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COVER STORY

Software & Controls
in the Age of AI and
Decarbonization

VENDOR SPOTLIGHT

Rolls-Royce:
mtu NautIQ and mtu EnergetIQ
Automation Systems

COMPRESSORS

Digitally Transforming
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The Age of AI

Our first issue of 2025 focuses on updates in software and controls. The introduction and integration of AI are changing, well, everything. But specific to our industry, it's largely streamlining and automating processes, increasing efficiencies, and reducing workloads and human errors.

Author Steven Baird, Head of Repair Technology in Compression at Siemens Energy, also takes a look at AI in his article, "Digitally Transforming Compressor Inspection and Repair." He talks about how combining 3D laser scanning and generative AI automates inspection processes, enhances service quality, and expedites equipment overhauls.

Our market trends piece explores six trends that have emerged in the turbomachinery industry. Decarbonization has been a big driver, challenging the limits of technology and spurring innovation. Supply and demand are two other industry drivers, as is the case with LNG and modular/mobile solutions. 2024 further magnified these trends as industry experts weighed in on the fate of gas turbines, the struggles with energy transport and storage, the booming LNG market, and the rise in carbon capture. This year was also host to many product launches supporting net-zero momentum.

Rolls-Royce is our winter vendor spotlight, focusing on the company's mtu NautIQ and mtu EnergetIQ automation systems. These systems allow marine vessel and power plant operators to fully control and monitor system data, assets, and user management from a single screen.

The Myth Busters debunk the myth that compressor transient surge analysis is highly accurate when, in fact, most transient surge analysis software relies on significant assumptions about one-dimensional versus 3D effects and presumes steady-state compressor maps. And Amin Almasi's column, "Diagnostics, Prognostics, and Condition Monitoring of Turbomachines," lays out how smart condition-monitoring strategies can mitigate unscheduled downtime by identifying faults before they occur, reinforcing continuous operation.

If you have any feedback for our team—what you'd like to see more of, topics you'd like covered, or even high-level discussions you want us to address via podcast, videos, or e-symposiums—feel free to email me.

Thank you for your continued support,



Alissa Espinoza
Assistant Managing Editor

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“

The turbomachinery control system of the future can work to minimize the immediate impact of a failure and give some time for the already-busy maintenance team to perform the right repair.”

—Shun Yoshida, CCC by Honeywell

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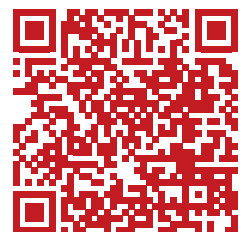


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▲ Welding at EthosEnergy repair shop. Credit: EthosEnergy

One Equity Partners Acquires EthosEnergy

OEP completed its investment and acquisition of EthosEnergy, taking on 3,600 employees across 23 global sites and facilities. CEO Ana Amicarella said OEP will enhance EthosEnergy's service offerings across all divisions, including its work in maintenance, turbine overhaul and repair, and aerospace and defense.

Baker Hughes Digest

Bechtel Energy ordered Baker Hughes' gas technology equipment for two liquefaction plants at Woodside Energy's Louisiana LNG development project. The plants will have a total capacity of 11 MTPA and be equipped with eight main refrigeration compressors driven by LM6000PF+ gas turbines and eight expander compressors. By 2030, Baker Hughes will also deliver an integrated gas recovery and hydrogen sulfide removal system to minimize routine downstream flaring at SOCAR's Heydar Aliyev Oil Refinery in Baku, Azerbaijan.

Baker Hughes and UC Berkeley formed a research partnership: the Baker Hughes Institute for Decarbonization Materials. It links academic research with commercialization to deploy and scale low-cost climate technology. Baker Hughes will fund research for CCUS, hydrogen, clean power generation, and more.

▼ Expander compressor. Credit: Baker Hughes



Chevron Digest

Chevron's Whale semi-submersible platform started oil production in the deepwater U.S. Gulf of Mexico, with a projected peak production of 100,000 gross boe/d and up to 15 wells under development. It contains gas turbines and compression systems and utilizes a design that may deliver lower emissions and lower costs.

Chevron Canada announced it's selling its 20% non-operated interest in the Athabasca Oil Sands Project in the Duvernay Shale.

Chevron U.S.A. and Energy Transfer LNG Export signed a 20-year LNG sale and purchase agreement that includes a 2 MTPA supply from its Lake Charles LNG project.

◀ Whale semi-submersible platform. Credit: Shell



GE Vernova Digest

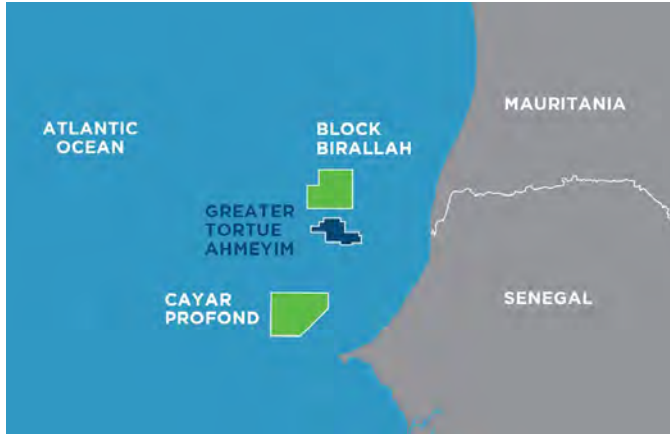
GE Vernova announced it will deliver the first H-Class gas turbine to Generadora San Felipe's 470-MW power plant station. The order includes several turbomachines. It also announced a \$20 million investment in developing repair technologies for new turbomachines at its Advanced Manufacturing Repair Technology center in Singapore, including AI-assisted robotics, lean methodology, and new recruits.

In January, the company completed a validation test campaign of its advanced DLN combustion technology and demonstrated successful operation on natural gas-hydrogen blends and 100% hydrogen for B- and E-class gas turbines. Dry emissions were below 25 ppm NOx. The new DLN system could be available as early as 2026.

GE Vernova also collaborated with Harbin Electric to equip Shenzhen Energy Group's Guangming power plant with three 9HA.01 gas turbines, steam turbines, and generators.

