each piece of equipment). A study is typically carried out to understand the various applications requiring compressed air and the duration of their operation.

However, the total air requirement is not simply the sum of maximum requirements for each tool, but rather the sum of the average air consumption of each. For example, in most plants the capacity of a compressor is the capacity required for operating both instrument and plant air. Typically, the tool air systems are kept separate from the instrument and plant air system. During plant shutdown, the tool air requirements are especially large and can be met by hired portable compressors. In this way, oversizing the instrument and plant air compressor to cover this temporary large demand of air can be avoided.

In case it is planned to supply tool air from the same compressor, then care should be taken to ensure that: there is no interconnection between piping of the two air systems downstream of the dryer; the receiver size is adequate enough to supply instrument air at all times; and that a low pressure switch is installed that can cut-off the tool air supply in case the instrument air pressure drops.

The tool air requirement can be calculated as the sum of the number of tools times the air consumption per tool times the load factor. The load factor takes care of the time a particular tool is being utilized. This total tool-air requirement can be used to size the tool air compressor.

When designing a compressed air system, the approach should be to minimize the demand and properly size the compressor; oversizing should be avoided. Variation in air demand over time is a major consideration. Plants with a wide variation in demand need a compressor operating efficiently under partial load. Though the air compressor efficiency will increase with size, oversized compressors are extremely inefficient because they use more energy per unit volume of air produced when operating at partial load.

In existing installations, the air demand is monitored with the help of flowmeters installed on main headers and at various points in the system. The electronic data loggers that track compressor activity over time also help monitor the demand. The data thus measured can be used to size a new plant. For new installations the compressor capacity may be calculated as the example shown in Table 2.

Sizing for future demand. Always keep in mind that a plant may need a new process unit sometime in the near future. As an example, say that this unit will have a requirement of approximately 500 Nm^3/h and the application lies in the same pressure and quality range as that of Table 2. Due to the availability of these data well in advance during the sizing stage, 500 Nm^3/h are added to the existing flow of 3,400 Nm^3/h and a new capacity is estimated as 3,900 Nm^3/h. Although in this case it may seem that the future requirements are taken care of, in reality the compressor has become oversized for current use. In such a case, the logical approach will be to install a smaller reciprocating unit of 500 Nm^3/h at a later stage when actually needed.

Thus care should be taken to avoid adding extra margins to cover future applications or supply tool air as this may lead to oversizing the compressor. When such demands are encountered, they can be met any time by future compressor installations or temporary rented installations.

Pressure level. Process engineers specify air-pressure requirements for the process in their basis while the valve and pneumatic tool manufacturers rate their valve and tools for specific purposes as given in their literature. Each air consumer has a certain operating pressure requirement to function correctly. The highest working pressure requirement of a consumer is used to determine the correct installation pressure (or the compressor discharge pressure). In the same system for the consumers where such high pressures are not required a self-regulating valve (or a pressure control valve (PCV)) can be installed upstream to reduce the pressure at the consumer's inlet.

To decide the installation pressure, the pressure at the compressor discharge flange needs to be estimated. To estimate this pressure, the losses encountered in the circuit due to equipment (filters, dryers, flow elements, heat exchangers, piping and so on) must be added to the maximum pressure value required at the consumer end. The example given in Table 3 clarifies this point.

Table 3 shows that the working pressure is determined by adding system pressure losses to the maximum pressure value required at the consumer end. The equipment pressure drops are dependant on vendor design and the values used in the example are typical values encountered. The pressure drop in the filters are low initially but increase over time. For example, a desiccant dryer after-filter may accumulate desiccant fines over time, which can cause an increased pressure drop and increased power consumption.

The flow regulation of a compressor may bring about flow variations in the system. As pressure drop through a given pipe is directly proportional to the square of flowrate ($\Delta P \propto Q^2$) through the pipe, the pressure drop will increase in case of a higher flow demand. To compensate for this varying pressure drop due to compressor regulation, a margin is considered.

As a rule of thumb for compressed air systems in the range of 100 psig

TABLE 2. ESTIMATING AIR COMPRESSOR CAPACITY

Symbols:	Assumptions:		
C = Compressor capacity, Nm^3/h	Air consumption / instrument	3.2	Nm^3/h
I = Instrument air requirement, Nm^3/h	Air consumption / utility station	200	Nm^3/h
P = Plant air requirement, Nm^3/h	% of utility stations working simultaneously	10	%
N = Number of instruments in plant			
u = Number of utility stations in plant	Flow margins to account for :		
U = Number of utility stations working	a) Leaks and future expansion	20	%
Formulae:	b) Air dyer regeneration	20	%
C = I + P	c) Compressor wear and efficiency (only		
I = N × (Air consumption / instrument)	for reciprocating type, in addition to a & b)	20	%
U = u × (% of utility stations working simultaneously)			
P = U × (Air consumption / utility station)			

Calculations:

For an example we consider the following figures:

N =	475	(say)	
u =	60	(say)	
U =	60 × 10%	6	
I =	475 × 3.2	1,520	Nm^3/h
I =	1,520 × 1.2 x 1.2	2,188.8	Nm^3/h (Considering centrifugal type and applying flow margins a & b to above flow)
P =	6 × 200	1,200	Nm^3/h
C =	2,189 + 1,200	3,388.8	Nm^3/h
		~ 3,400	Nm^3/h

Hence the estimated compressor size is 3,400 Nm^3/h

(approximately 7–8 barg), for every 2 psi (0.14 bar) increase in compressor discharge pressure, the following two changes occur:

1. Energy consumption increases by approximately 1% at full output flow.
2. Energy consumption increases by another 0.6–1% due to unregulated usage (unregulated usage is typically considered to be about 30–50% of air demand).

The combined effect is a net rise of about 1.6–2% [*1*].

With this information in mind, one should be careful in finalizing the system pressure. The calculated value of the compressor's discharge pressure should not be simply rounded to the nearest whole number. Instead, equipment manufacturers should be consulted for obtaining exact values of pressure drops across the equipment at maximum flowrates. These realistic values should then be used for calculating the compressor discharge pressure. Also, an attempt should be made to select equipment and instruments with minimum pressure drop.

Operating with a lower pressure than needed will lead to erratic function of instruments and endanger the process. A higher pressure, on the other hand, will cause more energy consumption and may lead to system leaks and thus increases of the plant operating costs in future.

A package enquiry specification

The whole idea of writing an enquiry specification for the package system is to do the following:

1. Build a basis of what is expected from the compressed air system.
2. Present sufficient and precise technical data to the equipment manufacturer to design this system.
3. Identify the scope of supply.

Some important points for the vendor and the buyer which should be put in the specification in a clear and concise way are given below.

1. Equipment, system and site details. Equipment details should contain some data given by the design engineer and some information left for the equipment manufacturer to confirm. Data, such as number of compressors and dryers; capacities required; operating and design conditions; fluid properties; allowed noise level; expected air quality at the dryer outlet; maximum pressure drop across dryers and filters; and dryer outlet temperature are to be given by the designer. On the other hand, data such as equipment-rated capacity confirmation; number of compressor stages required; absorbed power and efficiency at shaft; suction- and discharge-flange size and rating; consumption of utilities like cooling water and instrument air; design temperature based on compressor discharge temperature; dryer cycle time; drying period; regeneration period; cooling period; tie-in point list; instrumentation and control schemes; and so on, are given by the vendor.

System details should cover the operational and control philosophy, number of working and spare equipment, quality, quantity, pressure requirements of air, schematic sketch and so on.

Battery limit conditions, utility availability, meteorological and climatic conditions, site location, geotechnical data, and any limitations on plant dimensions details constitute the site details.

2. Scope of supply. A vendor must understand what exactly he has to furnish to the buyer. Commonly, vendors supplying compressors also supply receivers, filters and dryers together to form what is called as the air compression-and-drying package. Typical details listed in the scope of supply are equipment; interconnecting piping; control panel; instrumentation; platforms and ladders; bolts; lugs; skids; fabrication; surface preparation and painting; inspection and testing; first fill (desiccant, oil) supply; installation; documentation; site shipment; authority approval and certification.

3. Reference and procedure. Industrial equipment manufacturers have their own set of internal manufacturing quality standards. However, most chemical process industries (henceforth referred in this article as "client") require the vendors to adhere to global manufacturing codes, standards, guidelines, good recommended practices, directives (for instance, ASME, API, ANSI). International clients operating multiple industrial units at times have their own set of technical standards and guidelines that the vendor has to comply with. Typically, a list of such codes and standards to be followed is available in the design basis of a project and needs to be conveyed to the vendor through specification.

This section should also contain administrative, procedural and other temporary requirements to be followed, including submission of experience record proforma, complying to equipment qualification criteria, instructions for delivery to site, scheduling, warranties, and spare and maintenance agreements.

TABLE 3. ESTIMATING THE WORKING PRESSURE

Pressure required at consumer end	P	6	barg
Element		Typical pressure drop	
Final filter	ΔP_1	0.3	bar
Air distribution piping	ΔP_2	0.1	bar
Dust filter (dryer after filter)	ΔP_3	0.1	bar
Dryer	ΔP_4	0.15	bar
Coalescing filter (dryer pre filter)	ΔP_5	0.1	bar
Flow element	ΔP_6	0.25	bar
Compressor after-cooler	ΔP_7	0.1	bar
Compressor inter-cooler	ΔP_8	0.1	bar
Compressor regulation range	ΔP_9	0.5	bar
Total pressure drop	ΔP	1.7	bar
Pressure required at the compressor discharge flange	$P + \Delta P$	7.7	barg

Specifying equipment data

A compressed air and drying package contains many types of equipment, such as air-intake filters, compressors, inter-coolers, after-coolers, moisture separators, receivers and so on. The engineer who writes specifications for the package does not necessarily size all this equipment. Based on rules of thumb, good engineering practices and sound technical assumptions, he or she can fairly estimate the capacities and sizes of these pieces of equipment. This may help different engineers from disciplines like piping, static equipment, electrical and so on to get at least preliminary data to proceed with their work. For example, due to availability of equipment sizes, the layout engineer can assign preliminary locations for this equipment (which will be supplied as packages or skids) on the allotted plot plan and fix the area for the air unit in the basic stage.

