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SEPTEMBER 2022

Control Systems

Launching a Nationwide Equipment Network

Exploring Local, Remote, and Distributed I/O

Calculating Gas Compressibility

Protecting Hazardous Locations from Explosion

Automation Overhaul

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Introduction

At a growing rate, automation and control professionals are finding new ways to use edge-oriented control architectures to enhance complex control systems. Increasingly, industrial controllers provide new options for industrial control systems that combine the best features of programmable logic controllers (PLCs) and industrial PCs (IPCs). Advances in web-based supervisory control and data acquisition (SCADA) systems continue to transform the process of installing, configuring, and managing automation and control systems to enhance manufacturing performance.

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Case Study: Launching a Nationwide Equipment Network

By Benson Hougland, Opto 22

ALTA Refrigeration achieves faster, easier product development and servicing with edge controllers and MQTT.

ALTA Refrigeration knows the secret to providing superior service and staying competitive in a changing market. Within a 10-year period, it transformed from a custom engineering services company into a scalable industrial equipment manufacturer using an edge-oriented control architecture to efficiently manage a growing installed base.

Originally started in 1975 as Industrial Refrigeration Services, ALTA has been designing and installing refrigeration systems across the United States for more than 45 years. For a long time, they were large, custom-designed systems that used a central machine room to deliver refrigerant to various facility areas through long, overhead piping runs.

"Our customers' biggest concern is their power bill," says Peter Santoro, controls engineer at ALTA. The company's systems stood out for the level of control they offered, including multiple operating modes that allowed the equipment to be tuned for optimal efficiency. However, it required significant time to design and program each unique system, and competitors were able to steal some of the market share with cheaper, simpler offerings.

"Competitors could use 20 to 30 cheaper units with control limited to a dumb thermostat to compete against one of ALTA's large systems," says Santoro. ALTA knew it couldn't compete by reducing its product quality, so the company looked for a way to standardize its offering without sacrificing features.

Creating an expert

In 2013, ALTA introduced its EXPERT series of modular refrigeration control units. Each unit used a standard, more reliable design, and could be mounted on the roof above the area it served, simplifying installation (figure 1).

According to Santoro, ALTA poured its previous years of experience with system design into creating the EXPERT product line. "A single EXPERT has almost as much I/O [input/output] as an entire centralized system, and because the units are much smaller, the wiring and conduit runs are incredibly short, allowing us to cram in a ton of sensors," says Santoro. "The units are also incredibly efficient. We analyze both the external ambient conditions and refrigerated space, and do real-time thermodynamic calculations. This lets us do variable capacity refrigeration, and only run exactly the amount of refrigeration as needed."

All motors are on variable speed drives (VFDs), says Santoro. "We also design many of the sensors we use on the system, allowing us to get precise valve positioning and to monitor refrigerant levels throughout the system. We make good use of Hall-effect sensors in various configurations to monitor refrigerant levels and motor positions. There is also a dedicated energy monitor on each unit so we can monitor voltages and power usage," he adds.

Since all EXPERT systems are essentially the same, Santoro and his colleague Todd Hedenstrom could put a higher degree of focused engineering into creating a robust and complete solution that works with many different applications.

Figure 1. Each EXPERT follows a standard, reliable design that can be mounted on the roof above the area it serves.

A good problem to have

The product rollout worked. EXPERT sales quickly grew to become the bulk of ALTA's business. ALTA has sold nearly 600 units and is typically sold out into the next year.

But growth brings its own challenges. While a handful of EXPERTS can replace one of the older, custom systems, ALTA now averages eight units per site, and service contracts drive ALTA's revenue. With only a small control engineering team, servicing the growing installed base became time consuming.

"Since we are installing sites at a much faster rate, scalability was our main concern," says Santoro. "We service the vast majority of our sites, so we need visibility into everything. Our systems have a long lifetime, and service is super important to our customer relationships. We sell probably 70 of these a year, and it gets hard to manage all that."

On top of this, there were some aspects of the previous designs related to system maintenance that got in the way. The control system required many steps to properly update control strategies in the field, including exchanging files between the control engine and the web server used for remote connectivity. It was a sometimes fragile process that made it difficult to train technicians.

Previously, ALTA had also left the details of remote connectivity to each customer. This increased the team's workload, since they usually checked in on each site every day and had to use a different method to connect to each one (VPN, Citrix, LogMeIn, TeamViewer, etc.). If they were going to keep up with the pace of growth, Santoro and Hedenstrom needed a way to remove these bottlenecks in service delivery.

A more robust solution

ALTA's centralized control system design was built around an industrial PC (IPC) running custom C++ code on top of a distributed I/O system from Opto 22. "We've been Opto people for something like 37 years," Hedenstrom adds. So, when he and Santoro designed the original EXPERT, they simplified the system by replacing the IPC with an Opto 22 PAC.

This approach was an improvement in some ways, since all the components of the system could be managed through the PAC. But it didn't go as far as they needed. It still required a multi-step update process and didn't give them as much data access as they wanted. Consequently, they began exploring Opto 22's newer *groov* EPIC system (figure 2).

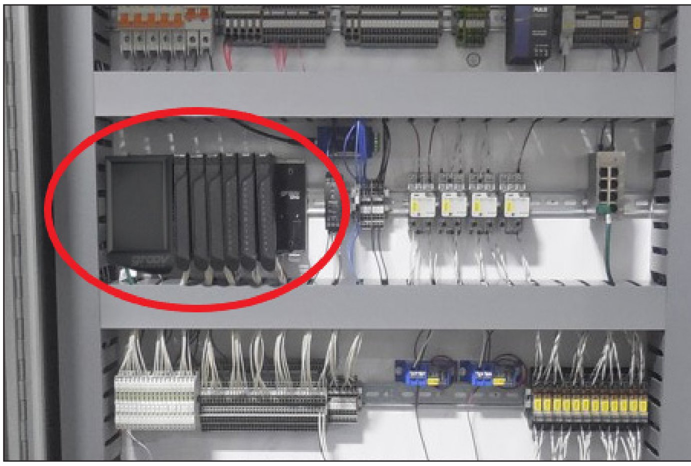

Figure 2. ALTA upgraded the EXPERT control system to Opto 22's *groov* EPIC to gain access to more flexible control and communication options.

EPICs, or edge programmable industrial controllers, provide a new option for industrial control systems that combines the best features of programmable logic controllers (PLCs) and IPCs. PLCs offer a rugged, purpose-built design with many typically expandable options for I/O and device communication. IPCs offer general-purpose processing power, storage, and networking options to support more demanding applications and broader functionality, such as cybersecurity, database management, and high-level programming languages. EPICs support all of these functions on a single backplane but typically without the complexity of maintaining a full Windows OS environment.

Santoro and Hedenstrom wanted to use the power and flexibility of an EPIC to develop a custom solution that reduced the effort required to deploy bug fixes and product updates. They also wanted a single solution for remote monitoring and thought that *groov* EPIC's array of communication options would make that easier.

Building a better fridge

Santoro and Hedenstrom dove seriously into using *groov* EPIC's operating system shell to port their PAC control application to C++, passing over other control engine options to leverage the language they were most familiar with. "We tried CODESYS on the EPIC," says Santoro, "but the freedom and flexibility of going with C++ was too good to pass on."

The *groov* EPIC uses a custom Debian Linux distribution that has been stripped down to the essential components, reducing its memory footprint and potential cyber-attack vectors. Additionally, it has been cryptographically signed with Opto 22's private key to prevent installation of any unapproved software. However, Opto 22 also exposes access to the EPIC's Linux command-line using the secure shell protocol (SSH) and a free Shell Access license (GROOV-LIC-SHELL).

"All development is done remotely through the SSH connection in [Microsoft] Visual Studio," Santoro explains. You can find the guide Todd Hedenstrom posted in the Opto 22 user forums explaining how he set up this connection, which allowed him to develop programs in VS and compile them directly on his EPIC. Once Hedenstrom figured out this basic process, he and Santoro were able to consolidate most of the control program into their C++ application along with many new features.

The program controls the installed I/O modules—voltage and current sensing inputs and discrete ac outputs—using Opto 22's C++ OptoMMP SDK, or software development kit. The application also includes its own Modbus server that creates and manages connections to VFDs, the local energy monitoring unit, and other remote devices.

"We [also] have our own REST API [application programming interface] and web server running on the C++ application," Santoro adds, "allowing us to create our own web page interfaces in HTML and JavaScript. It's a lot easier to build HTML stuff in familiar tools than with an HMI [human-machine interface] package. You can do anything." That includes things like using Google's Chart API to display energy metrics in the HMI.

Each EXPERT's web interface is served up from its EPIC controller (figure 3). It includes prebuilt templates for different unit configurations and verifies system settings to help technicians identify configuration values that are out of range or not recommended. It also generates alarms as needed. Alternatively, customers can access unit data through the EXPERT's Modbus server or REST API.

