in a similar fashion to a motor-load monitor; however, it must be interfaced to a control system to properly interpret the signals. Current transducers are relatively inexpensive and can often be installed without disconnecting the motor power wiring.

Phase-Monitoring Devices. A family of dedicated motor-protection relays offers supplementary protection functions. The devices are easily applied to three- and single-phase motor-protection circuits. They provide guards against the damaging effects of phase loss, under- and overvoltage, phase imbalance, phase reversal, and voltage quality of the incoming power line. These devices serve a protective role rather than acting as a motor operation-monitoring device; however, when used with a current-monitoring device, they can be used to create a motor-load monitor.

Flow Measurement and Control

Flow measurement and control are critical for both process optimization and, more importantly, safety. Using inputs from both the flowmeters themselves and from other sensors such as thermocouples, oxygen sensors, or various other types of analyzers, control systems must be able to adjust the flow of gases for process optimization. In the simplest form, the gas-air ratio can have an enormous effect on operational costs. Precise control of gases also is needed during various heat treating processes. In case of an emergency, such as temperature loss, flow becomes critical to a fast and effective purge of the furnace to prevent a serious accident.

Calibration Issues. With the exception of a rarely used class of flowmeters referred to as positive displacement meters, all flowmeters require regular calibration. Contaminants in liquids and gases can deposit dirt within the meters, thereby changing their flow properties.

It is important to note that the key parameters for any meter are the gas/liquid to be measured (specifically its specific gravity), operating temperature, inlet (supply) pressure, and the desired flow range for the meter. Without these parameters, flowmeter suppliers cannot provide calibration.

While most meters can be field verified—meaning technicians can confirm they are still responding with sufficient accuracy—the majority requires occasional factory calibration to maintain their optimal accuracy. Such calibrations may be required every one to five years.

For this reason, it is advantageous to install all flowmeters using pipe unions that allow the meters to be removed and replaced easily. The temptation to save a small amount of money by hard plumbing the meters should be resisted, because the long-term lack of flexibility and quick replacement will ultimately be a far more expensive option.

Calibration Conversions. Virtually all flowmeters are calibrated with air, even if their ultimate purpose is to measure some other gas. The reason is simple economics and safety in the calibration labs. Fortunately, there is a simple equation to use air to mimic other gases in terms of scale factor (*SF*), scale flow reading (*SR*), and actual flow rate (*AF*), such that (Ref 1):

$$SF \times SR = AF$$

where the scale factor is:

$$SF = \sqrt{\left[\frac{SG_1}{SG_2} + \frac{T_1}{T_2} + \frac{P_2}{P_1}\right]}$$

where SG_1 is the specific gravity of gas that the flowmeter is calibrated for, SG_2 is the specific gravity of the gas to be used in the flowmeter, T_1 is the absolute temperature of gas that the flowmeter is calibrated for, T_2 is the absolute temperature of gas to be used in the flowmeter, P_1 is the absolute pressure of gas that the flowmeter is calibrated for, and P_2 is the absolute pressure of gas to be used in the flowmeter.

Types of Flowmeters. Flow measurement of liquids and gases can be accomplished in many different ways, each with certain advantages and disadvantages. This section does not attempt to discuss and evaluate all the different ways for measuring flow but instead concentrates on the methods typically used within the heat treating industry.

A venturi meter is one of the oldest methods for measuring flow, dating back to antiquity. Essentially, a venturi meter relies on a constriction of the flow and the measurement of pressure before and at the point of the constriction. Venturi meters today (2013) are used to measure flow in gas pipelines. They have the advantage of creating relatively little pressure drop of the gas or liquid being measured.

The disadvantages of a venturi meter include high cost, because the units must be carefully designed and constructed to read accurately; relatively large size to prevent pressure drop while still maintaining sensitivity of the measurement; and the determination of flow relies on a fairly complex equation requiring either a table to look up the value or a computer/calculator to determine the flow.

An orifice plate is basically a cost-reduced version of a venturi meter. Instead of using a gradual constriction in the flow and measuring the pressure at the constriction, orifice plates rely on an abrupt constriction in the form of an orifice in a plate (hence the name) and pressure measurement before and after the orifice.

Unlike a venturi meter, this approach is relatively inexpensive and results in a significant pressure drop in the medium. This large pressure drop means that this type of meter has a limited measurement range. Like the venturi meter, the orifice plate meter requires significant math to convert the two pressure readings to a reading of flow, which adds additional complexity and cost.

Orifice plate meters are found in many heat treating applications. Because they have no integral indicator of flow, these types of meters should be paired with an external flowscope or other mechanical, visible flow indicator when used in purge applications. During a purge, even visual confirmation of purge flow is essential. Also, over time the orifice can become dirty when used with certain media, requiring regular calibration over the flow range of operation.

A paddle wheel meter, as it sounds, uses the rotation of a wheel to measure flow. While these types of meters are still in use, they are highly inaccurate because the paddle wheel only extends partially into the flow path, resulting in slippage of flow and momentum of the wheel as well as friction of the wheel bearings.

Rotary gear meters belong to a class of meters called positive displacement meters and are one of the most accurate means for measuring flow volumes. These meters are often used to calibrate other types of meters.

In a rotary gear meter, there are one or more gears arranged such that the fluid cannot pass without rotating the gears. During rotation, the portion of fluid that can pass the gear is captured in a space between the gears or the gear and the meter housing, thus allowing only a very specific volume to pass with each rotation of the gear or gears.

In addition to high accuracy, this type of meter works well with a broad range of fluids and even dirty fluids, if properly designed. However, rotary gear meters do result in a very large pressure drop and are physically large and expensive compared to other technologies.

Mass flowmeters rely on the measurement of heat transferred by the fluid to determine the flow rate of the fluid mass. Mass flowmeters are generally only used to measure flow rates of gases, and they operate in either a constant-temperature or constant-current mode.

The basic principle in a mass flowmeter is to heat a temperature sensor and then to measure the temperature some small distance away from this sensor with another sensor. In a constant-temperature design, the current heating the first sensor is controlled such that the temperature seen by the second sensor remains constant. As such, the current required to heat the first sensor is used to determine the flow rate of the gas passing between the sensors. The gas type (and its thermal mass) must be known, and the meter must be calibrated for this type of gas.

In a constant-current design, the current to the heater remains constant, and the temperature difference between the sensors is used to determine the flow rate.

A rotameter is a type of variable-area flowmeter. In a typical rotameter, there is a float located inside a conical section of the meter body. As the float moves in response to the flow of media through it, the gap between the float and the conical walls of the meter body increases, thus increasing the available area through which gas or liquid can flow.

To function as a reliable meter, rotameters need some sort of opposing force to prevent the float from simply moving to the widest part of the conical section. In many rotameters, this opposing force is simply gravity acting upon the float itself. Some meters, however, use a spring attached to the float to provide an opposing force. This has advantages, such as allowing the float to have any orientation with respect to the gravitational field (gravity-based rotameters must always have a vertical orientation) and providing a spring force that is independent of the float mass. The spring method has limitations, however, such as range of motion between full compaction of the spring and elongation to the point of plastic deformation, or the potential change in the spring constant over many cycles or heating.

Rotameters have found favor in heat treating over other types of meters, due to their simplicity, robustness (they can tolerate dirt and/or moisture, whereas many other types cannot), and the fact that they give an unambiguous, mechanical representation of flow even without electrical power. This can be very important in the case of purge systems during a power outage. While purge gas solenoids are installed to open in the case of a de-energize event (i.e., lack of power forces these open), without a visual, mechanical indication or purge gas flow, it is impossible to be completely certain that the purge line has no obstructions.

Because automation is key in modern heat treating, it is important to have a means for digitally determining the float position in a rotameter. For optical (human eyes) determination of the float position, the most common and widely used meters attach a float rod to the float. This rod then extends downward and out of the float meter body into a glass tube called a sight glass. An indicator is attached to the lower end of this float rod, inside the sight glass. The sight glass itself is filled with a clear oil to dampen the motion of the float and is surrounded by a secondary protective structure that also has gradations to serve as scale markers for the float rod indicator. By tracking the position of this float rod indicator, one also tracks the position of the float itself, even though the float is inside an opaque flowmeter body.