◀ Generadora San Felipe. Credit: GE Vernova

bp's Greater Tortue Ahmeyim Produces Gas



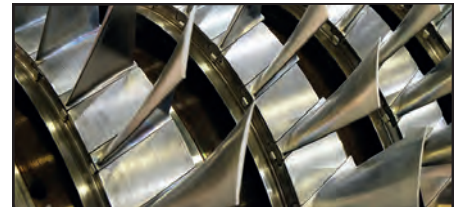
▲ Location of Greater Tortue Ahmeyim. Credit: Kosmos Energy

First gas production started at the Greater Tortue Ahmeyim (GTA) LNG project offshore Mauritania and Senegal. With BP as an operator, gas from GTA's initial phase flowed from wells to a floating production, storage, and offloading vessel before it was transported and liquefied in a floating LNG vessel.

Williams Expands Transco Pipeline

The Southside Reliability Enhancement entered full service on the Transcontinental Pipeline. The system-design capacity rose to 19.9 million Dth/d and will transport approximately 20% of the natural gas produced in the United States.

▶ Transcontinental pipeline construction. Credit: Southern Environmental Law Center



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NEW PRODUCTS

The latest turbomachinery industry innovations

Concepts NREC: VAROC Air Dynamometer V85

The VAROC Air Dynamometer V85 has been re-engineered to include angle testing at a lower price and with a smaller footprint. It offers a speed range up to 26,500 RPM, a power range up to 5,500 HP, and can traverse from low PP to maximum HP rating in 1 second or less. The V85 is customizable for government, private, and commercial entities.



▼ VAROC Air Dynamometer V85. Credit: Concepts NREC



▲ Model LPCMN. Credit: EBARA

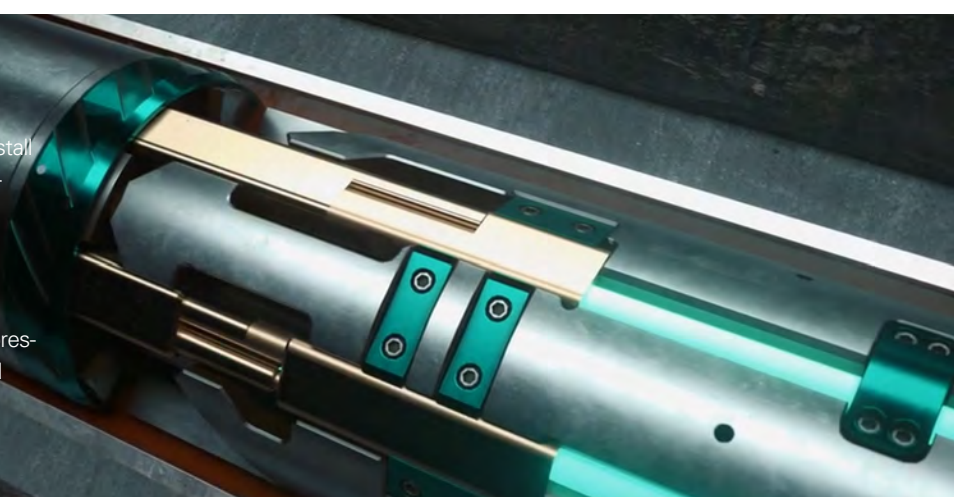
EBARA: LPCMN Exhaust Gas Abatement System

The Model LPCMN combustion-based exhaust gas abatement system neutralizes process gases by reducing byproduct adhesion and NO_x/CO_x emissions and offers a compact design, hydrogen fuel options, and high airflow capacity of 600L/min. It also has four inlet connections, with a six-inlet model arriving this year.

Baker Hughes: SureCONNECT FE

SureCONNECT FE allows operators to install fiber-optics monitoring, electronic monitoring, and electric intelligent completion systems across land- and sea-based wellbores without interventions, such as retrieving the lower well completion. It optimizes reservoir performance in high-pressure, high-temperature environments and lowers maintenance time.

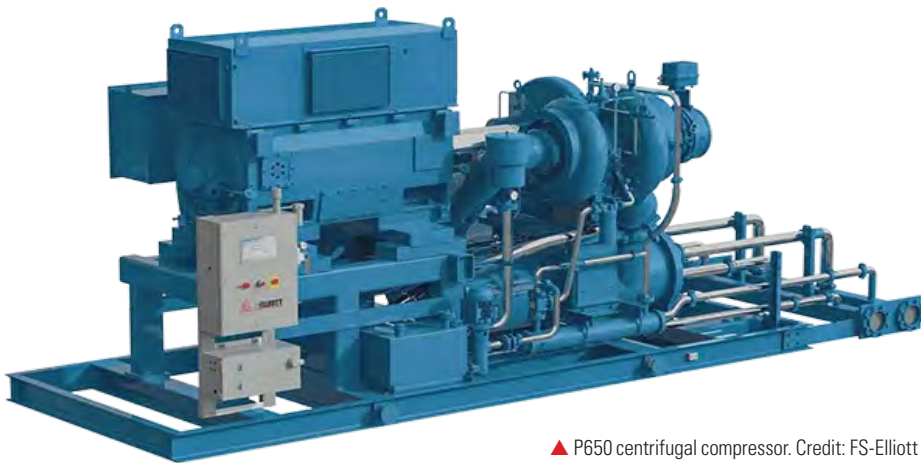
▶ SureCONNECT FE. Credit: Baker Hughes



Rolls-Royce: F130 Engine

The F130 aviation engine, intended for the U.S. Air Force's B-52J Stratofortress, passed the critical design review and is scheduled for altitude testing in 2025. It's been validated for crosswind conditions and will extend B-52 aircraft life by 30 years, with durability to remain on wing for the remainder of aircraft life.

▶ F130 engine testing.
Credit: Rolls-Royce



▶ P650 centrifugal compressor. Credit: FS-Elliott

FS-Elliott: P650 and FSE-TurboCool

The P650 centrifugal compressor features a removable air-end design and horizontally split air-end components to simplify field replacements, inspection, and maintenance without disrupting air piping. The large color human-machine interface and Regulus control system allow customers to save energy with low-carbon operation.

FSE-TurboCool lubricants and additives improve centrifugal compressor performance and lubrication, lengthen machinery lifespan, and help operators reduce unscheduled compressor downtime. This portfolio includes FSE-TurboCool CC, PG, and FG, as well as TurboCool 32 and 46.



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Diagnostics, Prognostics, and Condition Monitoring of Turbomachines

Smart condition-monitoring strategies can mitigate unscheduled downtime by identifying faults before they occur, reinforcing continuous operation.

