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Get To The Root Of Accidents

Systems thinking can provide insights on underlying issues not just their symptoms

By Nancy Leveson, Massachusetts Institute of Technology, and Sidney Dekker, Griffith University

AN OFTEN-CLAIMED "fact" is that operators or maintenance workers cause 70–90% of accidents. It is certainly true that operators *are blamed* for 70–90%. Are we limiting what we learn from accident investigations by limiting the scope of the inquiry? By applying systems thinking to process safety, we may enhance what we learn from accidents and incidents and, in the long run, prevent more of them.

Systems thinking is an approach to problem solving that suggests the behavior of a system's components only can be understood by examining the context in which that behavior occurs. Viewing operator behavior in isolation from the surrounding system prevents full understanding of why an accident occurred — and thus the opportunity to learn from it.

We do not want to depend upon simply learning from the past to improve safety. Yet learning as much as possible from adverse events is an important tool in the safety engineering tool kit. Unfortunately, too narrow a perspective in accident and incident investigation often destroys the opportunity to improve and learn. At times, some causes are identified but not recorded because of filtering and subjectivity in accident reports, frequently for reasons involving organizational politics. In other cases, the fault lies in our approach to pinpointing causes, including root cause seduction and oversimplification, focusing on blame, and hindsight bias.

ROOT CAUSE SEDUCTION AND OVERSIMPLIFICATION

Assuming that accidents have a root cause gives us an illusion of control. Usually the investigation focuses on operator error or technical failures, while ignoring flawed management decision-making, safety culture problems, regulatory deficiencies, and so on. In most major accidents, all these factors contribute; so to prevent accidents in the future requires all to be identified and addressed. Management and systemic causal factors, for example, pressures to increase productivity, are perhaps the most important to fix in terms of preventing future accidents — but these are also the most likely to be left out of accident reports.

As a result, many companies find themselves playing a sophisticated "whack-a-mole" game: They fix symptoms without fixing the process that led to those symptoms. For example, an accident report might identify a bad valve design as the cause, and, so, might suggest replacing that valve and perhaps all the others with a similar design. However, there is no investigation of what flaws in the engineering or acquisition process led to the bad design getting through the design and review processes. Without fixing the process flaws, it is simply a matter of time before those process flaws lead to another incident. Because the symptoms differ and the accident investigation never went beyond the obvious symptoms of the deeper problems, no real improvement is made. The plant then finds itself in continual fire-fighting mode.

A similar argument can be made for the common label of “operator error.” Traditionally operator error is viewed as the primary cause of accidents. The obvious solution then is to do something about the operator(s) involved: admonish, fire or retrain them. Alternatively, something may be done about operators in general, perhaps by rigidifying their work (in ways that are bound to be impractical and thus not followed) or marginalizing them further from the process they are controlling by putting in more automation. This approach usually does not have long-lasting results and often just changes the errors made rather than eliminating or reducing errors in general.

Systems thinking considers human error to be a symptom, not a cause. All human behavior is affected by the context in which it occurs. To understand and do something about such error, we must look at the system in which people work, for example, the design of the equipment, the usefulness of procedures, and the existence of goal conflicts and production pressures. In fact, one could claim that human error is a symptom of a system that needs to be redesigned. However, instead of changing the system, we try to change the people — an approach doomed to failure.

For example, accidents often have precursors that are not adequately reported in the official error-reporting system. After the loss, the investigation report recommends that operators get additional training in using the reporting system and that the need to always report problems be emphasized. Nobody looks at why the operators did not use the system. Often, it is because the system is difficult to use, the reports go into a black hole and seemingly are ignored (or at least the person writing the report gets no feedback it even has been read, let alone acted upon), and the fastest and easiest way to handle a detected potential problem is to try to deal with it directly or to ignore it, assuming it was a one-time occurrence. Without fixing the error-reporting system itself, not much headway is made by retraining the operators in how to use it, particularly where they know how to use it but ignored it for other reasons.

Another common human error cited in investigation reports is that the operators did not follow the written procedures. Operators often do not follow procedures for very good reasons. An effective type of industrial action for operators who are not allowed to strike, like air traffic controllers in the U.S., is to follow the procedures to the letter. This type of job action can bring the system down to its knees.

Figure 1 shows the relationship between the mental models of the designers and those of the operators. Designers deal with ideals or averages, not with the actual constructed system. The system may differ from the designer’s original specification either through manufacturing and construction variances or through evolution and changes over time. The designer also provides the original operational procedures as well as information for basic operator training based on the original design specification. These procedures may be incomplete, e.g., missing some remote but possible conditions or assuming that certain

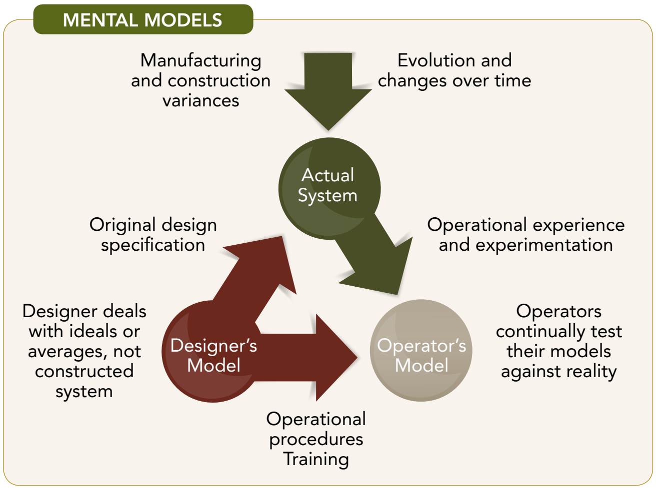

Figure 1. Designers and operators necessarily view systems differently.

conditions cannot occur. For example, the procedures and simulator training for the operators at Three Mile Island nuclear power plant omitted the conditions that actually occurred in the well-known incident because the designers assumed that those conditions were impossible.

In contrast, operators must deal with the actual constructed system and the conditions that occur, whether anticipated or not. They use operational experience and experimentation to continually test their mental models of the system against reality and to adjust the procedures as they deem appropriate. They also must cope with production and other pressures such as the desire for efficiency and "lean operations." These concerns may not have been accounted for in the original design.

