AUTOMATION 2023

VOLUME 6

IIoT & Industry 4.0

- The Smart Industry Readiness Index
- Control Valves for CO_2 Pipelines
- Energy-Harvesting IIoT Devices
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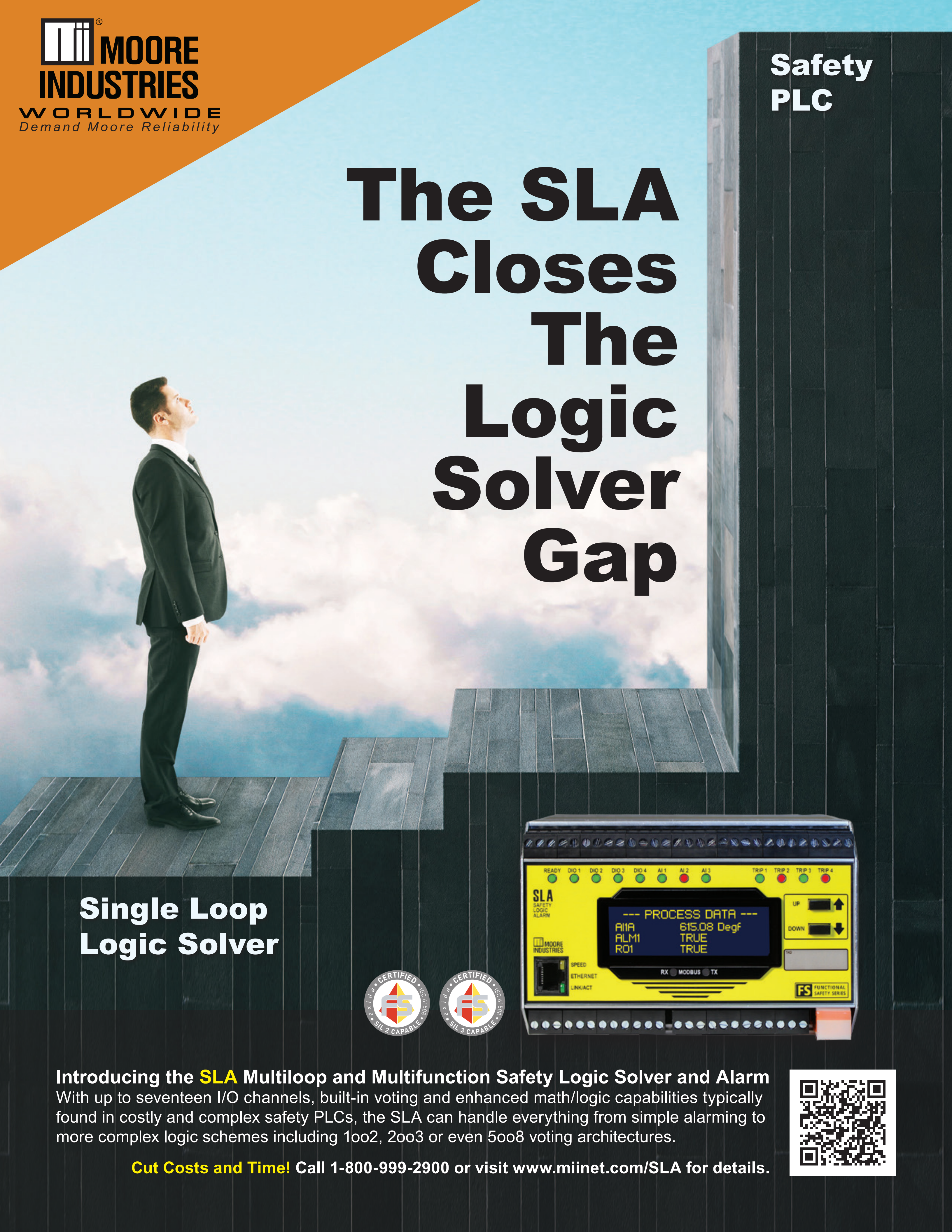
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IIOT & INDUSTRY 4.0

Introduction

Making the Most of Industry 4.0

Welcome to Volume 6 of AUTOMATION 2023, the last issue of the year from Automation.com, a subsidiary of International Society of Automation (ISA). The theme of this digital magazine is the Industrial Internet of Things and Industry 4.0.

Machine builders, operators, end users and other automation professionals are all looking for ways to make the most of Industry 4.0 technologies. They are working in a range of areas, such as designing and operating IIoT devices, smart manufacturing machines and increasingly integrated industrial systems. This publication, and other resources available through Automation.com, are here to help.

Dive in and make the most of these Industry 4.0 insights.

Renee Bassett
Chief Editor
rbassett@isa.org

About AUTOMATION 2023

The AUTOMATION 2023 ebook series covers Industry 4.0, smart manufacturing, IIoT, cybersecurity, connectivity, machine and process control and more for industrial automation, process control and instrumentation professionals. To subscribe to ebooks and newsletters, visit: www.automation.com/newslettersubscription.

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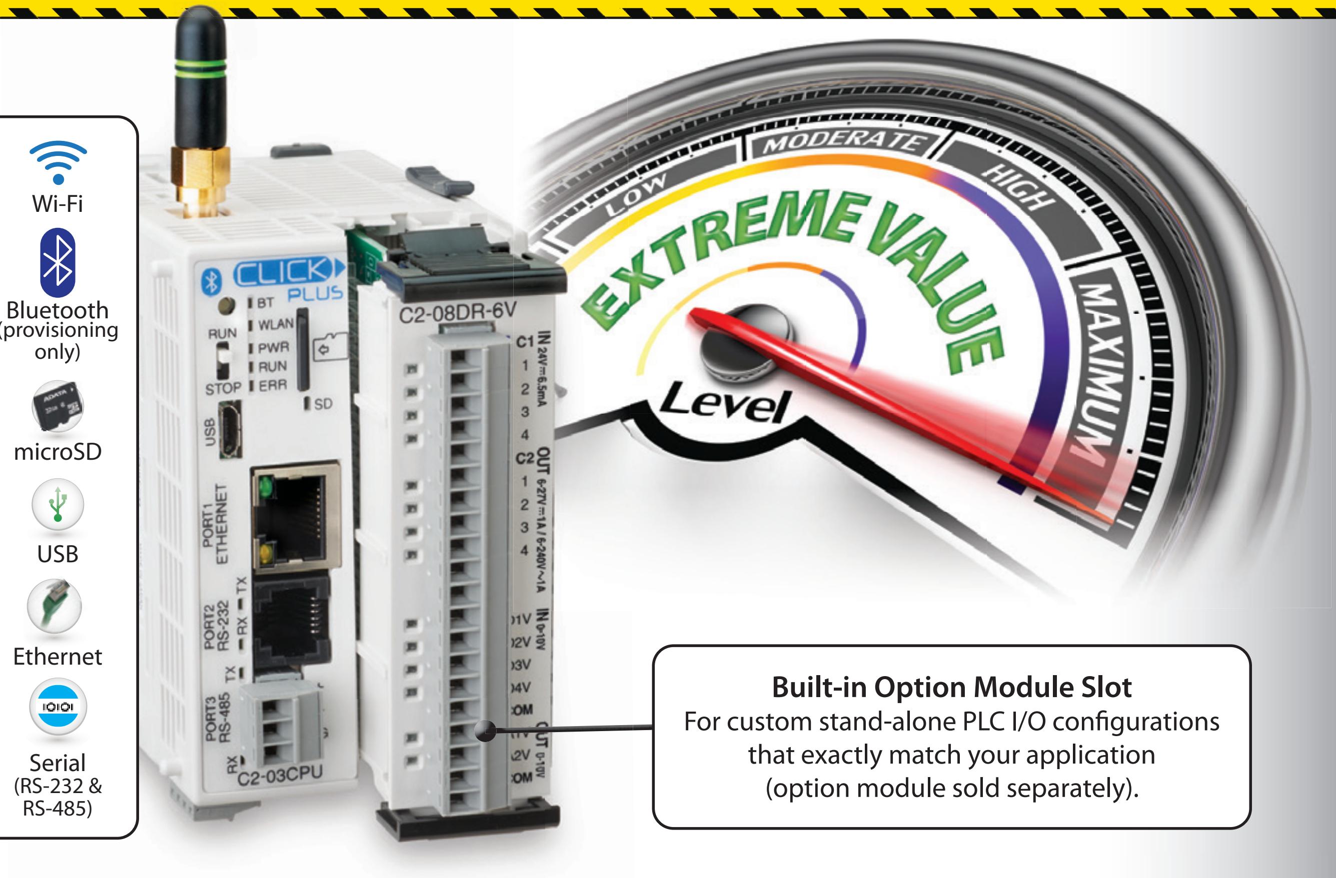

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Accelerating Digital Maturity with S.I.R.I. Assessments

The Smart Industry Readiness Index assesses digital transformation in 16 areas within three foundational pillars: process, technology, and organization.

By Karthik Gopalakrishnan, Yokogawa

In a time defined by the Fourth Industrial Revolution (Industry 4.0), a period transforming industries through advanced technologies, the manufacturing landscape is evolving beyond something we recognize as familiar. With the potential to automate processes, enhance data visibility, optimize operations, and redefine value chains, technology is revolutionizing industries globally. However, many organizations grapple with a critical question: “How can they assess their digital transformation (DX) readiness for this important paradigm shift?”

The shift is distinguishable if you consider a comprehensive DX—rather than just the act of digitizing processes—in which case it becomes a viable strategic advantage. Armstrong’s CIO, Dawn Kerchner-King, was able to streamline business operations and divert the savings to transformative technologies including cybersecurity and data analytics. And the Capital One CIO, Rob Alexander, helped champion the company’s apps to support Apple’s Touch ID biometric software.

This article dissects the Smart Industry Readiness Index (S.I.R.I.) framework and how it can help companies navigate DX challenges—especially if they are seeking to thrive and adapt to new market pivots.

On the precipice of change

Picture for a moment a base chemical company with 2,500 or more employees, perhaps a producer of methane or ammonia on the precipice of significant change. It is grappling with outdated processes and a rapidly evolving industry that demands they develop sustainable processes, reduce waste, and minimize environmental impact. The organization knows that DX can help ensure it meets business objectives; but it doesn't know where to start.

The key is starting by mapping the organization's key business objectives, linking those objectives with their current states of play, and drawing out a roadmap to ensure the organization has a blueprint to produce the outcomes it needs. DX need not always be just a technological solution. It can encompass a few organizational changes or some modifications to the existing protocols and processes. However, a holistic approach is the key to a truly successful transformation.

A holistic approach is the key to a truly successful transformation.

Digital maturity refers to the capability and readiness to effectively leverage and use digital technologies to drive business growth, innovation, and efficiency. The Yokogawa Digital Maturity Assessment is powered by S.I.R.I, which was developed by the Singapore Economic Development Board (EDB) and adopted by the World Economic Forum (WEF). S.I.R.I. helps break down the current maturity level into 16 dimensions that revolve around three foundational pillars: process, technology, and organization, thus, the S.I.R.I assessment offers an in-depth understanding of the company's current state. It provides clear insights to identify areas requiring improvement and paves the way toward stepping up an organization's digital maturity level.

By introducing digital assets and capabilities within an organization, organizations increase the likelihood of significant positive business impacts. These assets and capabilities are grounded

in six fundamental principles of digital transformation and Industry 4.0:

1. **Interoperability:** The capability of systems and devices to interact and communicate with each other.
2. **Virtualization:** The utilization of computer systems to replicate real-world processes.
3. **Decentralization:** The distribution of systems and resources away from a central location.
4. **Real-time capabilities:** The potential to collect and analyze data without delay.
5. **Service orientation:** Prioritizing service delivery and customer satisfaction.
6. **Modularity:** Designing systems as interchangeable and combinable components.

These principles, which are the keys to achieving digital maturity, are methodically evaluated within the S.I.R.I framework.

The S.I.R.I framework provides a comprehensive understanding of an organization's current state across the process, technology, and organization pillars. Each of the 16 dimensions scrutinizes a different aspect of a company's digital maturity, offering a comprehensive measure of its readiness for digital transformation.

The pillars of S.I.R.I.

The process pillar is about operations, supply chains, and product lifecycles. An operations view assesses the efficiency, predictability, and flexibility of a company's manufacturing and production processes. A supply chain evaluation looks at the integration, transparency, and flexibility of a company's supply chain. A product lifecycle view measures the efficiency of managing the lifecycles of products or services.

The technology pillar is concerned with automation, connectivity,

and intelligence. An automation view addresses the extent of automation in manufacturing and other operations. A connectivity examination reviews the capacity of a company's systems, devices, and people to share and exchange information. An intelligence analysis looks at the use of data analytics, artificial intelligence (AI), machine learning (ML), and other technologies to facilitate informed decision making.

The organization pillar looks at leadership, talent readiness, change management, and culture. The leadership view surveys the effectiveness of a company's leaders in driving digital transformation. The talent readiness lens evaluates the skills and readiness of a company's workforce to support digital transformation. Change management reviews the management of the human side of change, including communications, training, and employee engagement. The culture and collaboration overview assesses the company's culture, especially its support for innovation, risk taking, and collaboration.

By leveraging these principles and frameworks, manufacturers can devise actionable plans for Industry 4.0, helping them to effectively prioritize investments and initiatives for measurable benefits from digital transformation.

The assessment process

The process of measuring digital maturity using the S.I.R.I assessment also involves the assessment matrix, the world's first Industry 4.0 self-diagnostic tool, designed to look at and evaluate the current state of industrial factories and plants. The matrix strikes a balance between technical rigor, usability, and relevance. To date, the assessment matrix has been used by more than 2,000 companies worldwide, a testament to its versatility, effectiveness, and global acceptance.

