SPECIAL REPORT

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Pressure & Temperature Measurement

PART II

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TABLE OF CONTENTS

AD INDEX

Prevent pressure transmitter problems

Installation details make the difference in DP flow and level applications.

by Greg McMillan

Greg: You can’t control something if you’re not measuring it. There have been great advancements in measurement technology. Smart transmitters have increased accuracy an order of magnitude or more, and drift is so slow that calibration intervals can be significantly extended. However, a measurement is only as good as its installation. Not enough knowledge is published or presented on how to make sure the installation doesn’t limit performance or create maintenance and reliability issues. Here, Hunter Vegas and I (co-founders of the ISA Mentor Program) offer what we think is important. The newest resource to our ISA Mentor Program, Daniel Warren, has stepped up to offer his personal experiences to help guide our group. Daniel has over 35 years of experience as a senior instrument and electrical design specialist in oil, gas, chemical, food, mining, utilities, water & wastewater, and various pulp & paper facilities, and is the owner of D.M.W Instrumentation Consulting Services Ltd.

The most common flow and level measurements often use differential pressure (DP) transmitters with two impulse lines for flow, and one impulse and an equalization line for level. Pressure drops are also measured by a DP with two impulse lines. Many pressures must also be measured and controlled. Gauge pressure transmitters vent the low side. Absolute pressure transmitters have the low side sealed with a full vacuum. Gauge and absolute pressure transmitters (PT) have a single impulse line. Consequently, a production unit can have thousands of impulse lines that are often the weakest link.

The DP and PT installation method and location should be designed to:

- Prevent a non-representative process variable at the transmitter,
- Prevent extraneous effects at the transmitter,
- Keep the fluid density, composition and phase the same to both sides of the DP transmitter,
- Minimize accumulation of solids and bubbles,
- Minimize plugging, coating, corrosion, and fouling of the impulse lines,
- Minimize time lag(s) from impulse lines to the transmitter,
- Maximize signal-to-noise ratio, and
- Enable calibration and maintenance of the transmitter.

The impulse and equalization lines, valves and manifolds, as well as the transmitter, must all have wetted surfaces, including gaskets, O-rings and seals, constructed of materials that can withstand the worst process scenario. This could include corrosion, temperature swings, sudden pressure and vacuum swings, mechanical impact (hammering), clean-out procedures, etc.

Let's first address measurement of gases. The goal is to ensure only gases enter the lines, and any liquid drains back into the process. The transmitter must be mounted above the process connections with a uniform slope of at least 1 foot of elevation change for every 10 feet of length, with a greater slope being generally advantageous. For horizontal pipelines, the process connections should be at the top. For vertical pipelines, the process connections are on the same side as the transmitter. A vent at the DP transmitter may be useful for venting the accumulation of low-density gases (e.g., inerts) and for transmitter maintenance.

Hunter: Another potential problem with gas installations is gas condensation. If the boiling point of the gas at maximum operating pressures is less than ambient temperature, the gases can condense in the impulse line and cause intermittent negative pressure spikes. In this case, the process tubing must be heat-traced to eliminate this issue. Note that steam also can condense, but this case is handled differently. (See steam section below.)

Daniel: I've seen a number of cases where piping hasn't been installed adequately to ensure a sufficient slope for gravity drainage. I've also seen lines that are damaged and twisted when other mechanical components are installed as an afterthought. I have "blow-down" lines installed for gas venting when isolating and venting a transmitter. This also gives me a location to tie in a purge to blow any particulate, oils or condensate back into the process line.

Greg: When measuring liquids or steam, you need to ensure the lines are equal in length, and filled with liquid that has the same density and no phase changes. The transmitter must be mounted below the process connections with a uniform slope of at least 1 foot in elevation for every 10 feet of length. Valves at the transmitter should enable flushing and draining the lines and transmitter.

Heat tracing must provide enough heat to prevent freezing on the coldest day with the coldest fluid, but doesn't overheat the lines and cause flashing (vaporization or boiling) of the fluid on the hottest day with the hottest fluid.