Procedures, of course, periodically are updated to reflect changing conditions or knowledge. But between updates operators must balance between:

1. Adapting procedures in the face of unanticipated conditions, which may lead to unsafe outcomes if the operators do not have complete knowledge of the existing conditions in the plant or lack knowledge (as at Three Mile Island) of the implications of the plant design. If, in hindsight, they are wrong, operators will be blamed for not following the procedures.
2. Sticking to procedures rigidly when feedback suggests they should be adapted, which may lead to incidents when the procedures are wrong for the particular existing conditions. If, in hindsight, the procedures turn out to be wrong, the operators will be blamed for rigidly following them.

In general, procedures cannot assure safety. No procedures are perfect for all conditions, including unanticipated ones. Safety comes from operators being skillful in judging when and how they apply. Safety does not come from organizations forcing operators to follow procedures but instead from organizations monitoring and understanding the gap between procedures and practice. Examining the reasons why operators may not be following procedures can lead to better procedures and safer systems.

Designers also must provide the feedback necessary for the operators to correctly update their mental models. At BP's Texas City refinery, there were no sensors above the maximum allowed height of the hydrocarbons in the distillation tower. The operators were blamed for not responding in time although they had no way of knowing what was occurring in the tower due to inadequate engineering design.

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FOCUSING ON BLAME

Blame is the enemy of safety. "Operator error" is a useless finding in an accident report because it does not provide any information about why that error occurred, which is necessary to avoid a repetition. There are three levels of analysis for an incident or accident:

- What — the events that occurred, for example, a valve failure or an explosion;

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- Who and how — the conditions that spurred the events, for example, bad valve design or an operator not noticing something was out of normal bounds; and
- Why — the systemic factors that led to the who and how, for example, production pressures, cost concerns, flaws in the design process, flaws in the reporting process, and so on.

Most accident investigations focus on finding someone or something to blame. The result is a lot of non-learning and a lot of finger pointing because nobody wants to be the focus of the blame process. Usually the person at the lowest rung of the organizational structure (the operator) ends up shouldering the blame. The factors that explain why the operators acted the way they did never are addressed.

The biggest problem with blame, besides deflecting attention from the most important factors in an accident, is that it creates a culture where people are afraid to report mistakes, hampering accident investigators' ability to get the true story about what happened.

One of the reasons commercial aviation is so safe is that blame-free reporting systems have been established that find potential problems before a loss occurs. A safety culture that focuses on blame will never be very effective in preventing accidents.

HINDSIGHT BIAS

Hindsight bias permeates almost all accident reports. After an accident, it is easy to see where people went wrong and what they should have done or avoided or to judge them for missing a piece of information that turned out (after the fact) to be critical. It is almost impossible for us to go back and understand how the world appeared to someone who did not already have knowledge of the outcome of the actions or inaction. Hindsight is always twenty-twenty.

For example, in an accident report about a tank overflow of a toxic chemical, the investigators concluded "the available evidence *should have* been sufficient to give the board operator a clear indication that the tank was indeed filling and required immediate attention." One way to evaluate such statements is to examine exactly what information the operator actually had. In this case, the operator had issued a command to close the control valve, the associated feedback on the control board indicated the control valve was closed, and the flow meter showed no flow. In addition, the high-level alarm was off. This alarm had been out of order for several months but the operators involved did not know this and the maintenance department had not fixed it. The alarm that would have detected the presence of the toxic chemical in the air also had not sounded. All the evidence the operators actually had at the time indicated conditions were normal. When questioned about this, the investigators said that the operator "could have trended the data on the console and detected the problem." However, that would have required calling up a special tool. The operator had no reason to do that, especially as he was very busy at the time dealing with and distracted by a potentially dangerous alarm in another part of the plant. Only in hindsight, when the overflow was known, was

it reasonable for the investigators to conclude that the operators should have suspected a problem. At the time, the operators acted appropriately.

In the same report, the operators are blamed for not taking prompt enough action when the toxic chemical alarm detected the chemical in the air and finally sounded. The report concluded that "interviews with personnel did not produce a clear reason why the response to the … alarm took 31 minutes. The only explanation was that there was not a sense of urgency since, in their experience, previous … alarms were attributed to minor releases that did not require a unit evacuation." The surprise here is that the first sentence claims there was no clear reason while the very next sentence provides a very good one. Apparently, the investigators did not like that reason and discarded it. In fact, the alarm went off about once a month and, in the past, had never indicated a real emergency. Instead of issuing an immediate evacuation order (which, if done every month, probably would have resulted in at least a reprimand), the operators went to inspect the area to determine if this was yet another false alarm. Such behavior is normal and, if it had not been a real emergency that time, would have been praised by management.

Hindsight bias is difficult to overcome. However, it is possible to avoid it (and therefore learn more from events) with some conscious effort. The first step is to start the investigation of an incident with the assumption that nobody comes to work with the intention of doing a bad job and causing an accident. The person explaining what happened and why it happened needs to assume that the people involved were doing reasonable things (or at least what they thought was reasonable) given the complexities, dilemmas, tradeoffs and uncertainty surrounding the events. Simply highlighting their mistakes provides no useful information for preventing future accidents.

Hindsight bias can be detected easily in accident reports (and avoided) by looking for judgmental statements such as "they *should have* …," "if they *would only have* …", "they *could have* …" or similar. Note all the instances of these phrases in the examples above from the refinery accident report. Such statements do not explain *why* the people involved did what they did and, therefore, provide no useful information about causation. They only serve to judge people for what, in hindsight, appear to be mistakes but at the time may have been reasonable.

Only when we understand why people behaved the way they did will we start on the road to greatly improving process safety.

ESCAPING THE WHACK-A-MOLE TRAP

Systems are becoming more complex. This complexity is changing the nature of the accidents and losses we are experiencing. This complexity, possible because of the introduction of new technology such as computers, is pushing the limits that human minds and current engineering tools can handle. We are building systems whose behavior cannot be completely anticipated and guarded against by the designers or easily understood by the operators.

Systems thinking is a way to stretch our intellectual limits and make significant improvement in process safety. By simply blaming operators for accidents and not looking at the role played by the encompassing system in why those mistakes occurred, we cannot make significant progress in process safety and will continue playing a never-ending game of whack-a-mole. ●

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Virtual Reality Helps Field Operators Improve Performance

Immersive high-fidelity 3D visualization now is starting to play a role in the training of operators and maintenance staff at plants. Here's a rundown of some initiatives already underway

By Seán Ottewell, Editor at Large

THE ONGOING drive for higher efficiency and greater safety in an ever-more-stringent regulatory environment is prompting chemical makers to consider new ways to improve training of operators and other staff. Use of 3D visualization and virtual reality can significantly help, believe a number of vendors, including Siemens, Invensys and Honeywell.