The evaluation begins with the Official S.I.R.I Assessment (OSA), a two-day independent review of a factory or plant. This assessment provides a formal report with insights such as the characterization of the current state of a company's manufacturing plants/factories, benchmarking against industry peers or other companies within a specified geography, and identifying high-impact areas to prioritize for improvement. During the evaluation, the factory or plant undergoes rigorous scrutiny to determine its digital maturity. The organization is evaluated across the 16 dimensions of the S.I.R.I framework to be sure that elements such as strategy and objectives, organization and talent, operations, technology, and products and services, are assessed thoroughly.

Each dimension is a crucial insight that provides a granular view of the organization's current digital state and its potential for future growth. Upon completion of the evaluation, each dimension is classified into one of six maturity bands, ranging from Band 0 (lowest level of maturity) to Band 6 (highest). This classification serves as a baseline for understanding the current level of digital maturity and helps identify areas that need enhancement.

The S.I.R.I assessment also employs a prioritization component known as the prioritization matrix, which builds on the S.I.R.I matrix. This exercise leverages data such as the company's cost profile and key performance indicators (KPIs) or essential business objectives to uncover high-impact areas that the organization can target for improvements such as technology and infrastructure, data management and analytics, partnership ecosystems, and many others. This results in an accurate, data-driven roadmap for digital transformation initiatives that produce outcomes.

The digital maturity assessment allows organizations to gain insights into their strengths, weaknesses, and opportunities related to their digital transformations. This knowledge assists organizations in making informed decisions about which areas to prioritize and invest in, in line with their strategic and operational goals. Without first understanding their digital maturity level, companies could make misguided investments, potentially diverting resources away from areas that require more attention, and impeding the progress they intend to make.

With digital technologies continuously evolving, companies must keep pace with new trends to stay relevant. Understanding one's digital maturity level provides insights into the ability to adapt to these changes, thus ensuring business continuity and resilience in the face of technological market disruptions.

> **A high level of digital maturity** allows companies to be more agile, capable of rapidly adapting to business changes.

Beyond technological proficiency, digital maturity directly impacts a company's financial health. According to a study by Capgemini, digitally mature organizations are 26 percent more profitable than their industry peers. This is because such companies are better equipped to leverage digital tools and technologies, leading to enhanced efficiencies, lower costs, and improved customer experiences, all of which can positively impact the bottom line.

For example, General Electric has reported significant cost savings through its digital transformation efforts. By leveraging the power of the Industrial Internet of Things (IIoT) and big data analytics, GE has improved its operational efficiency, leading to substantial reductions in unplanned downtime and maintenance costs.

Also, a high level of digital maturity allows companies to be more agile, capable of rapidly adapting to business changes. This agility can be particularly valuable in a volatile market, enabling businesses to seize new opportunities and mitigate risks more effectively.

However, the path to digital transformation can often pose challenges, including resistance to change, a lack of necessary skills, and data privacy and security issues. Overcoming these challenges requires a systematic approach combined with strong leadership:

1. **Resistance to change:** This is often one of the biggest hurdles in the digital transformation journey. Employees may be apprehensive about new technologies and changes in their roles. This can be addressed by fostering a culture of digital learning and innovation. Training and development programs can help

employees understand the benefits of digital transformation and equip them with the skills needed for the digital age. The best way to support change is to employ an onsite digital champion, a knowledgeable digital enthusiast who can help support and communicate the value of adopting new technologies.

2. **Lack of skills:** The digital transformation journey often requires new skillsets that may not exist within the organization. Partnering with educational institutions, offering continuous learning opportunities, and hiring experienced digital consultants can help bridge this gap.

3. **Data privacy and security issues:** As businesses digitally transform, concerns around data security and privacy become more critical. Having robust cybersecurity measures in place and adhering to data privacy regulations can mitigate these risks.

Leadership commitment to digital transformation sends a strong message. Leaders can use insights from the S.I.R.I assessment to identify gaps and take ownership of the roadmap for transformation, paving the way for a successful digital journey. A case in point is IBM, which undertook a substantial digital transformation initiative aimed at becoming a cognitive solutions and cloud platform company. The process involved substantial internal resistance. However, by establishing a clear vision, engaging employees at all levels, and investing in upskilling initiatives, IBM successfully navigated the transformation, achieving a complete business model overhaul with services like infrastructure as a service (IaaS) and software as a service (SaaS).

Looking ahead

The path toward digital maturity is not a solitary step but an ongoing series of intentional actions that innovate and adapt, stay ahead of the curve, and reshape the future of the industry. The transformation story powered by the S.I.R.I assessment captures the essence of our digital times characterized by resilience, adaptability, and continuous growth. For¬¬¬¬ companies aspiring to accelerate meaningful change in the digital era, harnessing tools such as the S.I.R.I assessment is not just a strategic option. It is not a matter of “if,” it is a matter of “when.”

Digital transformation is a strategic endeavor that requires careful planning. Merely adopting isolated digital technologies without a broader vision will likely result in limited impact and eventual failure, as scalability will become a challenge. To be successful, it is crucial to embrace a holistic approach and leverage a proven, independent methodology such as S.I.R.I. to ensure comprehensive integration and scalability. Successful organizations do not end up changing for change’s sake but change for the strategic outcomes they want and need.

ABOUT THE AUTHOR

Karthik Gopalakrishnan (karthik.gopalakrishnan@yokogawa.com, https://www.linkedin.com/in/karthikgopalakrishnan21/ is a solution consultant for digital transformation for Yokogawa and a certified Smart Industry Readiness Index (S.I.R.I) assessor. He combines engineering experience, business acumen, and first-class customer service to ensure end-users advance on the spectrum of digital maturity. As a certified S.I.R.I assessor, his experience spans projects, policies, and technology for clients in digital transformation spaces and digital solutions tailored to meet customers’ key business objectives.

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Carbon Capture: Selecting Control Valves for Supercritical CO_2 Pipelines

Mitigating the effects of climate change by pursuing greenhouse gas (GHG) reductions has become an extremely important topic, with project numbers accelerating globally. Early efforts to lower GHG emissions were focused on methane, NO_X, and various fluorinated gases due to their high GHG potential. As these sources are currently being addressed, attention is turning toward carbon dioxide (CO_2) reduction due to the sheer volume of gas emitted into the atmosphere. In the U.S., (CO_2) makes up nearly 80 percent of the GHG emissions.

> Greenhouse gas reduction applications depend on carefully selected control valves to safely process, transport and sequester carbon dioxide.

By Suzanna Grills, Emerson

Spurred by a number of government subsidies and mandates, CO_2 transportation and injection/sequestration projects are being undertaken across the globe. Each of these projects depend heavily on carefully selected control valves to safely process and transport CO_2, and then inject it into suitable repositories. This article addresses some of the more difficult challenges encountered in these applications, and it offers suggestions for choosing the right control valves for these services.

A significant and growing problem

Globally, GHG emissions have been steadily growing for decades, leading to an increase in the average global temperature and causing changes in global weather patterns (Figure 1). The long-term prognosis appears grim, with many climate experts and government entities sounding warnings of significant and lasting impacts if GHG emissions are not curtailed immediately.

Like many countries, the U.S. has committed significant funding to address the climate issue at hand. In 2021, the Bipartisan Infrastructure law provided $62 billion to fund Department of Energy (DOE) investments in energy infrastructure, with $3.7 billion of that sum specifically targeted for CO_2 removal efforts, including direct air capture, carbon capture and utilization, and carbon capture and storage.

Approximately 5,000 miles of CO_2 pipelines already exist in the U.S., and most are used to carry CO_2 to aging oil fields where the gas is injected underground to enhance oil recovery.

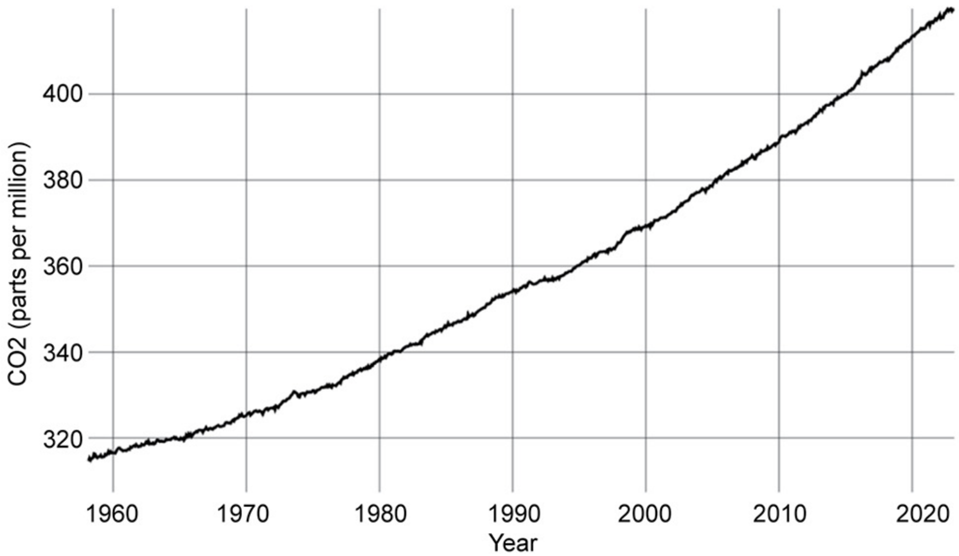

Figure 1. Atmospheric CO_2 has risen 47 percent since the industrial age and 11 percent since the year 2000, increasing the average winter temperature in the U.S. by 3 degrees F since 1896. *(Courtesy: Climate.nasa.gov)*

Direct air capture (DAC) pulls CO_2 directly from the atmosphere to remove CO_2 from ambient air. DAC is known as a carbon dioxide removal process as it has the ability to remove CO_2 from the atmosphere, ensuring negative CO_2 emissions. Utilization efforts seek to capture CO_2 from emitters—and then either use the gas directly (in industries like refrigeration, the food and beverage industry, etc.)—or convert it into useful fuels, chemicals, or plastics.

Carbon dioxide captured from man-made sources can be used as is or injected and stored deep in subsurface geological formations. Biological sequestration is being considered, but by far, the most promising storage option is injecting the gas underground into spent gas and oil fields where it will be sequestered indefinitely.

All these options will have a role to play in CO_2 emission reduction, but all depend on an extensive infrastructure to transport the CO_2 from the sources to the users/storage sites (Figure 2). While trucks, rail cars, and ships could be used, it is much safer and less expensive to transport the gas via pipeline.

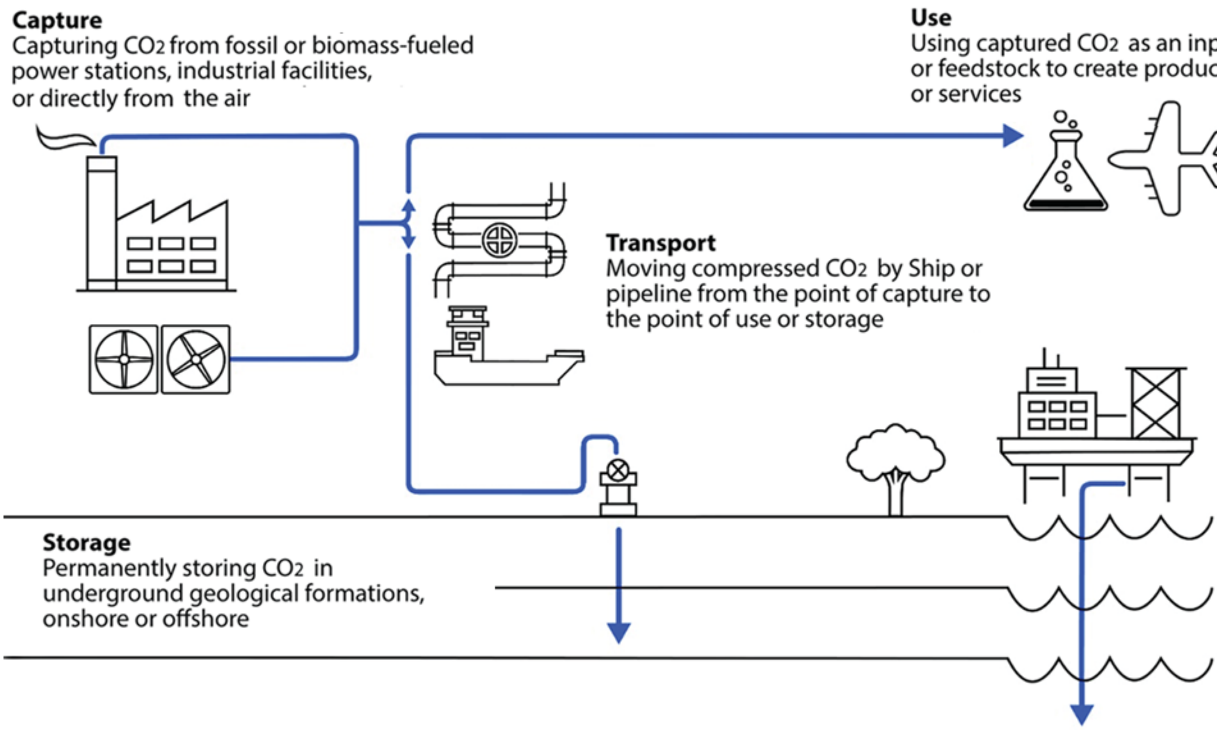

Figure 2. Shown are the prevailing techniques for CO_2 reduction capture CO_2 either from the air or from emission sources, and then transport the gas to be used in industry or stored underground. *(Courtesy: www.iea.org.)*