The sizes of some of the equipment estimated by the engineer may not necessarily match that given by the vendor. Though seeming correct on paper, such equipment may or may not give the desired result. This may be either due to the capabilities and limitations of the selected vendor's manufacturing and machinery or due to the vendor's proprietary design. There may be certain technicalities in terms of fabrication or state-of-art development that only the vendor may be better aware of. For example, air intake filters or moisture separators are entirely a vendor-supplied proprietary item. This will be designed by the vendor based on the particle-size retention and moisture data given by the design engineer.

During the technical bid analysis (TBA) stage based on the specification given by the designer, different vendors offer their proposals that have to be evaluated technically for energy efficiency and lifetime operating cost. The data furnished by the vendor need to be thoroughly checked by the engineer to see that all of his or her technical and operational requirements are in line with that given in the specification. Any other additional data furnished as a result of proprietary design should also be checked at least for correctness and compliance to standards.

Air compressor selection

During compressor and drive selection, it must be kept in mind that in most industries it is the compressor that utilizes more electricity than any other equipment. Records show that in many instances during the first year of operation, the operating cost was almost twice that of the initial purchase price of the equipment.

When selecting new compressors, industries with existing compressed-air installations have an advantage. They monitor their current air demand and supply trends and also the reliability and suitability of existing air compressors. The data thus obtained will prove useful to them in selecting and sizing any future compressed air installations.

The following variables, if analyzed correctly, will provide a fair idea of the compressor type to be selected before consulting a compressor vendor for details:

1. Hours of operation per month
2. Nature of demand (continuous or intermittent)
3. Pressure and flow requirements
4. Environment (clean or dirty)

A preliminary selection of the type of air compressor can be made from the typical graph of inlet flow versus discharge pressure, as given in the GPSA handbook [*2*]. For example, suppose we want to select an air compressor for 1,000 acfm and a discharge pressure of 122 psig. By using such a graph, we will observe that for our application we will end up selecting the following types of compressors: reciprocating (single and multiple stage), rotary screw and centrifugal (single and multiple stage). All three types of compressors can suit the application. So how do we decide which type of compressor is the best? The answer is that we must not select any compressor that simply fulfills the flow and pressure requirements, but the one that is best suited to the application (see Table 4).

Suppose for the same application given above we further know that the nature of load will be continuous, heavy (high flowrate) and the system has to be lubricant free. For high flowrates and oil-free conditions centrifugal compressors are a common choice. Also centrifugal compressors work well under continuous load rather than variable load. Due to these reasons a centrifugal compressor will become a first choice for our application.

Correct flowrate units

As air is compressible it will occupy different volumes at different tem-

TABLE 4. COMPRESSOR SELECTION			
Compressor type	Reciprocating	Screw	Centrifugal
Best suited for:			
Flowrates	Low	Medium	High
Nature of air demand	Fluctuating or varying	Continuous or steady	Continuous or steady
Nature of operation	Intermittent	Continuous	Continuous
Operating efficiency at lower / part loads	Most efficient	Good	Poor, susceptibility to surge
Reliability and maintenance	High wear	Good	Medium maintenance but frequent
	Complex and frequent maintenance	Easy and low maintenance	Check for unbalance and vibration

peratures and pressures. There is no global standard for specifying air compressor flowrates. Care should be taken to avoid confusion due to usage of different units like cubic feet per minute (CFM), standard air capacity (SCFM), actual air-compressor capacity (ACFM), inlet air capacity (ICFM), free air delivery (FAD), normal cubic meters per hour (Nm^3/h) and so on.

Compressor vendors rate their compressors in terms of volume. The vendor catalogs typically state compressor flows in CFM. It also seems logical and easy to visualize equipment size in terms of volume rather than mass. Sometimes mass flowrate (kg/h) of gas is given by a design engineer with the understanding that mass of a gas remains constant. In such cases, the moisture content in the gas (if any) should be subtracted from the given flowrate. The vendor should be told if the flowrate is wet or dry.

When dealing with process gas applications, the unit SCFM is commonly used while FAD finds a more common usage in compressed air applications.

Number of stages and drives

Multiple stages are used in compressors to achieve higher pressures. As high-pressure compression is carried out in multiple stages, intercoolers provided between the stages remove heat of compression and bring down the temperature to approximately that at the compressor inlet. As a result of this cooling, the density of air increases and volumetric flowrate of the gas going to the next stage reduces. Due to this volumetric reduction the work of compression and hence the power need reduces.

The number of stages required is determined by the overall compression ratio. The compression ratio is calculated considering both the initial pressure (P_1) and final pressure (P_2) in absolute units. A gage value is only a representation of pressure. It does not include the atmospheric pressure and hence is not the true pressure of the gas. Typically in instrument air systems, the overall compression ratio is about nine. Due to this high compression ratio we may need multiple stages.

The compression ratio per stage is limited by the discharge temperature and usually does not exceed four. However, sometimes for small sized air units with intermittent duty, a higher compression ratio may be used by the vendor. Table 5 can be used for choosing number of stages.

Though an engineer can state the value of the number of stages in the specification, this value is subject to the manufacturing capabilities of the vendor.

In general, variable speed control is achieved by using a steam turbine, gas turbine or diesel or gasoline engines. Constant speed control is achieved by electric motors. Variable speed can also be obtained from electric motors with variable speed drives. Drive selection can be done based on the chart given in the Instrument Engineers Handbook [*3*].

Operational philosophy/spares

Most plants install at least two compressors, one working and the other a spare or standby. A spare air compressor is required in the system to ensure maximum reliability and availability of compressed air during emergency scenarios, such as equipment failure. Mechanical failure of a compressor will directly affect instrument air supply in the plant after the stored air capacity of the air receiver is completely exhausted. A spare compressor is installed where process criticality of instrument air cannot be compromised at any cost. The capacity of the spare compressor is kept the same as the largest duty compressor.

Even to cater to the normal operation, sometimes multiple compressors are installed in a plant. For example, for a certain known capacity we have a compressor installation of 2 × 100%. This actually means that we have two installed compressors, out of which one is working and the other a standby. Selecting this installation may mean that we get a single compressor whose working capacity is very large. Instead we can opt for a combination of a number of smaller compressors, which may prove an attractive economic and operating alternative than having one large compressor. Likewise, a 3 × 50% combination where we have three installed compressors, out of which two are working and the third a standby is an another option. For critical services, the option of keeping a spare rotor handy is also considered at times.

Generally, a combination of different drives is used to run compressors. A petroleum refinery may have units, for instance a hydrogen generation unit (HGU) or a sulfur-recovery unit (SRU), where excess high-pressure (HP) steam is generated in the process. If the generated excess steam is not being used or exported elsewhere and is sufficient to drive a turbine, then a steam-driven turbine can be selected as the main drive while an electric motor may be used to operate the other compressors.

For example, a compressor with a steam-turbine drive may supply 65% of the total flow requirement while the compressor with electric motor and variable speed drive (VSD) may supply 35% of the total flow requirement. The spare will also be VSD driven and sized to supply 65% of the total flow requirement in case of emergency. This leads to electric power saving, increased reliability due to usage of a reliable source of utility (steam in this case) and also extraction of useful work from excess steam. All the three compressors will be sized for 65% of the air demand. The actual operating schemes are decided and approved by the chemical plant personnel along

TABLE 5. CHOOSING NUMBER OF STAGES BASED ON COMPRESSION RATIO

Compression Ratio (P_2/P_1)	Number of stages
1–4	1 stage, sometimes 2 stages
4–20	2 stage, sometimes 3 stages
20+	3 stages

TABLE 6. CALCULATING AIR RECEIVER SIZE

Ambient air temperature	T	°C	40
Capacity required	C	Nm^3/h	3,400
Capacity correction (free air delivery)			= 3,400 × (273 + 40) / (60 × 273) = 64.96
Hold-up time required	t	min	10
Ambient pressure	P_a	bar	1.01
Initial/storage pressure	P_1	barg	8
		bara	9.01
Final/destination pressure	P_2	barg	4.5
		bara	5.51
Volume	V	m^3	188

with the design engineer based on their previous experience, cost effectiveness and RAM studies.

Running a smaller compressor at full load proves more energy efficient than running a larger compressor at low load. Also if there is a large variation in air demand (like low demands during weekends) then we can switch off one of the two working compressors. There may be a combination of operating compressors based on sequential controls to avoid running the larger compressor at such times.

Air receiver sizing

The air receiver is used to store a certain volume of compressed air and supply it for use as needed. In the event of a failure or a shutdown of the operating compressor, the receiver provides the necessary air supply for the time needed to start (manually or automatically) the standby air compressor.

An air receiver located on the discharge side of a reciprocating compressor also helps to dampen pressure pulsations. Due to availability of a large vapor space, the receiver provides radiant cooling and also collects any condensed liquid.

The air receiver is sized such that it supplies a compressed air demand for an amount of time required for the air pressure to drop from compressor discharge pressure to the minimum pressure required at the air consumer end. The size of an air receiver can be calculated by the formula (based on Boyle's law, $PV = a\ constant$):

$$V = \frac{t \times C \times P_a}{(P_1 - P_2)} \quad (1)$$

Where,
V = Receiver volume, m^3
t = Time allowed for pressure drop ($P_1 - P_2$) to occur, min
C = Free air delivered at compressor discharge, Nm^3/h
P_a = Atmospheric pressure, bara
P_1 = Initial pressure or compressor discharge pressure, bara
P_2 = Final pressure or minimum pressure required at the air consumer end, bara

The time t, also known as the residence time for receiver sizing, is a function of criticality of the system, operator intervention for maintenance and piping diameter. This time typically varies from 5 to 15 min. In plants where provision of auto start of spare compressor is given, the residence time may be reduced to 1.5 to 2 min considering reliability of auto start and subject to client's approval and operating experience. An example is provided in Table 6.