BY AMIN ALMASI

Condition monitoring is the process of collecting, interpreting, and monitoring the different operating parameters of turbomachinery, such as vibration, temperature, acoustic emissions, performance data, etc. The ultimate goal is identifying a change that might indicate a developing fault or problem.

A condition-based maintenance plan or predictive-maintenance plan develops a smart strategy that shuts down turbomachinery and repairs or replaces parts as required rather than relying on historical data and associated crude-life estimation. Comprehensive condition monitoring allows a turbomachine to continue operating uninterrupted until a fault or issue is detected.

DIAGNOSTICS AND PROGNOSTICS

Diagnostics identify a turbomachine's current health and condition using applied logic, analytics, and experience to determine "cause and effect." They are used to determine

the causes of symptoms, mitigations, and solutions for the turbomachinery's current situation; in other words, diagnostics include anomaly detection, fault isolation, fault classification, and uncertainty.

Prognostics is an engineering discipline focused on predicting the time at which a system, turbomachine, or component will no longer perform its intended function. The lack of performance is usually a failure or a stop in the operation. This method is different from rough-life estimation based on some historical data (often used in preventive maintenance). Prognostics science is a prediction of the remaining lifetime based on condition monitoring and details of possible failure mechanisms. Prior knowledge of the machine's current health status (diagnostics) is required to develop prognostics capabilities. The predicted life (remaining useful life) is necessary data in the decision-making for maintenance planning and contingency mitigation. In addition to the estimation of remaining useful life, the prognostic results should include the uncertainty of the prediction and incipient fault detection.

Prognostics science forecasts future performance by assessing the extent of deviation or degradation from its expected normal operating conditions. It is based on analyzing failure modes and detecting early signs of degradation, wear, aging, and fault conditions. An effective prognostic solution requires knowledge of the failure mechanisms likely to cause degradation, leading to eventual failures. Therefore, it is necessary to have accurate and reliable data and information on the possible failures, including the failure modes, causes, and mechanisms, to identify the parameters to be monitored.

CONDITION-BASED MAINTENANCE PLAN

A condition-based maintenance plan can be optimized depending on the actual condition monitoring, diagnostics, and prognosis data. The main benefits of a condition-based maintenance strategy are:

- time and cost reductions due to better efficiencies and effectiveness
- optimized component life compared to time-based strategies and other traditional maintenance methods
- reduced mean maintenance time due to fault localization
- reduced operational disruption
- increased safety/reliability due to the reduction of unexpected failures

EVALUATING HEALTH AND CONDITION: PHYSICS-BASED MODELS

Different methods, such as physics-based, data-driven, and hybrid models, have been used to evaluate a turbomachinery's health and detect faults. These systems use mathematical models to describe the physics of the component/part/system and assess its current and future health. Their performance depends on accurately representing the failure and degradation phenomena.

Data-driven models are based on statistical and machine-learning techniques and do not rely on the knowledge of the physics that govern the system or its degradation mechanisms. The main advantage of these techniques is their potential to be used in several turbomachines, as their physics is not required. This is sometimes used for cases where physical models are too complicated or unknown; however, there are some problems with data-driven models, such as the risk of overfitting and the necessity of large training data sets.

Physics-based models are preferred because they synergize with models used during the turbomachinery design phase. The physical concept can also be derived and understood, which is helpful when evaluating the condition monitoring, diagnostics, and prognostics processes and their results.

Hybrid models integrate different systems using various approaches depending on the task; for example, they combine data-driven and physics-based models. Normally, for diagnostics, a fault is detected by comparing the outputs of the physics-based model with the measurements from the real condition monitoring system.

For prognostics derived from physics-based models, degradation models represent the degradation mechanisms of the turbomachinery or system, and the remaining useful life can be estimated as an output of these models. For example, degradation models that represent crack growth can be used to estimate the remaining useful life of a component subject to fatigue and crack(s). ■



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Software and Controls in the Age of AI and Decarbonization

OEMs are using AI- and ML-equipped software and control systems to improve data quality and reliability, automate tasks, monitor assets, assist smaller crews, and make predictive maintenance commonplace.

BY ALISSA ESPINOZA

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The turbomachinery industry stands at a juncture. Driven by the urgent need for decarbonization and the transformative power of artificial intelligence (AI) and machine learning (ML), software and control systems are evolving and revolutionizing turbomachinery operations, maintenance, asset monitoring, and more, paving the way for a more sustainable and efficient future.

ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

As AI steps onto the scene, experienced and knowledgeable workers are leaving, and AI is emerging as a crucial tool to address this experience gap and navigate the evolving landscape.

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“One of the defining challenges today is the Great Crew Change, where people with decades of experience and expertise are retiring in mass—being replaced by fewer people with less operational experience,” said Shun Yoshida – Engineering Manager, HMI Software at Compressor Controls

Corp. (CCC) by Honeywell. “This is while they are asked to manage energy efficiency, reliability of aging assets, and sustainability goals. They have a difficult job ahead in maintaining and even improving assets with less collective experience available in the team.”

Along this line, Yoshida named centralization and consolidation of data, analytics, and visualization as key trends “because many end users have increased their reliance on central SMEs to remotely support local operations teams where domain-specific expertise is hard to attain and retain,” he said. “And particularly for upstream offshore operations, there is a path toward unmanned platforms where connectivity is a foundational requirement.”

Ruben Alvarez, CEO of John Crane, sees growing pressure on manufacturers to capitalize on the potential of new technologies “to deliver measurable progress against sustainability targets while maintaining high performance and regulatory compliance.”

Integrating AI, ML, and even the Internet of Things (IoT) in turbomachinery applications has a lot of potential—from improving productivity to automating tasks, reducing the number of inspector tasks, and proactively adjusting controls.

According to Michael Domke, General Manager of Visual at Waygate Technologies, a Baker Hughes business, process automation, AI, and ML improve data quality and reduce inspection time. This is specifically seen in the close interaction between humans and the system: the better each side performs, the better the results.

“As with many other applications, the strength of ML and AI lies in the processing of substantial amounts of data and the automation of processes,” Domke said. “By moving some tasks away from the inspector and into the device, the inspector can focus on other tasks. For example, if we are inspecting a gas turbine, the AI-assisted software relieves the inspector of counting the turbine blades. The system also automatically recognizes a potential defect and notes the location. The inspector can then focus on the defects, check them, specify the details, and make the right recommendation regarding asset health to the owner.” The company’s video borescope, Everest Mentor Visual iQ+, does just that.