For managing groups of EXPERTs, ALTA uses a separate HMI server to read data from each unit and present a unified view of the entire system. "All of our sites are required to have a local interface for operators to see a global view of their refrigeration units, instead of having to manage network connections to hundreds of individual units," Santoro explains.

To create this site-level HMI, each EXPERT stores transient data in the shared memory "scratchpad" area of its *groov* EPIC. ALTA's HMI server runs on Microsoft Windows and uses Opto 22's .NET OptoMMP SDK to retrieve this data from all units in one-second increments. Data is stored in cyclical files that maintain a one-week buffer, and the HMI server uses this data to generate trends, charts, and email notifications.

ALTA can also access this data remotely for troubleshooting recent events. By default, *groov* EPIC does not route traffic between its Ethernet ports, so ALTA can use the controller to create a

Figure 3. Each EXPERT provides a local unit interface through an embedded web server that runs on the unit's EPIC.

security zone for each EXPERT. One port on each EPIC connects to a private network exclusively for the controller and its remote devices. The other port is connected to a common network between all the units at a given site, as well as the local HMI server.

This server is connected to the Internet and uses MQTT to send and receive data, acting as a middleman for each individual EXPERT to the MQTT broker that resides in ALTA's headquarters. When ALTA's remote HMI requires new data, it sends a request to the local server over MQTT. The data is queried and sent back. External connections to local HMI servers are restricted so that the only traffic allowed through is from outbound MQTT TLS connections.

Recently, ALTA also made it possible for its customers to access this remote server. The server has its own database that records temperatures and energy usage for each EXPERT in 10-minute intervals. Customers can log into a private web portal to generate reports directly from this data.

Since *groov* EPIC provides an embedded MQTT client and network firewall, ALTA "also tried doing unit-level MQTT [communications] to the broker," Santoro clarifies. "But with some of our units running on customer networks, it was impossible to guarantee they would allow a direct Internet connection to the [EPICs]. That's why we shifted focus to only have our local site server be the device connected to the broker."

The coolest service around

How are Santoro, Hedenstrom, and the ALTA team doing now? In Santoro's opinion, "Our service and warranty programs are unprecedented."

ALTA has built a nationwide HMI that aggregates data from its network of EXPERT units and highlights any issues the team needs to act on (figure 4, figure 5). Instead of spending hours every day to check on each site, they can monitor their entire installed base in minutes. They know when there is a problem, and they can input and track necessary work orders, track technicians' locations, and monitor energy usage per unit. When an alarm occurs, the system creates an interactive timeline of events before and after.

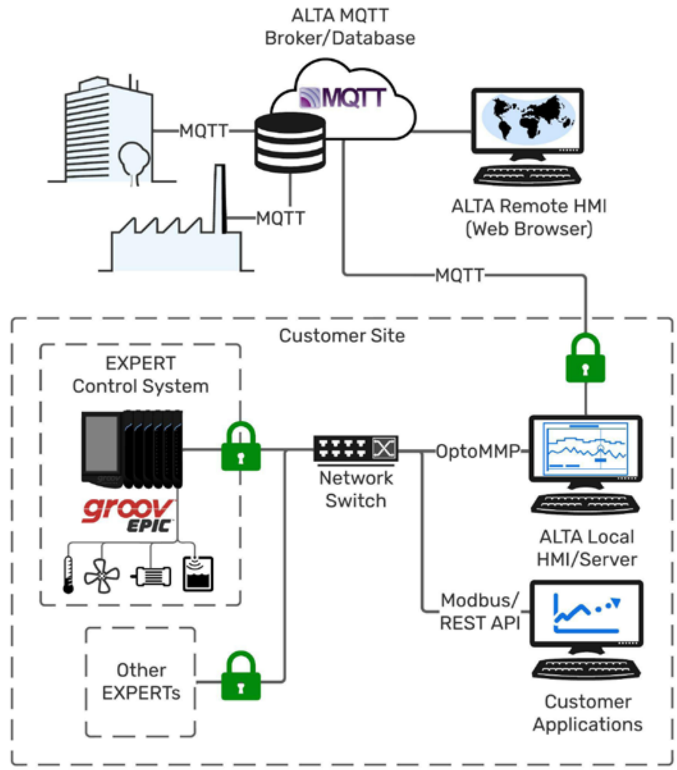

Figure 4. ALTA's nationwide network connects each EXPERT to its central server through a local HMI and MQTT gateway.

Figure 5. ALTA's central HMI aggregates data from across its installed base of EXPERT systems.

"Often, we know what the problem is before the customer calls. We just need to drive there and fix it," says Santoro. "With the amount of data we get from our units, we are capable of diagnosing the vast majority of problems remotely. This allows many of our end users to not even staff onsite maintenance. And [there's] no interfacing with third-party systems anymore. It's all integral."

> "With the correct key, a customer could grab the information from ALTA's nationwide system without needing to interface with their local hardware."

"When we used to do centralized systems, a lot of IoT [Internet of Things] stuff was near impossible with how the old systems were structured, he adds. "Because all the central systems could be drastically different, it was difficult to even consider a 'dashboard' to display them. Having a central web server or database was not even considered until we made the full transition to our EXPERT product line (figure 6). This solution was mostly developed to make our lives easier to support the systems. Having customers on here is just a big bonus now that everything is externally visible."

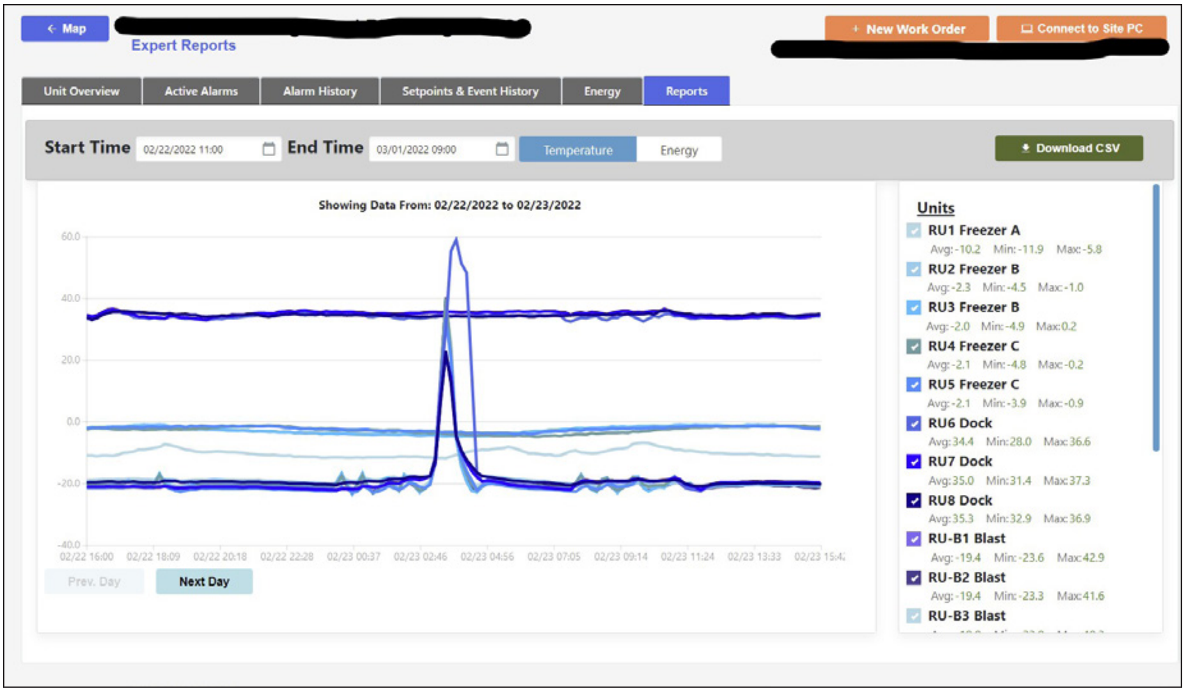

Figure 6. ALTA's central HMI continuously monitors its entire installed base, providing intuitive representation of system health across the country.

Servicing the systems themselves has also become much simpler now that Santoro and Hedenstrom can manage the entire platform—I/O configuration, control strategy, communications, and networking—through a single device (figure 7). "One of the best features we introduced was the ability to update the programs through our web interface. Now, a batch program packages up all the program files into a .gz (compressed) file. Technicians can upload the file and restart the system. We send the tarball [combination of multiple files], they click update, and the system takes care of the rest. Much easier," Santoro says.