Much like the human eye detection described previously, the first digital rotameters used optical sensors to locate this float rod indicator inside the sight glass tube. An array of light-emitting diodes (LEDs) were arranged on one side of the sight glass tube, with a corresponding array of photodiodes arranged opposite to act as detectors of the light emitted from the LEDs. As the float rod and indicator moved, they exposed light from LEDs below the indicator and obstructed light from LEDs above the indicator. As such, the detector diodes could easily determine the position of the indicator and thereby the float. Today (2013), this type of meter is prevalent within the heat treating industry. With this type of meter, it is important to keep the damping oil inside the sight glass clean (by means of regularly changing the oil), because dirty oil will transmit less light, which will bias the output of the digital measurement.

More recently, new sensing technologies have emerged that have improved upon the LED methods for determination of float position. To eliminate the need for clear and clean oil, newer rotameter designs make use of magnetic technology to locate the float rod indicator. In this design, a magnet is attached to the indicator, and its location is determined using a magnetic sensor rod.

"Smart" Rotameters. While rotameters are, by far, the most prevalent meters used in heat treating, another limitation of these meters is their linearity. Variable-area flowmeters tend to have a linear response only over their center range (approximately the middle 60%). Below and above this range, they have more error because of the nonlinear nature of the meter.

New rotameters include an embedded computer that can be programmed to eliminate the nonlinear response of the meters by fitting their response to a polynomial curve. This means that modern rotameters have greatly improved accuracy over their full operating range.

Using the same computer that corrects for rotameter nonlinearities, "smart" rotameters can do many other things, such as totalization (adding up all the flow through the meter over a given time), alarms, digital communications, and even include a web server for remote access and configuration.

Purge Systems. The most important flow system in any heat treatment process is, arguably, the purge system. The vast majority of atmosphere heat treatments involve the use of combustible gases. In most cases, such as carburizing, neutral hardening, carbonitriding, and so on, these gases are well above the temperature where the gas is explosive (typically >760 °C, or 1400 °F), but in some processes, the furnace operates at temperatures well below the explosive limit. In either case, the wrong sequence of events can lead to a very dangerous situation where a catastrophic accident is possible. Indeed, even with modern controls and safety systems, such accidents still happen.

To avoid such accidents, purge systems must be designed so that any dangerous situation results in a fail-safe configuration that causes the furnace to be made rapidly safe. In virtually all instances, this fail-safe configuration will require an immediate and complete purge of the furnace. With this in mind, such systems are designed to require power and certain external conditions (contact closures) to be deactivated.

For example, the solenoid valve between the purge gas (nitrogen) and the furnace may require power in order to be closed (energize-closed solenoid). This means that, without power, the system is in purge. The source for that power, in turn, may be routed through a contact that is controlled by a temperature monitor/controller that only closes the contact (thus allowing current to flow) when a minimum safe temperature is achieved. With such a configuration, power loss (either from the main electrical source or due to a cut wire) or temperature loss will immediately put the furnace into purge mode.

One final note about purging of furnaces is the need to totalize purge flow. What this means is that, under normal (noncrisis) operating conditions, a furnace cannot be considered fully purged and safe until a volume of furnace gas equal to four times the furnace volume has passed through the purge system into the furnace. This is where the advantages of more modern flowmeters come into play, because they have integrated totalization capabilities. Obviously, if there is power loss, then totalization can only be determined manually (flow rate $\times$ time = $>4 \times$ furnace volume).

Solenoid On/Off Control. A solenoid is a valve with a spring mechanism that is attached to a magnet, which can be used to push back against the spring. To accomplish this push-back, a solenoid has an electrical coil that, when energized with sufficient current, creates a magnetic field that pushes the magnet. The force of the magnet on the spring either opens or closes the valve (or switches, in the case of a three-way solenoid valve). Convention refers to an energize-open solenoid, meaning that a solenoid valve is closed in the absence of electrical current; the spring has nothing pushing back, so the spring closes the valve. Conversely, an energize-closed solenoid is one where the spring forces the valve open, and current through the coil is required to close it.

In most control schemes, other than purge, it is more typical to use an energize-open solenoid. Purging is the most basic of on/off control schemes, and the typical solenoid on/off control for purging is an energize-closed solenoid. The purge is off when the energized valve is closed. If current to the coil is removed or interrupted, the purge control valve would open.

On/Off Atmosphere Control. While purge is a simple control system, most heat treating processes are more complicated. Protective atmospheres, for example, require maintaining the right, sometimes variable, balance of two or more gases to achieve the proper surface properties in the work.

To use a simplified analogy, imagine trying to maintain a constant temperature in the water exiting a faucet. Now imagine that the hot and cold water can only be either on or off—there are no degrees of on, so the hot water cannot be adjusted to 50% or anything similar. Obviously, it would be impossible to have constant temperature in the water flowing from the faucet.

Fortunately for heat treaters, more can be done about the water in the sink than in the faucet. The drain on the sink is restricted so that it is approximately half-full with the water running, and, using the on/off control, it is possible to achieve a constant temperature in the reservoir of water accumulating in the sink. The trouble starts, however, when cold dishes are put into the sink. Depending on the temperature of the dish, its size, material, and even its shape, the temperature of the water will change as heat transfers from the water to the dish. Still, with careful measurement and control, a reasonably uniform and constant temperature can be achieved in that sink.

Heat treating works very much like the sink example. Instead of water temperature, in the case of carburizing, one would be trying to control the carbon potential and, like the dishes that soaked up the heat of the water in varying ways, so too the parts will absorb carbon at different rates based on material, surface finish, and surface area.

Proportional Atmosphere Control. One way to improve control of atmosphere and the quality of treated parts is to do exactly what one does with the aforementioned water example: vary the proportions of hot and cold water that are mixing to form the final temperature. This type of control is referred to as proportional control.

To accomplish proportional control, one needs a controller (PLC or dedicated) with an analog output that can tell a valve actuator how much it should open. One also needs a valve that can be opened incrementally (rather than something similar to a conventional solenoid that is either open or closed). This is normally done by using a 4 to 20 mA output from a controller to drive an actuator that, in turn, opens and closes a proportional valve.

A common configuration for proportional control in carburizing is to have a constant stream of base feed gas (endo) and then proportionally controlled enriching gas and/or air. In this configuration, enriching gas is increased to raise the carbon potential, or air is increased to lower the carbon potential. Due to the proportional nature of the control, it is possible to make very small and predictable changes with minimal overshoot. It is worth noting that in some zones of continuous furnaces, such as near an external door, there may be no air adder due to the air from the door opening and closing, and furthermore, some systems may use proportional control only on the enriching gas while using on/off on the dilution (air).

Knowing Valve Position—Slide Wire. When controlling a valve, the system requires some way of determining the valve current position (degree of full-open). For many years, the main method for determining the valve position was the use of what is called slide-wire feedback. In slide-wire systems, a potentiometer circuit (variable resistance) is formed by a wire that moves as the valve moves. As a result of the wire movement, the resistance of the circuit changes and, with voltage applied, this is measured as a change in voltage.

Although slide-wire systems are accurate and found widespread use, the use of moving parts and wear surfaces meant these feedback devices had finite lifespans.

Knowing Valve Position—Stepper/Servo. Stepper and servo motors are the most common actuator systems used today (2013). Stepper motors are generally considered simpler to implement because they are run on an open loop, meaning no feedback. With a stepper, the control system determines the motor position based on how many steps it has been moved, knowing that, for a given motor, there are a specific number of steps per revolution.

Servo motors, on the other hand, are closed-loop systems, where the motor sends back at least one signal (angular position) and often two (angular position and speed).

Proportional-Integral-Derivative Control. Today (2013), the vast majority of atmosphere-control systems use what is termed proportional-integral-derivative control. The PID system takes the concept of proportional control and further refines it to fine-tune how quickly the change in proportions is implemented. The fundamental idea is that by improving on proportional control, overshoot or oscillations in control can be eliminated or reduced.

Proportional Band. The proportional component in a PID system produces an output gain that is proportional to the error (how far the current reading is from the set point). A high proportional band means the system will react strongly to any deviation from the set point. High proportional bands can lead to oscillation in control as the system overshoots and then undershoots the set point.

Integral Band. The integral band contribution to the control signal looks at both the error and the duration of the error. (Essentially, it integrates the error multiplied by the time the system has been in error.) As such, an integral band responds more slowly to deviation from the set point at first, and then, as time away from the set point passes, it responds more strongly.