The initial pressure (P_1) is usually taken as the pressure at the compressor discharge flange considering line losses to be negligible; and the final pressure is taken as the pressure required at the instrument for proper operation. Sometimes the receiver volume calculated from the given formula may turn out to be too large to be economical. To reduce the receiver volume (V), the value of the term ($P_1 - P_2$) should be increased. To achieve this, the value P_1 should be increased. Storing air at a higher pressure by installing a smaller reciprocating machine will reduce receiver size and prove economical compared to installing a receiver with high storage volume. Sometimes for a critical system, an additional receiver operating in parallel can be installed for additional reliability, if required.

The assumptions for this exercise are the following:
1. The receiver volume is at ambient temperature.
2. No air is being supplied to the receiver by the compressor.

Location of air receiver

The air receiver is typically installed at two different locations in the compressed air system. The receiver located immediately downstream of compressor but before the dryer is known as the wet receiver or primary receiver. The receiver located downstream of the dryer is known as the dry receiver or secondary receiver.

The main function of the wet receiver is to act as a pulsation dampner (typically for piston reciprocating compressor) and bring about a stabilization in pressure. It provides additional radiant cooling to help condense some moisture and reduce load on the dryer. On the other hand, the dry receiver meets the high short-term air demand from consumers by the air stored in it, thus avoiding cycling of the compressor.

Most rotary screw compressors (lubricant injected) are equipped with capacity control by inlet valve modulation and are designed to match the output from the compressor with the demand from consumers. Thus it seems that an air receiver can be avoided in this case.

However, absence of an air receiver will not shield the compressor from pressure fluctuations from the demand side downstream of the receiver. Also the ability to keep the compressor unloaded for longer time during periods of light loads will not be available. Thus the requirement for an air receiver is a must.

The following mountings are essential for an air receiver:
1. Pressure gage
2. Safety valve
3. Automatic drain trap and manual drain tapping
4. Fusible plugs
5. Level transmitter
6. Manhole

The receiver inlet nozzle should be located in the lower portion of the vessel and the outlet nozzle should be located at the top to assist settling of liquid droplets

TABLE 7. AIR DRYER SELECTION

Dryer	Chemical deliquescent dryer	Refrigerant dryer	Desiccant dryer	Heat of compression dryer	Membrane dryer
Basic configuration	Single tower with a salt-packed bed	Combination of air-to-air heat exchanger followed by refrigerant-to-air heat exchanger. Variation: Cyclic dryers; indirect cooling through thermal storage medium	Twin towers with desiccant packed beds	Single or twin towers with desiccant packed beds	Membrane unit
Drying action	Moisture is absorbed by salt bed. Salt dissolves in water and is lost to drain during periodic draining	Cooling air from compressor discharge in air-to-air heat exchanger to reduce load on the dryer followed by direct cooling in refrigerant-to-air heat exchanger. Indirect cooling in thermal storage media	Moisture adsorption in desiccant bed	Moisture adsorption in desiccant bed	Selective adsorption. Moist air enters the dryer. Water permeates the membrane walls while dries air continues to travel further
Drying medium	Salt beds of sodium, potassium, calcium and those with a urea base	Refrigerant / thermal mass	Desiccant media like Silica gel, alumina and molecular sieves	Single tower: Rotating desiccant drum in single pressure vessel. It uses hot air taken directly at a point after compressor discharge for regeneration purge. Twin tower: Desiccant bed (heat regeneration by hot air taken directly after compressor discharge)	Membrane
Drying medium regeneration	Not possible, salt is used up and make-up of salt is required	Not applicable.	Possible	Possible	Not possible, membrane has to be replaced
Dew point attained	15–50°F below inlet air temperature	35–39°F	–40 to –100°F	–40 to –100°F	40 to –40°F
Approximate power requirement, kW/100 cfm	0.2	0.79	2 to 3	0.8	3 to 4

Materials of construction

The most common material of construction (MOC) used for a plant- and instrument-air system is carbon steel. The compressor and dryer package parts in contact with moist air shall be selected with care. Corrosion allowance will be included as per project standard or design basis. The equipment material is specified by the design engineer and is subject to confirmation and justification by the vendor.

The compressed air receiver is made of carbon steel. As the compressed air receiver also serves the purpose of condensate collection and most liquid is knocked off and collected at the receiver bottom, it is susceptible to corrosion. To avoid this, the receiver is typically provided with an internal protective resin coating (for example, heat-cured phenolic resin).

Pipelines are typically carbon steel, except lines with smaller diameter in the range 0.5 to 2 in. are galvanized carbon steel. This is done typically because lines that are smaller in diameter can get clogged by any rust, corrosion or other solids caused by carbon-steel corrosion or eroding, and may create problems for the instruments downstream to which they supply air.

Air dryer selection

Water in compressed air, either in the liquid or vapor phase, can cause a variety of operational problems for consumers of compressed air. Problems encountered may include freezing of outdoor air lines, corrosion in piping and equipment, malfunctioning of pneumatic process-control instruments, fouling of processes and products and so on. Hence, using an air dryer becomes necessary to remove the water vapor from the compressed air.

The air dryer is selected based on the required pressure dew point. To select the correct dryer, first it is important to understand the concept of dew point. Atmospheric air contains moisture. If we keep on cooling air we will attain a temperature where the moisture contained in air will begin to condense and drop out. This temperature at which condensation first occurs is the dew point of air at atmospheric pressure. If we compress atmospheric air, it will occupy a smaller volume. Due to compression the water molecules will come closer, coalesce and condense out. This temperature at which water vapor will begin to condense at the applied higher pressure is the dew point at the applied pressure, or pressure dew point. Thus the pressure dew point (dew point at higher pressure) will be different than the dew point of air at atmospheric pressure.

In general, air at a temperature

higher than atmospheric will hold more moisture, and air at a pressure higher than atmospheric will hold less moisture. The air leaving the compressor is both at a higher pressure and temperature than atmospheric. Thus at the compressor outlet a phenomenon occurs where higher pressure will cause some of the moisture to be removed off while the higher temperature will enable the air to hold on to some moisture. The pressure dew point is more meaningful as it indicates the dew point at the operating pressure.

The vendor must be provided with maximum flowrate, required dew point, maximum and minimum inlet-air pressures, maximum and minimum inlet-air temperatures, maximum cooling-water temperatures, maximum pressure drop for dryer design. Table 7 provides guidelines for dryer selection.

Pre-filters are installed upstream of the air dryer to protect the drying medium (example, desiccant) from getting contaminated. After-filters are installed downstream of the air dryer to prevent desiccant fines from entering the system downstream. After-filters also help in removal of vapor, harmful chemicals, micro-organisms and so on. Both the filters also serve to coalesce oil and moisture droplets, which can then be drained. Over time, the filters may get clogged and cause increased system resistance and energy consumption. Hence, timely filter maintenance is very important in compressed air systems. Differential pressure gages should be installed across filters to keep a check on the pressure drop through them.

Besides these filters, small filters may also be installed at the point-of-use end. Their function is to filter particles generated in the distribution piping.

Distribution piping

The compressed-air distribution piping will be sized based on the ACFM for a minimum pressure drop of 0.1 bar/100 m of piping. Air velocities of the order of 5 to 10 m/s are quite commonly maintained. Incorrect sizing may lead to excess pressure drop, hence piping systems should be designed properly. Every possible attempt should be made to minimize pressure drop. For example, locate air supply, storage and drying systems closer to the consumer end, and minimizing pipe bends.

Air distribution systems are mainly designed as closed-loop or ring main headers. In the ring header the air flow is split into two directions from a point and can flow to an end-user in two different directions. Thus for a particular air consumer the air flow is available from both directions of the header. As the air flow is halved, the velocity reduces and also the pressure drop.

Piping in air systems should not contain loops or be installed underground. In addition to instrument air, if other compressed air services like plant air or tool air are supplied from the same compressor then no cross connections should be kept between these three air services downstream of the dryer. ■

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Engineering Practice

Applying ASME Boiler Code to Steam Generation Systems

Determining when and how the ASME boiler code applies to steam systems in petrochemical operations can be difficult. Guidance on the requirements for boiler code stamping can help

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The ASME Boiler and Pressure Vessel Code (ASME BPVC), which is administered by ASME (New York, N.Y.; www.asme.org; founded as the American Society of Mechanical Engineers), is a well-established standard for the design and fabrication of boilers and pressure vessels. ASME code-symbol stamps show compliance with the requirements of the standard, but code stamping of steam systems in ethylene and other large heaters can be controversial.

Much of the challenge for those in the chemical process industries (CPI) stems from the fact that the main focus of the code is on power boilers, rather than on petroleum refinery or petrochemical heaters, so definitions are sometimes not clear. Furthermore, it can be difficult to define which authority has jurisdiction over steam generation systems in the CPI. Even in the U.S., state boiler codes vary among the states. In other countries, adherence to ASME standards may or may not be required, thus leaving it up to the owners of the asset to decide. This article provides guidance on the requirements for stamping within the ASME code and explains how state boiler codes can affect the requirements.