"We definitely see the chemical industry progressing in terms of adopting 3D visualization techniques for its training needs," says Bonn, Germany-based Andreas Geiss, vice president COMOS industry solutions for Siemens.

However, the conservative nature of the chemical industry means that 3D virtual reality training and its applications are taking longer to become universally adopted, notes Manchester, U.K.-based Peter Richmond, EYESIM Product Manager for Invensys. "Although it is now commonly accepted as best practice to use simulation-based training for control room operators, the inclusion of field operators, through 3D virtual reality training applications, has taken longer to be rolled out."

However, customers are showing increasing interest. "In a number of cases, we have seen 3D technology as part of project specifications, which is a good indication that it is becoming an accepted technology for field operator training," he adds.

Chemical manufacturers normally wait until technology has been proven elsewhere before investing in it, agrees Martin Ross, Bracknell, U.K.-based UniSim product manager for Honeywell Process Solutions. So, the industry still has some way to go in accepting 3D visualization technologies. "Currently, the price of 3D solutions is the main barrier, but this is likely to

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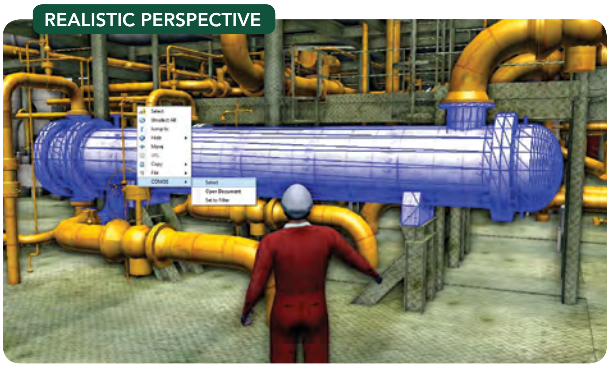


change as technology developments are made which the training industry can leverage."

IMMERSIVE EXPERIENCE

At the heart of Siemens' 3D offerings is the COMOS Walkinside immersive training simulator (ITS). Here, field operators can conduct their training in an authentic 3D virtual reality model — including geo-localization training, standard operating procedures (SOPs) and health, safety and environmental (HSE) incident scenarios (Figure 1).

"Innovative plant-specific simulations shorten learning times and enhance training retention, capitalizing on the human brain's ability to call back graphic memory and experiences. Trainees can virtually move around and test their own ability and comfort for making decisions during their work order navigation route, while interacting with one another as well as with the plant equipment — before physically seeing them. This strongly reinforces learning outcomes, reducing traditional on-site training and enhances operational safety," adds Geiss.

The Walkinside ITS environment includes an instructor training console option — similar to a control room operator-training simulator — to manage and monitor operator team training sessions, enable trainee-performance grading and promote greater collaboration. It also allows multi-trainee environments, supporting multi-avatar scenarios for more-complex work orders and to train how to communicate and coordinate actions in case of HSE incidents in the plant. Because the ITS doesn't need to be integrated into existing systems, users benefit from low deployment costs, notes Geiss.

ON-SITE DEPLOYMENT

Figure 2. Kiosk enables both new and experienced operators to sharpen their skills. *Source: Invensys.*

COMOS enables users to directly access equipment characteristics, maintenance history and documentation. Similarly, an engineer working with the engineering and maintenance database can call up the 3D view of the equipment and see it in its spatial context. With COMOS, all data created during the engineering stages — including 3D data — are available at any time and at all lifecycle phases of the plant. Even very large models can be rendered independently from the original CAD format, creating a real-life experience.

All this, says Geiss, is part of an unmistakable trend towards more-seamless 3D solutions. For example, in April 2013, Siemens announced a strategic alliance with information modeling specialist Bentley

Systems, Exton, Pa. The aim was to increase interoperability between Siemens' COMOS engineering software and Bentley's OpenPlant 2D/3D system for plant design and construction, to create a system that will allow the capture, exchange and further utilization of data and information spanning the entire plant lifecycle, from engineering through to plant operations across all disciplines.

Today, he notes, that relationship is very much focused on providing solutions for the process industries via the ISO 15926 data exchange standard: "Using ISO 15926 significantly reduces the engineering overhead for our customers by avoiding data inconsistency and duplication. We have deliberately avoided a proprietary approach, choosing instead ISO 15926 as the industrial standard model. This means both companies, Siemens and Bentley, can further develop the functions of their products, and exchange data via a neutral interface. We are convinced that our mutual commitment to ISO 15926 will result in faster market penetration and richer solutions, because only tools that can supply open data will enjoy long-term success and sustained growth for both companies."

As an example of the power of 3D training, he cites the case of a global company with upstream operations that recently decided to train field operators for a floating production storage and offloading (FPSO) vessel using COMOS Walkinside's ITS.

For five weeks, the operators spent eight hours a day "walking around" a detailed 3D graphical model of the FPSO. The primary purpose was to allow the operators to familiarize themselves with their future work environment, to know where they are located on the ship, where to find equipment and how to go there efficiently. A second purpose was to teach them to operate equipment and to execute SOPs — such as locating equipment on deck, going there, finding out its status, and taking appropriate action.

PHONE INTERFACE

Figure 3. Users can access 3D simulation on their smart phones. *Source: Invensys.*

"All operators who had used PCs before were capable of 'walking inside' with barely half a day of introduction to the tool because of its highly intuitive interface and functionality access. The operators readily embraced the tool and described the training environment as very practical, as opposed to theoretical. Though of course, the two are necessary to provide the operator a more-comprehensive understanding of the meaning and granularity of their tasks and duties," explains Geiss.

In addition, the instructor effectively was able to look over the operators' shoulders by observing their individual screens, following their actions in real time, and creating procedures with prompts to guide operators through their tasks.

While COMOS Walkinside currently is better known in the oil and gas industry, Geiss believes the chemical industry presents a huge opportunity for the technology — one that can only grow in the future as the industry has to juggle increased environmen-

tal regulation, raw material availability, the use of new materials, and fluctuating price and cost trends. “Changing market requirements are presenting ever new challenges for enterprises in the industry — and that opens up new opportunities for 3D visualization technology.”