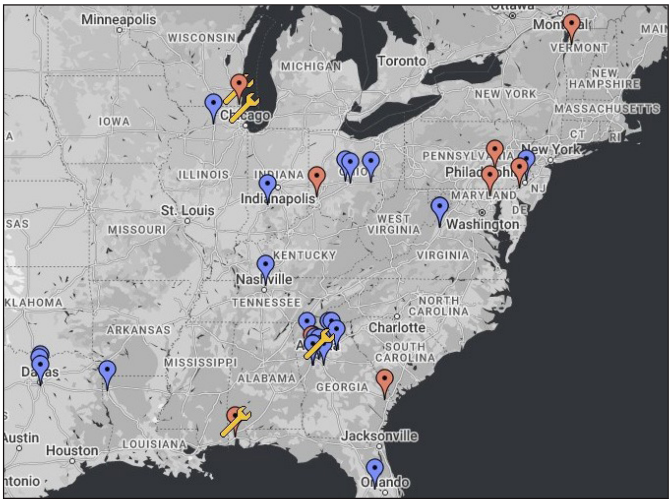

Figure 7. ALTA's nationwide network serves up performance data on every unit and allows the team to track and manage necessary work orders.

"We have a lot of experience with C++ here, so applying that to the EPIC controllers using Shell Access has allowed us to rapidly develop these custom solutions with a very small team. The lead engineer loves to make changes, so we've gone through hundreds of revisions."

ALTA also uses the *groov* EPIC's touchscreen as a maintenance interface inside the control cabinet. The native *groov* Manage application allows them to view and modify I/O and network settings directly on the controller without using a separate computer interface. Using the EPIC's native HMI server, *groov* View, ALTA also provides technicians with local control options and basic information about the Linux program's status.

But can it get even cooler?

With EPICs as a foundation for their control platform, Santoro and Hedenstrom continue to dream up even more service offerings. They are working on the ability to remotely update both the local servers and each individual EXPERT unit from their central web server. The server will soon have its own REST API as well. With the correct key, a customer could grab the information from ALTA's nationwide system without needing to interface with their local hardware at all. Additionally, ALTA is considering using the larger storage capacity of the *groov* EPIC PR2 processor (GRV-EPIC-PR2) to store the EXPERT's process history buffer directly on the EPIC, rather than its local Windows servers.

Other new features are on their way as well, potentially including real-time operational adjustments based on local power rates. And with a large network of performance data to draw on, the team has also been evaluating integration with a cloud IoT platform for long-term data storage and predictive control.

Santoro sums it up by saying, "It's nice to have the EPIC as the IPC with I/O. It's just simpler. We can do a lot with a little." As of writing this case study, ALTA has deployed 200 EPICs in the field. EXPERT sales are booked solid through the coming year.

All images courtesy of Opto 22.

ABOUT THE AUTHOR

Benson Hougland is vice president of marketing and product strategy at Opto 22. With 30 years of experience in information technology and industrial automation, Hougland drives product strategy for Opto 22 automation and control systems that connect and secure the real world of OT with the systems and networks of IT and cloud. Hougland speaks at trade shows and conferences, including IBM Think, ARC Forum, and ISA. His 2014 TEDx Talk introduces non-technical people to the IoT.

Exploring Local, Remote, and Distributed I/O

Input/output (I/O) devices have advanced rapidly in recent years; the differentiators are blurring the lines that separated them.

Figure 1. Local I/O is typically collocated within the same cabinet.

By Paul Harris

Process and factory automation controllers connect to sensors, instruments, valves, and other equipment through input/output (I/O) cards or racks that are either collocated within the same cabinet (local) at the controller/CPU or installed farther away (remote). Defining the difference between local and remote I/O is straightforward, but the defining differences between remote I/O and distributed I/O can have their nuances and are further confounded by each vendor's definitions or marketing collateral, just as many automation vendors prefer a name like process automation controller (PAC) over programmable logic controller (PLC).

The most used I/O type is local I/O (figure 1). It is most often from the same vendor as the controller/CPU, since it is ordinarily directly connected to the controller/CPU by integrated racks or cages that hold 4-, 8-, 16-, or 32-point I/O cards. Some local I/O expansion racks, or bricks, as they are often referred to, can be separate from the main CPU and connected over a digital bus or highway via twisted pair wires or Ethernet cables, albeit installed within the same physical cabinet. Since local I/O is typically intended to be installed within the same enclosure as the controller/CPU, environmental operational characteristics and hazardous area approvals are not as robust as remotely installed I/O.

Remote I/O characteristics

Next comes the challenge of outlining the different characteristics between remote I/O and distributed I/O, especially since many vendors refer to them interchangeably. If we use history and release to market timelines as a basis, remote I/O was first and thus less flexible, capable and smart as compared to later released distributed I/O. Initially, remote I/O was nothing more than local I/O reconfigured and housed to be remotely installed from its corresponding controller/CPU (figure 2).

Figure 2. Remote I/O was local I/O reconfigured and housed to be remotely installed from its corresponding controller/CPU.

Communication was no longer along a backplane but now designed to convert its connected analog I/O signals to a digital format that was transmitted back to the host controller over proprietary buses or highways. Remote I/O is limited in scope and does not contain a complex or advanced CPU or processor to handle math, complex control, and peer-to-peer communication with other remote I/O modules, or allow the connection of additional I/O modules. While operational characteristics and hazardous approvals exceed that of most Local I/O products, it is still somewhat more limited than its advanced cousin, distributed I/O.

Distributed I/O characteristics

Distributed I/O harnesses all the capabilities of remote I/O and more. It is likely, but impossible to determine, that distributed I/O derived its name from "distributed control." As the name suggests, distributed I/O is a more complex piece of equipment that can be distributed throughout a process plant or automation facility without the concern of continuous communication with its host controller/CPU. This is because most distributed I/O products contain an advanced CPU and often real-time operation system that allows localized control and monitoring, along with several other capabilities.

"Initially, remote I/O was nothing more than local I/O reconfigured and housed to be remotely installed from its corresponding controller/CPU."

Since distributed I/O (figure 3) is designed to exist on its own, it can be a preferred choice of remote I/O due to its ability to be redundant or fault tolerant should it lose communication with a primary controller/CPU. In addition, distributed I/O and its advanced capabilities can share signals between other peer distributed I/O systems from the same vendor or alternative vendors using industry open or standardized protocols such as MODBUS RTU. Designed to be used for remote installations, distributed I/O typically allows for installation in more harsh operating environments and often has a minimum of Class I, Div. 2/Zone 2 approvals and sometimes carry Zone 0/1 approvals.

With its diverse capabilities, distributed I/O can be well suited to not only be a local controller and I/O device, but it can also have additional built-in capabilities to support peer-to-peer communications, gateway functions such as HART to MODBUS RTU or MODBUS/TCP conversion, embedded webservers for ease of viewing real time process data with an off the shelf web browser, data logging, and even Industrial Internet of Things (IIoT) or Industry 4.0 capabilities employing message queuing telemetry transport (MQTT) protocol for seamless connections to cloud services like Amazon Web Services (AWS) or Microsoft Azure.

Figure 3. Distributed I/O can share signals between other peer distributed I/O systems from the same vendor or alternative vendors using industry open or standardized protocols.

Looking ahead

Recent advances in secure spread spectrum, long range, and mesh wireless telemetry have further enabled I/O products to provide solutions once thought impossible. WirelessHART, ISA 100, and many proprietary short- and long-range unlicensed solutions are now optionally embedded directly within the I/O product itself, spawning an entirely new category of remote or distributed type of I/O solutions.

Regardless of type, I/O products have advanced incredibly fast during the last decade. So much so that several of the abovementioned differentiators have blurred the once defined lines that separated them. For the user, it is imperative that each vendor's solution and technology offering be thoroughly examined to ensure functional, operational, and design compliance.

ABOUT THE AUTHOR

Paul Harris is the sales and operations manager of Moore Industries Europe Inc. Before being named SAOM in 2019, Harris held various roles within the company, rising from junior test engineer through to the position of export sales manager. Joining Moore Industries in 1983, he quickly became a progressor who could span a breadth of process control instrumentation technologies and is now accountable for implementing the company's policies while directing local strategies to enhance the overall growth of the EMEA regions.

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New Automation Technology **BECKHOFF**

Protecting Hazardous Locations from Explosion

Understand the types of hazardous areas and variety of explosion protection methods to best protect industrial operations.

By Jack Smith, Automation.com and *InTech*

An explosion is an exothermic, or heat-releasing, reaction of a substance at a high reaction rate. It requires the presence of an explosive mixture/atmosphere and an ignition source, plus an extraneous cause that triggers the explosion (figure 1). The potential for an explosion is present where electrical equipment and potentially explosive mixtures coexist. Protection and/or mitigation must be incorporated to prevent explosions. Approved methods that provide protection from ignition in potentially explosive areas must be designed into electrical equipment and processes.

Explosion protection methods include exclusion, containment, and energy-limiting technologies. A common form of the latter is known as intrinsic safety. We'll look at these methods for protecting various types of hazardous areas in process plants with the help of Jesse Hill, process industry manager at Beckhoff Automation LLC.