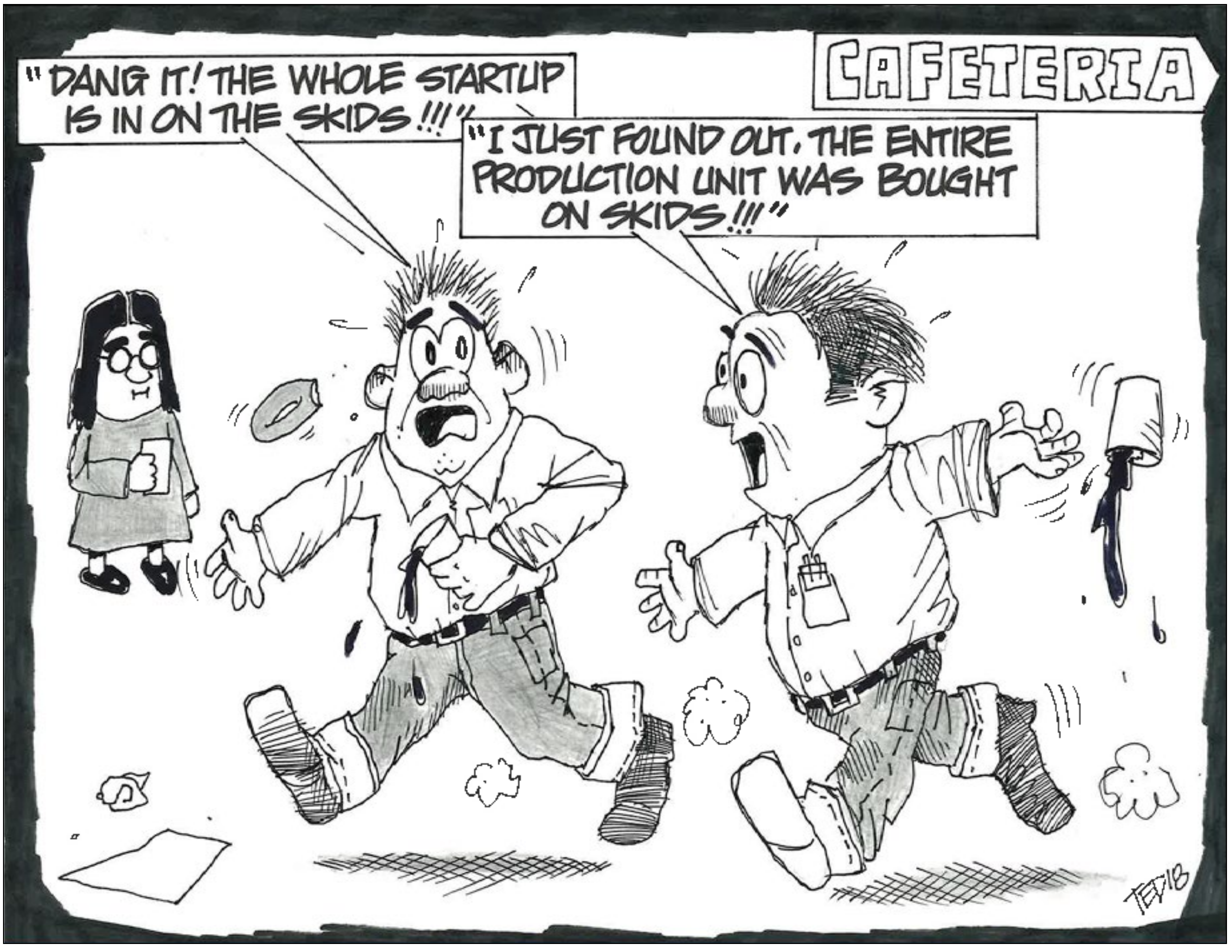
Hunter: It's very important that the tubing slope continuously from the process connection to the transmitter. Any high point along the way can trap vapors and cause an improper reading. Also, the transmitter connections usually branch off the main impulse run. This is done so if there are any solids in the impulse line, they'll drop into the line section above the blowdown valves and not impact the pressure measurement at the transmitter.

Daniel: The other thing to take into consideration is the liquid itself. The process conditions and product will make a difference in the materials and installation. As an example, what's used for water may not be suitable for liquid natural gas (LNG), diluent, chlorine, etc. Each of these are requires certain materials for wetted parts (tubing, diaphragms, O-rings, gaskets, etc.), and it's always best to confirm the requirements with the manufacturers' tables. The other thing to consider is the temperature and the specific gravity. The rangeability as well as the materials themselves may put a limitation on what can be used to accurately measure that particular process.

Greg: What more do we need to know about steam installations?

Hunter: One might consider steam a "gas" and mount the transmitter above the process line with a heat-traced line to avoid condensation. However, most transmitters cannot handle the process temperatures and will fail in short order. Therefore, a typical steam installation will mount the transmitter below the line, let the steam condense, and thus protect the transmitter from the high temperatures. As long as both legs are equally filled, the water in the line will not impact the DP reading, but it will cause an offset for a pressure transmitter that must be calibrated out. You also need to freeze-protect the impulse lines, and keep them warm enough to avoid freezing but cold enough to ensure the steam will condense.

Daniel: You don't have to wait for the steam to condense to fill the lines during commissioning. Distilled water can be used for this purpose. I've also used glycol to fill the lines when setting up transmitters in cold-climate locations. Seal pots are more of an old school practice. Their primary use is to act as a barrier between a harmful process, such as a corrosive gas/liquid or steam, and transmitter.



To keep trouble away from skid row, see the skid reality show preview and the top 10 things you don't want to hear about your differential pressure (DP) installation at www.controlglobal.com/articles/2018/prevent-pressure-transmitter-problems.

The ability to calibrate and maintain the DP installation generally requires the vent/fill/flush and drain valves mentioned above, and a manifold or equivalent piping of impulse lines that enable the same pressure to be applied to both sides of the DP for zeroing. The valves in the lines and manifold must also allow the transmitter to be safely removed with no exposure to the process fluid.

Daniel: How you calibrate a transmitter also depends on how it was installed and the type (style) of transmitter. I've seen a number of skid-mounted transmitters (and older installations) that aren't properly installed (isolated) to allow for a zero and/or span adjustment. It's also easier to do a bench calibration as compared to a field calibration. A field calibration can be cumbersome, especially if you must have an assortment of tools and test equipment (air or nitrogen cylinders, hand pumps, etc.). Also, testing is limited when you're dealing with an older style of DP as compared to the smart versions.