NEW MODELING CAPABILITIES

Two years ago, Invensys, London, U.K., started to pilot its SimSci-Esscor Kiosk 3D simulation training with ENI at the Italian company’s Gela refinery on the southern coast of Sicily. By using and applying gaming and other skill sets more familiar to younger employees, EYESIM is designed to appeal to both new and more-experienced engineering staff (Figure 2).

“Invensys has since delivered four additional Kiosk units to other refineries in the ENI group and has recently also provided one to an upstream oil and gas company based in the U.K. to help them evaluate the competency of their offshore operators,” explains Richmond.

The firm also has developed a 3D visualization tool for advanced understanding of a pressurized water reactor (PWR) for a training and service provider to the nuclear industry. “This project couples high-fidelity dynamic simulation of the reactor with a powerful 3D GUI [graphical user interface] that allows dynamic visualization of the behavior using transparency, color coding and dynamic animation,” he adds.

Also new is the EYESIM e-learning generic virtual crude unit system that has just been delivered to a major petrochemical company in Japan. This system enables a classroom of ten operators to self-train on both control room and plant scenarios based on a high-fidelity dynamic process model and a virtual reality model of a crude unit.

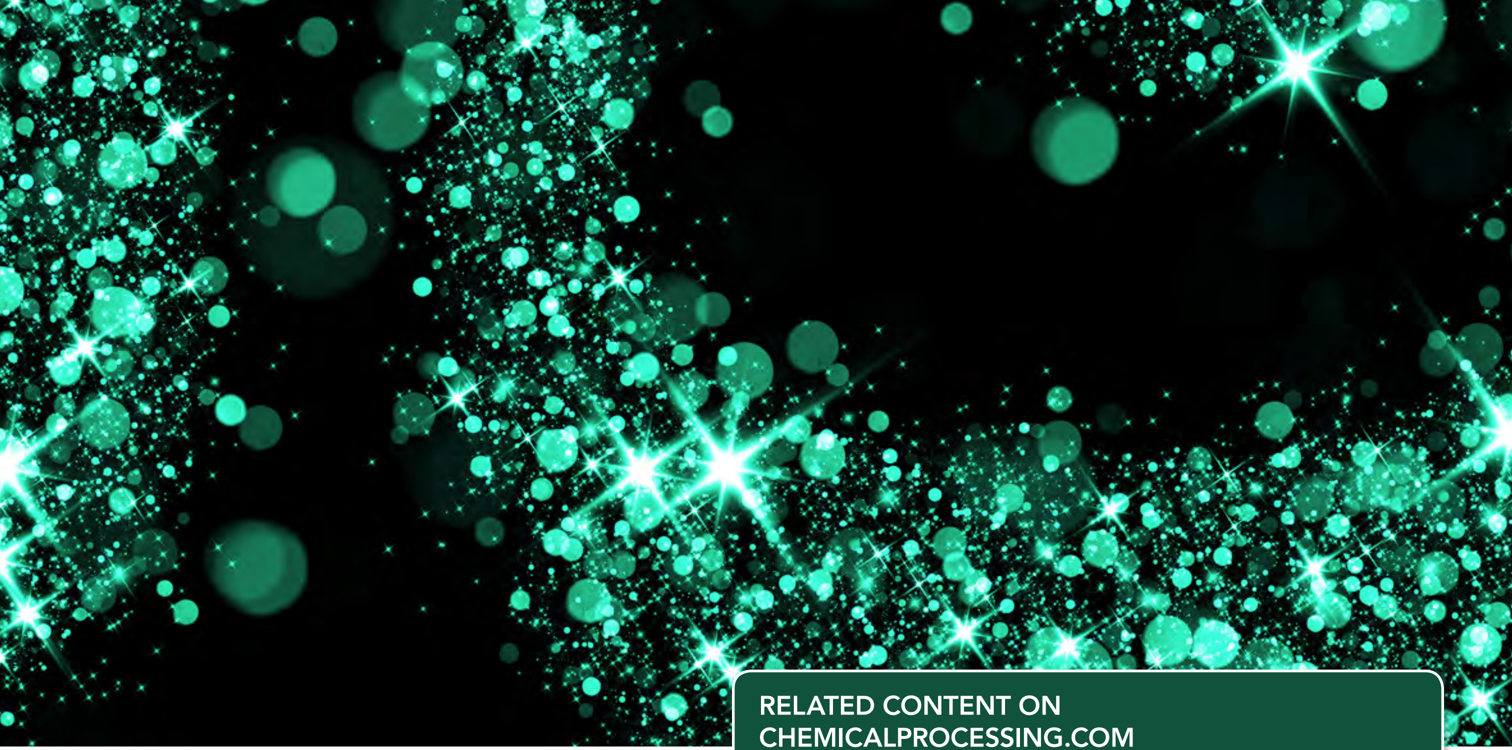
The benefits of such training are easily identified, he says, because better-trained operators will lead to safer and more efficient operation of plant assets. “To quantify those benefits, however, is a more subjective exercise. If a plant were to analyze their unplanned shutdowns, lost production, near misses and accident data, they would find that human error was a significant factor and that both control room and outside operators contribute to those incidents.”

However, chemical manufacturers normally wait until technology has been proven elsewhere before investing in it, he notes. “For that reason, the companies we work with today come from forward-looking technology groups or with a budget taken from innovation resourcing. The cost of these latest developments is on par or less than for the equivalent control-room-operator training systems. This means that we are able to provide a higher service at the same market price point.”

Invensys is focusing continuing development of EYESIM in four main areas.

First is a selection of new virtual-reality capabilities. Each new version of the engine includes faster rendering, shorter loading and enhanced animation and visualization of the virtual environment. “These all lead to a more-immersive environment to improve the training realism,” Richmond emphasizes.

Second is the provision of a more-powerful software development toolkit, which helps both



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to further automate the engineering process and reduce the cost of finding a solution.

Third is improved usability. Enhanced features include newly designed instructor station, iPad/iPhone (Figure 3) and tablet interfaces, location maps and contextual help.

Fourth is hardware and virtual reality (VR) technology. "We constantly evaluate the market for the best VR hardware available and build interfaces to the EYESIM environment. Exciting new technologies include Oculus Rift (VR headset), Omni (walking platform), LEAP Motion (hand motion detection), and new technologies to deliver cave automatic virtual environments (i.e., ones in which images are projected onto three or more walls of a room) at a fraction of the current costs," he notes.