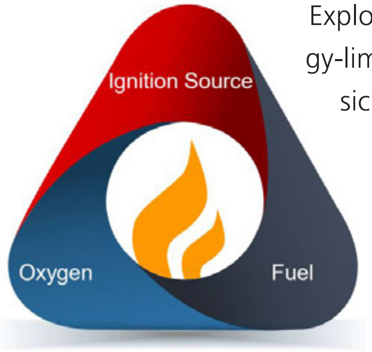

Figure 1. An explosion cannot occur if one of these three components is missing. *Courtesy: Beckhoff Automation*

The need for explosion protection

Piper Alpha was an offshore production facility operated by Occidental Petroleum Limited that exploded and sank in July 1988 and killed 165 people. Workers were performing maintenance on a pressure relief valve, and they didn't finish before the end of the shift. They put a temporary seal in place, and that communication didn't get to the next shift. There was a gas leak, which hit an emission source and caused the explosion. The economic impact was almost $2 billion.

Figure 2. Aftermath of the 2005 explosion at the BP refinery in Texas City, Texas. *Courtesy: U.S. Chemical and Hazard Safety Investigation Board*

In 2005, BP's Texas City Refinery was the second-largest oil refinery in the state and the third largest in the United States. On March 23, an explosion occurred when a vapor cloud of natural gas and petroleum ignited and violently exploded at the isomerization process unit and killed 15 workers, injured 180 others, and severely damaged the refinery (figure 2). Factors contributing to the explosion included serious issues with items of safety-critical equipment that had not been resolved prior to the startup: an inoperative pressure-control valve, a defective high-level alarm in the raffinate splitter tower, and a defective sight glass used to indicate fluid levels at the base of the splitter tower. Also, the vital splitter tower-level transmitter had not been calibrated.

These and other examples highlight the importance of explosion protection planning. Every plan involves assessing the risk to be found in a given area, and that requires an understanding of the definitions for hazardous classes, zones, and groups.

Understanding class, zones, and groups

The following categories define hazardous (also known as "classified") areas:

- Class: The type of hazard present. For example, in the United States, Class I denotes gases and vapors; Class II denotes dust.
- Division or Zone: The likelihood that the potential for a fire or explosion exists. Division 1 and Zone 0 or 1 are more dangerous than Division 2 and Zone 2.
- Group: The specific "type" of medium present creating the hazard.

International (ATEX, IECEx)

Flammable Material	Present continuously	Present occasionally	Present rarely
Gases	Zone 0	Zone 1	Zone 2
Dust	Zone 20	Zone 21	Zone 22

North America (NEC)

Flammable Material	Present continuously	Present occasionally	Present rarely
Gases and Vapors	Class I, Division I		Class I, Division II
Dust, fibers and airborne material	Class II, Division I		Class II, Division II

more dangerous ↔ less dangerous

Figure 3. Area classifications in North America compared to ATEX. *Courtesy: Beckhoff Automation*

Codes and standards in North America are NFPA 70: National Electrical Code (NEC) and CSA C22.1-2021: Canadian Electrical Code. In North America, there is an additional hazardous area, which is divided into Division 1 and Division 2. Throughout the rest of the world (e.g., ATEX), Division 1 is divided into two zones, with Zone 0 being more dangerous than Zone 1 (figure 3).

Explosion protection methods

Engineers designing electrical equipment and processes for use in hazardous areas have an abundance of explosion protection methods at their disposal. These methods are exclusion, containment, and energy-limiting technologies (figure 4). Examples of exclusion methods are oil immersion, purge, and pressurization. Containment includes explosion-proof or flame-proof enclosures. Energy-limiting technologies include non-incendive and intrinsic safety. Each method has advantages and disadvantages.

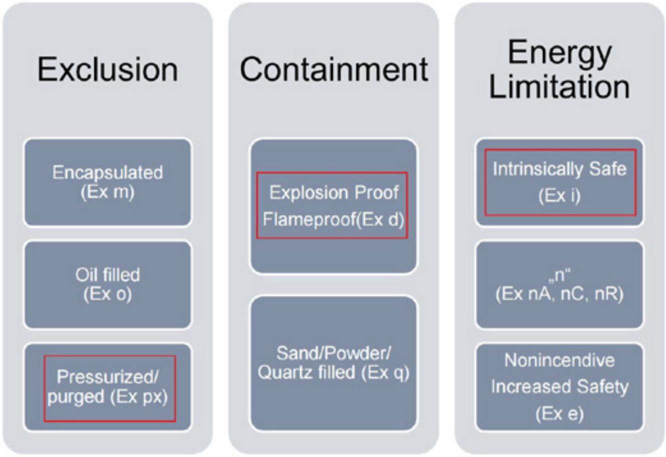

Figure 4. The three types of explosion protection technologies each have different methods for preventing explosions. *Courtesy: Beckhoff Automation*

Exclusion

Exclusion involves removing the fuel source from the ignition source. Examples of exclusion methods are encapsulation/oil immersion, purge, and pressurization. Encapsulation is an explosion protection concept whereby electrical equipment that could potentially cause an ignition is encapsulated within a compound or resin to prevent contact with an explosive atmosphere.

Oil filled is a type of explosion protection applied to an electrical apparatus so that all internal parts that are capable of igniting a flammable atmosphere are completely immersed in oil so they cannot come into contact with those atmospheres. Sand/powder/quartz filled is a method of explosion protection in which electrical equipment capable of ignition is in a sealed enclosure filled with quartz or glass powder particles. "However, the most prevalent exclusion method in North America is purge/pressurization," says Hill.

Before an enclosure with equipment not rated for that area is energized, it must be purged. A purge involves subjecting the enclosure to five times its volume of inert gas like nitrogen or air to purge any hazardous gases out of it, then maintaining a slight positive pressure so hazardous gases cannot get in. Applications where dust is present can't be purged, but protection comes from performing a meticulous cleaning, then applying positive pressure.

The three types of purge systems are X, Y, and Z, according to Hill. A Type X purge system reduces the classification within the protected enclosures from Division 1 to non-hazardous. General-purpose equipment can be operated within the protected enclosure. A disadvantage of X purge is that if the positive pressure air supply is lost, there must be an automatic shutdown in place.

A Type Y purging system reduces the classification within the protected enclosure from Division 1 to Division 2. All equipment used within the enclosure must be Division-2-rated. A Type Z purge system reduces the classification within the protected enclosure from Division 2 to non-hazardous. General-purpose equipment can be operated within the protected enclosure. With Y and Z purges, if purging air pressure is lost, an audible alarm must be activated, but an automatic shutdown is not required.

The purge and pressurization method has advantages and disadvantages.

Advantages	Disadvantages
• The only practical solution for some applications • Can protect large volumes, panels and even entire control rooms • Systems and expertise are readily available • General purpose equipment can be used in an area where they normally could not (X and Y purge)	• Clean air or a protective gas can be expensive and requires regular maintenance • May take up a lot of real estate or be too large for some applications • Loss of pressurization could shut down production • Safety concerns for personnel if nitrogen is used • Class 1 Div. 2 equipment still required for Y purge

Containment

Containment allows the fuel source to reach the ignition source, but it contains any explosion, thereby preventing a catastrophic event. Explosion proof or flameproof technologies are the only methods of protection that don't prevent explosions. They actually allow it. There are many applications for explosion proof containment, and materials are readily available. Many distributors seem to be always nearby with conduit, rigid conduit, and explosion proof enclosures.

According to Hill, gases are allowed inside explosion proof enclosures. A necessary defined gap is present in the flange (figure 5). If and when gases penetrate the enclosure and there is an arc or spark, there will be an explosion as hot gases and pressure try to escape the enclosure.

"The gases will try to escape via the conduit run because it's the biggest opening," says Hill. Explosion proof seals are poured at the conduit (and other) openings, which prevent the hot gases and pressure from escaping through that path. For these reasons, explosion proof installations must be properly designed, installed, and maintained.

Although the meticulously designed gap has normal clearance during equipment operation, they are made to expand when there is an explosion. There are specific torque ratings for the enclosure bolts. If not closed correctly, the gap may become slightly wider, which will cause a problem.

The explosion proof method has advantages and disadvantages.