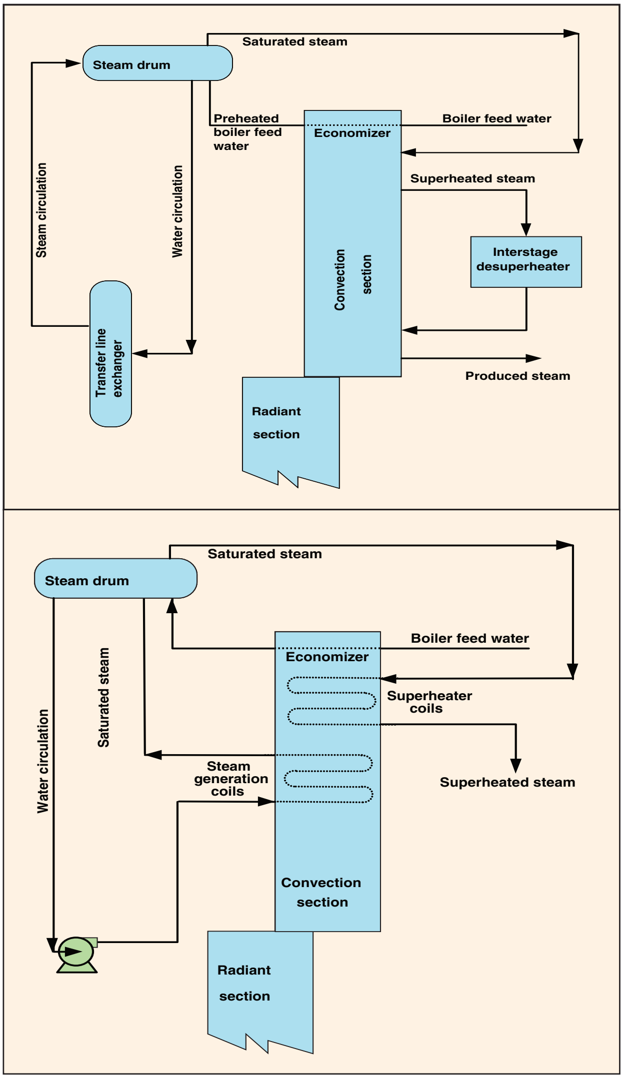

FIGURE 1. Most operators agree that Section 1 of the ASME Boiler and Pressure Vessel code is the most appropriate standard for steam-generation systems, such as the more common natural-circulation type (above) and the forced-circulation type (below)

Steam-generation systems

When it comes to steam-generation systems, safety is the primary concern for both the owners of the system and for the authorities that have jurisdiction over them. All parties want safe and reliable equipment designed for the intended purpose. Section 1 of the ASME BPVC contains the rules for construction of power boilers [*1*]. Power boilers are defined as boilers that generate steam at pressures in excess of 15 psig, for external use. Most designers and owners of steam-generation systems from fired heaters agree that ASME Code Section 1 is the appropriate design code for the steam system.

Steam systems in fired heaters typically consist of the following: steam drum; relief valves; boiler-feedwater preheat tubes; steam-generation tubes; steam superheating tubes; an end-stage or interstage de-superheater; startup vent and silencer; interconnecting piping; inline instruments; and, for ethylene heaters, a primary transfer line exchanger (TLE) as shown in Figure 1. The steam generation system can be one of two types: either natural circulation or forced circulation. The natural circulation type is more common. Figure 1 (bottom) shows a typical set-up for a forced-circulation system.

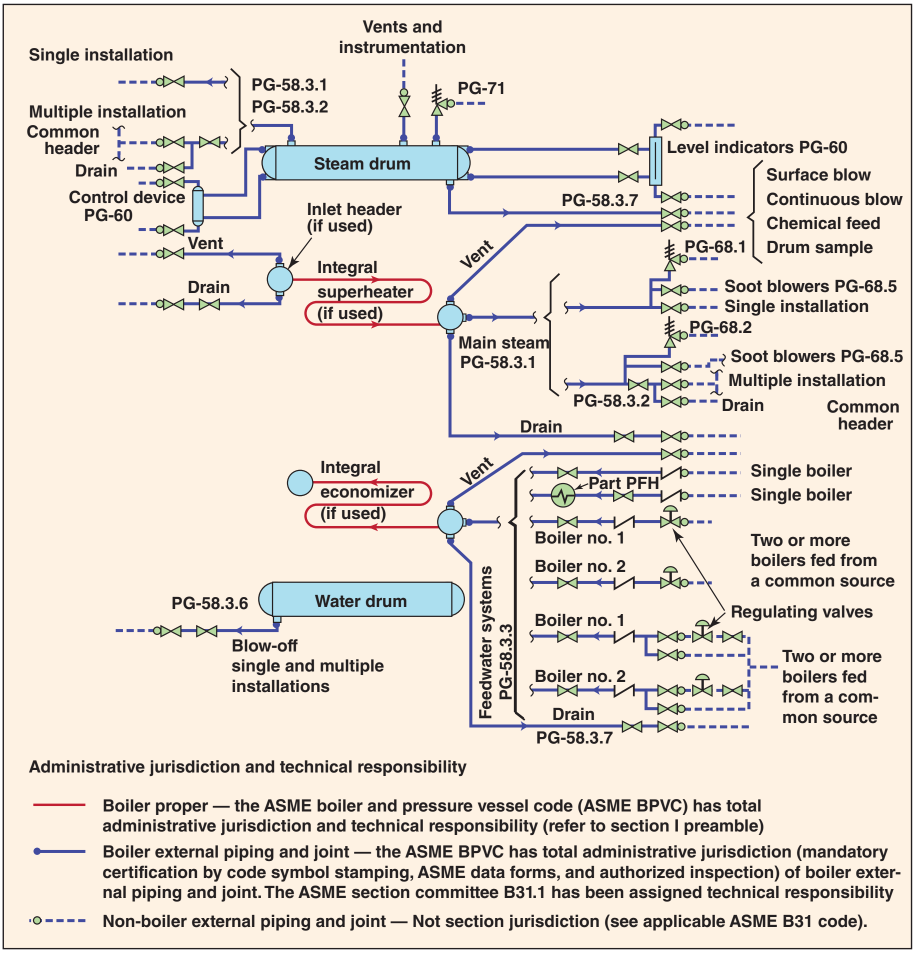

FIGURE 2. The ASME BPVC describes three areas of technical responsibility: boiler proper; boiler external piping and joint; and non-boiler external piping and joint

ASME jurisdiction

The jurisdictional limits of ASME from Section 1 of the BPVC are shown in Figure 2. The figure, "Code Jurisdictional Limits for Piping — Drum Type Boilers," was adapted from ASME 2010 BPVC Section 1, with permission of ASME [2].

The ASME BPVC describes three areas of technical responsibility: the boiler proper, the boiler external piping and joint, and non-boiler external piping and joint. The boiler proper falls under the administrative jurisdiction and technical responsibility of Section 1 of the ASME BPVC. The boiler proper and boiler external piping and joint fall under the administrative jurisdiction of ASME BPVC and require mandatory certification, along with code stamping, ASME data forms and authorized inspection.

Technical responsibility for boiler external piping is assigned to the ASME section committee of B31.1. Non-boiler external piping and joint is not considered to be within the jurisdiction of ASME BPVC section 1, and those components are usually designed according to B31.1 in utility applications or B31.3 in chemical or refinery plant applications.

Even the application of the "Code Jurisdictional Limits for Piping — Drum Type Boilers" to steam systems in ethylene heaters can be problematic, because the language of the section is clearly intended for a conventional boiler. Most engineers agree, and several U.S. state boiler codes require that the steam drum be designed to ASME Section 1. In non-code states, the drum may be designed to Section VIII.

Steam superheat tubes, economizer tubes and steam generation tubes are also designed to meet the requirements of ASME Section 1.

Stamp requirements

The ASME BPVC clearly requires all equipment considered to be "boiler proper" and "boiler external piping and joint" to be stamped. Steam systems for ethylene heaters are typically manufactured by multiple vendors and assembled in the field by a different contractor. The particular ASME stamp and partial data report produced depends on the type of manufacturer. Table 1 shows a common setup, where multiple vendors provide the various components of the steam system.

Master stamp

If compliance with ASME BPVC Section 1 is required by law, a master stamp is required. For a forced-flow steam-generation unit, the code is clear — manufacturers of forced-flow systems must provide a master stamp. For field-assembled boilers, a master stamp is clearly required.

The master stamp must be provided by whoever has responsibility for the entire boiler unit. In cases where the manufacturer is not the assembler, the manufacturer or engineering contractor may provide partial data reports to

TABLE 1. MULTIPLE VENDORS SUPPLY VARIOUS STEAM-SYSTEM COMPONENTS									
	Component name	Category	ASME Code	Code stamp (by vendor)		Code stamp requirement (by field assembler)		Assembler Stamp (by field assembler)	
				Stamp type	ASME partial data report	Stamp type	ASME partial data report	Stamp type	ASME partial data report
1	Boiler feed water (BFW) feed piping to pre-heater	Piping	ASME B31.1			PP	P-4A		
2	BFW feed piping to de-superheater	Piping	ASME B31.1			PP	P-4A		
3	BFW pre-heater	Equipment	ASME SEC. I	S	P-4A				
4	BFW piping to steam drum	Piping	ASME B31.1			PP	P-4A		
5	Steam drum	Equipment	ASME SEC. I	S	P-4A				
6	Pressure-reducing de-superheating stations (PRDs) on steam drums	Pressure relief valve	ASME SEC 1	V	P-7				
7	Riser and downcomer	Vendor piping	ASME SEC. I	S	P-4A	S	P-4A		
8	Primary transfer-line heat exchanger (TLE), steam-side	Equipment	ASME SEC. I	S	P-4A			A	P-3A
9	Primary TLE blowdown	Piping	ASME B31.1			PP	P-4A		
10	Super high-pressure (SHP) piping from steam drum	Piping	ASME B31.1			PP	P-4A		
11	Upper steam superheater (USSH)	Equipment	ASME SEC. I	S	P-4A				
12	De-superheater	Equipment	ASME SEC. I	S	P-4A				
13	De-superheater piping	Vendor piping	ASME SEC. I	S	P-4A	S	P-4A		
14	Lower steam superheater (LSSH)	Equipment	ASME SEC. I	S	P-4A				
15	SHP export piping	Piping	ASME B31.1			PP	P-4A		

the assembler, and the assembler may affix the stamp jointly with the manufacturer, according to the rules of section PG-106 in ASME BPVC Section 1. In this case, both the engineering contractor and the authorized inspector must sign the P-3A forms provided by the assembler.