At EthosEnergy, AI and ML are now synonymous with its remote plant and asset-monitoring solutions, and it considers them essential technologies. “ML has come a long way since first introduced over 25 years

ago, but at its core, modern software learns the normal behavior of assets based on the asset data received,” said Ashwin Kumar, VP of Marketing at EthosEnergy. “It automatically sets boundaries to proactively alert SMEs when there is a deviation from what was learned. This technology helps proactive engagement of an issue at the beginning stages of failure, avoiding costly downtime. With new advancements in AI, leveraging 25+ years of asset failure modes combined with ML, they aid in identifying the most likely culprits of the asset issue—vastly improving work scopes and urgency. The latest tech now blends ML and AI for forecasting failures, providing time perspective of what has been identified.”

Dinakar Deshmukh, Vice President of Data Science at GE Aerospace, said the company has been developing and deploying AI across its business for more than a decade. “During this time, we have more than doubled our investment in AI technology, positioning the company as one of the top AI patent holders within the aviation industry.”

Internally, GE Aerospace launched a companywide generative AI platform, AI Wingmate, in partnership with Microsoft to help improve employee productivity with daily work tasks and free up more time for employees to focus on problem-solving. The company leverages AI to optimize engine monitoring, part inspections, and the supply chain to improve efficiency, accuracy, and overall performance.

“[We also launched] a new generative AI solution to enable faster searching of critical maintenance record assets for our airline and lessor customers, dubbed Gen AI Assistant,” Deshmukh said. “That was developed in close partnership with Microsoft and Accenture. [And we] equipped all our software developers with generative AI-based code assistants to boost efficiency and productivity.”

AI and ML also support decarbonization efforts and enable companies such as GE Vernova and CCC to explore their uses in asset performance management (APM) software and improve compressor reliability and availability.

Let’s dive deeper into decarbonization’s impact on software and controls and where and how AI and ML fit in.

DECARBONIZATION

Decarbonizing global energy systems is driving a transformative shift in turbomachinery software and controls. OEMs are approaching this from different angles, including a controls platform that integrates carbon-capture plants and power plants; optimizing compressor operation to reduce energy consumption via controls and tests; and using APM to optimize assets, processes, and energy efficiency.

Carbon Capture

Carbon capture and storage (CCS) helps hard-to-abate industries decarbonize; however, operational flexibility is a common challenge.

GE Vernova developed a controls platform that enables tight integration between the power and carbon-capture plant to achieve greater than 95% CO₂ capture rates. In the short-term, the platform is providing additional control capabilities (beyond the typical power plant controls scope) for integration features specific to the carbon-capture plant, including:

- Controls related to exhaust gas recirculation (EGR), steam extraction, high backpressure, and CCS damper
- Control input/outputs for easier integration with the CCS controls system provided by the carbon-capture provider/EPC

The company also optimized the operations philosophy, such as early steam-extraction capabilities during start-up and minimizing emissions that negatively affect the CCS solvent life during steady-state operations. The EGR controls are developed to provide a concentrated flue gas stream with higher CO₂ concentration and lower oxygen concentration, resulting in lower CAPEX and OPEX for the CCS plant while protecting the gas turbine by controlling the amount of EGR.

Looking forward, GE Vernova is developing the capability to control both a full combined-cycle plant and a carbon-capture plant as an integrated system. “The key to this development has been the creation of a high-fidelity dynamic simulation that includes all aspects of both the combined-cycle power plant and the

carbon-capture plant,” said Matthew Davidsaver, P.E. CCS Product Line Champion, GE Vernova. “Using this tool, control strategies are being developed to optimize overall plant operability and performance. For example, controlling steam extraction to the carbon-capture plant takes advantage of information originating in the gas turbine control system. This control and simulation platform is a continuation of tools developed over the past several decades and proven in developing various power plants, including combined cycle, integrated gasification combined cycle, aluminum smelting, LNG, and more.”

John Crane offers solutions like Sense Monitor, which allows companies to optimize infrastructure and operations by providing real-time data on equipment health. “This empowers operators to make informed decisions that reduce downtime, emissions, and leakages,” said Alvarez. “This enhances operational efficiency and supports industries like hydrogen and carbon capture in meeting their decarbonization goals by reducing their environmental impact.”

Turbocompressors

“Turbocompressors are often some of the largest energy consumers in a plant,” Yoshida said. “Eliminating suboptimal operations—such as manual control of anti-surge valves, reducing control margins, and improving control quality—represents sizable energy-saving opportunities that contribute positively to decarbonization.”

To solve upstream and midstream challenges, CCC has worked closely with its customers across the oil and gas value chain to create solutions. “For example, plugging and stiction of anti-surge valves can be a frequent issue upstream due to hydration formation and contaminants,” Yoshida said. “This can result in reduced effectiveness of compressor surge protection. CCC has introduced Valve Exerciser, which will systematically perform a valve test while monitoring its effects on process measurements. In contrast to valve self-diagnostics, this approach enables us to evaluate the overall health of the recycle line from the actuator, valve cage, plug, piping, scrubber, and strainer.”



As instrument manufacturers continue to enhance their products, control systems can also concurrently increase their tolerance of instrument failures using substitute measurements. There are compelling AI/ML use cases for creating more graceful fallbacks.”

—Shun Yoshida, CCC by Honeywell

The company has also seen a buzz about its software’s ability to handle sensor drifts, freeze, and failures. “Further, our HMI software has been evolving to support seamless delivery of high-resolution data to remote experts with message queuing telemetry transport (MQTT) and web-based visualization,” he said. “We also continue to invest in cybersecurity at both organizational and product levels to help customers achieve digital transformation in a secure way.”

In critical compressor applications, CCC sees, in terms of IoT, end users moving toward centralized high-resolution time-series data and human-machine interface (HMI) screens. “On the other hand, we are still early in using AI/ML to take direct control actions,” Yoshida said. “We know from our customers that there is much to improve regarding compressor reliability and availability. For example, most turbomachinery controllers today are programmed with fallback modes that are triggered by instrumentation failures. These modes are designed to keep the compressors running without the risk of surging; however, this shift in operation modes can impact the process. As instrument manufacturers continue to enhance their products, control systems can also concurrently increase their tolerance of instrument failures using substitute measurements. There are compelling AI/ML use cases for creating more graceful fallbacks.”