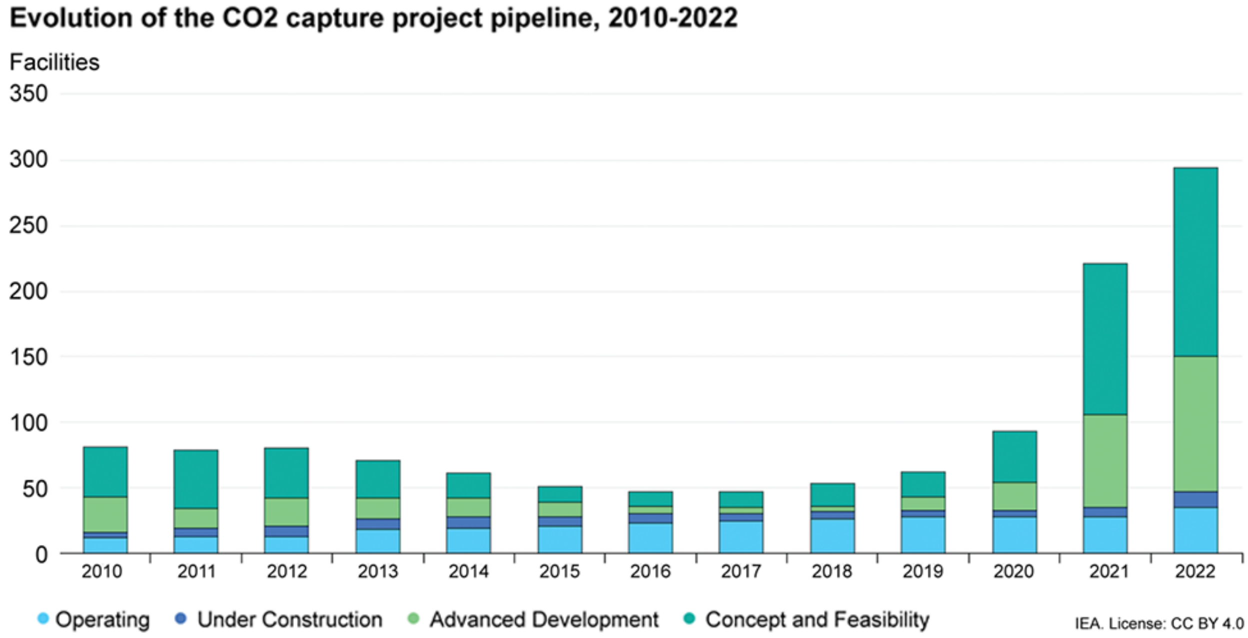

Figure 3. Most of today's carbon capture projects operate in natural gas processing plants, but new projects target power generation, chemicals, ethanol plants, and cement production. *(Courtesy: www.iea.org.)*

Approximately 5,000 miles of CO_2 pipelines already exist in the U.S., and most are used to carry CO_2 to aging oil fields where the gas is injected underground to enhance oil recovery. However, achieving the country's CO_2 emission goals will require an order of magnitude expansion of that pipeline infrastructure, with one study suggesting this pipeline network must be expanded to 66,000 miles by 2050.

These pipelines are just a small part of a burgeoning carbon capture project explosion. There are approximately 35 commercial facilities applying carbon capture and utilization projects, capturing 45 metric tons of CO_2 a year according to the International Energy Agency. However, there are more than 300 projects already in various stages of planning (Figure 3), with 200 facilities scheduled to begin operation by 2030.

Between those facilities and the CO_2 pipeline infrastructure, the processing, transport, and injection of CO_2 will figure heavily on upcoming project dockets.

CO_2 transport challenges

As mentioned previously, the most efficient way of transporting CO_2 is via pipelines, which are commonly used for this purpose worldwide. To improve transport efficiency, the gas is compressed to high pressures and temperatures to reduce its volume.

CO_2 has a low critical temperature and pressure, often exceeded by typical pipeline conditions (Figure 4). When the gas is compressed above its critical point (about 88 degrees F and 1,070 PSIG), it transitions from a vapor to a supercritical fluid.

In its supercritical fluid state, CO_2 has the density of a liquid but the viscosity of a gas, so it transports very efficiently in pipelines, with much reduced pressure loss, but CO_2 transport has its challenges as well. Even trace amounts of water in the gas will create carbonic acid, which attacks the piping. Water can also form hydrates, similar to ice crystals, when pressure is reduced, impeding flow and creating plugging problems.

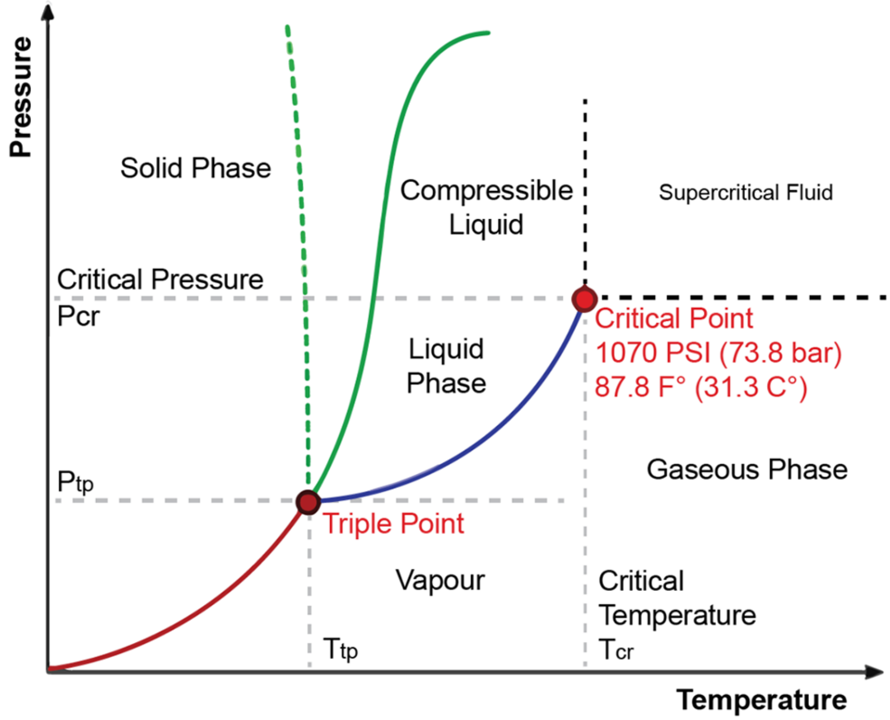

Figure 4. Above the critical point at 1,070 PSI (73.8 bar) and 87.8 degrees F (31.3 degrees C), CO_2 is no longer a liquid or a gas, but becomes a compressible dense-phase fluid with the properties of both a liquid and a gas.

Another potential issue is a phenomenon called explosive decompression, affecting control valve elastomers. This can occur when the fluid experiences a large pressure drop, creating a phase change from supercritical to vapor. This lowers the density of CO_2, and if this low-density CO_2 is entrained inside of an elastomer, it can blow the material apart.

Carbon sequestration through underground injection encounters the same issues as pipelines, but adds the potential of two-phase, and even three-phase, flow to the mix. Depending on the injection pressure, the CO_2 could be a supercritical fluid, a liquid, a vapor, or even a solid, creating a host of control valve challenges.

Pipelines are just a small part of a burgeoning carbon capture project explosion, but more than 300 projects are already in various stages of planning.

Control valve specification for pressurized CO_2 applications

Control valves in pressurized CO_2 applications must be carefully sized and selected to provide reliable and dependable service. Unfortunately, standard flow and sizing calculations do not work in supercritical regimes, so specialty sizing and modeling programs are required for this service. This takes critical thought and specialized knowledge, so consulting with a control valve expert is often needed.

Another challenge involves multiple phases and phase changes as the CO_2 moves through the valve. Predicting two-phase flow capacity also requires specialty models and calculations, which may not be available. Finding a vendor with a history of successful applications in very high-pressure CO_2, and a knowledge of sizing and selecting equipment for supercritical and/or multiphase flow, is a critical first step in valve selection.

The next big challenge for valve specification is material selection. Even trace amounts of water in CO_2 can have a significant impact on the material type decision, so it is important to fully understand what else is present with the CO_2 during normal, and potentially upset, conditions.

Elastomer and seal material selection also can be difficult. Supercritical CO_2 is a very strong solvent that readily penetrates certain elastomers at high pressure. When the pressure is released, the entrained gas can instantly vaporize, destroying the seal.

To avoid this problem, packing and body seal materials must be carefully considered, with alternative solutions evaluated depending on the type of valve required for the service. Elastomeric materials with explosive decompression resistance can be procured when required, but typically non-elastomeric materials are chosen for the service.

Typical valves designs used in supercritical CO_2 service

Beyond the difficulties of sizing and material selection, dense phase CO_2 applications obviously require the ability to handle very high pressures, and ideally offer little or no pressure drop when wide open (Figure 5). For this reason, full ported throttling ball valves are commonly used.

Figure 5. A 900-pound full-bore throttling valve (Fisher V280 shown) is commonly used in CO_2 pipeline applications. Attenuators for liquid and vapor service may be required for applications with high pressure drops.

When the valve is exposed to high pressure drop applications, it will often require an attenuator designed for either liquid or vapor applications, depending on the service, so this should be considered in the valve selection process.

Pipeline and CO_2 injection applications will invariably involve a multitude of compressors. During low flow conditions, these compressors can encounter a catastrophic condition called surge, where the vapor at the outlet instantly reverses flow through the compression stages and then slams forward moments later. It takes only a few surge cycles to destroy a compressor and take it out of commission for an extended time.

To avoid this condition, anti-surge valves (Figure 6) are installed to instantly bypass the outlet flow back to the compressor inlet and establish enough flow to protect the equipment. The valves must move very quickly and precisely to provide instantaneous and stable response.

Figure 6. The heart of any compressor system is the anti-surge control valve (Fisher easy-e EW shown), which must respond instantly to avoid severe equipment damage during surge events.

The difficulties of material selection and elastomer design apply to anti-surge valves as well, but there are additional challenges in specifying related valve components for this service. Anti-surge valves are usually very large and require specialized actuators and positioner components to provide extremely fast and accurate response. Trim selection is also difficult because it must be specified to handle the very high pressure drop and high flow conditions typically encountered in this service.

Consult an expert

While knowledge of liquefied natural gas and pressurized natural gas applications is commonplace, the number of experts in CO_2 pipeline and injection applications is much more limited, but they do exist. As a multitude of high-pressure CO_2 transport and sequestration projects get started, a key component to success will be partnering with a valve vendor that has successfully worked with these applications. These types of vendors will have the expertise and experience required to help end users choose the right valve design, trim, and material of components to handle the operating conditions.

The first step in the process is to understand the normal and potential upset conditions the valves could encounter, and to then partner with a knowledgeable vendor to evaluate the multitude of body design, trim, and material of construction options. The effort will not be trivial, but the long-term reliability, safety, and cost savings that result will justify the endeavor.

Figures all courtesy of Emerson except where noted.

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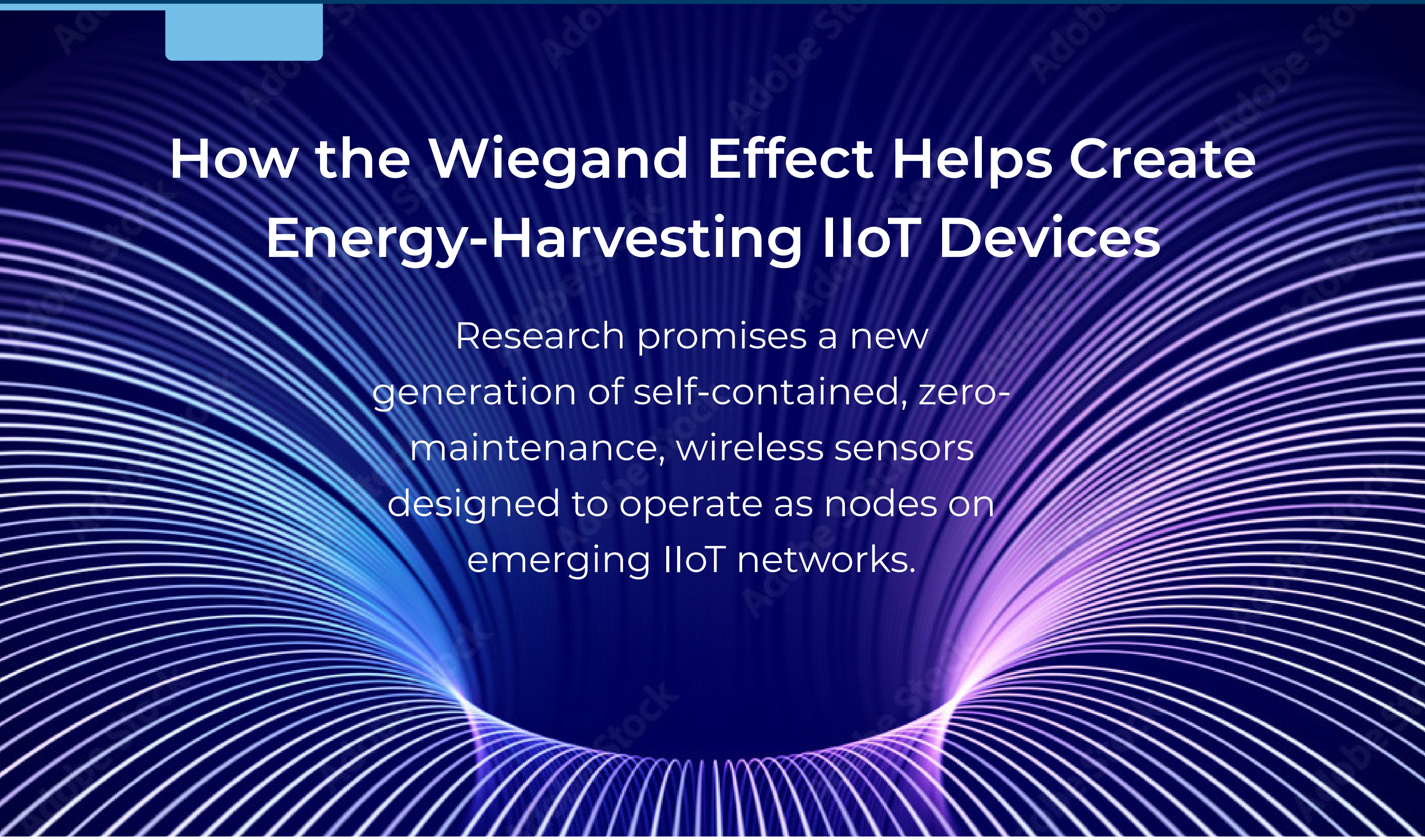
Suzanna Grills is a sustainable sales engineer within Global Industry Sales at Emerson. She has a chemical engineering degree with an emphasis in environmental from the University of Missouri-Columbia.