PRODUCTIVE PARTNERSHIP

"In some industries, 3D visualization techniques are very important, for example operation of machinery in the minerals extraction industry, and for training for command and control scenarios such as fire and evacuation. For the process industries, the main market potential is seen in the training of field operators," notes Ross. "The benefits for them include getting a more-realistic training experience and a motivating environment that really engages the trainee." [For his thoughts on how to make the most of operator training simulators, see "Improve Operator Training," www.ChemicalProcessing.com/articles/2013/improve-operator-training/.]

To realize this potential, Honeywell for two years has worked with Virthualis, Milan, Italy, an engineering and research firm focused on using 3D simulation to improve decision-making in the design and implementation of operator training. The Italian company's MindSafe solution now is fully integrated with Honeywell's UniSim process simulator, providing a holistic virtual environment that can be used to efficiently design, analyze and verify plant operations.

UniSim precisely models what happens inside the pipework and process equipment, while Virthualis' 3D technology and accident simulation does the same for the external environment. This creates realistic, interactive scenarios that respond to changing conditions, for example how heat from fires can influence pressures and other conditions in pipes and equipment, which in turn possibly can cause leaks.

At the plant level, tasks that can be accomplished include planning and monitoring different training/assessment sessions, and maintaining a history of human errors and operator performance indicators. At the corporate level, training efficiency is improved, accident probability and consequences are reduced while efficiency and safety in plant operations and maintenance are increased.

"While the benefits of 3D training of field operators has not yet been specifically quantified, users of these solutions tell us that such benefits are significant," Ross concludes.

Leaks Don't Lie

Treat them as calls for action against the underlying problem

By Dirk Willard, Contributing Editor

ON AUGUST 6, 2012, firemen and a work crew were investigating a leak in the light-gas-oil side-cut line of the crude atmospheric tower at Chevron's Richmond, Calif., refinery. An operator suggested shutting down the unit for repairs but was over-ruled. Firemen were instructed to pin-point the leak under the insulation, which they proceeded to do — with a fire hook. The firemen smashed a hole in the thinned pipe and then blasted the pipe with cold water to break loose the insulation. The pipe burst and 640°F oil spilled and ignited. This accident nearly incinerated a fire-man and has cost Chevron $12 million so far.

Chevron had been replacing this corroded line and others connected to it but, obviously, not fast enough. Leaks were evident. During an inspection after the accident, Cal-OSHA found nine clamps to stop leaks.

Unfortunately, Chevron isn't alone in such misfortune. On December 7, 2009, a high-pressure reactor at NDK Crystal's plant in Belvedere, Ill., ruptured, killing a truck driver 650 feet away. In this case, nearby reactors had leaked before — in 2003, 2006 and 2009. NDK was convinced that a protective coating formed inside the 8-in.-thick reactor walls protected these vessels. NDK never qualified this "theory" or inspected vessel interiors. Neither the state of Illinois nor the company's insurer challenged the theory, though. Illinois granted NDK a waiver from complying with the ASME code: the thickness of the wall made inspection and fabrication problematic. The Belvedere site remains closed.

What links these two accidents together? Leaks provided adequate warning that something was very wrong.

So, what's the best way to approach a leak? Obviously, the first line of defense is vigorous inspection. Chevron, to its credit, did that; NDK did not. (The fatal 2010 fire and explosion at Tesoro's Anacortes, Wash., refinery also was linked to poor inspection.)

Second, always evaluate whether to continue operating once a leak is detected. Who at Chevron and NDK decided to keep the units running?

Chevron had more warning, but slapping a clamp on a leak is a common practice at most refineries. Chevron had used clamps before, building confidence that this approach was sound. (For more on the perils of stopgap repairs, see "Fear Ad Hoc Fixes," www.ChemicalProcessing.com/articles/2013/operational-safety-and-maintenance-fear-ad-hoc-fixes/.) Let's hope regulators and operating companies are doing some soul-searching to understand the risks of temporary solutions.

Now, imagine you were the maintenance manager at Richmond assigned to seal the leak. Assume you can't shut down the refinery, because that's normally the case. Perhaps operations can do something such as cut the tower rate, or cool or heat the tower temporarily to reduce the side draw. Ask. Work out a cooperative plan.

Start by reviewing the work done recently and in the past on the pipe and vessel: look at the inspection reports, marked-up isometrics, hazard and operability studies, etc. Talk with the inspectors and include them in the preparation. *You now know this pipe is fragile.* The process and instrumentation drawings don't show isolation valves; besides, even if they did, you don't know when these valves were operated last.

So, you have a delicate pipe and must remove the insulation to inspect it. How will you pull the insulation off without endangering your crew? Involve them in developing the job plan. What is your backup plan if the leak gets worse? How will the crew egress? What other equipment will be affected? What will you do if insulation removal doesn't expose the leak point? Who is qualified to do the job? Consider how the crew's actions could affect their safety and the success of job. Finish the draft and review it. Ask the inspectors to look over the job plan, too.

Ideally, you should have written a template for this plan months ahead as a maintenance standard operating procedure. This is a common practice at Dow Chemical and elsewhere.

Before work begins, brief your crew: no heroics, and no deviations from the plan. Establish a rapport with operations — what are they expected to do to support the crew? If the job goes sour, what will operations do to shut down the tower and reduce pipe flow? Do they have enough people to quickly isolate the tower? Are refinery safety and communications people in the loop on the work? Are nearby units aware of and prepared for what's going on? What about contractors and others off the refinery radio network? ●

CO_2 Gets a New Fizz

Technologies transform greenhouse gas into a feedstock for chemicals

By Seán Ottewell, Editor at Large

EFFORTS TO exploit waste carbon dioxide as a raw material to manufacture chemical products are advancing, driven by economics and the quest for sustainability. Companies such as Novomer, Oakbio and Liquid Light in North America, plus the Solar-Jet project in Europe are at various stages of developing technology to use the greenhouse gas. Such work is prompting interest and investment from major chemical companies including Saudi Aramco, DSM, BP and Shell.

For example, on May 21, Novomer, Waltham, Mass., announced the commercial introduction of its Converge polypropylene carbonate polyols for use in polyurethane formulations targeted at coatings, adhesive, sealant, elastomers (CASE) products, as well as rigid and flexible foams.

The move is an important step for the company, which has developed two technology platforms — one for carbon dioxide and the other for carbon monoxide — based on proprietary catalysts to transform propylene oxide or ethylene oxide into economically competitive, high-performance industrial products.