Derivative Band. The main purpose of the derivative band is to minimize overshoot. By looking at the slope of the error, the derivative band can sense the system approaching set point (zero error) and, as it approaches the set point, reduce the gain of the system, thereby minimizing any overshoot.

Controllers

Generally, there are two main types of controllers used in the heat treating industry: PLCs and configurable controllers. There are many vendors of each type of controller, and the options are numerous, but each type of controller has its specific applications and appropriate uses. There is, of course, some overlap, and the nomenclature is not always properly applied; because of this, selecting which type of controller to use or understanding which tasks a controller performs in an existing system is not always straightforward.

The selection of a particular controller can be a very challenging process. The main considerations should be:

- Range of products offered by the manufacturer
- Manufacturer's support
- Manufacturer's reputation and knowledge of the industry
- Compliance to necessary standards
- Ability to interface with existing systems or future systems, if necessary
- Ability to upgrade at a later date, if necessary
- Budget
- Spares availability. (Consider keeping one uniform manufacturer throughout a plant.)

A furnace-control system specialist or system integrator can help to make the appropriate selection. Often, application knowledge of a wide range of systems can help a heat treater choose a platform with confidence.

Programmable Logic Controller

A PLC is an industrially hardened computer, designed to withstand harsh industrial environments such as those found in a heat treating shop. They have a sufficient resistance to dirt, dust, and heat to perform reliably in an industrial environment. The PLCs come in a wide array of formats, from an integrated processor with on-board input/output to a configurable rack with a wide array of central processing units and input and output cards. A PLC can be connected through digital communication to a human-machine interface such as a touchscreen or keypad. The PLCs are built by a wide range of manufacturers, and nearly all have similar capabilities. The selection criteria for a PLC manufacturer should include the consideration of spare parts; it is desirable to have one standard manufacturer throughout a plant, to allow one set of universal spare parts to cover all equipment.

The PLCs are well suited to most control tasks and are highly configurable by a trained PLC programmer. They can control virtually all of the tasks on a furnace but must first be configured to do so. Tasks such as the automated movements of a furnace, for example, transferring a charge from one chamber to another, are very well-suited tasks for a PLC. These steps could consist of several smaller sequential tasks, such as opening and closing a door or cover or running a conveyor, pusher ram, or elevator. Ensuring these tasks are performed in the correct order in a repeatable way is an excellent application for a PLC.

Advantages of Task-Specific Controllers. Because a PLC is essentially a blank slate when purchased from the manufacturer, some tasks that are more complicated to configure are better suited for a configurable controller. Configurable controllers are also industrially hardened computers, but rather than being a clean slate to be configured by the programmer, they come preconfigured to perform certain tasks. A configurable controller could range from a simple temperature controller with one or two inputs and outputs to a process computer that is programmed to handle alarms, recipes, atmosphere calculations, and many control loops for multiple zone controls.

Sensors in a PLC System. A wide range of sensors can be integrated into a PLC system, ranging from simple on/off devices, such as limit switches, to more complex signals, such as thermocouples and vacuum gages. There are two main categories of sensors: digital or discrete and analog or continuous.

Digital or discrete sensors have either a status of on or off. Some examples of digital sensors are limit switches that turn on or off (switch) when they are actuated by a physical item such as a door, pressure switches that switch once a certain pressure is reached, or temperature switches that switch when a specific temperature is reached. Discrete switches can switch different voltages as an input to the PLC. A relay can be added to isolate signals or change the voltage used.

Analog or continuous sensors provide a signal that is proportional to a continuous variable, such as a temperature or atmosphere measurement. The sensor can be connected directly through a PLC or could use a signal conditioner or transmitter between the sensor and the PLC. A signal conditioner or transmitter may be required, depending on the distance between the sensor and the PLC or because of an electrically noisy environment.

Typically in a heat treat furnace-control system, transmitters and signal conditioners are not used outside of the control panel, and most sensor wires run directly between the sensor and the control panel. Analog sensors can send a signal using voltage, current, or resistance. For each sensor type, an appropriate input card should be selected.

Configurable Controllers

Configurable controllers are often only configurable to a certain extent within the confines of their designed application. A simple temperature controller, for example, could be configurable for the type of temperature sensor (thermocouple type, resistance temperature detectors, etc.) and type of control output (analog signal, digital on/off control, etc.). A more advanced controller will be configurable for different process types, different alarms, or a wide array of control tasks. Often, configurable controllers are designed to seamlessly integrate with supervisory control and data-acquisition (SCADA) systems.

In the heat treating industry, configurable controllers are typically selected and configured by a heat treating controls specialist or system integrator. In a typical modern furnace-control system, a PLC and one or more configurable controllers will be integrated to work together. These systems will apply each type of controller based on their strengths and capabilities to provide the most efficient and easy-to-use system. On smaller systems or partial system upgrades, often only a configurable controller is used.

Types of Configurable Controllers. There are several typical types of configurable controllers used in the heat treating industry. Each is best suited for a specific application, and the applications are fairly straightforward.

Single-Loop Controllers. These controllers are programmed to control one control loop, such as one zone temperature or atmosphere loop. These controllers are relatively simple to implement, and most furnaces that are not controlled by a process controller will have at least one of these types of controllers. There are varying complexities, for example, some controllers can make a specific atmosphere calculation, such as carbon potential, based on inputs from the field sensors. Typically, these controllers are set to one set point, and to change that point, a furnace operator will manually adjust the unit, although some single-loop controllers do support recipes to adjust the set points. A single-loop controller may have the ability to generate a simple alarm, such as process deviation or a high- or low-level alarm.

Multiple-Loop Controllers. These are very similar to single-loop controllers; however, they have the ability to control multiple loops. These controllers are often found on carburizing furnaces, controlling the atmosphere and temperature in the treatment zone.

Configurable Process Controllers. These are typically much more advanced and can be configured to handle recipes (Fig. 1), multiple control loops, alarms, and possibly more. This category of controller can typically be ordered from the manufacturer with preconfigured inputs and outputs, and it also often has the capability of connecting to communication systems and SCADA. This type of controller is significantly more complicated to configure and integrate into a system, so a specialist may be required to assist.

Advanced Process Controllers. This category of controllers provides the most user-friendly and consistent process results. An advanced process controller typically has the ability to control multiple loops, recipe controls, alarm handling, and often has an on-board digital chart recorder. Some top-of-the-line controllers incorporate data storage to meet specific standards, such as the National Aerospace and Defense Contractors Accreditation Program (NADCAP) or Aerospace Material Specifications (AMS), and advanced processing capabilities to control nonlinear atmospheres and simulate process results for various types of treatment processes.

Additionally, some controllers can calculate expected results and adjust a running recipe to compensate for unexpected process deviations. These units can be configured to communicate with a wide variety of PLCs and control instrumentation.

Control Circuits for Fuel-Fired Furnaces*

The development of programmable controllers provides ease and precision for process monitoring and control. When a programmable controller is used in conjunction with combustion safeguard circuitry on fuel-fired systems, the combustion safety interlocks, listed combustion safeguards, and excess temperature limits shall be wired to directly de-energize the fuel safety shutoff valve(s).

Combustion-Air Blower Control. Combustion-air blowers must be interlocked with the combustion-limit circuits to shut down the process in the event of failure. The flow of combustion air must always be proven before and during a processing cycle with two independent sources of information. The motor should be protected from short circuits with fuses and from overheating or amperage draw with thermal breakers (heaters). The motor starter should be wired so that it will disconnect when any phase is interrupted or when the motor malfunctions. It should not be assumed that the blower is providing combustion air just because the blower motor is operating; combustion-air flow must be proven. At one time, an end switch, or rotary switch, on the motor was a common indirect method of gaining this information. A better method is to use a pressure switch in the air line for direct sensing. A sail or flag switch, although not quite as good because of the mechanical movements required, can also be used to directly sense air flow.

Gas-Pressure Control. Fuel must arrive at the burner in the correct quantity and at the correct time for safe combustion. Fuel pressure thus must be proven within an allowable range. Gas-pressure switches for both high and low gas limits are installed in the main gas lines. Visual pressure gages are also helpful to operators in setting burners and in verifying that the fuel is being supplied within the proper range and that pressure-limit switches are not malfunctioning. Mercury-wetted relay pressure switches are recommended for their easy setup and maintenance and for their reliability.