Major brewer redefines calibration process

When you're in charge of operations at a large brewery and realize that your team is spending too much time on instrument calibrations, using processes that are potentially hazardous, who do you call?

One major brewing facility in the United States recently faced this challenge. With close to 100 RTD thermometers installed at the plant, the manual calibration process had become time consuming, taking up nearly 80 hours of labor each year.

The brewery had been using a combination of portable micro-baths and other calibrators to perform calibrations on its RTD thermometers. The micro-bath calibrations involve the use of hot oil and an ITS-90 traceable reference thermometer. Each time the micro-bath was moved to a new location, the oil needed to be heated to the appropriate temperature and allowed to stabilize prior to performing the actual single point calibration.

Challenge:
Reduce the time required for manual calibration of nearly 100 RTD thermometers

Solution:
Endress+Hauser iTHERM TrustSens, self-calibrating thermometers deployed to replace portable micro-baths and other calibrators

Benefit:
Calibration time reduced substantially, improved safety and process efficiency

The TrustSens thermometer has a high precision reference built into the temperature sensor which aides in the calibration process.

Consequently, this process was taking the tech team around 45 minutes on average to calibrate each thermometer. Performing calibrations using the portable hot oil micro-baths also was creating safety concerns and challenges, as transporting a micro-bath containing hot oil from sensor to sensor had the potential to become a serious safety hazard if not done properly and carefully.

"Calibration is a very intimate process," says Robert Jennings, calibration and repair manager at Endress+Hauser. "Technicians have to stop production, so there's no money being made, and they also have to take instruments offline. There could be a lot of risk involved, not just with the device being calibrated, but then getting production back online successfully."

The brewery's lead instrumentation specialist was challenged to fix the situation. He was assigned to lead a project that would identify a safer and more efficient method of performing calibrations on its fleet of RTD thermometers.

"You can imagine the quantity of instrumentation needing to be calibrated," adds Jennings. "You have to be able to work fast, efficiently and effectively. And then from there, you have to get back online."

The project lead made a quick decision to purchase an Endress+Hauser's iTHERM TrustSens hygienic thermometer, the world's first self-calibrating thermometer, to see if it would save time and reduce risk and cost.

A SELF-CALIBRATING SOLUTION

Endress+Hauser's iTHERM TrustSens thermometer is designed to maximize product safety, plant availability and process efficiency. In particular, the TrustSens thermometer has a high-precision reference built into the temperature sensor which aides in the calibration process. Its automated and fully traceable inline self-calibrations reduce process downtime, helping to minimize risk and costs.

Nathan Hedrick, national product manager at Endress+Hauser, explains why automated calibration capabilities are critical in modern plants: "Assume you've got stable measurements that are unlikely to drift. When the schedule indicates that it is time to manually calibrate the instrument, you may be arbitrarily taking it out of calibration, inducing unnecessary cost and downtime, and increasing the risk of damage to a device that is working perfectly fine. Instruments that are self-calibrating in place enable you to achieve more frequent calibrations that are automatically triggered by pre-set deviations."

Employing the TrustSens temperature transmitter with Heartbeat Technology, calibration results are captured after every successful self-calibration. When technicians need the calibration history, they can connect directly to the transmitter or through a HART connection from the control system. Utilizing TrustSens' DTM the information is visible on the associated software or a printed calibration certificate can also be produced. The TrustSens thermometer eliminates the risk of undetected non-conformance issues without impacting existing validated procedures or GMP.

Typically, TrustSens is employed as a method of in-situ calibration for processes that undergo sterilize-in-place (SIP) on a regular basis. As steam is introduced to the process, the temperature passes through the 118°C threshold that triggers the TrustSens calibration. However, the brewery did not employ SIP, instead using a simple portable ceramic block heater in conjunction with TrustSens unique technology to perform the single point calibration.

In this case, the brewery technicians remove the TrustSens temperature probe from the thermowell and place it in the ceramic block heater. Once the temperature at the RTD exceeds 118°C, TrustSens then begins to cool and automatically initiates the calibration cycle. If the RTD is within the brewery's self-defined accuracy tolerance, a green light appears. The technician then reinstalls the probe into the thermowell and proceeds to the next RTD.

SIGNIFICANT TIME SAVINGS

The self-calibrating thermometer proved up to the task of delivering an efficient means for calibration while also improving worker safety. The brewery tested the TrustSens thermometer side-by-side with one of the facility's original RTDs and was extremely pleased with the results. Using the ceramic block heater, the calibration of the Endress+Hauser iTHERM TrustSens sensor takes no longer than 15 minutes, saving 30 minutes per RTD.

Jennings adds that when performing calibrations, depending on the discipline, the technician may have to rescale the device to get the best resolution out of the outputs. "That's also a risk, because not only are you pulling the device out of the production line, now you're also reconfiguring the device." In cases like this, Endress+Hauser service teams stand ready to support on-site calibrations as needed. "Part of the procedure in our documentation is that we save parameters and forward count. We reconfigure, if needed, to get the best resolution out of the device to see truly how it's performing and then restand the device, if necessary."