Advantages	Disadvantages
• Only method available for some applications	• Must be meticulously maintained
• Expertise must be readily available	• Internal electronics not easily available
• Can protect almost any type of device	• Cannot work on "hot"
• Readily available in many sizes and types	• Does not prevent explosions

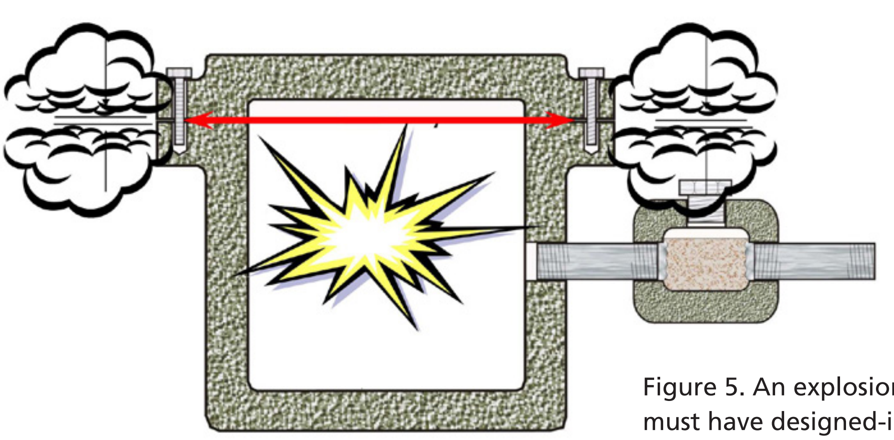

Figure 5. An explosion-proof enclosure must have designed-in gaps. *Courtesy: Beckhoff Automation*

Energy-limiting technologies

The "intrinsic safety" technique of energy-limiting explosion protection is universally accepted and applied worldwide as the preferred method of protection in potentially explosive atmospheres. The objectives of intrinsic safety are to limit current, limit voltage, and limit stored electrical energy.

Intrinsic safety is the safest form of explosion protection, the least expensive to implement, and the easiest method to deploy. It is the only method of explosion protection approved for Zone 0, the most hazardous area recognized by ATEX, IECEx, and NEC (Article 505). Zone 0 is considered to be "continuously" hazardous.

"Intrinsic safety is required to withstand two electrical faults and remain safe. It also is inherently safer for personnel, as its energy limiting principle typically only allows up to 30 volts or 100 mA to the hazardous area," says Hill.

The two types of intrinsic safety devices are Zener barriers and galvanically isolated barriers. Zener barriers are relatively inexpensive passive devices. They don't modify signals. They only limit the energy so no signal conditioning is required. The Zener diodes load the energy and shunt any overvoltage to ground, which means it is important to have an approved, intrinsically safe ground. Galvanically isolated barriers are active devices that also can perform signal conditioning. They are application specific and require no intrinsically safe ground.

Figure 6 shows a basic circuit design of a Zener diode barrier. The circuit includes an energy source, fuse, resistor, or Zener diode that shunts any overvoltage to the intrinsically safe ground.

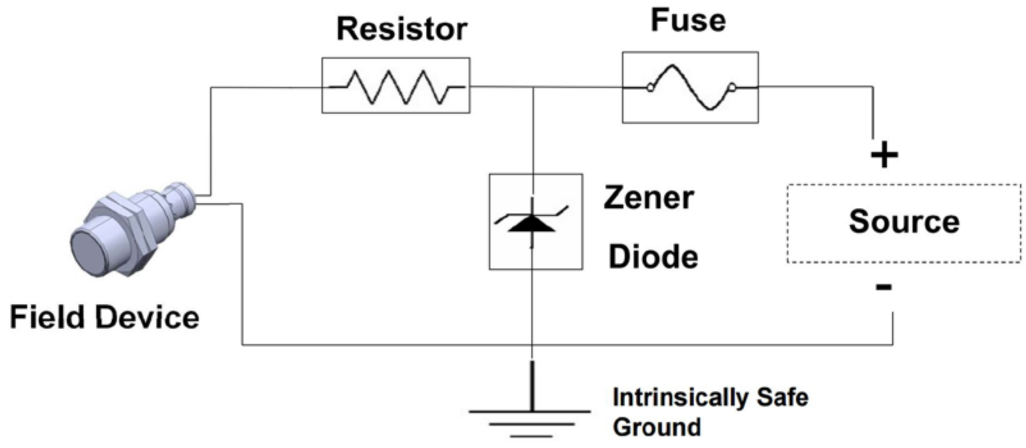

Figure 6. A basic circuit design of a Zener diode barrier. Courtesy: Beckhoff Automation

Hill says an intrinsically safe ground must be separate from other grounding, and it must be a minimum of 12 AWG. It must be labeled as intrinsically safe, and it cannot exceed 1 Ohm. ANSI/ISA recommended practice also recommends that there be redundant intrinsically safe grounds, which can simplify testing but also cuts the resistance in half. The resistance must be less than 1 Ohm.

Hill says a big advantage of intrinsic safety over explosion proof is that safe area wiring practices can be used. No rigid conduit and no cord seals are required. "When it comes to intrinsic safety, I.S. stands for intrinsic safety. But when it comes to wiring, it stands for identification and separation," he says.

Intrinsically safe wiring must be identified. Light blue is the universal color for intrinsic safety. If that is not practical, wiring must be labeled as intrinsically safe every 25 feet. In addition to identification, the wiring must be kept separate from non-intrinsically safe wiring. They must be separated by 50 millimeters or 2 inches.

The intrinsic safety method has advantages and disadvantages.

Advantages	Disadvantages
• Safest method of explosion protection • Least expensive to install and maintain • Only method that you can work on "hot" • Takes up less space than other methods • Only method approved for Zone 0	• Not viable for some high-powered applications • Requires approved field devices in many cases

Final thoughts

While explosion protection methods include exclusion and containment, energy-limiting technologies, especially intrinsic safety, are the most widely used. Intrinsic safety offers the safest, most cost effective, and easiest way to deploy solutions that safeguard process operations.

ABOUT THE AUTHOR

Jack Smith (jsmith@automation.com) is a contributing editor for Automation.com and ISA's InTech magazine. He spent more than 20 years working in industry—from electrical power generation to instrumentation and control, to automation, and from electronic communications to computers—and has been a trade journalist for 22 years.

Automation Overhaul Benefits Smaller Utilities

By Del Williams

A utility in Texas installed a monitoring and control system rivaling those at much larger utilities to improve service.

Traditionally, small municipal electrical utilities like the one in Seguin, Texas, have believed that implementing a supervisory control and data acquisition (SCADA) system was out of reach due to the perceived high initial costs, high licensing fees, and complexity.

However, advances in web-based SCADA systems have transformed the process of installing, configuring, and managing these systems to control substation performance. Modern web-based systems streamline installation and maintenance and provide engineers with a modern user interface they can easily configure—a factor that now allows even smaller cities to operate like large investor-owned utilities with hundreds of substations.

SCADA integration plan

Consider the scenario in Seguin, Texas. The utility embarked on an ambitious plan to integrate a new SCADA system with Outage Management System software, citywide Wi-Fi, advanced metering infrastructure (AMI) technology, GIS mapping, and energy efficiency software to improve customer reliability and education. The system was designed to enable utility engineering teams to manage a dispersed network and more efficiently support the cooperative's mission for reliable, cost-effective service.

The Seguin had no trouble justifying the SCADA investment, even though there are only three substations. The system provides the same degree of monitoring and control system as implemented by larger utilities. Seguin has a population of 25,090. Approximately 8,200 residential customers, as well as several large industrial facilities, rely on power from the electrical system. The utility operates three substations with 14 circuits, which requires 19 employees to manage 110 miles of overhead and 26 miles of underground electric lines.

To complete this ambitious SCADA implementation, the city turned to M&S Engineering, a full-service electrical, civil, and subsurface utility engineering and surveying firm, to develop all the specifications outlined in the initial bid.

"The system uses open-source web technologies and preconfigured template pages, which simplifies the building of interactive SCADA and local HMI screens."

Solutions for Seguin

For the physical infrastructure and sensors, M&S Engineering specified an AMI system from Aclara that includes nine collectors that gather smart meter readings. AMI systems enable electric utilities to collect and harness the power of smart meters, edge devices, and data to meet challenges such as substation monitoring, load monitoring, load control/demand response, fault detection/outage management, distributed generation, conservation voltage reduction, and customer engagement. The data is then transmitted over a newly installed, citywide Strix Wi-Fi system to a central network, which allows multiple users and departments to access the information.

To enhance communication and decision-making, assets such as electric poles and meters are now mapped and coordinated through ESRI, a geographic information system (GIS) mapping company. The GPS coordinates facilitate more efficient dispatching of utility trucks and service crews when needed. For the SCADA system, M&S Engineering selected the OrionLX system, a communication and automation processor, from the Power Division of NovaTech Automation (Lenexa, Kan.), a substation automation company that has served the power transmission and distribution market for more than 30 years.

The communication and automation processor can connect to nearly any substation device in its native protocol, perform advanced math and logic, and securely present the source or calculated data to any number of clients in their own protocol. The system can be integrated with practically any equipment, usually microprocessor-based relays, meters, and other intelligent electronic devices, as well. It is then connected to the SCADA system.