The question that arises for steam-generation units on ethylene heaters is this: When adherence to ASME BPVC Section 1 is voluntary, is a master stamp required? The answer is no. If compliance is voluntary, the owner of the system may opt to comply with some parts of the code, but not others.

Owner requirements

Almost all owner specifications require that the steam drum, primary transfer line heat exchanger (TLE; steam side), and boiler proper piping are designed according to ASME BPVC Section 1, and stamped by the supplier. Few owners require a master stamp unless a stamp is required by the local authority having jurisdiction.

Owner specifications for steam systems can sometimes be confusing, and at other times do not address the subject at all. Statements such as "the steam system shall be in accordance with ASME section 1" can be difficult to interpret.

State boiler code requirements

In the U.S., the individual states regulate boilers. There is no "federal" boiler code that applies to all states and territories. Not all 50 states have boiler codes. Most states that do have boiler codes require compliance with ASME BPVC Section 1. Some states go further and require National Board Registration and inspection. A sampling of three state boiler-code laws follows. While the language contained in the codes for both Mississippi and Texas are clear, the language of other states is not.

Mississippi State Boiler Code — commonly known as Title 15, Section III, part 76 — clearly defines any vessel that generates steam at over 15 psig as a power boiler [*3*]. It goes on to say that "Boilers and unfired pressure vessels to be installed for operation in Mississippi shall be designed, constructed, inspected, stamped and installed in accordance with the applicable ASME Boiler and Pressure Vessel Code, and these rules and regulations."

Texas State Boiler Code, commonly known as 16 TAC 65, requires that any heating boiler, nuclear boiler, power boiler, unfired steam boiler or process steam generator that is installed in Texas must be inspected, installed and stamped in conformity with the applicable section of the ASME BPVC. Such boilers must be registered with the National Board of Boiler and Pressure Vessel Inspectors. Exceptions include reinstalled boilers, as well as those exempted by the Health and Safety Code, §755.022 [*4*].

New Jersey Boiler Code is commonly called NJAC 12 subchapter 4. In New Jersey, the term "boiler" means a closed vessel in which water is heated, steam is generated, steam is superheated, or any combination thereof, under pressure or vacuum, for external use by the direct application of heat [5]. The term "boiler"shall include fired or waste-heat units for heating or vaporizing liquids other than water where these units are separate from processing systems and are complete within themselves. New Jersey requires compliance with ASME BPVC Section 1 and National Board rules.

Concluding remarks

While safety remains of the utmost concern, economics, more than engineering, play a great role in defining the boundaries where the ASME code may apply. Unless a more specific code is developed for ethylene units, the debate about boundaries will continue among owners, engineering contractors, technology providers and other stakeholders. In general, more stringent requirements of ASME are applied for ethylene plants in the U.S., compared to other places in the world. ■

Edited by Scott Jenkins

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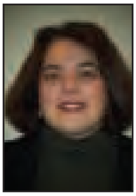

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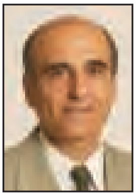

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Use Simplified Lifecycle-Cost Computations to Justify Upgrades

The methodologies presented here can be used to set goals, and will enable performance comparisons among different plants or industry segments

Heinz Bloch
Consulting Engineer

Virtually every process-plant manager pursues the commendable goals of safely extending equipment life and maximizing both the availability and reliability of plant assets. Achieving these objectives usually requires upfront effort and money — both of which can be scarce resources.

But even the realistic manager who knows that reliability comes at an ufront price may not want to authorize these expenditures on the basis of intuition or guesswork. Instead, he or she may ask for some cost justification that is linked to a payback period, a cost-to-benefit calculation, a lifecycle-improvement multiplier, or some other tangible factor. It is usually at this point in the sequence of events that the reliability engineer realizes that he or she has no data and the issue is placed at the bottom of the priority list. Things revert back to status quo and urgent repeat repairs siphon off precious resources.

Even in the absence of abundant data, many methods are available to allow us to determine, with reasonable accuracy, the monetary incentives or justification for equipment and component upgrading. Such upgrades are the key to future failure avoidance.

This article describes some options for determining the value of upgrading. The narrative and illustrations presented here highlight some methodologies that are available to reliability professionals who are ready to de-emphasize purely intuitive approaches, in favor of simple yet effective numerical pathways.

Lifecycle cost estimating

Lifecycle cost estimating is one of the reliability engineer's most effective improvement-justification tools. Lifecycle cost estimating takes into account the initial purchase and installation costs of the equipment, auxiliaries and software systems. It assesses the true cost of failures, including, of course, the impact of lost production [*1–3*].

A certain amount of information or general data is usually available from the plant's computer-based enterprise-asset management (EAM) or computerized maintenance-management system (CMMS). The existence of EAM and CMMS is assumed here because modern plants cannot compete without a CMMS. The plant CMMS is populated with accurate data related to work orders, expenditures and failure incidents. All data of interest should be specific enough to clearly describe the root causes of failures observed.

The annual cost of parts failure (C_y) can be assessed using Equation (1):

$$C_y = (C_g)(8{,}760)/(MTBF+MTTR) \quad \textbf{(1)}$$

where:
C_y = Annual cost of failures for a component (or subassembly) system
C_g = Cost per failure event
*MTBF** = Mean time between failure, h
MTTR = Mean time to repair or replace, h

The total lifecycle cost can be obtained by adding the initial acquisition cost (*AC*), the initial installation cost (*IC*), and the recurring yearly costs. A present value conversion [Equation (2)] takes into account the time value of money. The costs of future operations (*OC*), maintenance (*MC*), lost production (*LP*) and even decommissioning (*DC*) must be added to present acquisition and installation costs. Thus, the total lifecycle cost (*LCC Total*) = *AC* + *IC* + present value of (*OC* + *MC* + *LP* + *DC*).

TABLE 1. ESTIMATED YEARS OF RUN TIME BEFORE FAILURE OF FOUR PRINCIPAL WEAR-PRONE PUMP COMPONENTS

Pump component life, *L*	Estimated life for upgraded part, yr
Mechanical seals, L_1	2.5
Ball bearings, L_2	5
Couplings, L_3	7
Shafts, L_4	15

A "present worth" value can also be calculated. The cumulative present worth factor in Equation (2) can be obtained from many sources and tables as a function of interest rate and time (yr). It is usually available from the plant's accounting staff and can also be obtained as a computer spreadsheet program displaying a present value (*PV*) function. *PV* is cost multiplied by the cumulative present worth factor:

$$PV = \left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \quad \textbf{(2)}$$

where:
i = real annual interest rates, %
n = number of years

Except for data derived from well-designed, in-plant EAM-CMMS systems, precise failure frequencies and life expectancies are rarely available for process machinery and their components. There are simply too many variables that influence these numbers. Nevertheless, an experienced reliability professional will not be deterred in his

*The MTBF of a randomly failing. multiple-component, active-redundant system may be evaluated by the following equation:

$$MTBF = \frac{1}{\lambda}\left[1 + \frac{1}{2} + \ldots + \frac{1}{c}\right]$$

where the failure rate $\lambda = \frac{1}{MTBF}$, and c = number of parallel components or her search for data. Remember, you want to make the business case for upgrading and your managers are only asking for reasonable "ball-park" numbers that directionally show which upgrades should be pursued. Such numbers can be found elsewhere [*4–6*].

For precise estimates, calculated life expectancies of various component categories should ideally be based on the experience collected at the reliability engineer's facility. But the relevant data may never have been collected, or may have been lost when the source expert left the company. If that is the case — or whenever realistic life assessments or cost estimates are needed — a reliability engineer may want to, at least initially, use the data tables contained in the cited references. As experience is gained, similar tables will grow into ever-more-precise and locally applicable component-life databases. Needless to say, once developed, these should be preserved and passed on to others.

Using component life details

Many modern facilities are finding it progressively more advantageous to collect and classify component data and to then incorporate these in calculations that predict the probable run length, in terms of *MTBF*, of an entire machine. Some plants have successively improved the accuracy of this form of lifecycle cost computation. Basing decisions on improved computational accuracy has led to greater visibility and enhanced respect for the diligent contributions of the reliability professionals at those plants [*5*]. The monetary value of an improvement can be determined from yet another version of the lifecycle cost computation. Specifically, improvement value can also be expressed in even simpler terms, such as a benefit-to-cost. Whenever possible, parts that experience wear — the most failure-prone components of a machine — can be assigned by some experience-based criteria or previously published values of L_1, L_2 and so on, as shown in Table 1. Because of their position in Equation (3), low component-life values in Table 1 will have a real impact on overall machine *MTBF* and the influence or effect of individual component upgrading on overall machine *MTBF* can be readily visualized from this equation (that is, the number 1 divided by a large number yields a small number). Even a cursory look at Equation (3) — whether or not upgrading is involved — will make a significant difference in the quest to improve the life of weak components.