How the Wiegand Effect Helps Create Energy-Harvesting IIoT Devices

Research promises a new generation of self-contained, zero-maintenance, wireless sensors designed to operate as nodes on emerging IIoT networks.

By Tobias Best, FRABA Group

The “Wiegand effect,” discovered almost 50 years ago, has been used successfully in several specialized applications, but its full potential for energy harvesting and signal generation has received only limited recognition. With recent enhancements to the energy output from Wiegand devices and the emergence of a new generation of ultra-efficient electronic chips for wireless communications, the technology is showing significant promise, especially in the realm of the Internet of Things (IoT). UBITO, a member of the FRABA Group of technology companies, is leading research and development projects aimed at fulfilling this promise.

Wiegand effect explained

The Wiegand effect is a physical phenomenon discovered in the 1970s by John Wiegand, an American inventor who found that by repeatedly stretching and twisting a piece of ferromagnetic wire, he could alter its magnetic properties. When a sample of Wiegand wire is exposed to a reversing external magnetic field, it will initially retain its original magnetic state. However, when the strength of the external field reaches a critical threshold, a region of the wire that is magnetically soft will undergo an abrupt reversal of its polarity. This transition takes place within a few microseconds and can be harnessed to induce a pulse of electric current in a fine copper coil wrapped around the wire.

The electric pulse generated by a Wiegand wire is very brief, but its strength stays nearly constant, regardless of how quickly or slowly the external magnetic field changes. This is what makes the Wiegand effect special: While simple dynamos—which also use electromagnetic induction—are effective at converting rotary motion into electrical energy, their output power varies with rotation speed. When a dynamo is turned slowly, power levels can be too low to be useful. With a Wiegand wire however, the amount of electrical energy generated with each reversal of the magnetic field remains consistent over a wide range of speeds.

The combination of a short length of Wiegand wire and a surrounding copper coil is referred to as a Wiegand sensor. These are available commercially from UBITO in surface mountable device (SMD) packaging.

> **"The mechanical process** that produces Wiegand wires creates a combination of magnetically hard and soft layers in the wire, causing the wire to have a high level of magnetic hysteresis."

Using energy harvesting power for innovation

"Energy harvesting" refers to technologies that extract energy from the local environment to power electronic devices. Several are available, including photovoltaics (energy from light), thermoelectric and pyroelectric effects (energy from temperature variations), and piezoelectric and electrostatic devices (energy from mechanical motion).

Wiegand sensors are also a good candidate for energy harvesting. In their basic form, these devices produce modest amounts of energy—

about 200 nanojoules. However, recent developments have significantly increased energy output from Wiegand devices and opened possibilities for much more ambitious applications.

Building an energy self-sufficient IoT node

An R&D program, carried out by a team of researchers at FRABA's technology center and the Rhineland-Westphalia Technical University with support from the German Ministry of Science and Technology, has developed enhanced Wiegand devices that are optimized for power generation. These are called "Wiegand harvesters." The researchers have demonstrated that a set of Wiegand harvesters (figure 1) can generate up to 10 microjoules of energy (approximately 50 times the output from a commercial Wiegand sensor). This was sufficient to energize a low-power ultra-wide-band radio transceiver with a transmission range of 60 meters.

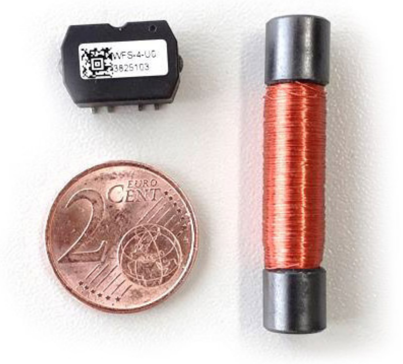


Figure 1. Wiegand harvester (right) and Wiegand sensor (top left).

This demonstration points to the feasibility of a new generation of entirely self-powered sensors that would be capable of monitoring a physical action such as a rotary motion or the opening or closing of a door and transmitting a notification signal to a monitoring system through wireless communications. Other condition data such as temperature could also be sent. This type of energy self-sufficient, maintenance-free device could become important components in IoT. As Christian Fell, FRABA's head of technology development explains: "The vision of the IoT calls for thousands of smart sensors distributed through homes, commercial facilities, and digital factories, collecting data for monitoring, security, and process optimization. If these devices can be made energy self-sufficient, harvesting electricity directly from their surroundings to power both their operation and a wireless communications interface, there will be enormous benefits in terms of simplifying network deployment and reducing maintenance costs including the cost of installing, checking, and disposing of thousands of backup batteries." The Wiegand effect could provide an excellent power source for remote sensors wherever there are changing magnetic fields present.

Along with an energy source, another key part of a viable IoT node is the communications interface. For their proof-of-concept demonstration, the FRABA-RWTS team used impulse-response, ultra wide band (IR-UWB) technology, based on an SR-1000 UWB transceiver from SPARK Microsystems. This device transmits very short electromagnetic pulses in a 2 to 11 GHz frequency band. Because this technology transmits data in short duration pulses, it uses less energy than narrow band radio transmitters. This intermittent transmission is also a good fit with the Wiegand effect's characteristic of generating electrical energy with the brief pulses. As noted above, this prototype was able to transmit small data packets over 60 meters in demonstration tests.

Energy harvesting for self-powered sensors

For small Wiegand sensors, the electrical energy produced with each polarity change, while limited, is sufficient to activate a low-power electronic counter circuit. This form of energy harvesting has been used successfully in more than a million encoders (rotation measurement instruments) built by POSITAL and other manufacturers (figure 2). Because of Wiegand energy harvesting, these encoders' rotation counter systems are entirely self-powered with no need for external power sources or backup batteries, significantly reducing maintenance requirements.

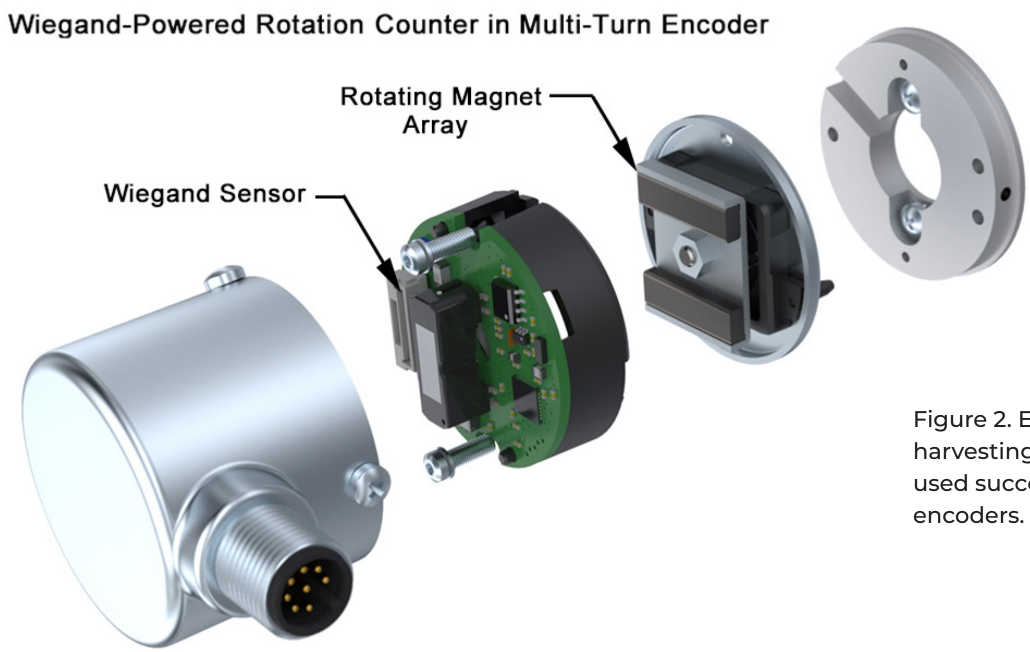


Figure 2. Energy harvesting has been used successfully in encoders.

A similar principle has bee used for water or gas meters. Here, a permanent magnet is mounted on the meter's rotating shaft, close to a Wiegand sensor (figure 3). As the shaft turns, the rotation of the magnetic field triggers abrupt polarity reversals in the Wiegand wire, inducing electric current pulses in the copper coil. As the strength and duration of each current pulse is independent of how quickly or slowly shaft rotates, Wiegand sensors provide much higher signal-to-noise ratios than other analog magnetic sensors (e.g., Hall effect sensors). This ensures the meter's counter circuit receives clear and unambiguous signals with each rotation of the shaft. Energy from the electrical pulse can also be harnessed to power the rotation counter circuitry, so the counter will keep a reliable record of shaft rotations in the absence of an external energy source.

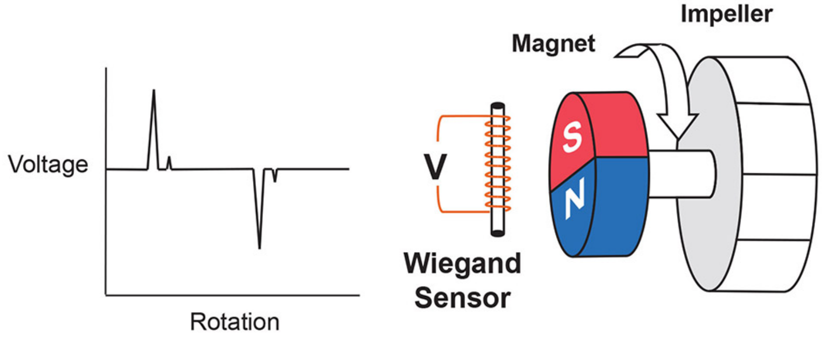


Figure 3. Wiegand sensors for rotation counting in fluid meters.

Wiegand-based event triggering also has been used for tachometers for rail cars and other equipment. For this application, the Wiegand sensor is located near two magnets with the opposite polarity. The presence of a large ferromagnetic (iron) body nearby can neutralize the effect of one of these magnets so the magnetic field at the Wiegand sensor is dominated by the other magnet (N-S in figure 4). As the ferromagnetic body rotates, it neutralizes the other stationary magnet, reversing the field (S-N)

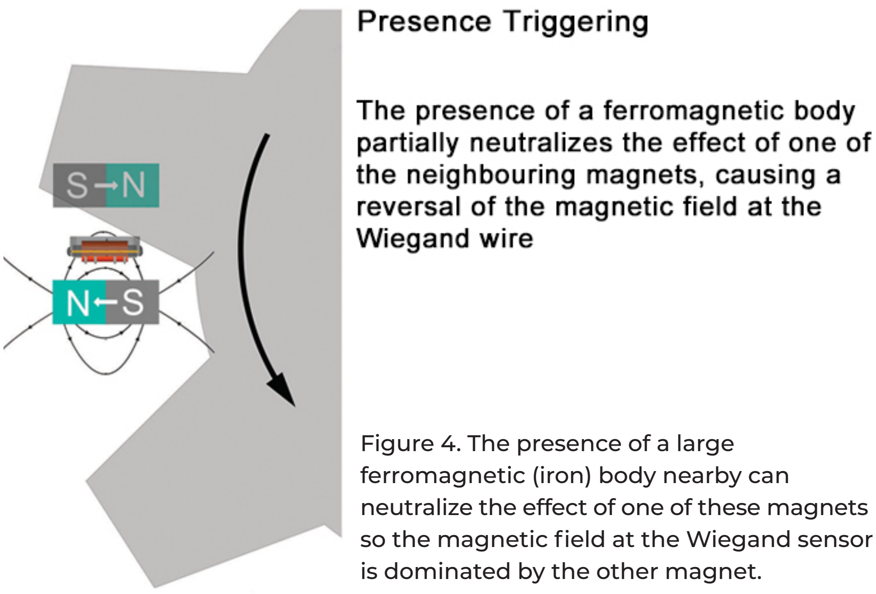


Figure 4. The presence of a large ferromagnetic (iron) body nearby can neutralize the effect of one of these magnets so the magnetic field at the Wiegand sensor is dominated by the other magnet.