However, if the brewery replaces the RTDs that are currently in the facility with TrustSens, it will save close to 80 hours in calibration time annually, considering some transmitters are calibrated once a year and others every six months. Using TrustSens as the new calibration solution also greatly reduces the risk to the brewery's technicians by eliminating the hot-oil microbaths that workers were carrying from location to location within the plant.

Jennings adds that the benefits of self-calibrating instruments extend into the realm of optimized inventory. "When the deviation gets to a certain point where it's been adjusted time after time—having that data to know how far you've drifted is critical to planning for replacements."

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How to size and select your next pressure relief valve

Thorough understanding of process dynamics is needed to ensure reliable operation of these 'last line of defense' devices

by Ghulam Farooq, Saudi Aramco

A pressure relief valve (PRV) is a safety device designed to protect a pressurized vessel or system in case of an overpressure event. An overpressure event refers to any condition that would cause pressure in a vessel or system to increase beyond the specified design pressure or maximum allowable working pressure (MAWP). As relief valves are the last line of defense, they should be independent and highly reliable.

The relief valve is designed to open at a predetermined set pressure. As fluid is diverted, the pressure inside the vessel stops rising and will begin to fall. Once it falls to the valve's reseating pressure, the valve will close. The difference between set pressure and reseating pressure is referred as blowdown.

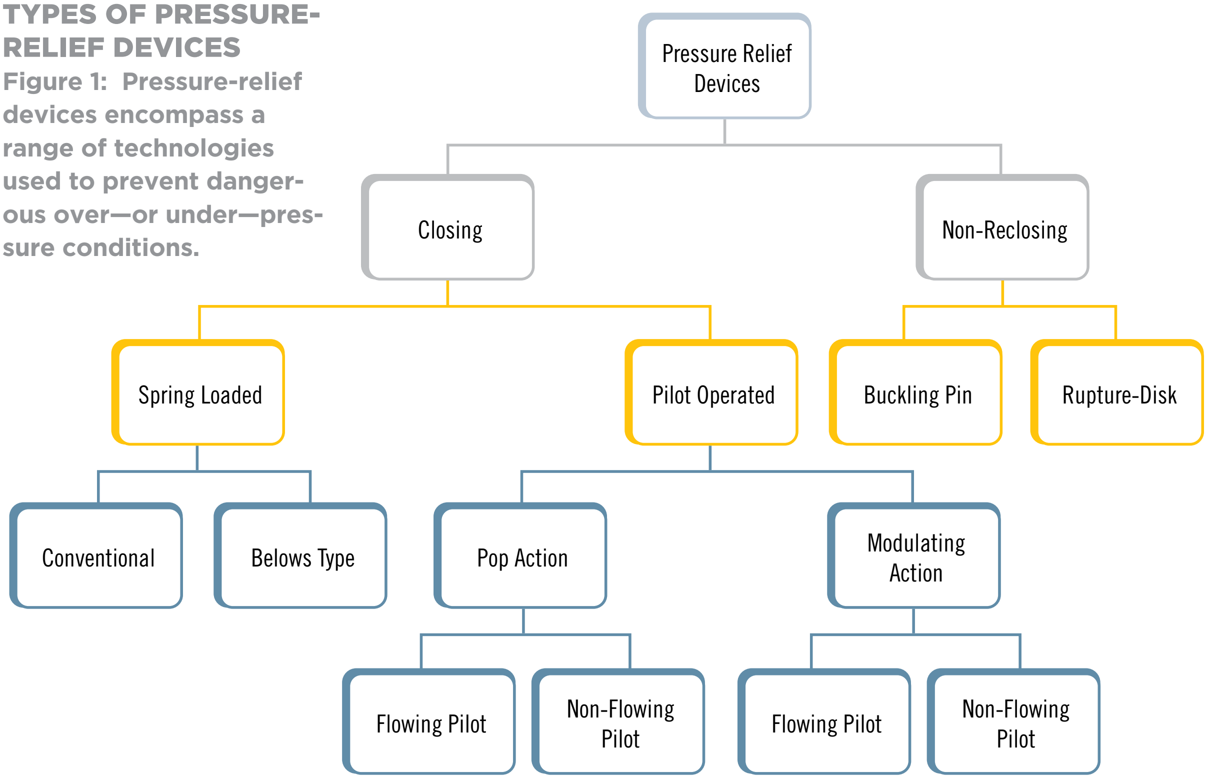
Similarly, equipment must sometimes be protected against an internal vacuum. In such cases, vacuum relief valves open at a predetermined low pressure limit, admitting air or an inert gas into the equipment to keep the pressure from going too low.

TYPES OF PRVS

Pressure relief devices can be divided into two main categories, closing and non-reclosing (Figure 1). The closing type are further divided into spring-loaded and pilot-operated. Spring-loaded can either be conventional or bellows type, while pilot-operated can either be pop-action or modulating-action. Each of these is further divided on the basis of pilot

TYPES OF PRESSURE-RELIEF DEVICES

Figure 1: Pressure-relief devices encompass a range of technologies used to prevent dangerous over—or under—pressure conditions.



type, either flowing or non-flowing. Non-reclosing types consist of buckling pins and rupture disks.