Converge polyols are designed to replace conventional petroleum-based polyether, polyester and polycarbonate polyols. The products, which are based on the co-polymerization of carbon dioxide and epoxides, contain more than 40% by weight carbon dioxide (Figure 1). Novomer says the use of waste carbon dioxide as a significant raw material gives the product an extremely low carbon footprint. In addition, because waste carbon dioxide is markedly lower in cost than conventional petroleum-based raw materials, production at full commercial scale is said to offer favorable economics compared to those of making conventional polyols.

The initial product offerings — 1,000- and 2,000-molecular-weight grades — are manufactured at a multi-thousand-ton commercial-scale toll facility in Houston. They currently are being tested by users and at the company's internal development center at Waltham.

"I can't name names yet but in June our first customer started buying one of our products in commercial quantities," says Peter H. Shepard, Novomer's chief business officer. "It's one thing to have the technology but a whole other thing to have someone else discover the value in a product and pay for it. That's a huge step forward. Once one customer starts using the product and getting good performance, it will help to springboard interest," he adds.

Interestingly, much of the interest in the technology is from companies that currently aren't in the CASE market but want to gain a foothold in it.

The success of Novomer's technology has attracted investment from Saudi Aramco Energy Ventures (SAEV), the corporate venturing subsidiary of Saudi Aramco, Dhahran, Saudi Arabia.

SAEV's investment will fund ongoing development of the technology platforms as well as construction of a

market-development plant to manufacture carbon-dioxide–based polyols, and the enhancement of Novomer's sales and marketing organization.

Shepard will not reveal the scale of SAEV's investment but does admit that it gives the company a good solid three years of operations. "Aramco are definitely into being a strategic partner, especially in the area of manufacturing. So if we meet certain targets, they would be very interested in housing a commercial plant." DSM also is involved but in a traditional venture capitalist role, he notes.

Novomer currently is developing a continuous production process at the Texas plant — an effort that will take about three years, he says — and working to make its catalysts less costly to use and more productive.

ALBERTA-BACKED INITIATIVES

Meanwhile Oakbio, Sunnyvale, Calif., and Liquid Light, Monmouth Junction, N.J., are among 24 groups that each will receive C$500,000 ($454,000) from the Climate Change and Emissions Management Corp. (CCEMC), Sherwood Park, Alberta, as part of its C$35-million (U.S.$31.8-million) international competition for technology to markedly cut greenhouse gas (GHG) emissions by creating new carbon-based products and markets. (For more details, see: "Carbon Competition Names First Round Winners," http://goo.gl/0bclv3).

Oakbio has created a technology that uses chemoautotrophic microbes to produce a number of chemicals from industrial waste, carbon dioxide and energy. Currently the company's main products are polyhydroxyalkanoate (PHA) polymers and n-butanol.

"Because we run a co-located flue-gas test laboratory at Lehigh Southwest Cement (Figure 2), Tehachapi, Calif., we were able to develop flue-gas-resistant strains using actual unadulterated flue gas and achieve up to 70% dry-weight yield of PHAs," says Brian Sefton, Oakbio's president and chief scientist.

The Lehigh project is significant because cement production currently accounts for 5–8% of global carbon dioxide release, according to Sefton. Lehigh itself produces 1 million t/y of the greenhouse gas.

Capture and conversion of carbon dioxide from the plant would yield over $1 billion/y of PHA or other products, Sefton notes. It also would increase the value of the cement produced there because builders could claim

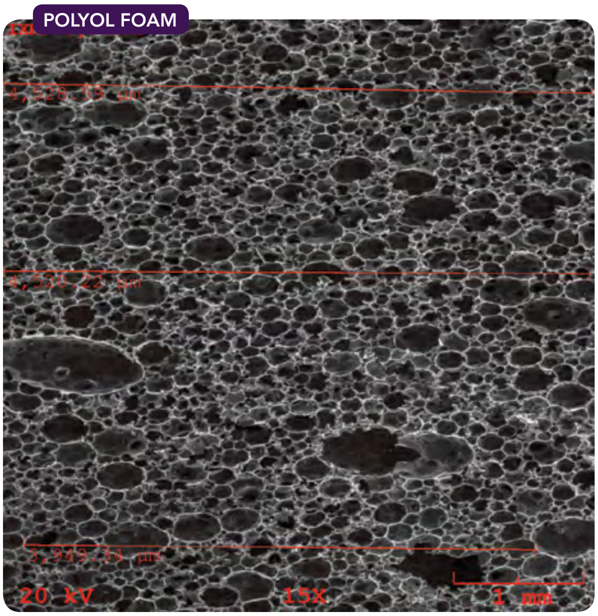

Figure 1. Foam contains more than 40 wt. % carbon dioxide and has an average cell size of about 150 microns. *Source: Novomer.*

credits for achieving green building standards by using it, he adds. On a broader note, capturing and converting the 2 billion t/y of carbon dioxide emitted by the worldwide cement industry could supply the entire global plastics market, he says.

Oakbio's n-butanol is the newer of the two products. "This is an important chemical feedstock as well as a drop-in biofuel with an octane rating similar to gasoline. This model is also capable of producing thousands of other compounds, many of which we have made in small amounts already such as diacids, ketones, esters, fatty acids and organic acids," notes Sefton.

The company currently uses bioreactors that vary in volume from 250 ml to 20 L. Oakbio is raising funds to take this program to pilot scale of 1,000–5,000 L.

The process has a number of advantages, says Sefton. First, it requires no costly extra ingredients such as promotors or antibiotics. This means the process water is very clean and can be re-used easily. "In addition, the process can uptake organic acids, acetone, benzene, diesel fuel and many other chemical compounds which are considered waste, including even dioxin, and break these down into energy and feedstocks for our target compounds."

Oakbio is working closely with Ohio State University, Columbus, Ohio, to leverage the school's molecular biology and enzymology expertise to increase n-butanol production to commercial levels. Sefton expects to achieve this in two years.

The PHA process is cost competitive and projected to be profitable at scale, he notes, while the n-butanol business is projected to be profitable once production levels reach the company target. Several chemical companies and fuel producers are watching developments closely, Sefton adds.

Meanwhile, Liquid Light has developed technology based on low-energy catalytic electrochemistry to use carbon dioxide to produce chemicals. By adjusting the catalyst design and combining hydrogenation and purification operations, the technology can make a range of commercially important multi-carbon chemicals including glycols, alcohols, olefins and organic acids.

The company believes that by using other feedstocks alongside carbon dioxide, a future plant would be able to manufacture multiple products simultaneously. "We are working on other catalysts to expand the list of possible products too," adds Kyle Teamey, Liquid Light's CEO.