Pressure Regulators. Pressure of gaseous fuel is most commonly regulated by pressure-regulating diaphragms. Good, safe design normally requires one regulator for pilot fuel and one regulator for main-burner fuel. The pilot gas, if taken from the main fuel line, should be drawn from a point between the gas supply and the regulator for the main fuel. Therefore, the pilot and main burner can be set up optimally, safely, and independently. The regulators should be vented to a safe location

* Adapted from R. Ostrowski, Furnace Safety in Heat Treating, *Heat Treating*, Vol 4, *ASM Handbook*, ASM International, 1991, p 657–663

outside the plant to ensure safety if a regulator diaphragm is damaged in service. Good practice and manufacturers' recommendations show that diaphragm life can be substantial if regulators are shielded from thermal radiation and are used below their maximum design limits. Positive lockup regulators are recommended to prevent downstream pressure buildup during shutdown periods.

Valves. Blocking valves normally are closed valves that are energized only by the combustion-control circuits. The pilot-gas blocking valve is placed downstream of the pressure regulator and a hand-operated gas cock. A pipe union should be inserted just ahead of the electrically operated blocking valve to allow safe removal if repairs are needed. The blocking valve is opened to the pilot assembly only after the furnace is purged.

Supervisory Gas-Cock System. A supervisory gas-cock system is used to ensure a safe light-off procedure on a manually ignited, multiburner furnace that does not have flame-safety equipment with a programmed sequence of piloting the main burners.

The system consists of specially designed gas valves that have inlet and outlet passages for checking a pressure medium such as air or gas. Air or gas—usually air from a combustion blower—can pass only through the valve when the valve is fully closed. When the individual burner valves and the main gas line valve are closed, the air flow enters a pressure switch that closes and completes an electrical or pneumatic circuit. This allows the main gas valve, usually of the manual-reset type, to be opened. The burners are then individually manually ignited.

Supervisory gas-cock systems are used on radiant-tube furnaces and other furnaces where flame-safety systems are difficult to apply. Fewer of these systems are being used on new furnaces because most burners now are adapted to flame safety and automatic ignition.

Burner Control*

Purging of Fuel-Fired Furnaces. The furnace must be purged of any possible combustible materials. This is best accomplished by opening the furnace doors, which should be equipped with a limit switch to ensure that they are opened adequately. Once the doors are open, the combustion blower or exhaust fans can be timed to allow for a minimum of 4 standard cubic feet (0.11 m^3) of fresh air per 0.028 m^3 (1 ft^3) of furnace volume. This purge cycle is required for safe startup and is standard practice for all well-managed operations.

Pilot Control. Pilot assemblies can be of either the atmospheric or the blast type. The atmospheric type is similar to an atmospheric burner, in which the air is inspirated from the atmosphere by the gas stream.

In the blast type, air and gas are brought to a mixer under pressure. The gas is then reduced to atmospheric pressure and pulled into the mixer by the pressurized air stream. This is the most positive means of pilot-gas control.

Ignition and Flame Detection. For ignition trials, a high-voltage transformer is used in conjunction with a spark plug designed for the pilot or burner assembly. The control circuit opens the pilot valve, and a spark is produced. The spark continues for a short period (normally 15 s) and establishes a flame that can be detected. If the flame is not established because the flame or signal is inadequate, the cycle returns to the purging stage.

The voltages normally employed are approximately 5000 to 6000 V, and the high-voltage transformer is normally mounted on the furnace and grounded to it. The spark in turn is grounded to the pilot assembly and then to the furnace; hence, a well-grounded furnace is an important safety requirement. Ignition systems have no provisions for providing flame and should not be used in lieu of combustion safeguards. Safety standards specify that spark energy is to provide only a source of ignition.

Depending on the burner used, the application, and the property-insurance requirements, it may be necessary to monitor both the main burner and the pilot flame independently. Common and serious errors in flame detection are made by operators who circumvent flame-safety equipment rather than correcting the usually minor problems that cause nuisance shutdowns.

Flame-safety equipment that uses totally enclosed relays is recommended over types with accessible relays that may be kept open with, for example, a piece of paper. This point, however trivial it may seem, has been profoundly recognized by those firms who have lost operators, furnaces, and product as a result of poorly designed flame-safety equipment that can be circumvented easily. Any employee found tampering with this equipment should receive disciplinary action, and all employees should be trained in the use of flame-safety equipment.

A thermocouple junction placed in intimate contact with the pilot flame is perhaps the most common means of flame detection, but thermocouples are useful only on very small pilot assemblies or burners (not to exceed 44 kW, or 150,000 Btu/h). The flame may no longer be present, but a hot burner block or refractory may retain heat and slow the rate of thermocouple cooling. Thus, thermocouple junctions are not recommended except for quench-tank heaters of the constant-pilot, open-grid burner design or for small atmospheric burners.

Flame electrodes, which are small anodes of heat-resisting alloy placed in intimate contact with the normal pilot flame, work on the principle that flame causes ionization within the burner atmosphere and thus allows a circuit to be formed to ground. The flow of a minute amount of current, at low voltage, is sufficient to sense and communicate the presence of a flame.

Flame electrodes are common on all industrial heat treating furnaces where the flame is kept on ratio or slightly oxidizing. The flame electrode tends to become carbon coated in a reducing flame, a condition that can cause nuisance shutdowns.

Ultraviolet (UV) scanners are the third common device for sensing flame. They are normally dependable if the lens viewing the flame is kept clean. The UV scanners must not be used in any application where UV light is present from a source other than the burner in question. The UV scanner is a useful and practical device for any clean-flame, clean-furnace operation if it is located and aimed properly. A flow of clean, filtered cooling air across the scanner face aids in keeping it clean and cool, extending scanner life appreciably.

Fuel-Air Control. The main fuel supply for fuel-fired heat treating furnaces normally is natural gas, propane-air, propane, butane, or one of the fuel oils. Although this discussion centers on natural gas, the same principles apply to the other gases and oils.

The main gas valve may be fully automatic or of the manual-reset type, requiring an operator. The manual type is usually preferred when the furnace is run intermittently or when operators must perform some other function, such as opening doors. When the operator opens the valve, he is in effect making a conscious decision that conditions are ready for the main burner heat. The valve may be made automatic when the furnace is designed and interlocked to preclude an unsafe condition.

For furnaces with capacities greater than 422 MJ/h (400,000 Btu/h), it is recommended that a second blocking valve be inserted into the main gas line. Revised NFPA 86 standards for ovens and furnaces have removed the requirement for the vent valve. Industrial Risk Insurers is the only insurance underwriter that requires the installation of a vent valve.

The gas-air ratio ordinarily is controlled to approximately 10 parts air to 1 part natural gas for good combustion efficiency. There are several devices involved in control of this ratio. Typically, the amount of blower air is varied by a butterfly valve to satisfy the demands of a temperature-control device. A pulse or static pressure line is connected from the combustion air line, downstream of the butterfly valve, to a proportionator valve located in the gas line. The gas is then regulated by the ratio-control valve in proportion to the air flow, and the air-to-gas ratio remains constant throughout the firing range. The devices used to regulate the ratio fall into two broad categories: the diaphragm type, or proportionator, which uses the pulse line to keep air and gas at a specified ratio; and the mechanical-linkage type. Both are effective and common, but the diaphragm type is the more positive, because there are no linkages

* Adapted from R. Ostrowski, Furnace Safety in Heat Treating, *Heat Treating*, Vol 4, *ASM Handbook*, ASM International, 1991, p 657–663

that can slip and require adjustment. Also, if air lines become dirty, resulting in a lessening of air pressure, the gas pressure will follow, maintaining the correct ratio.

Ratio control alone is not sufficient to ensure safe startup of the main burners. It is recommended that the burners be set to a low firing rate when the main burner is started. This can be done either automatically or manually. Once the main burners have been started, the furnace doors can be shut and the furnace brought up to temperature.

Temperature Control

Temperature-control devices fall into two categories: primary controls and process-limiting devices. Safe operation, especially when furnace practices require long cycles and little operator attention, dictates that limits be placed on the process. An excess temperature limit must be applied to all heating systems where it is possible to exceed a safe temperature limit. These limits should alarm and perhaps shut down the operation.