A variety of application-specific factors are considered when selecting PRVs. These include backpressure, service, discharge capacity and inlet pressure losses. Back pressure is an especially important factor in selecting the type of relief valve.

Conventional relief valves are used when the sum of the maximum variable superimposed backpressure plus the built-up backpressure is less than 10% of the set pressure. Bellows-type relief valves are used when the sum of the maximum variable superimposed backpressure, plus built-up backpressure, exceeds 10% of set pressure and up to the manufacturer-recommended limit. In practice, this is limited to 50% of the set pressure. If the backpressure increases more than 50%, then a pilot-operated relief valve should be used. Although pilot relief valves in theory can be used for up to 100% of the backpressure, in practice the backpressure should not increase more than 94% of the set pressure for reliable operation. This limit may vary for different manufacturers.

Pilot-operated relief valves have much higher discharge capacity compared to conventional relief valves of equivalent size. Also, due to availability of remote sensing line options, pilot valves can be used for high inlet pressure loss applications.

PRV type	CDTP formula	Basis of spring range
Conventional	CDTP = set pressure - constant superimposed backpressure	CDTP
Bellows or pilot	CDTP = set pressure	CDTP
Temperature correction only. ALL types of PRVs	CDTP = set pressure X temperature correction factor	Set pressure

CDTP CALCULATIONS
Table I: Different valve types require different cold differential test pressure, or CDTP, calculation formulas.

SET PRESSURE AND CDTP:

The pressure at which relief valve opens under service conditions is known as the set pressure, while the pressure at which he relief valve opens on a test stand is known as the cold differential test pressure (CDTP). As back pressure is not present during testing in the shop, it needs to be compensated for with a conventional relief valve. For bellows and pilot-operated relief valves, however, no adjustment is needed for the backpressure; CDTP and set pressure are the same. If the service temperature is higher than 250 °F, a temperature correction factor applies to all types of relief valves.

It's worth mentioning that spring selection for a conventional relief valve is based on the CDTP without considering the temperature correction factor. The CDTP formulas for different applications is shown in Table I.

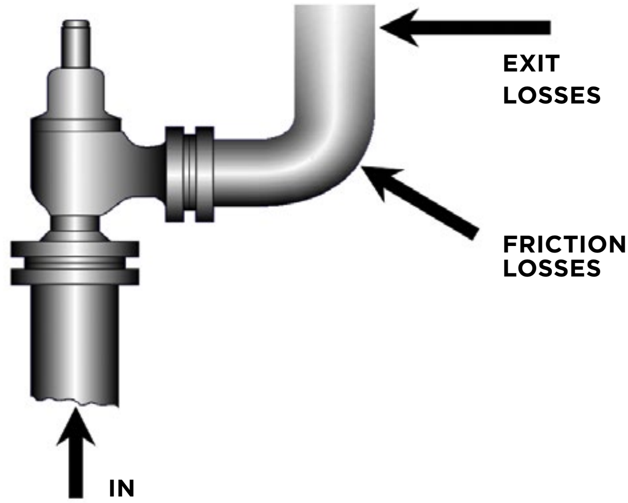
For selecting relief-valve setpoints, two limits are considered. The upper limit is decided by considering the MAWP of the vessel/equipment being protected. As per ASME SEC-VIII, the relief valve shall not be set higher than MAWP of the vessel/equipment being protected. If MAWP isn't known, then design pressure shall be considered as MAWP. The lower limit is based on the maximum operating pressure of the system. The relief valve setting(s) should be at least 10% or 15-psig, whichever is greater, above the maximum operating pressure. Where unstable process conditions exist, this differential should be at least 10% above the maximum operating pressure or 25-psig, whichever is greater. The purpose of this margin is to avoid any immature activation of the relief valve. Refer to ASME SEC-VIII for details of these margins for different pressure limits.

PRESSURE DEFINITIONS

Backpressure is the pressure that exists at the outlet of a pressure relief device as a result of the pressure in the discharge system. The total back pressure is the sum of superimposed and built-up backpressures.

Superimposed backpressure is the static pressure that exists at the outlet of a pressure-relief device at the time the device is required to operate. This is the pressure before the relief valve opens. Superimposed backpressure is the result of pressure in the discharge system coming from other sources and may be constant or variable.

Built-up backpressure is the increase in pressure at the outlet of a pressure relief device that develops as a result of flow after the pressure relief valve opens (Figure 2). This type of backpressure is caused by fluid flowing from the pressure relief valve through the downstream piping system. As built-up backpressure varies with the shape and size of the discharge piping, it's always variable.



SOURCES OF BUILT-UP BACKPRESSURE
Figure 2: In addition to static pressure downstream of a PRV, built-up backpressure due to the dynamic discharge of fluids also must be taken into account.

Blowdown is the difference between set pressure and reseating pressure. It refers to how much the pressure needs to drop, below the set pressure, before a valve reseats. Blowdown happens because, when a relief valve lifts, larger disc area is exposed to system pressure, and it will not be possible for the valve to close until the system pressure has been reduced to below the set pressure. The design of the control chamber, or huddling chamber, determines at what pressure the closing point will occur. Proper blowdown helps in reducing the chances of chatter or seat leakage. Test facilities may not have sufficient capacity to accurately verify the blowdown setting. In such cases, the settings can't be considered accurate, unless made in the field on the actual installation and in accordance with the valve manufacturer's specifications.