Asset Performance Management

APM also plays a key role in decarbonization efforts “by helping to optimize assets, processes, and energy efficiency,” said Ryan Finger, Global Director of Software Product Marketing for GE Vernova’s Electrification Software Business.

It wears many hats and is designed to help teams improve equipment reliability, extend asset life, and reduce unplanned outages.

“Besides the traditional condition monitoring system, we see approaches like APM being adopted more,” Yoshida said. “APM gives end users a consolidated view of asset health and performance across different equipment types. Overall, we see high interest in computing and tracking the

thermodynamic performance of turbomachines as an early indicator of equipment health degradation.”

APM supports company-driven sustainability efforts in industrial operations and boosts reliability and energy-efficient operations. Finger said it primarily impacts various maintenance aspects, including:

Renewable Energy Asset Maintenance/Reduce Waste:

APM uses predictive maintenance to ensure near-continuous operation of renewable energy assets, reducing reliance on fossil fuels during outages. Predictive maintenance also improves equipment precision and reduces product scrap and waste caused by poorly maintained equipment. It provides insights to help prevent asset failures by improving maintenance and reliability and reducing pollution risks from failures in critical infrastructure, such as pipelines.

Extended Asset Life: APM helps extend asset life, reducing the need for new equipment and supporting a circular economy.

Energy Efficiency: Proper maintenance enabled by APM helps equipment operate at peak efficiency, reducing energy consumption.

Work Planning: Operators/inspectors are often dispatched for distributed organizations. APM’s data insights help users better identify the work that needs to be done beforehand to validate the need for maintenance and only dispatch workers when necessary.

APM Strategy gives users access to APM Health for condition-based maintenance; APM Reliability for root cause and production loss analysis; SmartSignal for predictive and prescriptive diagnostics; and APM Mechanical Integrity for fixed asset inspections. This adds up to increased reliability with access to advanced monitoring so they can adjust their maintenance programs with near real-time data and deploy new strategies.

“APM is designed to focus on the ability to optimize organizations to get the most reliability/availability of their assets at the best cost and lowest risk,” Finger said. “For GE

Vernova, the path to this starts with integrating data from all systems that store and use information that directly impacts reliability. Once correctly centralized, GE Vernova's APM Strategy, designed to help organizations assign criticalities to assets, layer in 'what-ifs' and ultimately devise a scalable plan across identified assets."

Its Autonomous Inspection leverages AI-powered computer vision in fixed cameras/robotics to help remotely monitor assets and eliminate manual inspections. This reduces risks for monitoring volatile assets and O&M costs required for manual inspections. Data is then turned into a time series within APM to be leveraged along with additional collected information.

"As the rise of AI continues, GE Vernova's APM is also running pilots with customers that include a built-in co-pilot for APM, the ability to ingest large documents with Generative AI, and more functionality for prescriptive analytics—all innovations that are designed to help keep a human-in-the-loop for more control and validation," Finger said.

Use Cases

Some specific use cases of GE Vernova's APM end-to-end value include the State Oil Company of the Azerbaijan Republic. It experienced:

- 20% reduction in maintenance costs
- 10% reduction in health, safety, and environmental incidents
- 10% increase in employee productivity

OQ, Oman's global integrated energy group, saw a total savings of approximately \$59 million. It avoided three turnaround events, saving \$833K in maintenance costs and over \$42 million in production losses. The company bypassed inspection costs for the removed damage mechanisms, saving an estimated \$16 million, and optimized 1,320 assets by removing irrelevant damage mechanisms and adding relevant ones.

LOOKING AHEAD

"As we face the future of operations where fewer people are managing more assets, the responsibility of turbomachinery control

systems should grow," Yoshida said. "We can take early detection of faults as inputs and adjust control responses to achieve more uptime, reduce equipment damages, maintain process outputs, etc. For a given failure, some maintenance action is

eventually necessary. However, the turbomachinery control system of the future can work to minimize the immediate impact of the failure and give some time for the already-busy maintenance team to perform the right repair." ■



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TOP TURBOMACHINERY TRENDS 2024

The 2024 turbomachinery industry was characterized by several trends—from carbon capture to gas turbines’ supporting role in renewably integrated grids.

BY JAMES COOK AND ALISSA ESPINOZA

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Over the past few years, several trends have emerged in the turbomachinery industry. Decarbonization has been a big driver, challenging the limits of technology and spurring innovation. Supply and demand are two other industry drivers, as is the case with LNG and modular and mobile solutions. 2024 further magnified these trends as industry experts weighed in on the fate of gas turbines, the struggles with energy transport and storage, the booming LNG market, and the rise in carbon capture. This year was also host to many product launches supporting net-zero momentum.

Check out the 2024 macro and micro trends.

1

GAS TURBINES + RENEWABLES

In a world increasingly integrating renewable energies like solar and wind, the role of gas turbines in the short and long term has been in question. But, as many industry experts have pointed out over the past year, gas turbines are here to stay and offer a hybrid solution to the uptick in renewable-based power.

“Gas turbines enable flexibility,” Giuseppe Tilocca, Scientific Officer at ETN Global, said in his 2024 podcast. “In decentralized energy systems, clean and dispatchable solutions such as gas turbines enable the energy transition—in fact, there is no energy transition without dispatchable solutions. To maintain electricity and meet demand in Europe, we’ll need more than double the current flexibility by 2030 and five times more by 2050. There are not many available, affordable, and scalable alternatives for gas turbines’ long-term flexibility.”

During his gas turbine sales presentation at WTUI 2024, Tony Brough, President of Dora Partners and Company, reassured that “gas turbines are not going away; the renewable offset/peaking market continues to have long-term potential. Ten years from now, the gas turbine market will still be going strong.”

Renewables should account for 30 - 40% of a large grid, according to Mark Axford of Axford Turbine Consultants, “But gas turbines are an essential part of creating a reliable, affordable, and sustainable grid.”

Brough predicts that \$22.3 billion will be spent on aeroderivatives between 2024 and 2033—GE/Baker Hughes will gain almost \$20 billion of that share. The aeroderivative aftermarket will generate \$31.5 billion over the next decade; \$23 billion of that will be spent on GE/Baker Hughes machines.