The typical temperature sensor is either a thermocouple or a resistive temperature device (RTD). The thermocouple is most common (see the article "Temperature Control in Heat Treating" in this Volume for more details). Several types of thermocouple junctions are available, with the choice depending on such factors as temperature range and furnace atmosphere. They are comparatively inexpensive and can be easily protected from atmospheres with protective wells, which are immersion tubes that project into the furnace zone to be controlled. The RTDs, although more accurate than thermocouples by factors ranging from 10 to 1 up to 50 to 1, are expensive and less rugged. For most purposes, thermocouples are satisfactory. Some firms use heat-flow sensing to remotely ascertain interior temperatures and to provide an element of redundancy for protection of furnaces and their contents. Good temperature-sensing devices will detect failure of a thermocouple or RTD, cause the process firing rate to be reduced to its minimum rate, and perhaps provide an alarm.

Furnace temperature can be regulated by one of two very common procedures. Simple high and low firing rates are used when temperature can be allowed to vary within a fairly large range. A common method in heat treating is the use of proportional control, wherein the temperature is held nearly constant through the use of a bridge circuit. This circuit balances the signal between the controller and the butterfly valve and holds the latter at the proper opening to maintain the desired temperature.

Optimizing temperature control obviously can help reduce energy consumption and process time. Even a few minutes reduction in a process time can add up to large savings over the course of an operating year. Uniform heating within a furnace is important in process optimization issue, and control recipes can help ensure that the parts are processed consistently, independent of their loading position in the furnace. Some recipes and loads will require a specific heating or cooling ramp rate.

Vacuum System Controls

Vacuum heat treatment of certain alloys requires careful consideration of the cooling rates required. Cooling requirements are generally provided by the alloy manufacturer, NADCAP, or part manufacturer's metallurgical requirements. Items that affect cooling rates are cooling pressure, gas flow, blower size, and load size. These critical elements are generally part of the mechanical furnace design; however, depending on the furnace design, the control system could play a critical role by adjusting the cooling-gas pressure, cooling-gas flow, or varying the blower speed.

A dedicated process controller is critical to proper functioning of a vacuum furnace. The precision control required on a vacuum furnace can be achieved with a properly configured PLC, connected to a process controller. A vacuum furnace process controller should bring together all of the critical items required for furnace control. Critical tasks such as the vacuum pump and valve sequencing are best performed by the PLC, while calculation-intensive tasks such as temperature control are best performed by a dedicated process controller.

The process controller should be able to perform the advanced recipe handling, load thermocouple evaluations, controlled cooling, partial pressure, and data recording required to meet the specifications required. The process controller typically will also handle the temperature control and therefore must be capable of the advanced temperature controls.

Vacuum furnace recipe programming can be a very complex task. A proper specification for the heat treating process should include details about the critical steps, such as preheating and soaking at a certain temperature or controlled cooling using the work thermocouples. A good process controller will allow the heat treating engineer to program in a flexible manner, allowing steps to be controlled using the furnace control or work thermocouples. Flexibility in the event of a failed work thermocouple is a critical feature that could make the difference between a scrapped load and a successful run.

Data recording rates and storage methods are determined by standards such as NADCAP. Any modern vacuum furnace-control system should have the capability to record process values at rates and security levels that meet or exceed these standards. Electronic chart recorders offer features that enable operators to determine at a glance the status and results of a processing run. The precision control requirements in a vacuum furnace are very well suited to a precision electronic chart recorder, either external to the process controller or integrated within it. Chart recorders configured with multiple sheets and multiple selectable pens to record all temperatures, vacuum readings, set points, and so on can give a furnace operator a much more precise view of the critical parameters. Modern control systems connected to a SCADA system can significantly reduce operator error in determining if a particular run met the proper requirements.

Partial Pressure Control. All materials have a characteristic evaporation curve, and metals processed in vacuum furnaces are not an exception. The evaporation rate curve is dependent on the temperature of the material, the surrounding pressure, and the molecular weight of the element. Treatment of alloys without consideration of their evaporation rate can cause some of the molecular materials to evaporate from the surface of the material, creating undesired metallurgical problems and deposits on the inner furnace surfaces. For example, the greenish deposit sometimes found inside a vacuum furnace is a product of chromium vapor oxidizing with air leaking into a furnace.

Argon, hydrogen, and nitrogen are all popular partial pressure gases. The selection of the appropriate gas depends on the alloy being treated. For example, nitrogen may react with some stainless steels, causing an undesired nitriding effect. Argon is typically preferred because the atomic structure helps to reduce the evaporation when compared with other gases.

Some consideration must be given to the vacuum gages used. Some technologies of vacuum measurement are sensitive to the gas composition within the furnace and could give a very incorrect reading, resulting in a system controlling to an incorrect partial pressure value.

Vacuum Gages. There is a wide range of available vacuum gages and transmitters. The different measuring principles give each type of sensor a distinct profile. Vacuum sensors are often nonlinear, and it is common to have a signal-conditioning unit between the sensors and the control system inputs.

A Pirani gage, also referred to as a convection gage or thermal conductivity gage, uses the resistance measurement of a thin filament of wire to convert the vacuum inside of a chamber to an electrical signal. The gases used within a furnace can influence the vacuum reading from this type of gage, so calibration may be necessary, depending on the filament type and process gases used. This sensitivity to certain gases can be used as an advantage to find leaks in a system. Pirani gages are typically more accurate than thermocouple gages and react quickly to vacuum changes. Pirani gages are typically used in the vacuum range of 1 to 10^{-4} torr.

A thermocouple vacuum gage works on the same principle as the Pirani gage, but the measurement is based on the temperature of the filament rather than the resistance. Thermocouple gages are typically used in the vacuum range of 5 to 10^{-4} torr.

Cold Cathode Sensors. There are two types of cold cathode sensors: the Penning sensor and the inverted magnetron sensor. Both sensors use a high internal voltage between an anode and a cathode (positive and negative) to measure the current created by the ionization of the process gas within the sensor. This current is proportional to the vacuum in the chamber.

Cold cathode gages are typically used in the vacuum range of 10^{-3} to 10^{-7} torr or lower when using an inverted magnetron sensor.

Hot ion sensors are also referred to as hot cathode sensors. A hot ion gage works in a similar fashion to a cold cathode gage; however, the hot ion gage uses a triode rather than simply an anode and a cathode. The triode consists of a collector plate, a grid, and a filament. The three elements of the triode work together to create and measure the current created by the ionization of the process gas. A hot ion sensor can be damaged if it is exposed to atmospheric temperatures while hot. Hot ion gages are typically used in the vacuum range of 10^{-4} to 10^{-12} torr.

Smart Gages. Some manufacturers offer configurable vacuum sensor interfaces, which can act as a signal conditioner to interface with the other elements of the control system. These interfaces can interface multiple sensor types to cover a wider operational range. These units may also have the ability to set discrete outputs based on configurable set points.

Vacuum Temperature-Control Systems. Temperature control on a vacuum furnace can be achieved within a tight tolerance by a well-tuned industry-standard proportional-integral-derivative (PID) loop. Loop tuning is critical to achieving good temperature control and is best performed by an experienced technician. Most problems with temperature control, such as overshoot, oscillations, or problems reaching set point, can be eliminated with good tuning. The heating characteristics, or behavior in a vacuum furnace, can be very different at different temperatures. Temperature controllers that can select different PID parameters based on the temperature set point are available and should be seriously considered when tight temperature control over a wide range of temperatures is desired.

Two key features to look for in a vacuum furnace temperature controller are the ability to automatically select different PID parameters based on the active temperature set point, and some level of transparency into the inner calculations of the loop calculations. Vacuum furnace temperature-control tuning is a very challenging task, and often, even very experienced loop-tuning professionals struggle to achieve acceptable results. The ability to watch what is happening inside of the controller calculations is invaluable in the tuning process.

Element Trim. Transformer-controlled systems typically have an element trim potentiometer for each bank of heaters within the furnace. The element trim adjustments are used to bring the temperature uniformity of the work zone into a tighter band. During a temperature uniformity survey (TUS), the potentiometers can be used to increase or decrease the temperature within a zone relative to the other zones. These potentiometers should be adjusted by an experienced technician.

Work thermocouples should be carefully controlled. Most standards such as NADCAP and AMS require that work thermocouples be changed at regular intervals. These intervals vary depending on the type of thermocouple used and the processing temperatures and atmospheres required. Often, a furnace will be set up for a large number of work thermocouples typically required for a TUS, while only a few of these work thermocouples will be used during normal processing.

Graphics and Operator Interface

The operator interface of a furnace-control system (Fig. 2) displays critical information such as the furnace temperature, atmosphere status, and other information such as alarms, electronic chart recorders, recipe information, and maintenance information on additional screens that are quickly accessible as touchscreen elements.