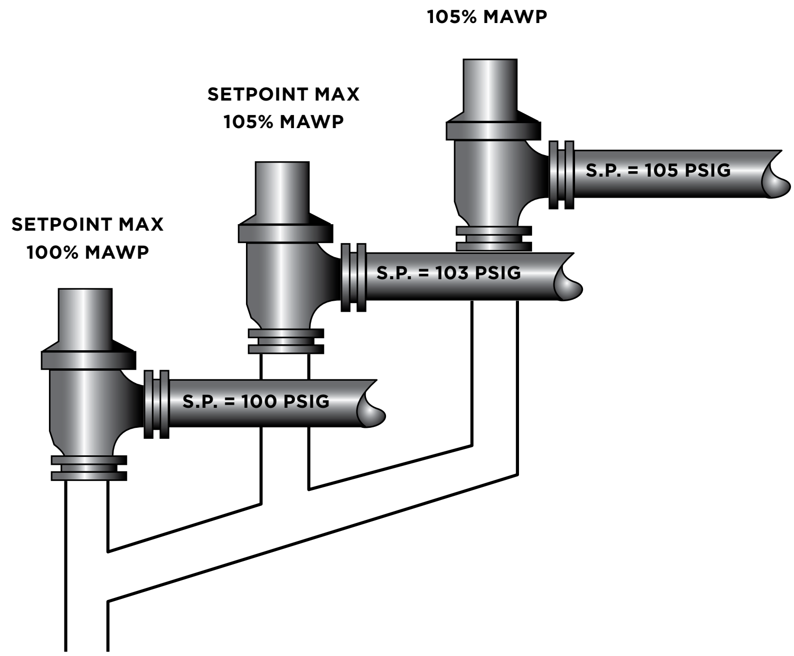
Relief valve inlet piping should be sized so that, at the combined maximum rated capacity of all operational PRVs, the pressure drop between the protected equipment and the PRV(s) shall not exceed 3% of the lowest PRV set pressure. The estimated inlet piping pressure drop should be also stated on the relief valve specification sheet.

EXAMPLE CALCULATIONS

Imagine, for example, an application with a PRV set pressure of 100-psi and 7% blowdown. The valve will close when the inlet flange pressure drops to 93-psig (100 – 7). Assuming inlet pressure losses of 3%, the system pressure at closing will be 96-psig (93 + 3).

Now, assuming that inlet losses are 10-psig, the valve will close at 103-psig, which is 3-psig higher than the set pressure. The valve will immediately try to open again, resulting in chattering and potentially damage to the valve. To avoid this situation, inlet pressure losses for any greenfield project should be limited to 3%.

It's worth mentioning that this inlet pressure loss criteria alone isn't sufficient to predict PRV stability. Additional factors that need to be considered include blowdown, relieving pressure and overpressure. Consequently, due to the complex nature of PRV instability behavior, a detailed engineering analysis should be performed as per API-520 for an existing installation, where inlet pressure losses are higher than 3%. This engineering analysis is referred to as a force-balance calculation. If the force-balance is passed and relief valves haven't shown any abnormal behavior or chattering previously, then inlet pressure losses higher than 3% may be acceptable.



PRVS WITH STAGGERED SETPOINTS
Figure 3: Staggering the set pressure of multiple pressure-relief valves prevents valve chattering and potential damage caused when valves attempt to open at the same time.

STAGGERED SETPOINTS

If multiple relief valves are being used to protect a vessel or equipment, then staggered setpoints are recommended. With this arrangement, the relief valve with the lowest setting will be capable of handling minor upsets, and additional relief valves will open as capacity requirements increase. This arrangement will avoid the chattering, as all relief valves will not open at same time. Staggered pressure settings also minimize emissions or product loss from relief valve operation.

For this arrangement, at least one of the relief valves shall be set at or below the MAWP of the vessel. The additional pressure relief valves may be set to open at higher pressures, but in no case at a pressure higher than 105% of the MAWP. In the example shown in Figure 3, the first relief valve is set at the MAWP of the vessel (100-psig), the second relief valve is set at 103-psig, and the third relief valve is set at 105% of the MAWP of the vessel.

It's also very important to know the correct backpressure at the outlet of the relief valve, as this will determine what type of relief valve—conventional, bellows or pilot—that's suitable for the application. Moreover, it will help to adjust the set pressure of the relief valve when being tested in shop. Selecting the correct set pressure of relief valves is also crucial, allowing enough margin between maximum operating pressure and the relief valve set pressure. This margin will help minimize the immature activation of the relief valves. The use of this staggering arrangement will help avoid chattering and emission loss. All of the above parameters, when correctly determined will make sure that the installed relief valves, which are considered as the last line of defense against unsafe conditions, are designed and operated in a way that will make facilities safe for operation.