Centrifugal pump example

Table 1 shows estimated-life values for four different weak, or (relatively) wear-prone, pump components (mechanical seals, ball bearings, couplings and shafts). We can use these numbers to calculate *MTBF* values for an entire pump. Of course, our calculation is somewhat general and might pertain only to a particular application — say, a given pump size in water service. Calculated *MTBF* values refer to the anticipated running time of such a pump, if the life expectancies of its components are as given in Table 1. These pumps had been previously "upgraded" by converting from sealed ball bearings to bearings that can be periodically refilled with fresh grease (these are commonly called "regreasable" bearings). Using the values for *L* from Table 1, the estimated *MTBF* (operating time) of the entire pump was calculated with reasonable accuracy using Equation (3), and the numerical result is shown in Equation (4).

$$MTBF = \frac{1}{\left[\left(\frac{1}{L_1}\right)^2+\left(\frac{1}{L_2}\right)^2+\left(\frac{1}{L_3}\right)^2+\left(\frac{1}{L_4}\right)^2\right]^{0.5}} \quad (3)$$

Here, *L* = estimated life, in years, of the component subject to failure [*6*].

$$\left[\left(\frac{1}{2.5}\right)^2+\left(\frac{1}{5}\right)^2+\left(\frac{1}{7}\right)^2+\left(\frac{1}{15}\right)^2\right]^{-0.5} \quad (4)$$

The stipulated 2.11-yr operating life determined by Equation (4) meets the expectations of many reliability engineers in U.S. process plants for "upgraded" ANSI/ISO pumps (Such pumps were first marketed in the mid- to late-1980s). But, suppose one later had the option to convert from grease to liquid oil lubrication. Assume one had also selected a cartridge-style mechanical seal (Figure 1) where component-style seals had been used previously, and that the user had added an advanced bearing-protector seal (Figure 2). Suppose these improvements would increase the operational lives of mechanical seals and bearings from the previous value of 2.5–5 years to 3.5–10 years, and would also make the pump more suitable for working in a mild lime slurry service. In that case, the expression in Equation (5) would apply, and we would probably have reason to expect a continuous pump operating life of 2.93 yr [*6*].

$$\left[\left(\frac{1}{3.5}\right)^2+\left(\frac{1}{10}\right)^2+\left(\frac{1}{7}\right)^2+\left(\frac{1}{15}\right)^2\right]^{-0.5} \quad (5)$$

Then, it is reasonable — and probably quite conservative — to anticipate an increase in pump *MTBF* of close to 40% from these two upgrades. Seeing a 40% increase in predicted component life should prompt a more-detailed analysis of the pump's lifecycle cost.

It may be worth paying a certain price for upgraded parts if lifecycle costs go down as a result. Calculating a simple, straightforward cost-to-benefit ratio would be another way

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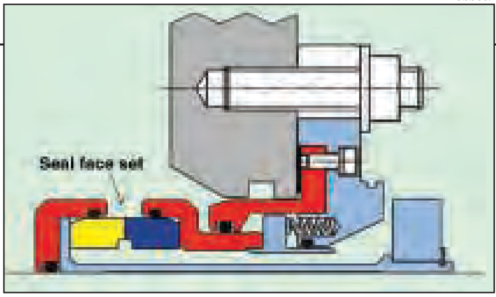

FIGURE 1. A single-type, heavy-duty mechancial seal for lime slurry service is highlighted in this pump illustration.

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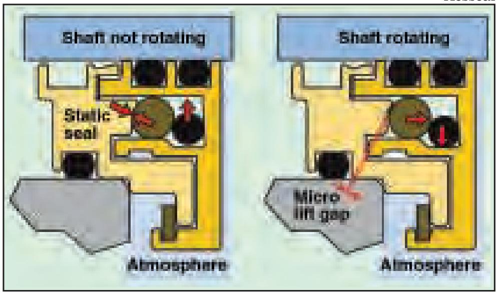

FIGURE 2. Shown here is a half-section of a modern bearing housing protector seal — with the shaft not rotating (left) and with the shaft rotating (right)

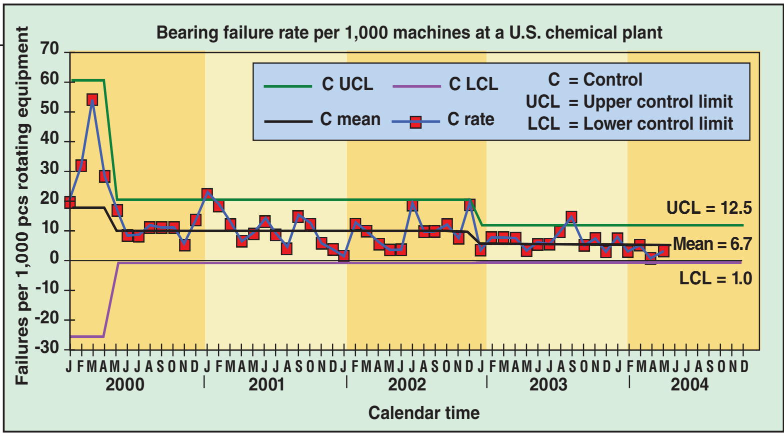

FIGURE 3. Bearing failure rate per 1,000 machines at a U.S. chemical plant, plotted using the author's field data

to quantify the value of equipment upgrades. If the incremental cost of upgrading is $400 each year and the benefit of an upgrade is avoidance of a $4,000 repair each year, then the cost-to-benefit ratio is 400/4,000 = 1:10.

Cost-to-benefit ratios

Perhaps the most familiar form of cost justification practiced on a wide scale compares the incremental cost of an upgrade option with the yearly value of maintenance cost avoidance. With that goal in mind, let's take another look at the pump-upgrade example discussed above. Recall that for the proposed upgrades, an older-style mechanical seal would be replaced with the cartridge seal shown in Figure 1. Also, the bearing protectors with the lip-seal style in this centrifugal pump would be discarded and the bearing-housing-protector seal with an advanced design — in this case, a rotating labyrinth design, as shown in Figure 2 would be used instead [*6*]. We make the following two assumptions:

- That the two upgraded components would incrementally cost $800 and result in shifting the pump *MTBF* from the previous value of 2.11 yr to 2.93 yr
- That repairs to a mid-size pump will cost $7,000 by the time materials, labor, overhead, benefits, spare parts procurement, shop supervision, planning, vibration monitoring and reliability engineering have all been factored in

Based on these two assumptions, our yearly pump-repair cost will have dropped from $3,318 (based on $7,000/2.11 yr) to $2,389 (based on $7,000/2.93 yr). The ensuing cost savings (or benefit) of $929/yr will go on for years, while the one-time incremental outlay (the cost) of $800 will have a payback of (800/929)12, or 10.3 months. The cost-to-benefit ratio is 1:1.16 in the first year, and (5 × 929)/800 = 1:5.8 over a 5-year period. That is a substantial result and is not difficult to achieve.

Meanwhile, a secondary benefit can be attributed to the systematic extension of equipment life: Instead of getting bogged down in frequent breakdown-related maintenance tasks, reliability engineers will be able to devote their attention to other, more-proactive reliability-improvement opportunities, thereby putting their effort to use to save money for their employers over the long run [7].

Make use of in-plant data

Important reliability-related data are available [4] and such data can be effectively used and applied to carry out simple *MTBF*, cost-justification, and lifecycle-cost studies. However, while published data sources are valuable, the use of in-plant data may be even more directly applicable and should never be overlooked.

One in-plant data example is displayed in Figure 3. This figure shows the reduction in total bearing failures that were actually experienced by a U.S. Gulf Coast petrochemical company over the span of 54 months (4.5 y). Although these improvements were undoubtedly attributable to a combination of procedural, organizational and hardware-specific upgrades, the reliability staff made the simplifying assumption that such downturns in the number of bearing replacements related entirely to pumps. It was further assumed that incorporating improved bearing-protection components only during shop repairs would typically add $500 to the average small or mid-size pump repair cost of $6,700.

In sharp contrast, it had been estimated that removing good pumps from field locations and taking them to the shop to implement various upgrades would cost, on average, $3,470 per pump. That particular option was obviously far less attractive and was not pursued.

Again, note that the incremental cost of $500 per pump pertained only to pumps that were expected to be sent to the shop in the following year. An elementary plot, shown in Figure 4, demonstrates the anticipated reduction in the pump-failure rate; the plot was used to calculate (in the 1990s) the cost-to-benefit ratio of bearing protector seals that would replace lip seals. The calculation was performed by taking total incremental cost per year and dividing it by the projected value of all avoided pump repairs.

Attractive and reasonable projections along the lines of what we just discussed contributed to wider use of a variety of different bearing-protector seals in the mid-1990s. Then, with time, more-advanced styles became available. Figure 2 shows a successful configuration, which was first marketed in 2003. If we decided to install it today and used the same calculation approach, we find its cost-to-benefit ratio surprisingly attractive.

Upgrading mechanical seals

Earlier in this article, we had encouraged reliability professionals to extend their horizons by reviewing data published elsewhere. In 1992, a British reliability engineer published the results of failure-reduction programs at three petroleum refineries [*8*]. As shown in Figure 5, Refinery A started with a pump *MTBF* of 29 months at the end of Year 2. The refinery's pump *MTBF* had risen to 71 months at the end of Year 7. Accordingly, the run lengths of the pumps there had experienced an increase of 42 months in the span of five years. Since these increases are attributable to upgrade efforts that went beyond seal improvements, we will temporarily put them aside and focus instead on Refineries B and C, whose reports dealt with

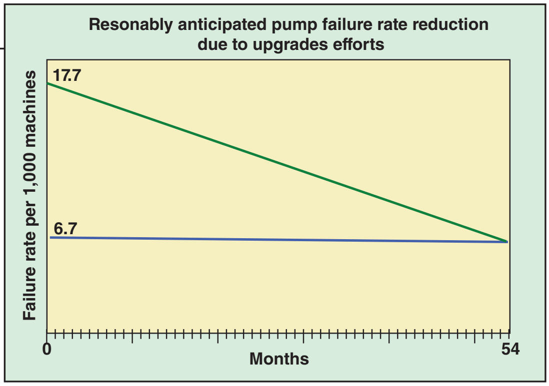

FIGURE 4. A facility starting with 17.7 pump failures per 1,000 pumps per month might upgrade these 17.7 pumps and then, over a period of 54 months, reduce its monthly statistics so as to meet a best-of-class number of 6.7 failures per 1,000 pumps per month

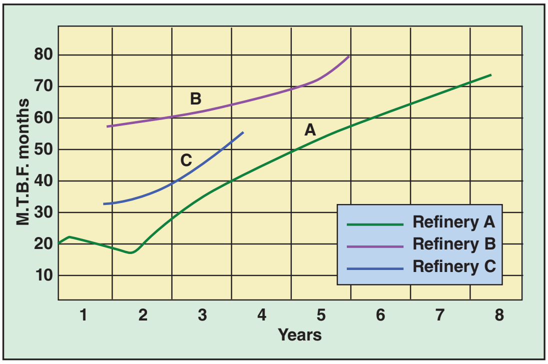

FIGURE 5. Shown here are data demonstrating improvement in pump MTBF, from experience at three British petroleum refineries

mechanical seals only.