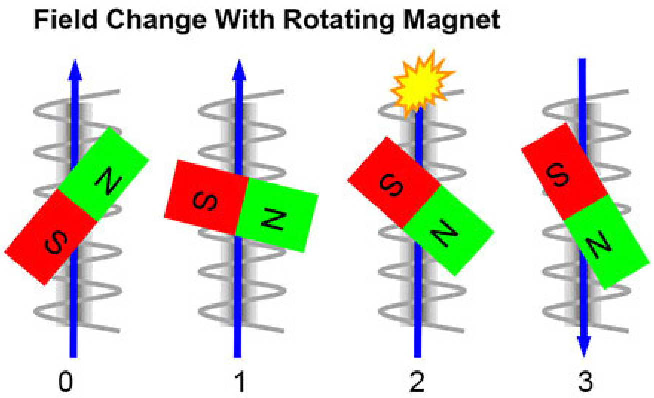


Figure 5. As the ferromagnetic body rotates, it neutralizes the other stationary magnet, reversing the field (S-N) and triggering a polarity flip in the Wiegand wire.

and triggering a polarity flip in the Wiegand wire (figure 5). The benefit of Wiegand technology in this application is that it operates reliably over a wide range of rotation speeds. Moreover, with no mechanical contact between the sensor and the moving component, there is no wear, and the systems have service lifetimes of billions of operating cycles.

The Wiegand cycle

The mechanical process that produces Wiegand wires creates a combination of magnetically hard and soft layers in the wire, causing the wire to have a high level of magnetic hysteresis (figure 6).

As the external magnetic field changes, the Wiegand wire will initially retain its initial polarity (Point A in figure 6). However, when the strength of the external field reaches a critical threshold, the polarity

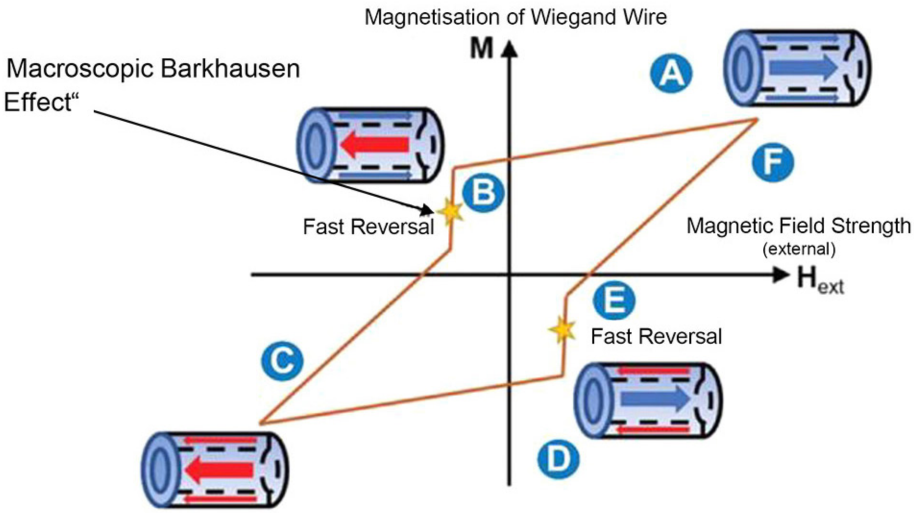


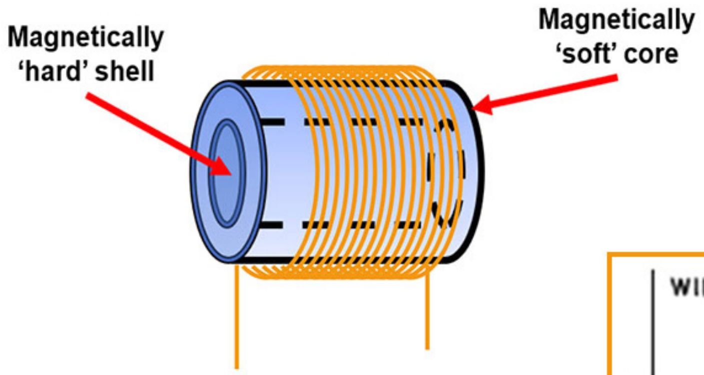
Figure 6. The mechanical process that produces Wiegand wires creates a combination of magnetically hard and soft layers in the wire, causing the wire to have a high level of magnetic hysteresis.

of the magnetically soft zone of the Wiegand wire suddenly reverses (Point B). As the external field continues to strengthen, the magnetically hard zone will also reverse its polarity, so the whole wire reaches a new magnetic state (Point C). When the external field changes back toward its original polarity, a sudden reversal of the soft material will occur again (Points D, E). The wire will eventually return to its earlier state (Points F, A).

These rapid changes in the magnetic polarity of the wire core induce short pulses of electrical current in the fine copper coil wrapped around the Wiegand wire (figure 7).

Manufacturing Wiegand wire

Wiegand wire is produced through a process that involves annealing a spool of Vicalloy wire (an alloy of vanadium, iron, and cobalt), then simultaneously stretching, and twisting the wire. This aggressive cold working alters the crystalline structure of the metal and creates two regions—an inner core and outer shell—with significantly different levels of magnetic coercivity. (Coercivity is a property of ferromagnetic materials that defines how easily the material can be magnetized by an external magnetic field. Magnetically soft materials, such as mild steel, have low coercivity and change their magnetic state easily. Magnetically hard material, such as the alloys used to make permanent magnets, will



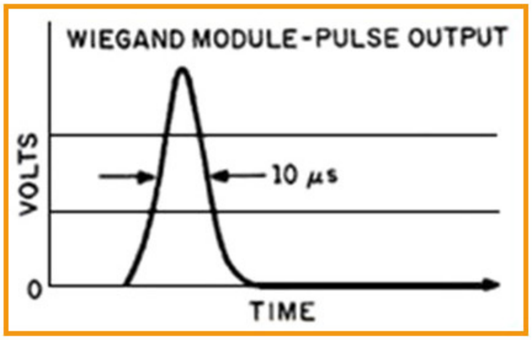


Figure 7. Rapid changes in the magnetic polarity of the wire core induce short pulses of electrical current in the fine copper coil wrapped around the Wiegand wire.

retain their magnetic state unless they are exposed to very strong external fields.) The interaction of these two regions causes the wire to have a high level of magnetic hysteresis.

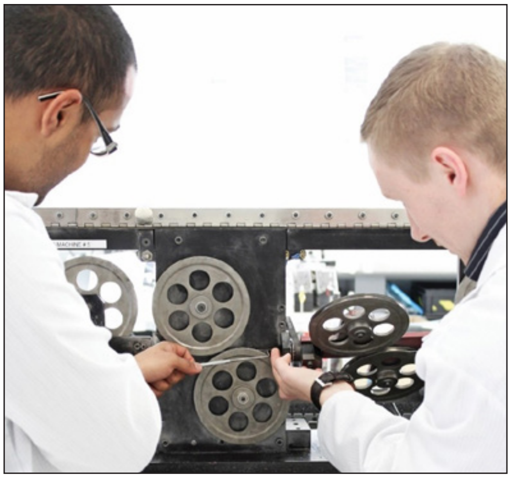


Figure 8. Research carried out by FRABA and its partners has automated and optimized the process of creating Wiegand wire.

The “recipe” for producing a satisfactory batch of Wiegand wire was determined by John Wiegand and his collaborators through trial and error. The machine they developed to produce Wiegand wire features a series of rotating frames that stretch, twist, then un-twist the wire at various rates. This machinery was acquired by FRABA, along with John Wiegand’s lab notes. Since then, research carried out by FRABA and its partners has automated this process and optimized it for quality and consitency (figure 8).

Wiegand technology has a strong track record, with proven successes in niche applications such as fluid metering and rotary encoders. It also has significant potential for more advanced uses, both as a sensor for detecting mechanical motions and as an energy harvesting device for self-contained electronic devices. The advantages of Wiegand technology include consistent performance over a wide range of operating speeds and long-term reliability, since the underlying physical phenomenon is completely non-contacting

R&D carried out by FRABA’s UBITO business unit is enhancing the energy output from Wiegand generators and creating possibilities for new generation of self-contained, zero-maintenance, wireless sensors designed to operate as nodes on emerging IoT.

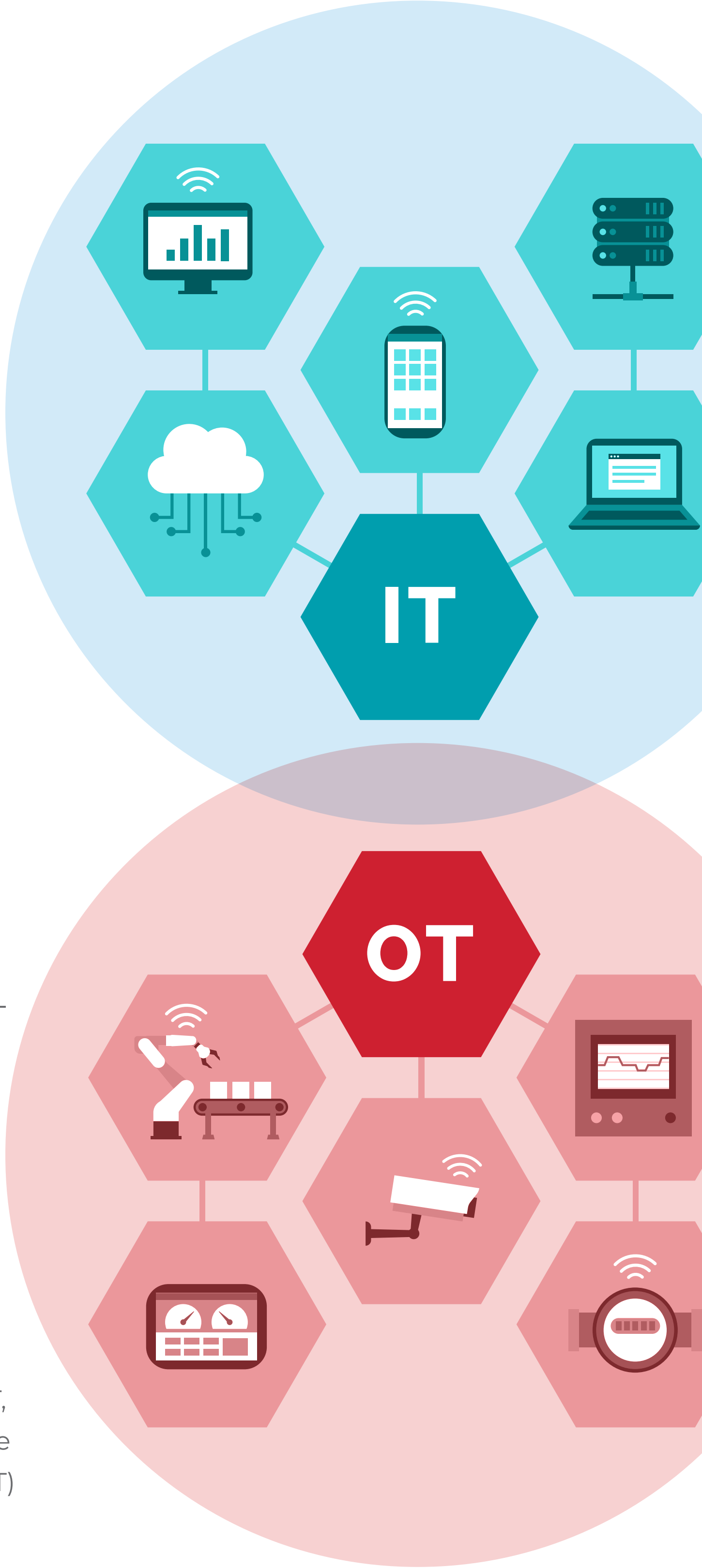
All figures courtesy of FRABA Group.

ABOUT THE AUTHOR

Tobias Best (tobias.best@fraba.com) is based in the FRABA Group’s Asia Pacific Headquarters in Singapore. Best has been promoting Weigand sensor technology for UBITO globally since 2017.

MQTT and Sparkplug 3.0:

The Future of Industrial OT-IT Integration



Technologists should understand why MQTT, why Sparkplug, and how they work together to enable OT-IT integration.

By Arlen Nipper, Cirrus Link

Twenty-five years ago, when I sat down with Andy Sanford Clark and invented MQTT, I couldn't have imagined it would become the future of Industrial OT-IT integration. MQTT adoption has grown rapidly, and several years ago the Industrial IoT industry realized that to achieve true interoperability between industrial-based data producers and consumers, we needed to define a common namespace, payload and session awareness, which led to the creation of the Sparkplug specification on top of MQTT.

With the release of Sparkplug 3.0 recently, it may be helpful for technologists to understand: why MQTT, why Sparkplug, and how they work together to enable operational technology-information technology (OT-IT) integration.

What is MQTT?

The MQTT specification describes how to implement a message-oriented middleware, publish/subscribe infrastructure. MQTT was originally designed for a real-time, mission-critical supervisory control and data acquisition (SCADA) solution with the following design goals:

- **Simple:** Easy to implement on very constrained devices
- **Efficient:** Uses as little bandwidth/footprint as possible
- **Stateful:** Required for OT-centric messaging
- **Open:** No vendor lock-in.

MQTT enjoys two open standards: the OASIS standards and the ISO standard. There are numerous products and solutions on the market today and IT uses MQTT extensively. Amazon AWS IoT, Microsoft Azure IoT Hub, IBM Watson IoT, and Facebook Messenger all use MQTT.

Sparkplug is a newer specification within the Eclipse Tahu project that defines how to use MQTT in a mission-critical, real-time environment.

MQTT has two application types: MQTT servers, or brokers, and MQTT clients. An MQTT message has three components: topic, payload, and quality of service (QoS). Topics are slash-delimited strings and can be used as a hierarchy for message routing. There are three QoS levels: fire and forget, at least once, and once and only once.

What Andy and I didn't do is we didn't define a payload definition. The payload is a binary byte array with no schema or format defined in the specification. By leaving the namespace and payload open, everyone can optimize MQTT for their application at hand. That's why MQTT is so prevalent in marketing today: because it is great—but it isn't enough to do anything without further definition. Both the good and the bad thing about MQTT is, you can publish anything you want on any topic. Without those definitions, we are not able to get the interoperability necessary to bridge the gap from OT to IT.