A major chemical company is partnering in the work. This partner already has a variety of heterogeneous, homogenous and hybrid catalysts for the electrochemical reduction of carbon dioxide and also has developed catalysts for downstream processes, he notes.

In March, Liquid Light unveiled its first process — for the manufacture of monoethylene glycol (MEG). In lab-scale test runs, the demonstration electrocatalytic reaction cell met targets for energy needed per unit of output, rate of production, yield and stability/longevity of cell components.

Its process requires \$125 or less of carbon dioxide to make a ton of MEG versus an estimated \$617 to \$1,113 of feedstocks derived from oil, natural gas or corn needed by other processes, claims the firm. These differences are especially significant because MEG sells for between \$700 and \$1,400 per metric ton.

The company says that current estimates indicate that licensees would gain more than \$250 in added project value by opting for its process instead of the best currently available technology for a 400,000-t/y MEG plant. A 625,000-t/y plant would have a 15-year

net present value of over $850 million to a licensee, it adds.

An added bonus is that intermittently available renewable energy sources such as solar and wind can power the process. The result is that chemicals can be made directly from renewable energy sources and carbon dioxide, boasts the firm.

The plan now is to build a pilot plant in Canada to produce a ton of products per day and help to further validate the technical and economic feasibility of the technology.

LABORATORY AT CEMENT PLANT

Figure 2. Vertical pipes provide laboratory (blue container) with flue gas directly from stack. *Source: Oakbio.*

SEEKING A SOLAR SOLUTION

In Europe, a joint research/industry project has demonstrated the production path for so-called "solar" kerosene. Known as Solar-Jet, the project uses concentrated sunlight to convert carbon dioxide and water into a syngas via a redox cycle with metal-oxide-based materials at high temperatures (Figure 3). The syngas, a mixture of hydrogen and carbon monoxide, then is converted into kerosene using commercial Fisher-Tropsch technology.

ETH Zurich, Zurich, Switzerland; Bauhaus Luftfahrt (a research institute funded by four aerospace companies), Munich, Germany; the German Center for Aerospace, Cologne, Germany; research and technology development consultancy ARTTIC, Paris, France; and Shell Global Solutions, Amsterdam, The Netherlands, are pioneering the development of the new pathway.

The Swiss university is working on the solar splitting of water and carbon dioxide to produce solar syngas, while Shell is addressing the syngas-to-solar-kerosene step.

SOLAR SYNGAS

Figure 3. Process uses concentrated sunlight to convert carbon dioxide and water into a syngas that then is used to make kerosene. *Source: ETH Zurich.*

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The solar reactor consists of a cavity receiver with a 4-cm-diameter aperture through which concentrated solar radiation can pass; the aperture incorporates a compound parabolic concentrator to further boost the concentration. A 24-cm-diameter, 3-mm-thick clear fused-quartz disk window seals the reactor front. Sunlight comes from ETH's high-flux solar simulator.

The solar cavity receiver contains a reticulated porous ceramic foam made of pure cerium oxide. (The oxides of cerium have emerged as attractive redox active materials because of their ability to conduct oxygen ions faster than either ferrite-based oxides or other non-volatile metal oxides.)

This two-step thermochemical reaction's big advantage is its elimination of the gas separation steps needed after traditional thermolysis.

"Increasing environmental and supply security issues are leading the aviation sector to seek alternative fuels which can be used interchangeably with today's jet fuel, so-called 'drop-in' solutions," states Andreas Sizmann, the project coordinator at Bauhaus Luftfahrt. "With this first-ever proof-of-concept for 'solar' kerosene, the Solar-Jet project has made a major step towards truly sustainable fuels with virtually unlimited feedstocks in the future."

"The solar reactor technology features enhanced radiative heat transfer and fast reaction kinetics, which are crucial for maximizing the solar-to-fuel energy conversion efficiency," adds Aldo Steinfeld, who leads fundamental research and development of the solar reactor at ETH Zurich.

Although the solar-driven redox cycle for syngas production still is at an early stage of development, a number of companies including Shell already are processing syngas to kerosene on a global scale. "This is potentially a very interesting, novel pathway to liquid hydrocarbon fuels using focused solar power," says Hans Geerlings, principal research scientist at the Shell Technology Center in Amsterdam. "Although the individual steps of the process have previously been demonstrated at various scales, no attempt had been made previously to integrate the end-to-end system. We look forward to working with the project partners to drive forward research and development in the next phase of the project on such an ambitious emerging technology."

Within four years 50-kW solar reactor technology will be available but the first commercial, MW-scale application won't appear for 15 years, believes Steinfeld.

"Commercial scale-up will take place in a region of rich solar irradiation, where there is at least 2,000 kWh per square meter annually. The technical challenges involved in such a scale-up include efficient heat transfer and rapid reaction kinetics for maximum solar-to-fuel energy conversion efficiency," he adds.

Carefully Consider Nozzle Loads

Choices can impact piping design as well as equipment reliability

By Amin Almasi, rotating equipment consultant

PIPING LOADS that can be imposed on machinery nozzles (such as those of pumps, compressors, etc.) should be restrained within certain limits. Piping designers always want higher allowable nozzle loads to simplify piping designs while machinery manufacturers want smaller allowable nozzle loads to ensure good alignment, higher reliability and fewer complaints about operation. Process plant operators place great importance on long-term reliability of equipment and, so, generally should side with the machinery manufacturers. Regardless, it's essential for all parties to agree upon optimum nozzle loads for any machinery package.

Let's look specifically at nozzle loads for pumps and compressors.

Pump nozzle loads. These are specified in the pump's codes and standards (for example, API 610). The API 610 standard covers nozzle loads for horizontal pumps, vertical in-line pumps and vertically suspended pumps for nozzle sizes up to 16 in. (400 mm). For larger pump nozzles, come to an agreement with the vendor about nozzle loads before placing the order. Figure 1 depicts a piping design for horizontal pumps. Figure 2 shows real piping of an electric-motor-driven pump in a process plant.

Generally, small pumps not anchored to their foundations can tolerate higher nozzle loads than anchored ones. Allowable nozzle loads for vertical in-line pumps with supports not anchored to the foundation could be twice those of anchored pumps.