Dynamic screens that constantly update the displayed information are standard on a modern control system. Elements such as bar graphs can be easily integrated to give an easy-to-understand quick reference. For example, a bar graph showing the furnace temperature set point and actual temperature could be placed side by side to quickly determine if the furnace is operating within acceptable tolerances.

The use of color in the graphics is an important function. Color can be used to quickly call the operator's attention to abnormalities. For example, an element could be green or gray in color when normal, yellow in a warning condition, and red when in an alarm state. The difference in color can be spotted from a long distance and provide the ability for a quicker response time, possibly avoiding damage to parts and equipment. In the event of personnel who are color blind, additional elements can be added to the graphics to distinguish between different operating states.

Supervisory Control and Data-Acquisition Systems

A supervisory control and data-acquisition (SCADA) system provides a central system to monitor, collect, and store data from multiple pieces of equipment. A few manufacturers produce heat-treatment-specific SCADA packages that have modules specifically designed to optimize the operations of a heat treating shop. These systems have modules (Fig. 3) that can offer insight into a plant's operations to make gains on plant efficiencies and throughput.

The SCADA systems have their roots as centralized data-acquisition systems. They are designed to interface with multiple pieces of machinery and store the data from those systems in a useful and secure manner. Because

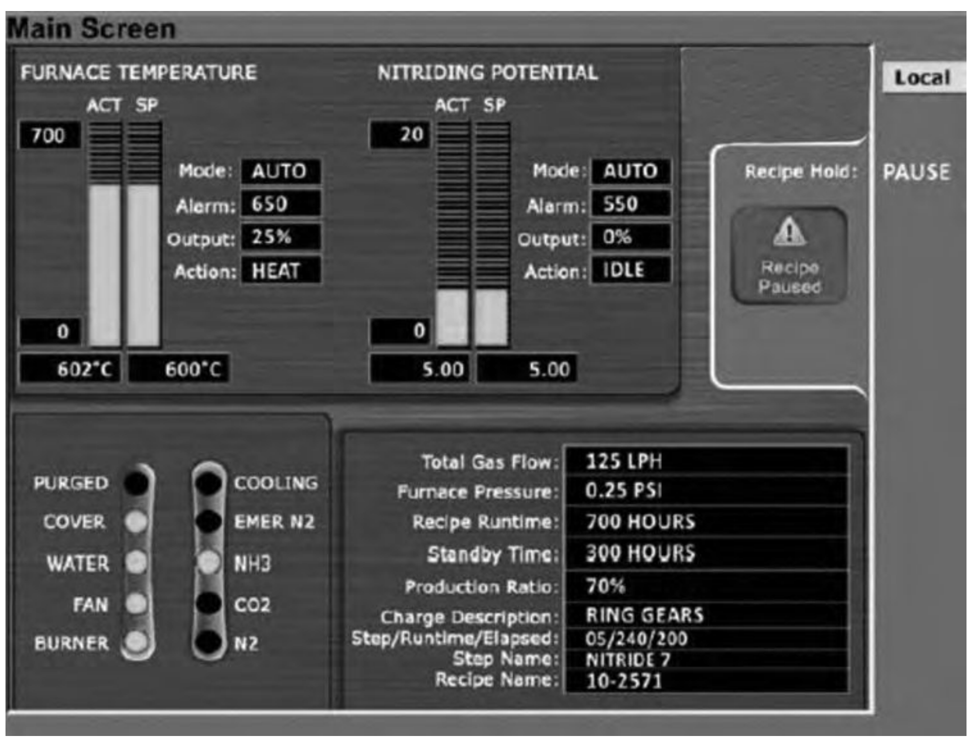

Fig. 2 Operator interface showing critical data

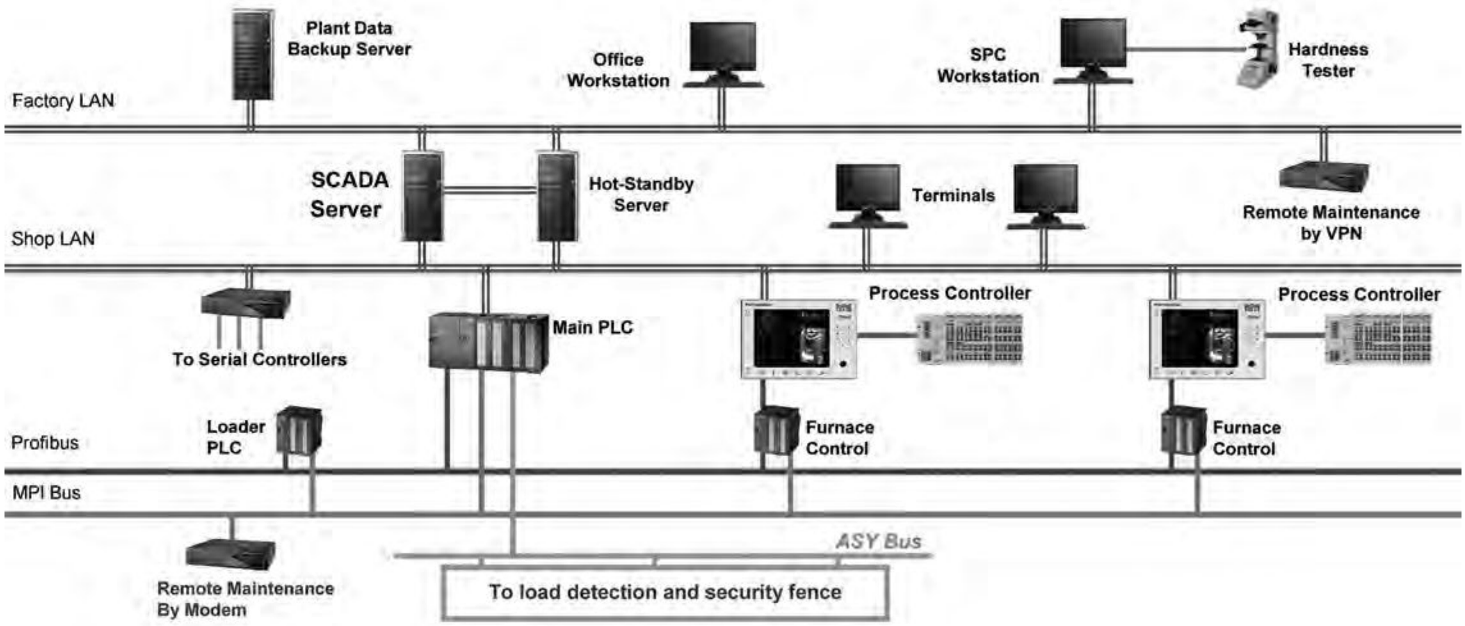

Fig. 3 Advanced supervisory control and data-acquisition (SCADA) network. LAN, local area network; SPC, statistical process control; VPN, virtual private network; PLC, programmable logic controller; MPI, multipoint interface; ASY, asynchronous

the SCADA system is centrally connected to multiple pieces of equipment, it can be used to monitor the condition and status of those pieces of equipment in one convenient location. Having a global shop layout interface of connected equipment can save time and free operators from the need to check each piece of equipment individually.

A good heat treatment SCADA system should have the ability to link part numbers, batch numbers, and so on with an individual and unique load identifier. These numbers should be able to be used as search keys, along with the inclusion or exclusion of pieces of equipment and times of processing. These data can be used in process optimization, to pinpoint problems with individual production loads, to analyze the condition of a piece of equipment over time, and so on. Data representation can be done in multiple ways, depending on the type of data to be analyzed. For example, the actual recipe as it was executed for that run, including stage times, could be similar to the recipe programming format, the process variables such as temperature could be displayed in a digital chart recorder form, and alarms could be shown in a list with start and stop times.

Modern SCADA systems, when connected to an appropriate process controller, eliminate many of the basic problems with older record-keeping methods. Some examples are:

- Data cannot be misplaced.
- The system is always recording and cannot run out of ink or paper while charting during a running process.
- Stored data are tamperproof.

A good system should allow access to the stored data for analysis and validation, without the ability to falsify the records. In any heat treating operation, compliance to applicable standards is extremely important, whether those standards are International Organization for Standardization, NADCAP, or client specifications.

A heat treating SCADA system should meet or exceed the NADCAP standards for data storage and encryption.