Adding context to MQTT with Sparkplug

OT data consists of proprietary protocols, multiple data formats, and no contextual information. It is designed for operations, varies across market segments, is directly coupled to applications, and often lives in isolated networks. IT data needs are often in direct opposition, requiring data objects and modeling, standard data formats, contextual information, decoupled to the enterprise, and easy and secure integration. These two are at odds, but there is an open-standard answer: Sparkplug.

Sparkplug is a newer specification within the Eclipse Tahu project that defines how to use MQTT in a mission-critical, real-time environment. Sparkplug defines a standard MQTT topic namespace, payload, and session state management for industrial applications while meeting the requirements of real-time SCADA implementations. The Sparkplug B specification provides the data model needed to define a tag value for use with OT, also providing data to IT, making it 100 percent self-discoverable and easy to consume.

The Sparkplug B specification provides the following benefits (Figure 1) that all add up to a single source of truth for models, assets and tags at the origin:

- **Defines an OT-centric topic namespace for auto-discovery:** Defines a well-known topic namespace, so you can subscribe and when messages come in you know the structure of the namespace, where it came from, and what to do with it.

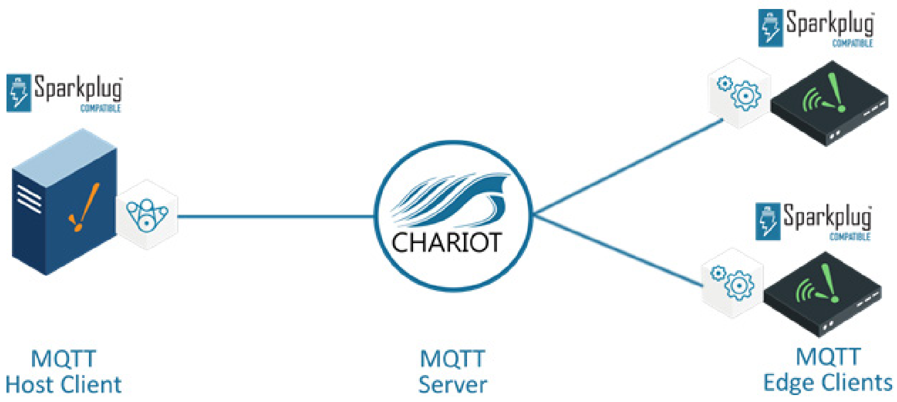


Figure 1. The Sparkplug B specification provides benefits that add up to a single source of truth for models, assets, and tags at the origin.

- **Define models/assets from the edge:** The Sparkplug "template definition" allows messages to define data models and be used many times.
- **Defines an OT-centric extensible process variable payload:** Adds context like name, value, timestamp, data type, engineering units/ranges, and other custom properties as required.
- **Defines MQTT state management:** Provides report by exception, bidirectional command and control, and allows for store and forward.

Sparkplug works over an MQTT server or broker, between edge nodes, or producers of the data, and the host application. The goal is to get data from one MQTT client to another, and Sparkplug was built around that idea to satisfy the needs of both sides of the equation.

Sparkplug 3.0: The latest frontier

Several years ago, Cirrus-link released Sparkplug to the Eclipse Foundation, and we continue to work to keep it updated and evolving to meet the needs of IIoT deployments. There were a lot of things that needed to be cleaned up in the specification for the most recent release of Sparkplug 3.0. This was the first release under the Eclipse Foundation's specification process, and we worked to make it easy to implement with more precise language, improvements to STATE messages, and improvements to Eclipse Tahu to be the first compatible implementation.

Sparkplug 3.0 includes a Technology Compatibility Kit (TCK) for compatibility validation. The TCK is run via a web user interface (UI) against your Sparkplug profile, or implementation, and with that, we're able to use tooling to generate a coverage report that shows if the implementation passed or failed by meeting every nominative statement in the specification. Products that have already been listed as fully "Sparkplug Compatible" include the Cirrus-Link MQTT Server, Distributor, Engine and Transmission, Eclipse Tahu, the HiveMQ Broker

Community and Professional Edition, HiveMQ Sparkplug-Aware Extension, Ignition by Inductive Automation, and the N3uron Client for Sparkplug.

We released a Sparkplug specification with ISO/IEC global standardization in June 2023.

Single source of truth

Imagine an environment where every piece of process equipment you have, whether it be in a factory or spread out over a wide geography, is the single source of truth of its information. Then think about every authorized data consumer throughout your enterprise having access to this information, 100 percent self-discoverable, and being able to use it to derive insights, to drive innovation, and recognize the true value of your process information. That is the promise of MQTT Sparkplug.

Figure courtesy of Cirrus Link.

ABOUT THE AUTHOR

Arlen Nipper is president and CTO at Cirrus Link and co-inventor of MQTT. He has more than 40 years of experience specializing in the Industrial Internet of Things (IIoT), SCADA software solutions, and the design and manufacture of embedded computer systems.

How Primary Lithium Batteries Can Achieve Ultra Long Life

To avoid costly replacement, the ideal battery will last as long as the device.

By Sol Jacobs, Tadiran Batteries

Choosing the right battery is essential for situations where ongoing maintenance and replacement costs of failing batteries would be prohibitively expensive or impossible.

Primary batteries are used in standalone applications that do not draw enough current to warrant recharging. These are mainly low-power devices that draw average current measurable in micro-amps with pulses in the multi-amp range. Rechargeable Lithium-ion (Li-ion) batteries are used in low-power applications that draw average current measurable in milliamps with pulses in the multi-amp range.

Choosing a primary battery is far more challenging for devices being deployed in remote off-grid locations that are subject to extreme temperatures, which can impact battery performance. These applications include asset tracking, safety systems, tank level and flow measuring, environmental monitoring, machine-to-machine (M2M), artificial intelligence (AI), and wireless mesh networks, to name a few.

Numerous primary battery chemistries are available for low-power devices (Table 1), the least expensive of which is the ubiquitous alkaline cell, which delivers high rates of continuous current with a very high self-discharge rate (up to 60 percent per year), making them unreliable for long-term deployments. Alkaline cells also suffer from very low capacity and low energy density, resulting in added size and bulk. Additionally, alkaline cells cannot survive extreme temperatures due to their water-based chemistry.

The advantages of lithium-based chemistries

Lithium-based chemistries are far better suited for industrial applications. As the lightest non-gaseous metal, lithium features an intrinsic negative potential that exceeds all other metals, delivering the highest specific energy (energy per unit weight), highest energy density (energy per unit volume), and higher voltage (OCV) ranging from 2.7 to 3.6 V. Lithium cells are also non-aqueous, making them less prone to freezing than alkaline cells.

Primary Cell	$LiSOCL_2$ Bobbin-type with Hybrid Layer Capacitor	$LiSOCL_2$ Bobbin-type	Li Metal Oxide Modified for high capacity	Li Metal Oxide Modified for high power	$LiFeS_2$ Lithium Iron Disulfate (AA-size)	$LiMnO_2$ Lithium Manganese Oxide
Energy Density (Wh/Kg)	700	730	370	185	335	330
Power	Very High	Low	Very High	Very High	High	Moderate
Voltage	3.6 to 3.9 V	3.6 V	4.1 V	4.1 V	1.5 V	3.0 V
Pulse Amplitude	Excellent	Small	High	Very High	Moderate	Moderate
Passivation	None	High	Very Low	None	Fair	Moderate
Performance at Elevated Temp.	Excellent	Fair	Excellent	Excellent	Moderate	Fair
Performance at Low Temp.	Excellent	Fair	Moderate	Excellent	Moderate	Poor
Operating life	Excellent	Excellent	Excellent	Excellent	Moderate	Fair
Self-Discharge Rate	Very Low	Very Low	Very Low	Very Low	Moderate	High
Operating Temp.	-55°C to 85°C, can be extended to 105°C for a short time	-80°C to 125°C	-45°C to 85°C	-45°C to 85°C	-20°C to 60°C	0°C to 60°C

Table 1. Various primary battery chemistries are available for low-power devices.

Figure 1. Bobbin-type $LiSOCl_2$ batteries are preferred for remote wireless applications, delivering high energy density, up to 40-year service life, and the widest possible temperature range, making them ideal for use in inaccessible locations and extreme environments.

Remote wireless devices are predominantly powered by bobbin-type lithium thionyl chloride ($LiSOCl_2$) batteries, which are unmatched in their ultra-long-life potential of up to 40 years for certain cells. Bobbin-type $LiSOCl_2$ cells (Figure 1) deliver the highest capacity, highest energy density, and widest temperature range of all (-80°C to +125°C). They also feature a self-discharge rate as low as 0.7 percent per year, enabling certain cells to last up to 40 years. The benefits of bobbin-type $LiSOCl_2$ chemistry include:

- Longer operating life of up to 40 years to lower the total cost of ownership
- A wider temperature range of -80 to 125°C for extreme environments
- High energy density and capacity to permit the use of fewer or smaller batteries
- Higher voltage, which could permit the use of fewer batteries.

Alternatively, $LiSOCl_2$ batteries can be manufactured with a spiral wound design, which raises their potential energy flow, but also results in a higher rate of self-discharge to shorten operating and storage life.

A key variable in determining a battery's potential lifespan is storage capacity, which is measured in amp-hours (Ah). The overall storage capacity of a cell dictates the maximum run time based on the average current being drawn. For example, a device consuming 1 mA of average current with a storage capacity of 1,200 mAh can have a maximum run time of 1,200 hours.

Harsh environments impact battery performance

Long-term battery performance is heavily influenced by temperature extremes during storage and deployment. A battery used indoors under ambient temperatures will naturally outlast a cell that is continually exposed to extreme temperatures that affect the cell's electrochemistry to reduce its long-term performance.

Self-discharge results from internal chemical reactions that occur even when there is no connection between the electrodes or to any external circuit. As a result, remote wireless devices often lose more energy each year to self-discharge than is required to operate the device.

The self-discharge rate can vary based on a number of variables, including the peak current, the consumption profile, the temperature range, the age of the cell, the leakage current drawn by components within the device, and more.

Moderately low temperatures can have a positive effect on reducing the rate of annual self-discharge as electrochemical and diffusion reactions slow down and the electrolyte viscosity rises. Low temperatures also tend to reduce energy flow and cause a drop in voltage. Conversely, prolonged expose to high temperatures can accelerate the self-discharge rate, cause voltage delays and drops, power delays during pulses, and depletion of the electrochemical elements.

A key variable in determining a battery's potential lifespan is storage capacity, which is measured in amp-hours (Ah).

Lithium thionyl chloride ($LiSOCl_2$) batteries are least impacted by self-discharge due to their unique ability to harness the passivation effect, whereby a thin film of lithium chloride (LiCl) forms on the surface of the anode to act as a separation barrier from the electrode, thus limiting the chemical reactions that cause self-discharge. When a continuous current load is applied to the cell, the passivation layer initially causes high resistance and a drop in voltage until the discharge reaction begins to dissipate the passivation layer: a process that repeats each time a load is applied.

The level of passivation can vary based on several factors, including the cell's construction, current discharge capacity, the length of storage, storage temperature, discharge temperature, and prior discharge conditions, such as partially discharging a cell and then removing the load.

Experienced battery manufacturers are able to harness the passivation effect through proprietary cell construction and higher quality raw materials. For example, the highest grade bobbin-type $LiSOCl_2$ battery can achieve a self-discharge rate as low as 0.7 percent per year, able to retain roughly 70 percent of its original capacity after 40 years. Conversely, an inferior quality bobbin-type $LiSOCl_2$ cell can have a self-discharge rate of up to 3 percent per year, exhausting roughly 30 percent of its available capacity every 10 years, making 40-year battery life impossible.

Understanding the power demands of the application

Battery life is dictated by the amount of average energy being consumed in "standby" mode along with the intensity, duration, and frequency of energy pulses during "active" mode.

Figure 2. Bobbin-type $liSOCl_2$ batteries can be combined with a patented hybrid layer capacitor (HLC) to offer up to 40-year operating life while providing high pulses to power two-way wireless communications.

Pulses of up to 15 A are required to initiate two-way wireless communications. Standard bobbin-type $LiSOCl_2$ cells cannot deliver such high pulses due to their low-rate design but can be easily modified with the addition of a patented hybrid layer capacitor (HLC) (Figure 2). Using this hybrid approach, the bobbin-type $LiSOCl_2$ cell delivers low-level background current required during "standby" mode while the HLC delivers high pulses during "active" mode. The patented HLC also features a unique end-of-life voltage plateau that can be interpreted to deliver "low battery" status alerts for proactive battery maintenance.

Supercapacitors also generate high pulses but are mainly limited to consumer applications due to serious drawbacks, including short-duration power, linear discharge qualities that do not allow for the use of all available energy, low capacity, low energy density, and very high self-discharge rates of up to 60 percent per year. Supercapacitors linked in series require the use of bulky cell-balancing circuits that add expense and drain current to further shorten their operating life.

Supercapacitors can be used in conjunction with bobbin-type $LiSOCL_2$ cells to enhance voltage response as minimum cut-off voltage can be an important consideration. As batteries age, voltage tends to fluctuate, especially approaching end of life.

Considerations when specifying an ultra-long-life lithium battery

The ideal power source should last as long as the device to reduce or eliminate the need for costly battery replacement. However, distinguishing a higher quality battery from a lower quality cell can be challenging since the effects of a high annual self-discharge rate

Water/wastewater application

Ayyeka is a developer of remote monitoring technologies that provide digital transformation for critical infrastructure. The company's technology embeds edge AI into field assets. With its combination of edge, Internet of Things (IoT), and AI/machine learning (ML), it propels the critical infrastructure space, enabling infrastructure stakeholders to create, manage, and use remote field assets data.