References

ASME BPVC SEC-VIII DIV-1 – Rules for construction of pressure vessels

API-520 – Sizing, selection and installation of pressure-relieving devices

API-521 – Pressure relieving and depressuring systems

API-526 – Flanged-steel, pressure-relief valves

ABOUT THE AUTHOR

Farooq Ghulam is an instrument engineer working with Saudi Aramco's, Process and Control Systems Department. He is an SME for pressure relief valves, surge relief valves, control valves and gas detection systems. He has more than 20 years of experience in the design, technical support, and maintenance of instrumentation and automation systems, and also teaches several courses, including pressure relief valves and control valves. He completed his MS degree in electrical and computer engineering at the University of Alberta, Canada, and BS in electrical engineering at the University of Engineering & Technology, Lahore, Pakistan. He is a registered Professional Engineer with APEGA, Canada, and FS Engineer with TÜV Rheinland. He can be reached at ghulam.farooq@aramco.com.

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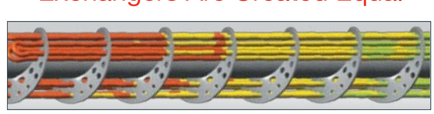

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Controlling global warming

Transitioning to a 'green future' can become the motor of global recovery

by Béla Lipták

In past articles I've covered the controls needed to transfer from the present fossil-fuel-based energy economy to a future solar-hydrogen-based energy economy. This green energy economy system will have a collector-electrolyzer-compressor (CEC) at the source end and a hydrogen storage-fuel cell (HFC) combination package at the user end. In past articles, I've also described the controls of the reversible fuel cell (RFC), the versatile device that generates hydrogen for storage when solar energy is in excess and reverses to generate electricity from hydrogen when solar energy is insufficient.

I've argued that our stone-age ancestors didn't switch to using bronze because they ran out of stones; they switched because it was better. So should we switch to green energy and leave fossils where they are. In past articles, I've also shown that robotization and artificial intelligence can provide the workforce needed to accomplish this transformation, and that present goals that hope emissions will peak by 2025, that they'll drop some 45% by 2030 and 100% by 2050 are overly optimistic in an age when there are leaders who question the very existence of global warming (GW).

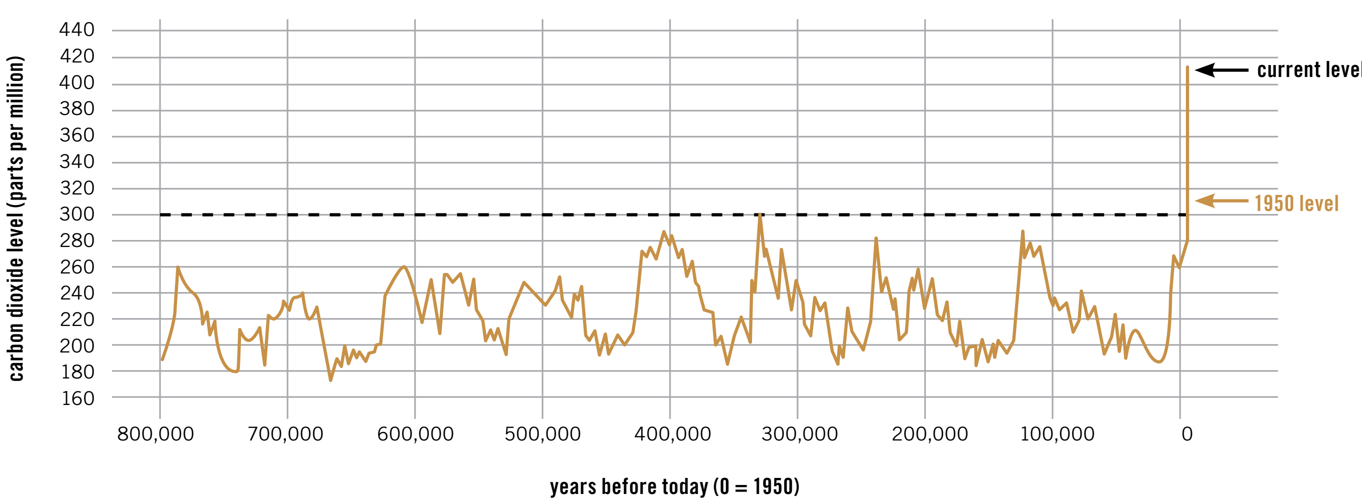
In this article, I'll show that the GW process is self-stabilizing, and that it contains many positive feedback processes and tipping points. Unfortunately, many future-prediction models disregard these positive feedback processes and as such are highly inaccurate. I'll end with some comments on the economy of the conversion.

POSITIVE FEEDBACK AND TIPPING POINTS

GW is a multivariable, heat-transfer process. It consists of a warm object (the Earth) rotating in a cold environment (outer space). The Earth has to be heated to maintain its temperature. It has two heat sources, one is outside (the Sun), the other (a much smaller one) inside, which I will neglect in this analysis. The heat balance will be stable if the following three variables are constant: 1) the amount of solar energy received, 2) the insulation of the planet, and 3) the reflectivity of the Earth's surface. Let us look at all three.