Refinery B documented an increase in seal-related *MTBF*, from 57 months to 80 months, calculated as (80–57) / 57 = 40%, in four years. Seal-related *MTBF* values at Refinery C improved from 33 months to 50 months in the span of two years — an increase in *MTBF* of 51%. To determine this, we picked the numbers off of Figure 5 and put them into the expression: (50–33)/33 = 0.51.

It makes good sense to expect more substantial improvement possibilities for the refinery that has the lower starting *MTBF* rate. We note that Refinery C started with a seal *MTBF* of 33 months, and that "our" refinery (as an arbitrary example) is presently at 28 months *MTBF*. Returning to Refinery A and its overall pump *MTBF* (which had increased from 30 months at the end of Year 2, to about 71 months at the end of Year 7), we would calculate an *MTBF* increase of (71–30)/30 = 36% in 5 years.

If we take into account the observation that refineries starting with *MTBF* figures of 30 months have experienced *MTBF* increases around 25%/yr it is reasonable to expect that our own plant could go from an *MTBF* of 28 months to one of 56 months in the span of five years.

Such a reasonable assumption now allows our refinery operator to embark on a program to improve mechanical seal *MTBF*. As reliability professionals, we will accede to our management's request to develop an appropriately referenced cost and benefit projection. We have 1,474 centrifugal pumps at our plant site. Our seal *MTBF* was originally calculated from (1,474 pumps installed) × (12 mo/yr)/632 seal failures / yr = 28 mo. Furthermore, it is assumed here that upgrading to superior seal configurations and improved seal materials would add $1,700 to each pump repair and that typical pump repairs, using traditional grades of seals, would cost approximately $5,000.

Assuming a linear *MTBF* increase from 28 months presently to 56 months five years from now, we could calculate our yearly repair cost outlay in the most straightforward manner and list our results in tabular format. We could pick one of the approaches described earlier in this article and would review it with one or two competent mechanical seal manufacturers — ones that would agree to a partnership or alliance that rewards them for failure reductions instead of lowest cost per seal. The ultimate results will be tangible and will, after five years, have saved the refinery many millions of dollars.

Different methods

We have attempted to show how a number of straightforward calculation approaches can be used to determine lifecycle costs, cost-to-benefit ratios, and payback periods for reliability improvements in process plants. A resourceful reliability professional will, of course, diligently collect and compile failure statistics for equipment and components at his or her plant site. At many locations throughout the world, competent professionals use this factual information to cost-justify equipment improvements. Many reach out for other data sources to augment and validate in-house data. It has been shown that data published in the past can form the core material of fairly accurate savings projections made today. The methodologies presented in this article can be used to set goals, and will enable performance comparisons among different plants or industry segments. ■

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I lost

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Based especially on FRI's productivity statistics for 2010 and 2011, I was nominated for the ChemInnovations Plant Manager of the Year Award. On November 13, I attended the Awards Banquet, but I lost the award to a very worthy candidate — Mr. Chris Witte of BASF Freeport. Here is the acceptance speech that I never had a chance to give:

I started supervising people at age five. The neighborhood needed a sports organizer. For the next 12 years, games were played every day after school and all weekend long. In college, I was the leader of every project group that I was assigned to, even though I preferred to follow. At my first job assignment in 1974, I had two technicians to supervise. For the 38 years thereafter, I led R&D groups of technicians and engineers — as many as 42 at a time.

Supervising people becomes more difficult every year. Laws and court rulings protecting employees become more constraining every year. In 2010, American universities graduated 6,000 chemical engineers and 40,000 attorneys. Every dismissed employee has seven hungry attorneys lined up to represent her or him. Even if an employer does everything right with a non-productive subordinate, that company should still anticipate a lawsuit. The key to the avoidance of such lawsuits is to hire the right people in the first place.

Marv Levy, head coach of the Buffalo Bills football team, said, "It's not my job to motivate people; my job is to hire motivated people." My son, Steve, the human resource specialist has a sign on his desk that reads, "Hire for Attitude — Then Train." I concur. (See Hire Happy People, *CE*, June 2011, p. 27). I also suggest the longest possible training and probation periods. Do not hesitate to release questionable trainees during such periods.

Leopards can not change their spots. This proverb has far-reaching consequences. Poor technicians, engineers, writers and speakers will never become great ones. Do not over-spend any training budgets. No employee is indispensable (including you). Many companies have survived and thrived following the defections and retirements of their best people. When should somebody be released? Consider this question, "If we were to release a certain person, would we change the door locks?"

Regarding supervising, people can not be managed by Emails. Attend to your Emails twice per day. Otherwise, get out of your office and get face-to-face. Give praise often. For good employees, all performance evaluations should be 80% positive and 20% improvement possibilities. Every day and all day, avoid the word "I", replacing it with "We." Be humble, in words and indeed.

My Six Sigma training emphasized something that no employee should ever forget. All employees have customers — internal and external. We thrive or we fail based on their projects, input, purchases and payments. The best way to please them is to work together like one big happy family.

I believe I am going to nominate myself again next year. The November 13 Banquet was great! ■

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8	23	38	53	68	83	98	113	128	143	158	173	188	203	218	233	248	263	278	293	308	323	338	353	368	383	398	413	428	443	458	473	488	503	518	533	548	563	578	593
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12	27	42	57	72	87	102	117	132	147	162	177	192	207	222	237	252	267	282	297	312	327	342	357	372	387	402	417	432	447	462	477	492	507	522	537	552	567	582	597
13	28	43	58	73	88	103	118	133	148	163	178	193	208	223	238	253	268	283	298	313	328	343	358	373	388	403	418	433	448	463	478	493	508	523	538	553	568	583	598
14	29	44	59	74	89	104	119	134	149	164	179	194	209	224	239	254	269	284	299	314	329	344	359	374	389	404	419	434	449	464	479	494	509	524	539	554	569	584	599
15	30	45	60	75	90	105	120	135	150	165	180	195	210	225	240	255	270	285	300	315	330	345	360	375	390	405	420	435	450	465	480	495	510	525	540	555	570	585	600

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Advertisers' Index

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Classified Index January 2013

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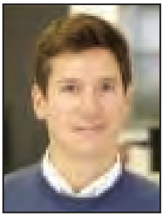
E-mail: dhammes@che.com Tel: 512-250-9555

People

JANUARY WHO'S WHO

Philippault



Weser

McCarthy

Raty

Azibert

Peter Bigelow joins the board at engineering firm **Integrated Project Services** (Lafayette Hill, Pa.).

Ton Büchner returns to **AkzoNobel** (Amsterdam, The Netherlands) as CEO, after a medical-related absence.

Matthieu Philippault joins the international sales team at **Flexicon (Europe) Ltd.** (Kent, U.K.), a provider of bulk-solids-handling systems.

Andy Mackintosh has resigned as executive vice president in charge of the hydrocarbons and chemicals business unit of **SNC-Lavalin** (Montreal). *Ric Sorbo*, senior vice president and general manager of that unit, is the acting head until a permanent replacement has been selected.

Florian Weser is now managing director at **Krüss GmbH** (Kent, U.K.), specialists in surface and interface chemistry.

Mike McCarthy becomes sales account manager for **Intelligrated** (Cincinnati), a provider of automated materials-handling solutions.

At **The Fluid Sealing Assn.** (Wayne, Pa.), *Greg Raty* is now president of the board of directors and *Henri Azibert* is now vice president of the board. Raty is vice president of Slade (Statesville, N.C.). Azibert is the CTO at A.W. Chesterton (Woburn, Mass.).

Laura Rathbun becomes the purchasing manager for **Cashco Inc.** (Ellsworth, Kan.), a maker of control valves and regulators. ■

Suzanne Shelley

BUSINESS NEWS

PLANT WATCH

Stamicarbon wins contract for urea plant in China

December 6, 2012 — Stamicarbon B.V. (Sittard, the Netherlands; www.stamicarbon.com), the Licensing and IP Center of Maire Tecnimont S.p.A. (Milan, Italy; www.mairetecnimont.it), has been awarded a contract for a new urea plant with Inner Mongolia Erdos Chemical Industry Group Co. in China. The plant will have a capacity of 2,860 metric tons per day (m.t./d) of prilled urea and will be located in Qi Pan Jing, Ordos City, Inner Mongolia. Startup is planned for 2014.

AMEC is awarded a contract for a new refinery in Kuwait

December 4, 2012 — AMEC (London, U.K.; www.amec.com) has been awarded a $528-million project-management consultancy contract by the Kuwait National Petroleum Co. (KNPC) for a new petroleum refinery at Al Zour, Kuwait. When completed in 2018, the multi-billion dollar refinery is expected to be the largest in the Middle East and will increase Kuwait's refinery capacity by 615,000 bbl/d.

Tecnimont lands contract for a low-density polyethylene plant in Mexico

December 4, 2012 — Maire Tecnimont S.p.A. says that its main subsidiary Tecnimont S.p.A. (Rome, Italy) has been awarded a contract by Etileno XXI Services B.V. for the realization of a 300,000-ton/yr low-density polyethylene (LDPE) unit, to be constructed within the Etileno XXI petrochemical complex. The LDPE unit will be built using the Lupotech T technology of LyondellBasell industries and the value of the contract is $191.4 million. The engineering and procurement activities will be completed in the 4th Q 2014.