Hybrid systems that combine gas turbines with renewable energy play to the strengths of both technologies, “providing reliable baseload power from gas turbines and intermittent clean energy from renewable sources,” Carter Palmer, an Industrial & Marine Turbine

Analyst at Forecast International, said in his *Worldwide Gas Turbine Forecast 2025*. “Hybrid systems enhance grid stability, optimize energy efficiency, and reduce fossil fuel reliance.”

So, what does this mean for gas turbines? Palmer said they have the potential to gain even more popularity.

2

ENERGY TRANSPORT AND STORAGE

Alternative forms of energy, like hydrogen and ammonia, are garnering increased attention as turbomachinery seeks to decarbonize on an international scale. Still, there are several challenges associated with transporting and storing them.

“Unfortunately, hydrogen itself has a lot of nasty characteristics,” Klaus Brun, Director of R&D at Ebara Elliott Energy and Rainer Kurz, Principal at RKSBEnergy, said in their 2024 podcast on ammonia. “It’s hard to compress, highly flammable, as a gas it’s not easy to deal with, etc. From a transportation and storage perspective, it leaks, has many safety issues, causes hydrogen embrittlement, etc., making it difficult to transport.

“Another option for transporting and storing gaseous hydrogen is lowering the temperature of hydrogen to form a liquid, like what is currently done with LNG for transport by tanker or ship,” the duo said. “The downside of liquefaction is the amount of energy needed to reach the necessary low temperature that has to be maintained during any transport process. This means the energy required for the refrigeration process to liquefy hydrogen is equivalent to 30 - 40% of the energy content of the hydrogen itself.”

Another option is to create hydrogen-containing compounds, such as gaseous methane or liquid organic carriers. But right now, the hot transport vehicle of choice for hydrogen is ammonia. “It can be transported as a liquid, which makes the transport process efficient,” Brun and Kurz said. “Certainly, making ammonia is well understood, as it is a key ingredient in fertilizer manufacturing. Having

hydrogen available in fertilizer production avoids several production steps that ultimately lead to making ammonia, such as in the well-known Haber Bosch process.”

From a handling perspective, “ammonia is a very toxic gas. If you touch it in liquid form, it causes skin burns rapidly. In vapor form, even at less than 100 PPMs, it’s very irritating,” Brun said. Transporting ammonia is difficult because ammonia is toxic and, when combined with water, becomes caustic. At ambient conditions, ammonia forms a toxic gas. In liquid form, under pressure, risks of exposure increase because large quantities have the potential to release into the air rapidly.

Peter Kutne, Head of the Department Gas Turbine at the Institute of Combustion Technology of the German Aerospace Center (DLR), said to supply larger power plants with hydrogen, “a pipeline infrastructure is needed.”

Hydrogen storage solutions are critical to buffer mismatches between production and consumption. But in terms of cost, “storage systems based on pressure vessels or multi-tube arrangements are only suitable for small- to mid-sized peak-load gas turbine power plants. Underground salt caverns offer the most promising option for large-scale hydrogen storage for mid-merit and large gas turbines,” Kutne said.

3

CARBON CAPTURE AND STORAGE

Carbon capture and storage (CCS) increased significantly during 2024. According to the Global CCS Institute’s *2023 Global Status of CCS Report*, there was a 102% increase in CCS facilities in the pipeline compared to 2022. As of April 2024, 564 commercial CCS facilities are in the project pipeline. North America is leading the way: The United States leads in deployment with 73 new CCS facilities entering the pipeline in 2023. Top applications in the United States are ethanol, ammonia, hydrogen, fertilizer production, power generation, and heat.

Spencer Schecht, Senior Business Development Lead, Honor Iosif, Public Affairs Manager, and Joey Minervini, Public Affairs Manager at the Global CCS Institute, said: “The Institute is seeing accelerating momentum for CCS in industries beyond the lower-cost applications of gas processing, ethanol, and ammonia production. CCS is being integrated into industries such as cement, steel, chemical plants, power plants, and even carbon-removal technologies, such as direct air capture, bioenergy with CCS, and waste-to-energy plants.”

One of the challenges of integrating CCS is cost, so companies are exploring ways to reduce operational and capital costs. GE Vernova conducted a FEED study to reduce CCS costs and its overall footprint through its exhaust gas recirculation (EGR) system, which increases the concentration of CO₂ in the exhaust gas.

The study findings, released by the U.S. Department of Energy’s Office of Fossil Energy and Carbon Management, found integrating GE Vernova’s EGR system, which is capable of capturing up to 95% of CO₂ emissions:

- could reduce more than 6% of the total cost of the carbon-capture facility compared to installing carbon capture without the EGR system
- could reduce total carbon-capture operational costs per year (total costs include reductions to capital and operating costs)

4

TECHNOLOGICAL ADVANCEMENTS

The industry has been adapting technologies to support net-zero goals, and throughout 2024, several exciting turbomachinery advancements were announced.

GE Vernova announced its LM6000 aeroderivative gas turbine will operate on 100% renewable hydrogen with commissioning slated for early 2026.

“The new design ... overcomes the challenges of hydrogen’s higher flame speed through precise design enhancements to the

fuel nozzle, optimized water injection schedules, and advanced control modifications,” said Midhat Mirabi, Managing Director at GE Vernova’s Gas Power Aeroderivatives New Units. The unit is equipped with safety features, such as nitrogen purge systems and hydrogen fire detection systems.

In his latest gas turbine forecast, Palmer said: “While existing turbines can be retrofitted with hydrogen-compatible burners, the combustion characteristics of hydrogen differ significantly from natural gas, necessitating modifications to ensure efficient and stable operation.”

GE Vernova and IHI announced earlier in the year that they are developing a two-stage combustion system with a rich dome to resolve the ammonia-NOx problem. The system will build on the 2-MW gas turbine, developed in collaboration between the companies, that uses 100% liquid ammonia.

“GE Vernova’s technology either runs at or near stoichiometric—i.e., fuel and air in perfect chemical balance—or on the lean side, but the rich side of the stoichiometric dome—fuel-rich and oxygen lean—provides less air for the nitrogen to turn into NOx when using ammonia,” explained Dr. Jeffrey Goldmeier, Global Hydrogen Value Chain Leader at GE Vernova.

Siemens Energy developed a series of decarbonized turbomachines to accelerate the energy transition and close technological gaps. The three technologies are in the early stages of commercialization: an advanced rotor hydrogen compressor, a Turbo Heater, and a rotating olefins cracker.