The system uses open-source web technologies and preconfigured template pages, which simplifies the building of interactive SCADA and local human-machine interface (HMI) screens to view data from connected intelligent electronic devices and remote terminal units (RTUs) using standard web browsers. Engineers can open multiple browsers to have graphical interfaces for the different substations and key remote monitoring features on different tabs, which eases network monitoring. Multiple users can be logged in simultaneously.

For the most economical setup, Seguin opted to install a communication and automation processor in each of its three substations that connect wirelessly to a browsing PC with multiple monitors, each representing a substation. Another configuration option for smaller utilities is a centralized model, in which a communication and automation processor is installed in the central office (taking the place of the browsing PC) that accesses each substation communication and automation processor, then serves up the information to connected networks.

The communication and automation processor RTU (figure 1) has improved in the integration of functions previously accomplished by separate physical devices. For example, separate alarm annunciators and PCs do not have to be connected to the RTU—only a monitor, keyboard, and mouse need to be connected. The communication and automation processor tile annunciator is a pre-engineered product that can be set up in minutes to provide alarm status. When combined with sequence of events recording, relay event retrieval, intelligent electronic device faceplates, one-line diagrams, control screens, and trending, the communication and automation processor can serve as a complete substation HMI or an economical small SCADA system.

One-line diagrams in the HMI show the status of the entire substation at a glance. This enables

Figure 1. Typical communication and automation processor RTU panel with direct video monitor, input/output (I/O), panel metering, and intelligent electronic devices.

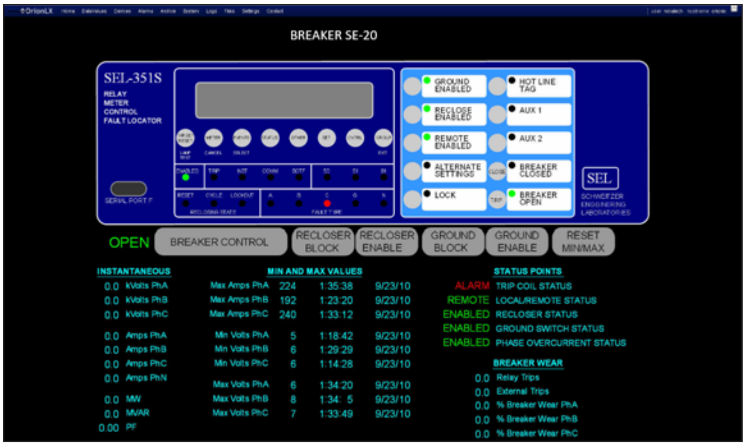

Figure 2. Intelligent electronic device "Zoom screen" showing real-time animation of feeder relay status. In this example, more than 80 real-time values from the relay are available on this page.

dispatch teams to quickly tell which feeders are open and if there are voltage issues. Feeder breaker zoom screens allow more detailed information to be viewed at the office, including ground trip blocked, non-reclosing, max amperage, power factor, and fault currents (figure 2). History of events can be accumulated, such as breaker trips, breaker lockouts, reclosers blocked or enabled, low voltage events, high voltage events, and maximum amperage for each circuit.

M&S Engineering also was asked to integrate the SCADA system with Milsoft's Outage Management System (OMS). OMS's are efficient at identifying outage locations and providing real-time alerts. The systems also record the history of outages and alert customers about the status of outages and repairs.

As part of the project, M&S also specified an upgrade of all electromechanical relays to microprocessor relays from Schweitzer Engineering Laboratories (SEL). NovaTech developed settings that allowed the SEL relays to be accessed by the communication and automation processor, including real-time data and fault information.

"Relays keep detailed records of the electrical conditions at the time of a fault, and that information can be accessed remotely to provide technicians with critical information on where to go and what might need to be corrected," says Ray Wright, Senior Vice President of Marketing for NovaTech. "You don't want to have a technician going out and searching the line for miles to find the problem and then have to go back to the shop to get the needed equipment. Ideally, you want to say, 'Drive to this GPS location, bring a spare fuse, and fix the [known] problem.' "

Minimizing dispatches

After the SCADA system, microprocessor-based relays, and other components were installed, the city could respond to issues more quickly, resulting in shorter outage times for customers. Previously, personnel would have to drive out to a substation when there was an issue with a feeder or transformer. Now, most issues are diagnosed remotely.

"Now, the monitoring is done from the office. The engineering team remotely logs into the substation devices to view the data, settings, sequence of events, and make changes if needed. They usually do not have to visit the substations in person, so the labor involved in monthly checks is significantly reduced," says Wright.

"With SCADA, they can monitor and capture events such as low voltage or high voltage at the bus, which helps when troubleshooting customer complaints and enables remote manual control of voltage regulators," adds Wright. SCADA also allows the city to monitor the power factor on individual circuits and then to switch capacitors in or out, without having to depend on other companies.

The city of Seguin plans additional system upgrades, including an energy efficiency program featuring a new VoIP phone system and approximately eight additional Wi-Fi units and accompanying antennas to improve "self-healing" properties. The utility is also investigating automated switching, which would involve adding control panels and motors to the existing air break switches to facilitate operations through the SCADA system.

ABOUT THE AUTHOR

Del Williams is a technical writer based in Torrance, Calif. He writes about health, business, technology, and educational issues, and has an MA in English from C.S.U. Dominguez Hills.

Gas Compressibility Factor and Control Valve Sizing

By Jon F. Monsen, Ph.D., PE

A valve-sizing veteran provides perspective on calculating a gas's compressibility for control valve sizing.

The basic gas control valve sizing equation can be found in ISA-75.01.01-2012, "Industrial-Process Control Valves, Part 2-1: Flow Capacity," and in "IEC 60534-2-1 (Second Edition)." These standards show the valve sizing equation to take this form when arranged to be solved for "C":

$$C = \frac{W}{N_6 F_p Y \sqrt{x P_1 \rho_1}}$$

C is defined as being either C_v or ¬K_v (calculated required valve capacity) depending on the value of N_6. This equation requires a value for the upstream gas density where the symbol for density is ρ (rho). The equation assumes that the user knows an accurate density value. There are accurate tables for a few gases, the best example being steam, but such accurate information is not readily available for most industrial gases. The standards—the ISA and IEC standards are, for all practical purposes, identical—make allowance for this by including two additional equations.

These equations, one based on mass flow units (symbol W) and one on volumetric flow units at standard conditions (symbol Q_S) substitute for the upstream density a calculation of density based on the ideal gas equation using the molecular weight of the gas, its upstream pressure, and upstream temperature. To correct for the fact that a gas density calculation using the ideal gas equation does not always duplicate actual behavior, the standards include the compressibility factor (symbol Z) to include the degree to which a particular gas does not follow ideal gas behavior.

The equation for mass flow is:

$$C = \frac{W}{N_8 F_p P_1 Y}\sqrt{\frac{T_1 Z}{xM}}$$

A method for determining the value to use for the compressibility factor is outside the scope of the standards.

Experience has shown that for most gases used in industrial processes, and at the pressures and temperatures that they are normally used, for valve sizing purposes, assuming a compressibility factor of 1.0 is usually (but not always) sufficient. There are equations of state that predict the real density of gases, with varying degrees of accuracy. Some of these are included with piping system analysis applications. These applications can be expensive, at least from my point of view.

"To correct for the fact that a gas density calculation using the ideal gas equation does not always duplicate actual behavior, the standards include the compressibility factor (symbol Z)."

Spreadsheet development background

In 1987, when I was developing Hammel-Dahl's first control valve sizing application, I chose to use Van der Waals equation of state, though it is not as accurate as more complex equations, to account for the non-ideal behavior of gases. Advantages of using Van der Waals equation are that it is fairly simple and can be written in terms of the compressibility factor and the reduced pressure and reduced temperature of the gas1:

$$Z^3 - Z^2\left(\frac{P_r}{8T_r}+1\right)+Z\left(\frac{27P_r}{64T_r^2}\right)-\frac{27P_r^2}{512T_r^3}=0$$

It is significant to note that this is of the same form as the generalized compressibility chart, namely, $Z = f(\mathrm{Pr}, T_r)$. An iterative solution is required.

Gas Compressibility Factor (Z) for Control Valve Sizing Purposes

GAS: Carbon dioxide   TAG: PV-123

		COND 1	COND 2	COND 3	COND 4
CRITICAL TEMP	DEG F	88.00	=========>	=========>	========>
CRITICAL PRESS	PSIA	1070.00	=========>	=========>	========>
UPSTREAM TEMP	DEG F	90.00			
UPSTREAM PRESS	PSIA	750.00			
COMPRESS. FACTOR (Z)		0.70			
Reduced Temperature (Tr)		1.004			
		Tr within limits			
Reduced Pressure (Pr)		0.701			
		Pr within limits			

Data input
Final results

Figure 1. Calculation for carbon dioxide—process data for this application yields a compressibility factor of 0.70.