HORIZONTAL PUMP PIPING

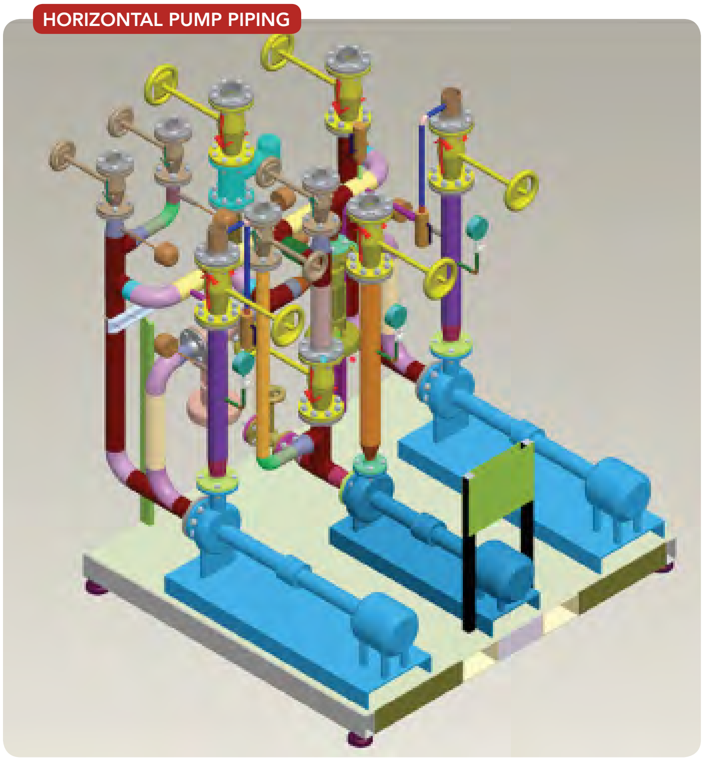

Figure 1. This layout typifies piping design for horizontal pumps.

Compressor nozzle loads. For centrifugal compressors, the API 617 standard specifies the nozzle load limits. However, many purchasers usually ask for two times the API 617 nozzle loads (2×API 617) to make piping design easier. While some machinery engineers and vendors may consider the API nozzle-load values optimum, in many situations piping engineers and stress analysis specialists can't achieve these values. A higher value (particularly 2×API 617) is a good solution to allow piping without expansion joints at nozzles or to avoid very complex piping systems. For special applications with very large differences between operating and ambient temperatures and very large nozzle sizes, it may make sense to specify a nozzle load three times the API 617 values (3×API 617). Figure 3 shows an example of large compressor piping.

Assign relatively low nozzle loads to integrally geared centrifugal compressors or rotating machines primarily designed for low pressures (such as some axial compressors, low-pressure overhung compressors, and machinery with open impellers) that rely upon close radial and axial clearances of rotating components (impeller or rotor assemblies) to machinery casings. For these compressors, allowable nozzle loads above conventional values in the API 617 standard aren't feasible. While the nozzle loads in AP I 617 usually can be achieved, the nozzles loads often instead are limited to 0.9×API 617. In any event, come to an agreement with the vendor on suitable nozzle loads before ordering such machines.

For screw compressors, the API 619 standard recommends nozzle loads. The nozzle loads of reciprocating compressors are left for the purchaser and vendor to jointly set. Generally, screw or reciprocating compressors come as packages; the purchaser and vendor should agree upon allowable nozzle loads at vendor interfaces.

Figure 2. Electric-motor-driven pumps such as this are common at process plants.

WHY THE FUSS?

To achieve maximum reliability, a machinery engineer's goal usually is to keep nozzle loads as low as practical. However, piping designers and stress analysis engineers generally design piping systems based on allowable (i.e., maximum) or even sometimes slightly higher than allowable nozzle loads to avoid very complex and expensive piping systems. The piping should have optimum flexibility to prevent distortion of machinery alignment or component damage.

So, it's important to carefully consider two effects of nozzle loads:

1. Internal alignment problems, i.e., distortion of a machine's casing and internals. Misalignment of internal machine components will create accelerated wear, rubbing or even early failure.

2. External alignment problems, i.e., misalignment of various shafts in a machine's train — for example, between a driven shaft and a driver shaft. The effects of external misalignment might not be as obvious as those from internal misalignment. However, external misalignment in time will take a toll.

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Vibration levels increase as couplings become misaligned. A high vibration trip could result in an unscheduled outage. Extended operation at high levels of misalignment could cause coupling failure, possibly bearing damage or even catastrophic failure.

To minimize misalignment of various shafts in a machine's train because of piping load effects, it's crucial to ensure that train casings, casing supports and baseplate(s) have sufficient structural stiffness to limit displacements of casings and shafts. Differences in thermal growth as well as errors in piping fabrication, and alignment all contribute to actual deflection values and final nozzle loads achieved in the field.

COMPRESSOR PIPING

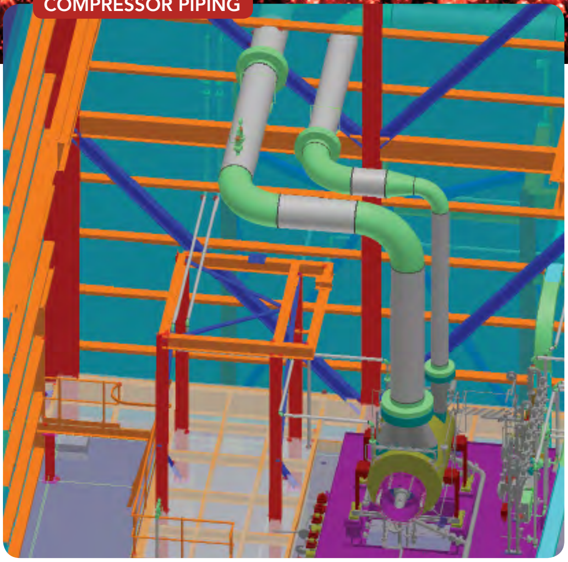

Figure 3. Large centrifugal compressors often are piped in this way.

Avoid to the maximum extent possible the use of expansion joints — they are expensive and maintenance-prone. Instead, put in more bends or loops to accommodate expansion. Also, avoid conservative stress analysis. One modern approach is to have the vendor model the entire system (including the piping and the machinery) at the same time. Concurrent modeling can reduce inherent conservatism and could allow the thermal movements to be accommodated correctly by both systems. This may result in a more-flexible combined system and can allow better optimization. Elimination of the expansion joint often can pay for the engineering time needed to remodel, re-evaluate and redesign the entire system. Ideally, include such an optimization-simulation in the vendor scope before the order.

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