First, the amount of solar radiation received by the Earth varies because the Earth orbits the Sun at an angle. The solar energy reaching different parts of our planet isn't constant, but varies during the course of a year. This is the reason we have different seasons and why the seasons are opposite in the Northern and Southern hemispheres. There are three reasons for the variation: eccentricity of the Earth's orbit, which varies the planet's distance to the Sun (and triggers ice ages every 100,000 to 200,000 years); the orientation of the Earth's axis, which cycles off-center every 26,000 years; and the tilt-angle of the Earth's axis, with a cycle period of 41,000 years. It's obvious that none of these variables can be responsible for GW because they're all several magnitudes slower than the fast-increasing GW.

Second, life on Earth is made possible by the existence of our atmosphere, which, among other functions, insulates us from the cold of outer space. This insulation also keeps the "back side" of the Earth (the side



CARBON DIOXIDE ON THE RISE

Figure 1. According to NASA ice core analysis, the carbon dioxide concentration in our atmosphere hasn't exceeded 300 ppmv in the past million years. Today, it is 415 ppmv and rising. Source: NASA, https://climate.nasa.gov/evidence/ Credit: D. Luthi et al., 2008; D. M. Etheridge et al., 2010; Vostok ice core data/J. R. Petit et al.; NOAA Mauna Loa CO2 record.

not facing the Sun) warm. This insulation is facilitated by greenhouse gases, which reflect radiated heat back to Earth. The concentration of these carbon-dioxide-equivalent gases did not rise above 300 ppmv during the last 1 million years (Figure 1). Today it's 415 ppmv and rising. So, this "insulation" is now a variable, owing to the accumulation of our emissions during the Industrial Age. Today, every human being emits 3.6 kg of carbon daily. At the beginning of the industrial age, the total carbon in the atmosphere was 600 gigatons (GTC), and today it's 880 GTC and growing.

Third, the albedo, or reflectivity, of Earth's surface is about 0.3 and is dropping. In other words 30% of the solar radiation received is reflected back into outer space. The albedo varies with the nature of the surface. For example fresh snow reflects 90% (albedo = 0.9) of incoming radiation, while water reflects less than 10% and absorbs the rest. As GW melts the polar ice caps, Earth's surface is replaced by water and permafrost, so its albedo drops drastically, even as the heat absorption of the surface rises. Therefore, the changing reflectivity of the earth's surface is not only a variable, but a self-accelerating one. In the process control profession, we call this phenomenon "positive feedback."

SECONDARY INTERACTIONS

Two of the three main components of the Earth's heat-balance are variables (carbon dioxide in the air and albedo of the surface). Their variations can be influenced by positive and negative feedback sub-processes. Let's review the positive ones.

When snow/ice cover melts over land and the permafrost is exposed to GW, this material—that was frozen for several millennia—also melts and releases immense amounts of carbon. The total carbon dioxide content of the permafrost is estimated to be twice as much as that in the atmosphere. In addition, it contains large amounts of methane, which is a greenhouse gas 26 times more powerful than carbon dioxide.

The oceans are by far the largest carbon reservoirs on the planet. When GW increases, the oceans release immense amounts of carbon dioxide (degassing) because the rise of water temperature lowers its solubility. At the same time, more carbon dioxide in the air also increases acidification (lowers the pH) and increases the solubility of carbon dioxide. Acidification already has killed 30% of the coral reefs (the rain forests of the oceans). The combined effect of the oceans isn't well understood, and the various future models disagree about it or disregard it.

A SELF-STABILIZING PROCESS

The present extent of GW (anomaly), which is about 1.1°C, has already exceeded all temperatures that occurred during the past 100,000 years. Further, during the last 1 million years, this anomaly has never exceeded

3 °C. On the other hand, during a presentation of its 2020 report to the U.N., World Meteorological Organization Secretary-General Petteri Taalas stated we're now on a path to 5.4 °F (3 °C).

The "personality" of the GW process is a self-stabilizing one because the energy that the Earth radiates back into space diminishes as the plane's temperature rises. This is because the Earth loses more and more heat to outer space as its temperature rises, and when this increased cooling offsets the heat gain caused by the greenhouse effect, the global temperature stops increasing—the heat-balance of the planet is reestablished.

This sounds like a happy conclusion, as it suggests that all we need to do is wait and the GW will stop rising on its own. Well, yes it will eventually stop rising, but that will be too late for human civilization. If GW rises to just 3 °C, 1 million plant and animal species will be decimated and a large part of the Earth will no longer be able to support human life. In addition to disease and starvation, it will trigger a Biblical scale migration that could destroy human civilization.

The UN's Intergovernmental Panel on Climate Change estimates that exceeding the GW limit of just 2°C will cost some $54 trillion in damages. This sum is double U.S. GDP. The transition to a "green future" will also cost immense amounts of money, but it will also create an immense numbers of jobs. This transition is already happening in Utah where Mitsubishi is replacing a coal plant with a solar-hydrogen one.

So, we have reached a fork in the road of human evolution. We must take the one with the sign "Trust Science," because the other reads: "Dead End." We must not only leave the fossil fuels where they are, but must also start preparing our profession, the instrumentation and control profession, to automate all these new systems, plus we must start preparing our coal workers to learn how to maintain wind turbines and our oil workers how to install solar panels. This conversion will be a new Marshall Plan and will become the engine of economic growth, a motor of global recovery, while we complete the transition to a safe, free and inexhaustible energy future by mid-century.