In later years, whenever I needed to size a valve for gas service when I suspected that the compressibility might become a factor, I would look up the compressibility factor using the Nelson-Obert Generalized Compressibility Charts[2]. These charts can be found at: http://eon.sdsu.edu/testhome/Test/solve/basics/tables/tablesRG/zNO.html.

Some time ago, I got tired of reading the charts, which requires some visual interpolation (and eye strain), and made a Microsoft Excel spreadsheet where I tabulated many reduced pressure and reduced temperature points from the Nelson-Obert charts and included a two-dimensional interpolation scheme that yields a compressibility factor for most gases for which I can find the critical pressure and temperature. The use of this spreadsheet is the topic of this article.

Figure 1 is a screenshot of the sheet showing a calculation for carbon dioxide. The calculation in figure 1 shows a compressibility factor of 0.7. In this case, assuming a compressibility factor of 1.0 when it is really 0.7 would result in a C_v calculation that would be about 20 percent high. When the compressibility factor decreases, so does the calculated required valve capacity (C_v or K_v).

The worksheet can be downloaded at no charge from: www.Control-Valve-Application-Tools.com. An alternate site is: www.industrydocs.org/.

Spreadsheet construction procedure

The Gas Compressibility Factor for Control Valve Sizing worksheet can also be constructed using the following instructions:

	A	B	C	D	E	F
1	Gas Compressibility Factor (Z) for Control Valve Sizing Purposes					
2						
3	GAS:	Nitrogen		TAG:		
4						
5			COND 1	COND 2	COND 3	COND 4
6	CRITICAL TEMP	DEG F	-232.52	=========>	=========>	========>
7	CRITICAL PRESS	PSIA	492.52	=========>	=========>	========>
8						
9	UPSTREAM TEMP	DEG F	100.00	10.00	10.00	-100.00
10	UPSTREAM PRESS	PSIA	500.00	500.00	1000.00	2000.00
11						
12	COMPRESS. FACTOR (Z)		1.00	0.98	0.96	0.85
13						
14	Reduced Temperature (Tr)		2.464	2.068	2.068	1.583
15			Tr within limits	Tr within limits	Tr within limits	Tr within limits
16	Reduced Pressure (Pr)		1.015	1.015	2.030	4.061
17			Pr within limits	Pr within limits	Pr within limits	Pr within limits
18						Data input
19						Final results

Screen 1. User interface.

	K	L	M	N	O	P	Q	R
1		Units used	Conv Factor	Conv Factor	Input Data Converted to Col L Units			
2		In	From Col B	From Col B	--			
3		Worksheet	Units to	Units to				
4		Formulas	Col L Units	Col L Units	Cond 1	Cond 2	Cond 3	Cond 4
5			(multiplier)	(adder)				
6	CRITICAL TEMP	DEG R	1.0000	459.67	227.15	==>		
7	CRITICAL PRESS	PSIA	1.0000	N/A	492.52	==>		
8								
9	UPSTREAM TEMP	DEG R	1.0000	459.67	559.67	469.67	469.67	359.67
10	UPSTREAM PRESS	PSIA	1.0000	N/A	500.00	500.00	1,000.00	2,000.00
11								
12			For consistency, all process and critical conditions					
13			are converted to PSIA and degrees R.					
14								
15			•To convert Deg C to Deg R, Multiplier is 1.8					
16			and adder is 491.67					
17			•To connvert Deg R to Deg R, Multiplier Is 1.0,					
18			and adder is 0.0.					
19			•To convert Deg K to Deg R Multiplier is 1.8					
20			Adder is 0.0					
21			•To convert Deg F to Deg R Multiplirer is 1.0					
22			Adder is 459.67					
23								
24			•To convert pressure units to PSIA,					
25			multiplier is the conversion factor from					
26			your presure units to PSIA					

Screen 2. Unit conversion inputs.

COMPRESSIBILITY FACTOR CALCULATION (for T r ≥ 1.0)

Cond 1	Cond 2	Cond 3	Cond 4		
2.464	2.068	2.068	1.583	Reduced Temp, Tr (Limited to a min of 1.0, Max of 15)	
1.015	1.015	2.030	4.061	Reduced Press, Pr	
2.000	2.000	2.000	1.400	Tr1	
2.500	2.500	2.500	1.600	Tr2	
13.000	13.000	15.000	17.000	Pr1 Column	
14.000	14.000	16.000	18.000	Pr2 Column	
1.000	1.000	2.000	4.000	Pr1	
1.500	1.500	3.000	5.000	Pr2	
0.975	0.975	0.955	0.745	Z(Tr1,Pr1)	
0.965	0.965	0.960	0.790	Z(Tr1,Pr2)	
0.975	0.975	0.955	0.748	Z(Tr1, Pr)	Interpolate above 2 lines
1.005	1.005	1.010	0.855	Z(Tr2,Pr1)	
1.005	1.005	1.015	0.880	Z(Tr2,Pr2)	
1.005	1.005	1.010	0.857	Z(Tr2, Pr)	Interpolate above 2 lines
1.003	0.979	0.963	0.848	Z(Tr,Pr)	Interpolate Z(Tr2,Pr) and Z(Tr1, Pr)

Screen 3. Calculations.

TABLE 1. Tabulated values of compressibility factors (Z) taken from the Nelson-Obert charts

Column Number / Pr, Reduced Pressure / Z

Tr Reduced Temperature	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	Tr1	Tr2	0.01	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.5	2.0	3.0	4.0	5.0	6.0	7.0	10.00	20.00	20.01
	0.00	1.00	OOR	OOR	OOR	OOR	OOR	OOR	OOR	OOR	OOR	OOR	OOR	OOR	OOR	OOR	OOR	OOR	OOR	OOR	OOR	OOR	OOR
	1.00	1.05	0.9950	0.9650	0.9300	0.8900	0.8500	0.8100	0.7600	0.7000	0.6300	0.5200	0.3000	0.2500	0.3050	0.4400	0.5600	0.6800	0.7900	0.9000	1.2400	2.2800	2.2800
	1.05	1.10	0.9960	0.9700	0.9400	0.9050	0.8750	0.8350	0.8000	0.7600	0.7200	0.6700	0.6050	0.3300	0.3300	0.4500	0.5600	0.6800	0.7700	0.8800	1.1850	2.2000	2.2000
	1.10	1.15	0.9970	0.9750	0.9500	0.9200	0.8950	0.8640	0.8350	0.8050	0.7750	0.7400	0.7000	0.4800	0.4000	0.4700	0.5750	0.6800	0.7800	0.8800	1.1600	2.1400	2.1400
	1.15	1.20	0.9980	0.9770	0.9550	0.9300	0.9100	0.8820	0.8600	0.8300	0.8100	0.7850	0.7560	0.6000	0.5000	0.5050	0.6000	0.6950	0.7900	0.8800	1.1600	2.0900	2.0900
	1.20	1.30	0.9990	0.9840	0.9600	0.9400	0.9300	0.9000	0.8800	0.8500	0.8350	0.8150	0.7950	0.6700	0.5850	0.5550	0.6250	0.7100	0.8000	0.8900	1.1600	2.0300	2.0300
	1.30	1.40	0.9990	0.9850	0.9700	0.9550	0.9400	0.9250	0.9100	0.8980	0.8800	0.8690	0.8500	0.7800	0.7100	0.6580	0.6800	0.7450	0.8250	0.9050	1.1600	1.9600	1.9600
	1.40	1.60	0.9990	0.9880	0.9770	0.9670	0.9580	0.9450	0.9350	0.9220	0.9100	0.9000	0.8880	0.8300	0.7900	0.7340	0.7450	0.7900	0.8550	0.9250	1.1600	1.9000	1.9000
	1.60	2.00	0.9990	0.9950	0.9880	0.9800	0.9740	0.9700	0.9600	0.9550	0.9500	0.9400	0.9300	0.9100	0.8850	0.8550	0.8550	0.8800	0.9200	0.9800	1.1600	1.8000	1.8000
	2.00	2.50	1.0000	0.9970	0.9950	0.9900	0.9900	0.9880	0.9860	0.9820	0.9800	0.9800	0.9750	0.9650	0.9550	0.9600	0.9600	0.9750	1.0050	1.0400	1.1600	1.6700	1.6700
	2.50	5.00	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0050	1.0050	1.0100	1.0150	1.0250	1.0400	1.0700	1.1000	1.1850	1.5500	1.5500
	5.00	15.00	1.0000	1.0010	1.0020	1.0030	1.0040	1.0050	1.0070	1.0080	1.0100	1.0100	1.0100	1.0200	1.0280	1.0350	1.0600	1.0800	1.0980	1.1500	1.1700	1.3500	1.3500
	15.00	15.01	1.0000	1.0000	1.0000	1.0000	1.0000	1.0010	1.0010	1.0010	1.0020	1.0030	1.0050	1.0080	1.0100	1.0180	1.0240	1.0320	1.1000	1.0500	1.0730	1.1400	1.1400
	15.01		1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0010	1.0020	1.0030	1.0040	1.0080	1.0100	1.0180	1.0240	1.0320	1.1000	1.0500	1.0730	1.1400	1.1400

"OOR" Stands for "Out Of Range"

Screen 4. Worksheet Table 1.