Process Optimization and Efficiency

Equipment usage is one of the easiest ways to optimize a heat treatment cell. A heat treatment SCADA system can monitor all running furnaces and calculate the usage of each furnace, considering load weights, plant working hours, downtime due to loading, downtime due to maintenance, and so on. The SCADA is the best-suited tool to interface with process controllers in a heat treatment operation. By comparing the data from all connected equipment and presenting that data in an easy-to-understand graphical display, some otherwise hidden control inefficiencies become obvious. In order for this function to be accurate, the SCADA system must be connected to an advanced process control system and have all of the required information, such as the status of a running recipe (running or not) and the ability to enter if a recipe is being run for maintenance reasons. Other factors, such as the weight of the processed charge, can help generate information on the efficiency of each production run individually.

Modern control platforms have the capability to communicate with each other, SCADA systems, and even some field instruments and sensors using various industrial communication protocols. There are various items to consider when selecting which control networks to use. Some of these considerations are the cabling type, including the expense and availability; speed and data capacity; security; and which protocols are supported by the chosen hardware manufacturer. Each manufacturer typically has a preferred or in-house protocol; however, simply choosing one of these may limit the choices for external devices. Many devices support multiple protocols, and this can be used as an advantage for selecting interfacing hardware and even using multiple protocols as they are best suited, for example, using a serial protocol with field devices, sensors, and so on, and using an ethernet protocol between the PLC, configurable controller, and SCADA system. The possibilities are complicated, and a furnace-control system specialist or system integrator can help make the best choice for a given application.

Alarm Analysis

Alarm analysis is an important step in an optimization process. Alarm analysis consists of several steps but can provide greater gains in operating efficiency than almost any other component in the optimization process. Alarms should be selected to provide an immediate notification to the furnace operator of an abnormal furnace condition. Conditions that could generate an alarm could be excessive temperature, electrical motor failure, atmosphere out of tolerance, and so on.

Alarm handling can be performed by either a PLC or a configurable controller with alarm functionality. Some configurable controllers could be prepackaged with this feature, while a PLC would need to be programmed with all of the alarm-handling logic. A heat treating controls expert or system integrator can configure the system that is best suited for each application.

Nuisance alarms can be a costly problem that is often overlooked. A nuisance alarm is any alarm that happens on a regular basis and is either not critical to the process or is incorrectly configured. It is understood that if the alarm siren rings, someone should pay attention to what is happening. Unfortunately, when a particular alarm occurs "every time we run that load" or "whenever we start that furnace," it creates an atmosphere where operators become normalized to ignore furnace alarms.

Nuisance alarms may occur because of an improperly set up recipe or a startup parameter that was not set correctly, for example, delay before trigger, delta deviation too small, or even a malfunctioning limit switch or sensor. Experienced operators who have been running furnaces for long periods of time can easily tell which alarms are important and which alarms are simply nuisance alarms, but less experienced operators could develop a bad habit of ignoring alarms, which could create a critical safety situation.

Alarm Frequency. Analysis of the frequency of alarms can be used to pinpoint the origin of repetitive alarms. The ability to view alarms from a given date/time (for example, all alarms since the installation of a new instrument) or all alarms on a certain shift is a valuable feature. Without proper logging of alarm times and the ability to select a list of alarms based on a certain timeframe, alarms that are actually occurring regularly may seem random or be incorrectly blamed on operator errors. One example of a cyclical alarm is a system that would mysteriously have alarms indicating a controller reboot. Using the alarm frequency analysis led to the discovery of a cyclical nature that allowed the department to discover that the reboots were being triggered by the radio carried by the security personnel during their rounds.

Pareto graphs are a type of graph that contains bars and a line graph in one representation. They can be used to provide information with respect to the timing, frequency, duration, and number of occurrences of each alarm while comparing them to the total number of alarms overall. This can help with maintenance issues and to gage progress in the optimization process. Knowing which alarms occur most frequently can help with the decision about where to focus the optimization process.

Duration. Knowing the duration of each alarm can help to gage the impact of the alarm on the operator's time, the potential impact to the parts, and possibly pinpoint the cause of the problem. A very short duration spike in temperature could cause an out-of-tolerance alarm that actually points to a failing thermocouple. Knowing which alarms cause the largest distractions in terms of operator time is a good starting point to gain efficiency by freeing the operator's time for other tasks.

Recipe Based. The ability to properly log and store alarms with the stored data from each process run can help determine if the programming of the recipe is the root cause of a nuisance alarm. For example, a recipe has a heating stage to heat from ambient to 815 °C (1500 °F), and the stage is configured to generate an alarm after 20 min if the temperature is not reached. This alarm could be very useful in the event of a heater element failure or tripping of the heating circuit breaker; however, if the furnace is simply incapable of heating the load fast enough, this alarm will occur each run, and operators will learn to ignore recipe-stage timeout alarms. By analyzing alarms on a recipe-based criterion, these types of problems can be corrected, and the alarm point can be adjusted to a value that can provide a critical alarm function.

Concurrent Alarms. Having all furnaces connected to one SCADA system makes it very easy to pinpoint common source alarms. An example of a common source alarm could be a cooling-water flow alarm that occurs on all furnaces at the same time. The alarm in the example could point to a failure of the cooling-water system, a pump that needs maintenance, or that the system does not have the capacity to supply all furnaces when a certain piece of equipment comes online.

Automation

Automation of repetitive furnace tasks can help free furnace operators for value-added work. An up-to-date control system can use sensors on the furnace to ensure a proper sequence of events based on a furnace recipe and sequence of operation.

For example, in a standard batch integral quench furnace, a charge is transferred between the vestibule, heat chamber, and quench chamber at different stages of the process. On older furnaces, these tasks are performed by hand by the furnace operator. In the event that the furnace operator is busy on another task or does not notice that the processing time has completed, the charge could stay in a chamber too long, creating production inefficiencies and possible damage to parts. An automated system (Fig. 4), equipped with the proper furnace sensors, can have the ability to transfer a charge automatically.

There are many levels of automation that can be considered, for both new furnaces and upgrading older furnaces. The most common divisions of automation found in heat treating operations are as follows.

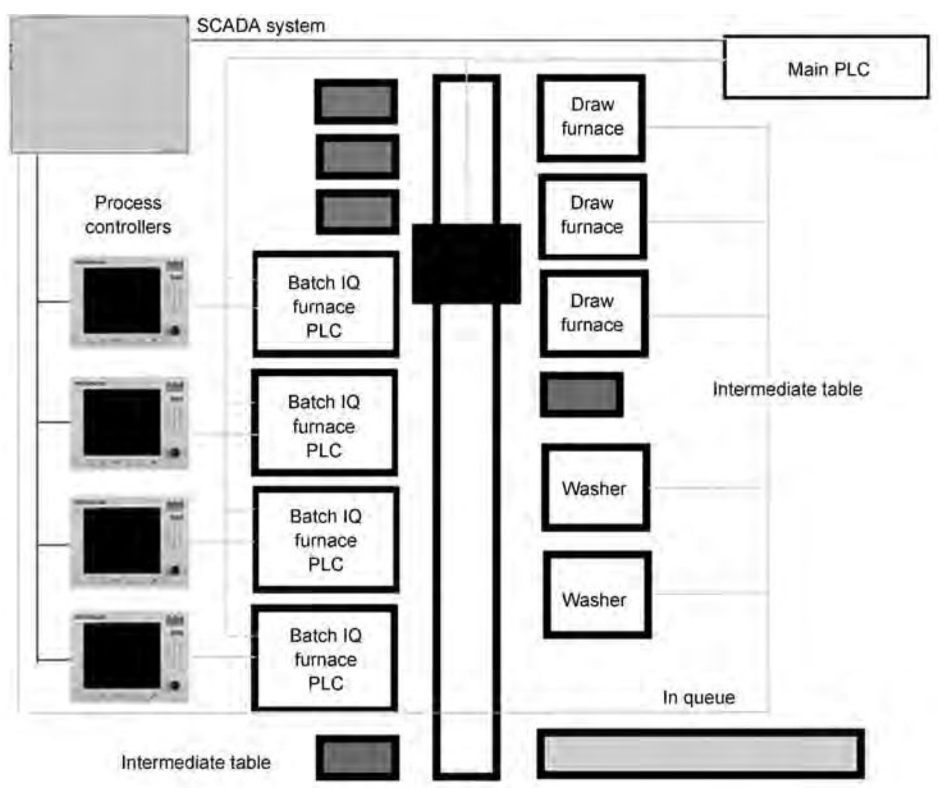

Fig. 4 Basic representation of an automated cell. SCADA, supervisory control and data acquisition; IQ, integral quench; PLC, programmable logic controller

Recipe automation allows the furnace variables, such as atmosphere, temperature, and time stages, to progress automatically. With recipe control, the furnace operator does not need to change the temperature or atmosphere controllers manually and can be alerted when the charge is ready to be transferred. This type of automation is popular on single-chamber furnaces or older furnaces when the control system budget is limited. This type of system ensures that each stage of the process can be performed correctly, but its drawbacks are that the furnace operator is responsible for the charge transfer between chambers. This type of automation is best suited to a configurable process controller and can allow for the use of an electronic chart recorder, alarm handling, and so on.