Ayyeka's AI-enabled smart sensors monitor sensors used in solid waste and wastewater management (Figure 3), public utilities, transportation, energy exploration and distribution, smart cities, environmental monitoring, and other hard infrastructure. Tadiran bobbin-type $LiSOCl_2$ batteries power two-way wireless communications to maximize operating life, detect unusual events, enable predictive maintenance and repairs, and counter cyber security threats.

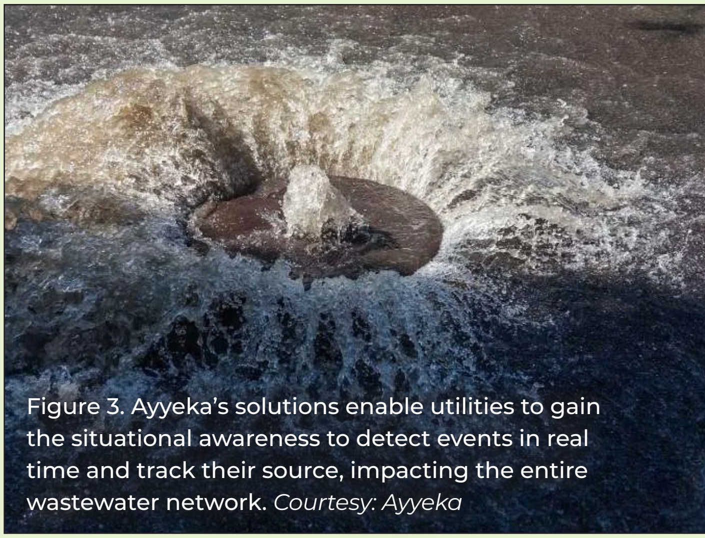


Figure 3. Ayyeka's solutions enable utilities to gain the situational awareness to detect events in real time and track their source, impacting the entire wastewater network. *Courtesy: Ayyeka*

could take years to become fully measurable. Additionally, short-term results are often highly inaccurate in predicting long-term battery performance since theoretical models tend to underestimate the passivation effect as well as long-term exposure to extreme temperatures. Therefore, thorough due diligence is required to ensure that the ideal battery is being specified for long-term deployments at remote sites.

To properly evaluate competing battery brands, potential suppliers should be required to provide fully documented and verifiable test reports, as well as in-field performance data from comparable devices with similar energy demands and environmental conditions. For this purpose, Tadiran has generated a massive database accumulated over decades to monitor long-term battery performance under laboratory conditions as well as through random customer-supplied samples from the field.

Identifying the battery that best matches the application's long-term performance requirements is essential to ensuring long-term IIoT connectivity. With so many variables to consider, it is highly recommended that you consult with an applications engineer who can review your operational profile to identify a power supply solution that is both cost effective and maximizes long-term product performance.

If the expected lifetime of the device is under 10 to 15 years, then several primary battery

Structural integrity application

Resensys provides a powerful platform for remote monitoring of strain (stress), vibration (acceleration), displacement, crack activity, tilt, inclination, temperature, and humidity. For protecting infrastructure systems against aging and malfunction, the company developed a global network to supply its high precision, durable, and reliable structural monitoring solutions to customer applications including bridges, tunnels, buildings, dams and cranes.

Resensys wireless sensors are mounted beneath bridge trusses (Figure 4) to measure structural stress. These locations are highly inaccessible and use of a bobbin-type $LiSOCl_2$ battery serve to maximize return on investment by maximizing the operating life and increasing product reliability in extreme temperatures.

Figure 4. Resensys structural stress sensors mounted beneath bridge trusses require extended life bobbin-type $LiSOCl_2$ batteries to reduce the need for costly and dangerous work to replace batteries in such hard-to-access locations.

chemistries may be considered. However, if an ultra-long-life battery is required that can last for up to 40 years, then your choice is limited to bobbin-type $LiSOCl_2$ chemistry due to its ability to harness the passivation effect.

When specifying a battery, it is also important to consider whether the cell will be used as the main power source or as a back-up source of energy. When used as a back-up power supply, and potentially sitting idle for extended periods, you must be especially mindful of the operating environment, self-discharge rate, and requirements for fast battery response.

A knowledgeable applications engineer can assist you throughout this decision-making process.

Figures courtesy of Tadiran Batteries.

ABOUT THE AUTHOR

Sol Jacobs is vice president and general manager of Tadiran Batteries.

Sensor Technology for Machine Health Monitoring

A comparison of piezoelectric and MEMS technology for early detection of bearing faults.

By Matthew Negaard, PCB Piezotronics

In an industrial era marked by interconnectivity and seamless data-sharing between devices, the preventive maintenance sector is now strongly trending toward accelerometers with capabilities such as wireless transmission, digital outputs like IO-Link, and edge processing of data at the sensor level. But even as advances are made in how data is output, the most trusted sensing technologies for machine health monitoring remain the same; they are either piezoelectric or capacitive micro-electro-mechanical systems (MEMS).

This article explores these two leading sensor types and evaluates their performances at frequencies associated with common faults. We find that piezoelectric sensors outperform MEMS accelerometers in terms of frequency range for early detection, making them the preferred option for machine health monitoring applications.

Why frequency range is important

In the realm of consumer electronics, MEMS accelerometers have earned their popularity due to their low production costs and ability to measure frequencies down to 0 Hz. However, when it comes to machine health monitoring, the requirements change drastically. The low-frequency vibration range detectable with MEMS devices are typically associated with the late stages of rolling-element bearing failure, while wider range capabilities become critical to catching early fault warnings. Consequently, relying solely on MEMS accelerometers for machine health monitoring could lead to delayed detection and significant damage to the equipment. To ensure the earliest detection of potential issues and prevent catastrophic failures, piezoelectric sensors prove to be the superior choice (Figure 1).

To visualize the importance of broad frequency range capabilities, consider the vibration frequencies associated with the four stages of bearing failure.

During the preliminary stages of bearing failure, the first signs of deterioration begin to emerge. This stage (Figure 2) is characterized by metal-to-metal impacts most commonly caused by lack of lubrication.

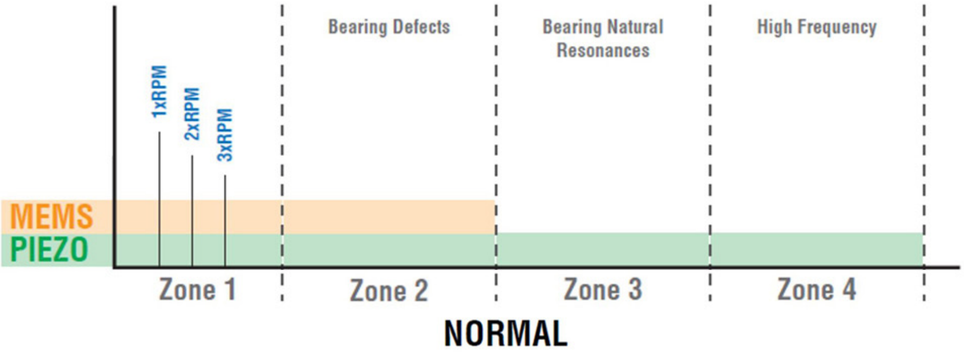


Figure 1. Comparison of piezoelectric sensors with MEMS to detect failures. This graph shows normal operation.

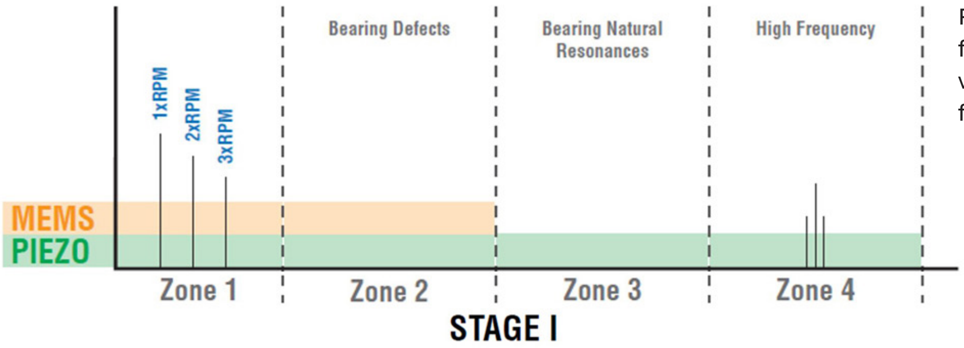


Figure 2. Vibration frequencies associated with Stage 1 of bearing failure.

Bearing-generated fault energy begins as ultrasonic frequencies from about 1,200 K to 3,600 K (machine rotation) cycles-per-minute (CPM) (20 kHz to 60 kHz), typically detectable only with spike energy or shock pulse instrumentation. Piezo-based accelerometers begin to detect the early onset of microscopic cracks or pitting at the lower end of the high frequency range. Assessing lubrication conditions or alignment at this early phase can prevent significant issues. However, without intervention, the damage progresses, leading to the next stage of failure.

Piezoelectric sensors outperform MEMS accelerometers in terms of frequency range for early detection.

In the second stage of failure (Figure 3), the damage from the preliminary stage begins to manifest more noticeably. Minor defects excite a resonance response of the accelerometer assembly, which is picked up with a spectrum analyzer in the middle of the spectrum as frequencies of about 120 K to 480 K CPM (2 kHz to 8 kHz). The deterioration becomes visible on the bearing surface, and the wear or damage may start affecting the overall life of the bearing.

At this stage, the bearing may start exhibiting increased noise, vibration, and sometimes increased temperature. It is likely that the bearing will need to be replaced, and associated machine shutdown times may lead to loss of productivity. Nonetheless, it is crucial to detect and address the issues early in this stage to prevent further deterioration and potential equipment failure.

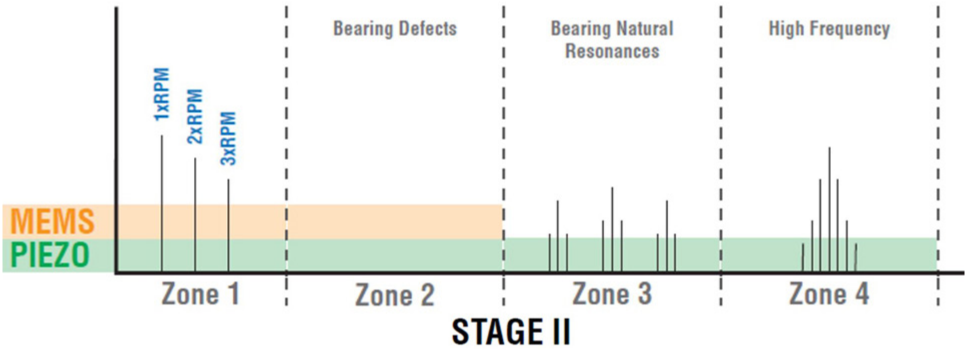


Figure 3. In Stage II failure, minor defects excite a resonance response of the accelerometer assembly, which is picked up with a spectrum analyzer in the middle of the spectrum as frequencies of about 120 K to 480 K CPM (2 kHz to 8 kHz).

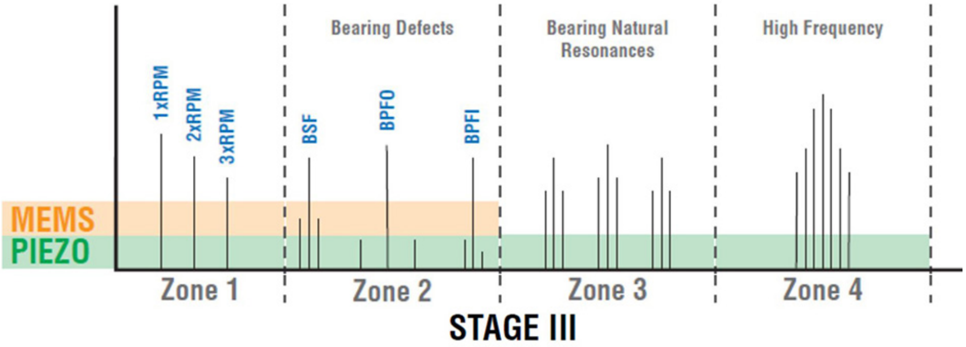


Figure 4. As bearing failure progresses to Stage III, the damage becomes severe, and the bearing's performance significantly declines.

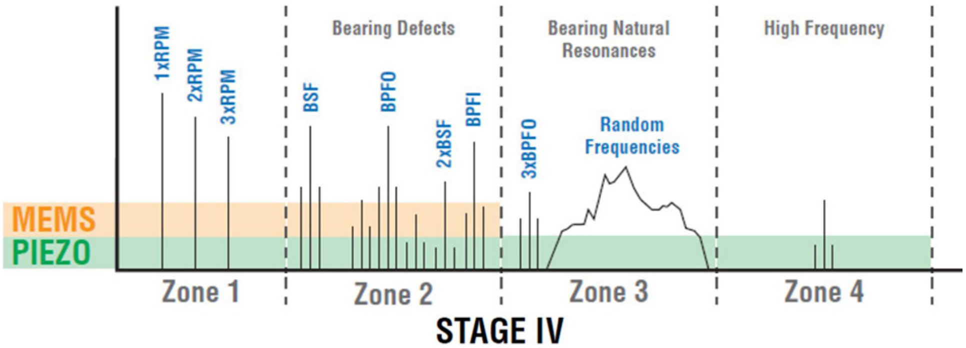


Figure 5. The catastrophic Stage IV is the final and most severe stage of bearing failure. At this point, the bearing experiences a complete breakdown.