5

LNG AND MOBILE APPLICATIONS

The LNG industry experienced significant shake-ups in 2024, with the Russia-Ukraine conflict and the Department of Energy’s LNG export pause disrupting production, imports, and exports. Despite these and other events, the global LNG market experienced a shift starting in late 2024, as a wave of new liquefaction projects came online.

In April 2024, the U.S. Energy Information Administration anticipated a modest increase in U.S. LNG exports for the year (2%) followed by significant growth in 2025 (an additional 18%). This growth is mirrored by expectations for a rise in U.S. natural gas exports by pipeline (3% in 2024, 4% in 2025) and a slight dip and recovery in pipeline imports in 2024 and 2025, respectively.

The United States, Australia, and Qatar produced three-fifths of the world’s LNG in 2023, with the United States leading the pack as the top global LNG exporter after Russia fell behind when the Nord Stream pipeline exploded in 2022.

The Institute for Energy Economics and Financial Analysis expects global LNG production capacity to grow by roughly 193 MTPA from 2024 - 2028, rising from ~474 MTPA of nameplate capacity at the beginning of 2024 to 666.5 MTPA by the end of 2028—the fastest capacity growth in the global LNG industry’s history, representing a 40% increase in five years.

A couple of trends have emerged from this sector of the industry: modularization and e-LNG. “LNG projects require modularization to eliminate risk in the field, i.e., stick built, in addition to a decline in available field labor,” said Joel Schubert, Director of Business Development LNG at Siemens Energy. “We also see a trend for future LNG projects going forward with e-LNG (electric motor drives) to reduce emissions and their carbon footprint.”

The modularization trend is mirrored by Baker Hughes’ launch of NMBL LNG: a modular solution for mid-scale gas liquefaction. It consists of modules capable of processing from 0.8 up to ~2 MTPA each and is based on the single-mixed refrigerant liquefaction process. Each NMBL liquefaction train includes a process module, a turbo or electric motor-compressor for the mixed refrigerant, the surge vessel for refrigeration storage, the cold box of brazed aluminum heat exchanger type, and the e-room.

“The global LNG market is responding with an unprecedented surge of additional export capacity,” said Andrea Intieri, LNG Platform Leader of Gas Technology Equipment, Industrial, and Energy Technology at Baker Hughes. “According to Baker Hughes, over the next three-year period (2024 - 2026) approximately 100 MTPA of liquefaction capacity is expected to reach a final investment decision.”

6

AMMONIA IN MARINE PROPULSION

A micro trend our team has observed is the use of alternative fuels such as methane, ammonia, and methanol to propel marine vessels.

In September 2024, Amogy's carbon-free, ammonia-powered maritime vessel—the NH3 Kraken—successfully completed its maiden voyage on a Hudson River tributary, upstream from New York City. The vessel is a tugboat originally built in 1957, equipped with Amogy's ammonia-to-electrical power system. In the coming months, the company will release a case study with additional technical details.

"Ammonia is the world's second most produced chemical, with around 20 million tons moving around the globe through 200

ports each year," said Seonghoon Woo, CEO and Co-Founder of Amogy. "With that track record, shifting the industry mindset to use it as a fuel is completely achievable and can happen at an accelerated pace."

In late 2024, MAN Energy Solutions announced a significant development for its marine-based ammonia engine work: the AmmoniaMot 2 research project. With funding from the German government and extensive industry partnerships, the project aims to develop a four-stroke, medium-speed, dual-fuel test engine that operates on ammonia for large-scale ship applications. This follows the design and testing of its first two-stroke ammonia engine.

"We are using synergies between two-stroke and four-stroke in both directions with a deep technological exchange," said Christian Kunkel, Head of Combustion Development and Four-Stroke R&D at MAN Energy. "[In terms of ammonia], we can copy and adapt some of the technical concepts and

ideas from two-stroke engine development, mainly in the fields of safety concepts, compatibility of materials, and lube oil."

The first AmmoniaMot project focused on fundamental investigations regarding the combustion of ammonia in an internal combustion engine. The main takeaways from the AmmoniaMot project [that apply to developing four-stroke engines] were:

- ammonia seems to be a suitable fuel to operate four-stroke medium-speed engines
- a greenhouse gas reduction potential of up to 90%
- usual exhaust-gas after-treatment systems can be used to fulfill the IMO Tier 3 emission limits

Hanwha Power Systems may get involved in this field as well, deploying its supercritical CO₂ technology to utilize waste heat from ammonia-fueled gas turbines being developed for marine propulsion. ■

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Automating Power: Rolls-Royce's Software Offers Full Control

The mtu NautIQ and mtu EnergetIQ automation systems allow marine vessel and power-plant operators to fully control and monitor system data, assets, and user management from a single screen.

BY JAMES COOK

Rolls-Royce Power Systems provides mtu-brand high-speed engines and propulsion systems for ships, heavy land, rail, defense vehicles, and the oil and gas industry. The portfolio also includes diesel and gas systems and battery containers for mission-critical, standby and continuous power, combined heat and power generation, and microgrids. In addition to reciprocating engines and electrical hybrid systems, Rolls-Royce supplies ship and power-plant automation software that allows complete control over complex infrastructures.

mtu EnergetIQ Manager for energy applications and mtu NautIQ Master for ship applications are specifically tailored for their industries, but each serves the same purpose: allowing operators to oversee and control the entire ship or plant.

MTU ENERGETIQ

The mtu EnergetIQ Manager platform is a comprehensive solution for power plant controls that can be individually customized to customer requirements. Its most recent update reinforces security, scalability, and

intuitive use, allowing operators to manage data, assets, and loads with full control and monitoring from one screen.

"[Its] job is to work out the ideal mix in terms of power generation, power storage, and the power demand—both currently and for the future," said Jan Henker, Senior Expert of Automation and Controls, Rolls-Royce Power Systems. "In the specific case of a microgrid, mtu EnergetIQ Manager, keeping in line with the customer's wishes, would determine the current energy mix based on contemporary and future weather data, the prices on the electricity exchange, and the customer's energy demand using AI (neuronal networks) for predictions and sophisticated problem-solver algorithms for optimization."

It offers three key advantages:

- **Scalability:** The system can be scaled on demand, separating control units for real-time control, monitoring, and protection from high-performance PCs for data management, visualization, and reporting. Operator stations can be added throughout the facility, across workshops and offices, and mtu and third-party components can be integrated on different levels.