Charge movement automation allows a charge to be automatically moved between chambers when the elapsed time is reached. This option is used in conjunction with recipe automation to create repeatable and reliable results. The furnace operator is simply charged with loading the charge into the furnace and starting the recipe. The automation system then proceeds to treat the parts and transfer the load between chambers as configured in the treatment recipe. This level of automation is best suited to a system using both a configurable controller and a PLC. The configurable controller will handle the atmosphere, temperature, and time control, and the PLC will control the movement of the charge. This level of automation is well suited to most applications for multichamber furnaces.

Full-cell automation allows a "lights-out" type of automation. This level of automation normally consists of a gated-off cell containing several separate pieces of equipment, including washers, temper furnaces, carburizers, nitriders, holding stations, and automated charge cars. In some cases, parts can even be fixtured automatically. This type of system typically consists of several PLCs and configurable controllers controlled by a process-management SCADA system. This type of system allows multiple pieces of equipment to be used in the most efficient and repeatable manner. The furnace operator has very minimal interaction in the system, and, in fact, no personnel should be within the cage, due to the danger surrounding the automatically controlled equipment.

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Vacuum Heat Treating Processes

Revised by Real Fradette, Virginia Osterman, and William R. Jones, Solar Atmospheres; and Jon Dossett, Consultant

VACUUM ATMOSPHERES have become the first choice of many heat treaters as a result of the advent of space age materials and the need to process more sophisticated components. *Vacuum heat treating* consists of thermally treating metals and alloys in cylindrical steel chambers that have been pumped down to less than normal atmospheric pressure. In most applications, gas molecules are pumped out of the vessel to reach a certain vacuum level dictated by the process requirements. A true vacuum is devoid of all molecules or matter—a condition that does not even exist in the deepest regions of outer space. The term *vacuum* used in the context of heat treating more correctly describes a partial pressure where the pressure within the vessel is less than atmospheric (760 torr, or 1 atmosphere). The use of a vacuum furnace helps reduce the concentration of oxygen and water vapor within the chamber to very low levels and, in many cases, can eliminate the need for inert or reducing gas atmospheres for successful processing.

Vacuum Furnaces

Vacuum furnaces were first developed for processing of electron tube materials and refractory metals for aerospace applications. They are now also extensively employed in brazing, sintering, heat treating, and diffusion bonding of metals. Heat-treating applications can include hardening, annealing, nitriding, carburizing, ion carburizing and ion nitriding, tempering, and stress relieving. Furnace equipment used in vacuum heat treating differs widely in size, shape, construction, and method of loading. Furnaces are equipped for work loads ranging from several pounds to 70 tons, and heated working chambers range in size from 0.03 m^3 (1 ft^3) to hundreds of cubic feet. Most vacuum furnaces are batch-type installations, but some are continuous furnaces that have multiple zones for purging, preheating, high-temperature processing, and gas or liquid quenching.

The partial-pressure atmosphere of a vacuum furnace makes it possible to perform a number of different operations. Vacuum heat treating furnaces can:

- Prevent surface reactions such as oxidation or decarburization on workpieces, primarily because of the lack of oxygen
- Remove surface contaminants, such as oxide films and residual traces of lubricants resulting from fabricating operations
- Alter metallurgical properties of the surface layers of the work (e.g., carburization, nitriding, ferritic nitrocarburizing, etc.)
- Remove dissolved contaminating substances from metals by means of the degassing effect of a vacuum (e.g., removal of hydrogen from titanium)
- Remove oxygen diffused on metal surfaces by means of vacuum erosion techniques
- Join metals by brazing or diffusion bonding

Pressure Levels in Vacuum Furnaces

When most people think of a vacuum, they think of a theoretical or complete vacuum. As stated previously, a complete vacuum doesn't contain any matter—gas, liquid, or solid—and does not exist in a vacuum furnace. In heat treating, the term *vacuum* simply refers to an absolute pressure below that of the normal atmosphere. The standard absolute pressure of the atmosphere at sea level, 45° latitude, and 0 °C (32 °F) can be expressed in various values and units: 1 atm = 760 torr = 760 mm Hg = 760,000 μm Hg = 29.921 in. Hg = 14.696 psia.

In most vacuum furnaces, pressure levels are expressed in terms of absolute pressure rather than gage pressure. Normally, the units of measure used are torr, millimeters of mercury, or micrometers of mercury. The vacuum or pressure value of mercury refers to the height of a mercury column sustained by the difference between standard atmospheric pressure and the level of vacuum or pressure being measured.

When vacuum furnaces are pressurized above atmospheric pressure, such as for gas quenching, the pressure is expressed in terms of bars. Although one bar is actually slightly less than 1 atm, for heat-treating purposes, it is considered equivalent to 14.50 psia, 29.53 in. Hg, 760 torr, 760 mm Hg, or 760,000 μm Hg.

Table 1 compares vacuum and pressure to standard atmospheric pressure. The normal pressure range of vacuum heat treating should be noted.

Comparison of Vacuum and Atmosphere Furnace Processing

In most heat treating processes, when materials are heated, they react with normal atmospheric gases, which consist of approximately

Table 1 Pressure ranges required for selected vacuum furnace operations relative to standard atmospheric (0 gage) pressure

Gage pressure classification	Furnace application	Vacuum classification	Equivalent pressures								
			Pa	torr	mm Hg(a)	μm Hg	in. Hg	psia(b)	psig	atm	bar
Pressure	Pressure quenching, high gas	. . .	. . .	. . .	. . .	. . .	177.17	87.02	72.32	5.92	6
			. . .	. . .	. . .	. . .	147.65	72.52	57.82	4.93	5
			. . .	. . .	. . .	. . .	118.12	58.02	43.32	3.95	4
			. . .	. . .	. . .	. . .	88.59	43.51	28.81	2.96	3
			. . .	. . .	. . .	. . .	59.06	29.01	14.31	1.97	2
Zero	Pressure quenching, gas	. . .	1.01×10^5	760	760	7.6×10^5	29.92	14.696	0	1	1.01
Negative	Vacuum treatment, normal backfill	Rough	1.00×10^5	750	750	7.5×10^5	29.53	14.5	. . .	0.99	1
			1.3×10^4	100	100	10^5	. . .	. . .	. . .	. . .	. . .
			1.3×10^3	10	10	10^4	. . .	. . .	. . .	. . .	. . .
			130	1	1	10^3	. . .	. . .	. . .	. . .	. . .
	Vacuum treatment, normal range	Soft	13	0.1	0.1	100	. . .	. . .	. . .	. . .	. . .
			1.3	0.01	0.01	10	. . .	. . .	. . .	. . .	. . .
			0.13	10^{-3}	10^{-3}	1	. . .	. . .	. . .	. . .	. . .
	Vacuum treatment, maximum	Hard	0.013	10^{-4}	10^{-4}	0.1	. . .	. . .	. . .	. . .	. . .
			1.3×10^{-3}	10^{-5}	10^{-5}	0.01	. . .	. . .	. . .	. . .	. . .
			1.3×10^{-4}	10^{-6}	10^{-6}	10^{-3}	. . .	. . .	. . .	. . .	. . .
			1.3×10^{-5}	10^{-7}	10^{-7}	10^{-4}	. . .	. . .	. . .	. . .	. . .
			1.3×10^{-6}	10^{-8}	10^{-8}	10^{-5}	. . .	. . .	. . .	. . .	. . .

(a) Equal to 133.322387415 Pa, it differs from torr by one part in 7×10^6. (b) psia = psig + 14.7 psi