As bearing failure progresses to the third stage (Figure 4), the damage becomes severe, and the bearing's performance significantly declines. Increased vibration and elevated operating temperatures are common indicators of this advanced stage. Sideband frequencies may also be present above and below the defect frequencies. Critical machines should undergo additional vibration analysis to assess for damage. If the bearing reaches this stage without intervention, the risk of catastrophic failure and associated machinery breakdown is significant.

The catastrophic fourth phase (Figure 5) is the final and most severe stage of bearing failure. At this point, the bearing experiences a complete breakdown, rendering it unable to support the load or operate effectively. Bearing fault derived frequencies will now be evident in the low frequency domain below 5 kHz. Catastrophic failure can result in collateral damage to surrounding machinery, extensive downtime, and costly repairs. This stage is characterized by complete bearing seizure, fragmentation, or total loss of functionality.

Essentially, the detection of higher frequencies could mean the difference between simple preventive maintenance and costly repair. Unlike MEMS devices, piezoelectric accelerometers accurately measure vibrations across a wide frequency range, including the high-frequency region. This capability is invaluable for machine health monitoring applications, as it enables the detection of subtle anomalies and vibrations at the earliest stages of equipment deterioration.

Early detection prevents catastrophic failures

Machine health monitoring aims to identify potential issues and failures before they escalate into catastrophic events. By using piezoelectric sensors (Figure 6), engineers and technicians can detect and analyze vibrations across a wide range, encompassing both low and high frequencies. This versatility makes piezoelectric sensors ideal for a

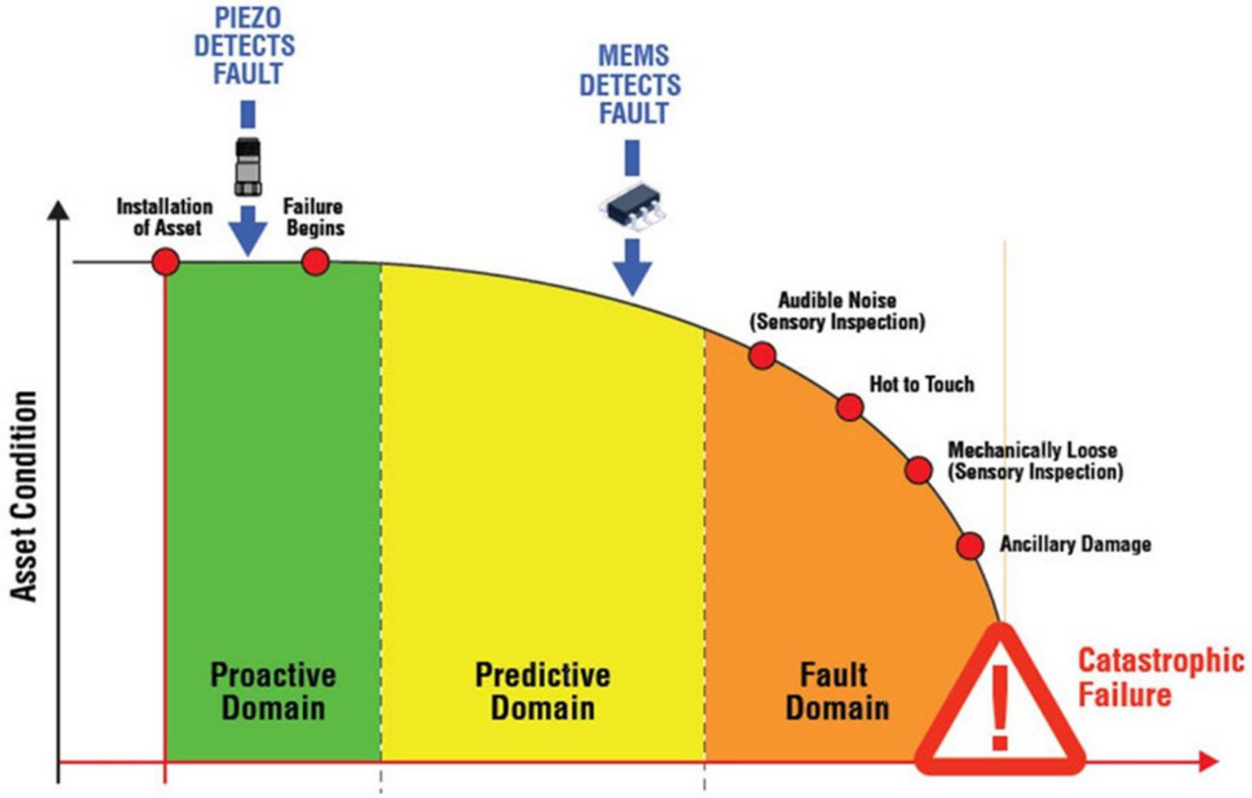


Figure 6. The broad frequency range of piezoelectric sensors allows for earlier fault detection compared to MEMS sensors, enabling technicians to take corrective action well before failure is imminent.

variety of machine health monitoring applications, including rotating machinery, industrial equipment, and structural health monitoring. The ability to detect subtle vibrations at an early stage empowers maintenance teams to take prompt action, preventing costly breakdowns and minimizing downtime.

In addition to their wide frequency range, piezoelectric sensors offer exceptional reliability and accuracy, providing a comprehensive view of the equipment's health. With reliable and precise data, maintenance professionals can make informed decisions, optimize maintenance schedules, and prevent costly unplanned downtime.

All figures courtesy of PCB Piezotronics Inc.

ABOUT THE AUTHOR

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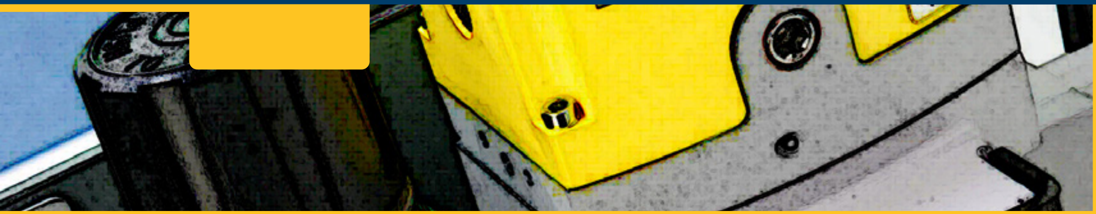
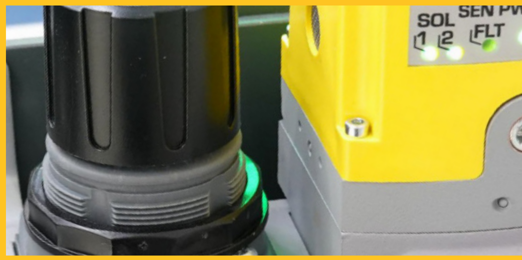


Understanding Standards-Based Safety System Design



By Linda Caron,
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Regardless of the products selected for a safety circuit, the machine designer is responsible for ensuring compliance with the standards.

The use of standard components in the design of safety applications is fundamentally possible because of the EN ISO 13849 and Annex V of the Machinery Directive 2006/42/EC. When designing safety and controls, there is no legislation prescribing the specific use of safety-rated products. There is only legislation requiring safe function and the use of redundancy, high diagnostic values, and high mean time to dangerous failure values (MTTFD)—depending of course on the level of safety an application requires. USA standards such as EN ISO 12100 and ANSI B11 have followed suit and are harmonized to this effort.

The components used to achieve safety typically include an input device, a logic controller and an output device commonly referred to as ILO. Common input devices are light curtains, e-stop buttons, and laser scanners. The logic controllers can vary from simple relays up to safety PLCs based again on the safety level required. Output devices are devices that perform a safe function (stopping, blocking, holding, reversing, or exhausting).

The standard EN ISO 13849-1 offers simplified charts for achieving the required category and performance levels needed (Figure 1). These variables work together to ensure that safety is not just focused on component reliability but instead introduces common sense safety principles such as redundancy, diversity, and fail-safe behavior of the safety-related control parts. When determining the performance level, the greater the risk, the higher the requirements of the control system.

Regardless of the products selected for a safety circuit, the machine designer is responsible for ensuring compliance with the EN ISO 12100 and ANSI B11 standards. In effect, there are three levels of products a machine builder can choose from: standard fluid power components, standard fluid power components deemed suitable for use as a safety-related part of a control system (SRP/CS), and safety-related products. Each requires different levels of work or attention from the machine builder.

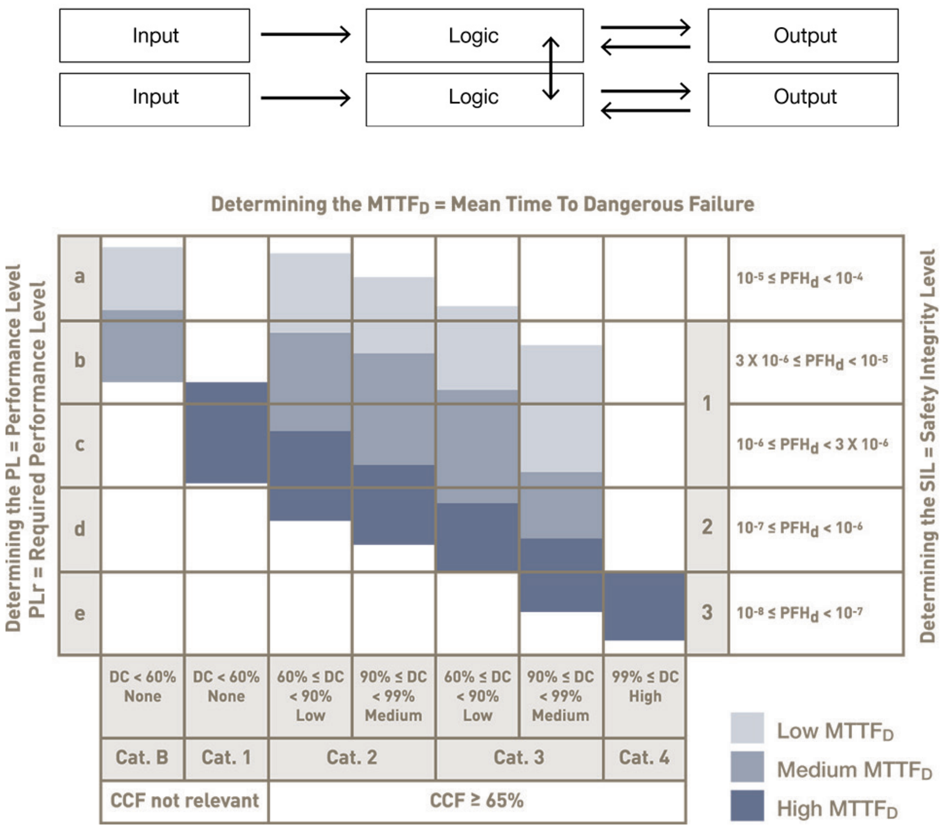

Figure 1. The standard EN ISO 13849-1 offers simplified charts for achieving the required category and performance levels needed.

Standard fluid power components

These can be any component the machine designer chooses. All relevant testing, documentation, and validation to ensure integrity become the liability of the machine designer. He or she must prove the components they selected are suitable for safe function in the system design.

In addition to the familiar basic framework of the categories, the current standards EN ISO 13849 Parts 1 and 2 (Safety of machinery – Safety- related parts of control systems – Part 1: General design principles [1] and Part 2: Validation [2]) also describe a probabilistic assessment of the functional safety achieved. Because there have been misinterpretations during the application of the standards about the use of standard components, the complexity and work required to prove safe function are significant. For this reason, most machine designers seek products in the next category.

For standard fluid power components, all relevant testing, documentation, and validation to ensure integrity become the liability of the machine designer.

Standard SRP/CS fluid power components

These are "well-tried and trusted" components that may have an associated endurance B10 or MTTF value. These standard products have been deemed suitable for use as an SRP/CS by the manufacturer of the component.

This component is typically endurance tested and the manufacturer will provide the life expectancy value as either a B10 value, a B10D value, or a MTTF value. (Hydraulic products typically offer an MTTFD value, whereas pneumatics will publish a B10D value given that MTTFD in pneumatics is highly dependent on the number of operations (Nop) of the system.) It is then up to the system designer to use this data to calculate his or her probability of failure based on the safety circuit components chosen. In essence, using this category of product saves time and money in testing, and it provides some level of assurance of the component's reliability, even though it has not been third-party validated.

Safety-rated products

Products designed and placed on the market specifically for safety applications bear significant upfront testing and costs by the manufacturer. These products must be tested extensively and evaluated for fault performance to ensure they are fail-safe and pass all applicable electrical certifications. They are then passed to an authorized notified body for full third-party evaluation and certification.

Safety-rated products are provided with: the assurance of testing; a documented performance level or MTTFD; documented diagnostic coverage capability and CCF (evaluations of common cause failure); and third-party verification of the same. These tests mitigate a significant amount of work and liability for the machine builder.

Validation

An essential step in system design is the validation of the safety circuit and components. Validation must be done on the safety circuit to ensure the circuit will function properly and fail safely. Testing must consider faults to ensure the machine responds accordingly and that the interconnect means provide the proper level of performance as noted in the risk assessment.

Regardless of which type of products are selected for the safety circuit, it is the responsibility of the machine designer to ensure compliance with the standards. Safety-rated products offer significant advantages in that they are certified to conform to specific safety Categories thereby saving time and reducing liability.

All images courtesy of Parker Hannifin.

ABOUT THE AUTHOR

Linda Caron, CMSE and a Certified Machinery Safety Expert (TÜV Nord), is a global product sales manager at Parker Hannifin, Pneumatic Division. She is responsible for Functional Safety products and has 20+ years of expertise in the design and marketing of technical products including industrial automation, robotics, mechatronics, and electrical interlocks.