Sasol commences FEED phase for GTL and ethane cracking complex

December 3, 2012 — Sasol (Johannesburg, S. Africa; www.sasol.com) has announced that it will proceed with the front-end engineering-and-design (FEED) phase for an integrated, gas-to-liquids (GTL) facility and an ethane cracker with downstream derivatives, at its Lake Charles site in southwest Louisiana. The GTL facility, said to be the first of its kind in the U.S. will produce 4-million ton/yr, or 96,000 bbl/d of high-quality transportation fuel, including GTL diesel and other value-adding chemical products. Current project costs for the GTL facility are estimated at $11–14 billion. The GTL project will be delivered in two phases, with each phase comprising 48,000 bbl/d. The first phase is planned to begin operating within the 2018 calendar year and the second phase in 2019.

Toyo wins world's largest single-train urea plant in Nigeria

December 3, 2012 —Toyo Engineering Corp. (Toyo; Chiba, Japan; www.toyo-eng.co.jp) and its consortium partner Daewoo Nigeria Ltd. will jointly build what is said to be the world's largest single-train urea plant for Indorama Eleme Fertilizer and Chemicals Ltd. The proposed facility will be built at Indorama Eleme Petrochemicals Ltd.'s (IEPL) existing petrochemicals complex at Port Harcourt, River state, Nigeria, and is scheduled for startup by the 4th Q of 2015. The proposed facility will manufacture 2,300 ton/d of ammonia and 4,000 ton/d of granulated urea from natural gas feedstock employing technology licenses from KBR (Houston; www.kbr.com) and Toyo.

JGC awarded contract for CO_2 capture, storage and compression facilities

November 28, 2012 — JGC Corp. (Yokohama, Japan; www.jgc.co.jp) has received a contract from Japan CCS Co. to construct the core facilities at a carbon-dioxide capture and storage (CCS) technology-demonstration project. The site for the demonstration project is located adjacent to an oil refinery in Tomakomai, Hokkaido, owned by Idemitsu Kosan Co. The contract calls for the engineering, procurement, construction and commissioning work for a yearly capacity of 200,000 ton/yr of CO_2. Performance testing is scheduled to be completed at the end of January, 2016.

Foster Wheeler awarded contract for Lanxess' EPDM plant in China

November 26, 2012 — Foster Wheeler AG (Zug, Switzerland; www.fwc.com) says that a subsidiary of its Global Engineering and Construction Group has been awarded a contract by Lanxess Changzhou Co. for a new ethylene propylene diene monomer (EPDM) rubber plant to be built at the Changzhou Yangtze Riverside Industrial Park at Changzhou, Jiangsu Province. Foster Wheeler is currently executing the FEED for this facility, which will be designed to produce 160,000 m.t./yr of EPDM rubber with an expected startup in 2015.

KBR to execute oil-sands tailings-management project in Canada

November 20, 2012 — KBR was awarded two contracts for Syncrude Canada Ltd. to execute module fabrication and field construction for its Fluid Fine Tailings — Centrifuging Full Scale Plant (FFT-CFSP) in Fort McMurray, Alberta, Canada. Plant startup is planned for 2015. The process is designed to pump fluid fine tailings (the byproduct of the bitumen extraction process) through a series of centrifuges to separate the maximum amount of water from the solids. Released water will be recycled for plant operations and the soil product of the centrifuge process will have sufficient density and strength to be placed in deposits, then capped and reclaimed.

Bechtel's ThruPlus Coking technology to be used in Kazakhstan refinery

November 16, 2012 — Bechtel (Houston; www.bechtel.com) has signed a license agreement with JSC Pavlodar Oil Chemistry Refinery (POCR) for a major modernization and process design of a delayed coking unit (DCU) complex in Pavlodar, Kazakhstan. The DCU complex will use Bechtel's ThruPlus Coking technology to significantly increase the refinery's feed processing capabilities from 600,000 to 925,000 m.t./yr. It will also make high-quality liquid products for transportation fuel use and petroleum coke suitable for further processing and use in the aluminum industry.

MERGERS AND ACQUISITIONS

Hovione and Solvias announce a collaboration for improved drug solubility

November 28, 2012 — Hovione (Lisbon, Portugal; www.hovione.com) and Solvias (Basel, Switzerland; www.solvias.com) are planning a collaboration focused on the development and supply of pharmaceutical co-crystals. This strengthens Hovione's experience in overcoming drug delivery challenges with Solvias' expertise in solid-state chemistry.

BASF completes acquisition of Becker Underwood

November 28, 2012 — BASF SE (Ludwigshafen, Germany; www.basf.com) has completed the acquisition of Becker Underwood from U.S.-based Norwest Equity Partners, for a purchase price of $1.02 billion. Most businesses of Becker Underwood will join the newly established global business unit Functional Crop Care as part of BASF's Crop Protection div. Within this new unit, BASF will merge its existing research and development, and marketing activities in the areas of seed treatment, biological crop protection, plant health, and others, with those of Becker Underwood. Becker Underwood's animal nutrition business will be integrated into BASF's Nutrition & Health div. ■

Dorothy Lozowski

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

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FOR MORE ECONOMIC INDICATORS, SEE NEXT PAGE

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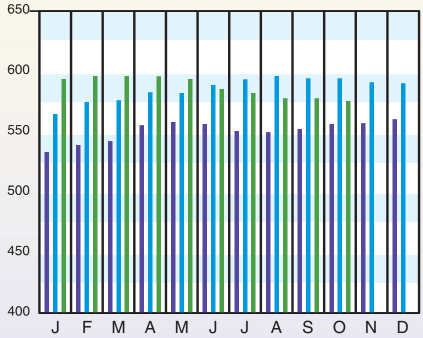
CHEMICAL ENGINEERING PLANT COST INDEX (CEPCI)

(1957-59 = 100)	Oct.'12 Prelim.	Sept.'12 Final	Oct.'11 Final
***CE* Index**	575.4	577.4	594.0
Equipment	698.2	700.7	724.7
Heat exchangers & tanks	638.5	643.9	691.5
Process machinery	658.3	662.2	674.9
Pipe, valves & fittings	899.4	895.7	906.3
Process instruments	424.3	424.1	432.5
Pumps & compressors	929.0	929.0	911.5
Electrical equipment	512.2	510.6	508.8
Structural supports & misc	734.2	742.3	769.8
Construction labor	324.0	324.9	330.0
Buildings	525.6	527.3	521.2
Engineering & supervision	328.1	328.5	330.4

Annual Index:

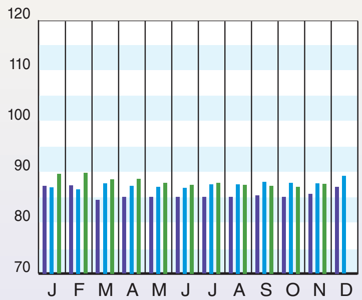
2004 = 444.2
2005 = 468.2
2006 = 499.6
2007 = 525.4
2008 = 575.4
2009 = 521.9
2010 = 550.8
2011 = 585.7



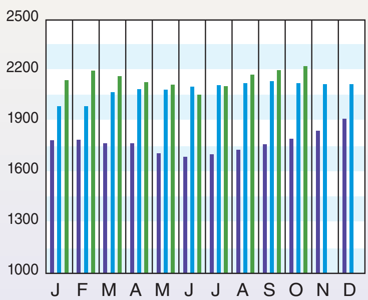
CURRENT BUSINESS INDICATORS

	LATEST		PREVIOUS				YEAR AGO	
CPI output index (2007 = 100)	Nov.'12	= 87.7	Oct.'12	= 87.1	Sep.'12	= 87.3	Nov.'11	= 87.731
CPI value of output, $ billions	Oct.'12	= 2,226.7	Sep.'12	= 2,203.2	Aug.'12	= 2,175.3	Oct.'11	= 2,126.63
CPI operating rate, %	Nov.'12	= 75.7	Oct.'12	= 75.2	Sep.'12	= 75.3	Nov.'11	= 75.702
Producer prices, industrial chemicals (1982 = 100)	Nov.'12	= 297.3	Oct.'12	= 299.7	Sep.'12	= 300.1	Nov.'11	= 315.6
Industrial Production in Manufacturing (2007=100)	Nov.'12	= 94.0	Oct.'12	= 92.9	Sep.'12	= 93.8	Nov.'11	= 91.5071
Hourly earnings index, chemical & allied products (1992 = 100)	Nov.'12	= 157.6	Oct.'12	= 157.6	Sep.'12	= 158.6	Nov.'11	= 155.674
Productivity index, chemicals & allied products (1992 = 100)	Nov.'12	= 105.4	Oct.'12	= 103.3	Sep.'12	= 103.6	Nov.'11	= 106.597

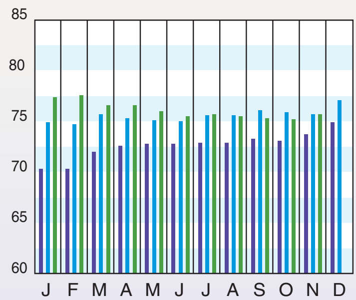
CPI OUTPUT INDEX (2007 = 100)



CPI OUTPUT VALUE ($ BILLIONS)



CPI OPERATING RATE (%)



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

CURRENT TRENDS

Preliminary data from the *CE* Plant Cost Index (CEPCI; top) for October 2012 (the most recent available) indicate that capital equipment prices dropped 0.35% from September to October. The current-year plant cost index is 3.2% lower than it was in October of the previous year (2011). Within the CEPCI, most of the equipment-class subgroups were down from a year prior — including: heat exchangers and tanks; process machinery; pipes, valves and fittings; process instruments; and structural supports and miscellanous equipment. Pumps and compressors and electrical equipment show higher values compared to a year ago. The construction labor and engineering and supervision indexes also dropped compared to a year ago, while the buildings index edged higher compared to the same time in 2011. Meanwhile, the Current Business Indicators from IHS Global Insight (middle), show a slight increase in the CPI output index from October to November 2012, and a 1.1% increase in the CPI value of output over the same time period. Industrial chemical producer prices are down 0.81% from October to November 2012, and down 6.1% compared to November a year ago. ■