TABLE 2. Reduced Pressure

Specify the TABLE1 column to lookup Z factor in

Pr	Column *	
0.01	3	0.10
0.10	4	0.20
0.20	5	0.30
0.30	6	0.40
0.40	7	0.50
0.50	8	0.60
0.60	9	0.70
0.70	10	0.80
0.80	11	0.90
0.90	12	1.00
1.00	13	1.50
1.50	14	2.00
2.00	15	3.00
3.00	16	4.00
4.00	17	5.00
5.00	18	6.00
6.00	19	7.00
7.00	20	10.00
10.00	21	20.00
20.00	22	20.01
20.01	23	

Screen 5. Worksheet Table 2.

Creating the worksheet

Create an Excel worksheet based on Screen 1 through Screen 5. In these images, color coding of worksheet entries is as follows:

- Black cell entries are text typed into the cell.
- Red cell entries are formulas that are listed in Table A and must be typed into that cell.
- Green cell entries are copies of each red cell entry, but instead of typing in the formula, copy the formula in the red cell and paste it into the three cells to the right of the red cell.

CELL	FORMULA
	Screen 1, User Interface
C 12	=IF(OR($C$6="",$C$7="",C9="",C10=""),"",S21)
C 14	=IF(OR($C$6="",$C$7="",C9="",C10=""),"",O9/$O$6)
C15	=IF(OR($C$6="",$C$7="",C9="",C10=""),"", IF(OR(C14<1,C14>15),"Tr outside of limits","Tr within limits"))
C 16	=IF(OR($C$6="",$C$7="",C9="",C10=""),"",O10/$O$7)
C 17	=IF(OR($C$6="",$C$7="",C9="",C10=""),"",IF(OR(C16<0,C16>20),"Pr outside of limits","Pr within limits"))
	Screen 2, Unit conversion inputs
O 6	=$C$6*$M$6+$N$6
O 7	=C7*$M7
O 9	=C9*$M9+$N9
010	=C10*$M10
	Screen 3, Calculations
S 6	=IF(O9/$O$6<1,"OOR",IF(O9/$O$6>15,"OOR",O9/$O$6))
S 7	=IF(O10/$O$7<0.01,0.01,IF(O10/$O$7>20,"OOR",O10/$O$7))
S 9	=VLOOKUP(S6,TABLE1,1)
S 10	=VLOOKUP(S6,TABLE1,2)
S 11	=VLOOKUP(S7,TABLE2,2)
S 12	=S11+1
S 13	=VLOOKUP(S7,TABLE2,1)
S 14	=VLOOKUP(S7,TABLE2,3)
S 15	=VLOOKUP(S9,TABLE1,(S11))
S 16	=VLOOKUP(S9,TABLE1,(S12))
S 17	=S15+((S7-S13)*((S16-S15)/(S14-S13)))
S 18	=VLOOKUP(S10,TABLE1,(S11))
S 19	=VLOOKUP(S10,TABLE1,(S12))
S 20	=S18+((S7-S13)*((S19-S18)/(S14-S13)))
S 21	=S17+((S6-S9)*((S20-S17)/(S10-S9)))

Table A. Formulas to be entered into the Excel sheet.

There are two tables in the worksheet: Table 1 in Screen 4 and Table 2 in Screen 5. Type in the numerical values as shown. Then name the tables by highlighting the data shown inside the red box, and from the Excel Formulas tab, select "Define name" and type in the name of the table (TABEL1 or TABLE2) and click OK.

The Nelson-Obert charts are said to have an accuracy within 1 to 2 percent for Z values greater than 0.6 and within 4 to 6 percent for Z values of 0.3 to 0.6. The generalized compressibility factor graphs may be considerably in error for strongly polar gases, with errors as great as 15 to 20 percent.

The quantum gases hydrogen, helium, and neon do not conform to the corresponding states behavior, and the reduced pressure and temperature for those three gases should be redefined in the following manner to improve the accuracy of predicting their compressibility factors when using the generalized graphs:

$$T_r = \frac{T}{T_c + 8} \text{ and } P_r = \frac{P}{P_c + 8}$$

where temperatures are in Kelvin and pressures are in atmospheres.

The worksheet is valid for reduced pressures between 0.0 and 20 and for reduced temperatures between 1.0 and 15. The Nelson-Obert low pressure chart gives some data for reduced temperatures less than 1.0, but there is not enough data to lend it to the present method of tabulating data and interpolating between given data points. I think the reason for this scarcity of data is that the authors of the chart were not able to find much good agreement between various gases and their compressibility factors in the area between the reduced temperature (T_r) = 1.0 isotherm and the saturated vapor line.

Although the worksheet is configured for conventional U.S. units (degrees F and pounds per square inch absolute), there is a space to the right of the user interface where the user can easily change the conversion factors for other temperature and pressure units. If you change the conversion factors, you also can edit the unit designations in column B of the user interface to agree with your revised conversion factors. Keep in mind that all the calculations are carried out in absolute pressure and temperature units.

The Nelson-Obert charts are said to have an accuracy within 1 to 2 percent for Z values greater than 0.6 and within 4 to 6 percent for Z values of 0.3 to 0.6.

How it all works

A brief explanation of how the worksheet functions follows:

- The worksheet calculates the compressibility factor (Z) based on a table (TABLE1) of tabulated values of compressibility factors taken from the Nelson-Obert Generalized Compressibility Charts for a range of reduced pressures and reduced temperatures. To account for pressures and temperatures between the tabulated reduced pressures and temperatures, the worksheet does three sets of linear interpolations.
- At the tabulated value of T_r below, the user's given value of T_r, the worksheet finds Z at the user's given value of P_r by interpolating between the tabulated value of P_r above the user's given value of P_r and the tabulated value of P_r below the user's given value of P_r.
- The worksheet then repeats the above process at the tabulated value of T_r above the user's given value of T_r.

- The worksheet then has values of Z at the user's input value of P_r, at the tabulated values of T_r below, and above the user's input value of T_r.
- The final step is to interpolate between these two values of Z to find the value of Z at the user's input values of P_r and T_r. You can follow the above process in columns S, T, U, and V, rows 6 through 21, where each step is briefly described in column W.
- The worksheet determines the correct column to use in Table 1 by using a VLOOKUP function in Table 2.
- It then determines the correct row to use in Table 1 by using a VLOOKUP function in Column 1 of Table 1.

Using the worksheet

The worksheet has room for up to four sets of process conditions, making it compatible with many of the valve manufacturer's control valve sizing programs, which typically are configured to perform simultaneous calculations for up to four sets of process data.

The user interface is in the upper left corner of the worksheet. You can optionally enter the name of the gas and the tag number of the valve for which you are doing calculations, for your reference, if you are going to either save or print out the worksheet.

Enter the critical temperature and critical pressure of the gas, and up to four upstream temperatures and pressures. The fields where the calculated compressibility factor(s) appear will remain blank until all required data has been entered. It is possible to use other units than PSIA and degrees F for either and/or both upstream and critical pressure and temperature. See the area just to the right of the user interface.

For your reference, below the data and results area, the reduced temperature (T_r) and reduced pressure (P_r) being used in the calculation are displayed along with a note stating whether T_r and P_r are within or outside the limits of the worksheet.

If you have entered temperatures or pressures that result in T_r or P_r that are outside the stated limits, the COMPRESS. FACTOR (Z) field will read #NA and the notes below that will state which parameter is out of limits.

When the process approaches the critical point (T_r and P_r both equal 1.0), the compressibility factor changes very rapidly, making it difficult to accurately read the charts or interpolate between points. This is especially notable at the critical temperature (T_r = 1.0) and reduced pressures (P_r) between about 1.0 and 2.0. Also, if you look at the medium pressure Nelson-Obert chart, the T_r isotherm of 1.0 is almost vertical as it approaches the critical pressure (P_r = 1.00).

This is because, in this area, the compressibility factors of various gases do not all appear at the same point on the T_r = 1.0 isotherm. When the worksheet returns a compressibility factor (Z) of less than 0.35, the compressibility factor will be shown in red to remind users that their process conditions are close to the critical point.

Link to ISA-75.01.01-2012, Industrial-Process Control Valves, Part 2-1: Flow Capacity: https://www.isa.org/products/ansi-isa-75-01-01-2012-60534-2-1-mod-industrial-pr

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