- **Redundancy:** 24/7 data synchronization between master and backup controllers provides a range of redundancy options, with additional offerings for redundant control networks and related assets.
- **Future-Proof:** In addition to information and control availability from various operating stations, new assets can be integrated with minimal software parameter changes to future-proof the system.

Zooming out, the solution's full functional scope includes energy and power management, switchgear controls, and data and alarm management, covering all control and data acquisition tasks—from sensor to cloud. mtu EnergetIQ Manager automates generation, storage, and demand.

"In pure generation plants without storage, the mtu EnergetIQ Manager maximizes the efficiency of the generator sets (depending on load factor) by calculating the number of generator sets required to meet power demand and capacity reserve and by performing load-sharing between running generator sets," Henker said.

The system also has differing functionalities across on- and off-grid applications: On-grid operation is used for power trading, grid services, and peak-load shaving. Off-grid applications include stabilizing the power supply and lowering costs and emissions.

Rolls-Royce Power Systems plans to update mtu EnergetIQ Manager for new applications, including equipment health management, analytics for battery systems, and predictive maintenance. New genset controllers are also coming soon.

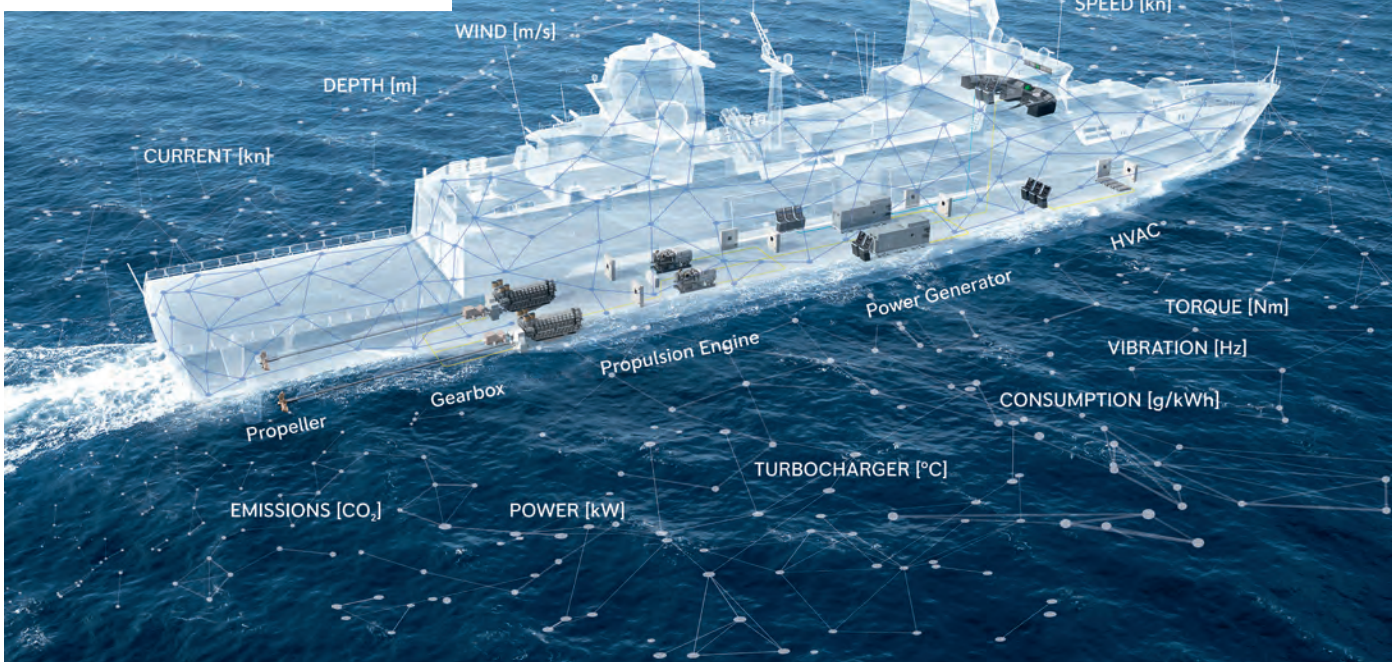
MTU NAUTIQ

The mtu NautIQ automation portfolio, applicable to new-builds and retrofittable to older vessels, allows monitoring and control from "bridge to propeller." The "Master" iteration is Rolls-Royce's most recent Integrated Platform Management System (IPMS), which enables the integration or future-proof upgrade of additional hardware, software, and auxiliaries throughout a vessel's lifecycle, offering customers long-term planning and reliability.



◀ mtu NautIQ Foresight equipment health management system ensures the Halunder Jet catamaran shuttles between Hamburg and Heligoland with maximum uptime and minimum fuel consumption.

▼ Rolls-Royce's solution for navies and commercial ships is the automation system mtu NautIQ Foresight.



“There are several advantages to our automation systems: The crew can focus on its main tasks and competencies—for small crews, this is a big advantage,” said Simon Gallagher, Director of mtu NautIQ Solutions, Rolls-Royce Power Systems. “The technical complexity and maintenance tasks can be managed by the fleet-management team on land. Decisions are made based on live data, not on historical data. Cloud analytics and AI technologies can be made available for operators.”

- Future-proofing is its primary feature:
- System parts are selected from suppliers capable of delivering components well into the future, and Rolls-Royce can manage obsolescence with partners to support customers.
 - It can be installed on vessels with high-sensor/actuator counts and complex automation requirements, accommodating large data-set interfaces emerging with the “big data” trend.
 - Similar to mtu EnergetIQ, the system allows a high degree of integration with third-party systems, with all system elements fully traceable through detailed system configuration.

There are plenty of upcoming developments for mtu NautIQ: “A new version of the platform software, Winmon, is being upgraded to Winmon9_1,” Gallagher said. “This is significantly faster than the previous version and runs on lower-power hardware. It will also include some enhancements: an OPC-UA interface for third-party system integration; a feature-rich damage control system with dynamic kill cards; vector graphics for improved HMI performance; and multi-language capabilities. Another area of improvement is cybersecurity: The system is being developed in alignment with IEC62443 and has significant cyber features. Another system using Winmon9_1 is the new BVNG Premium system.”

FUTURE TRENDS

“Rolls-Royce Power Systems recognizes the importance of combating cybersecurity as a critical trend in power-plant automation, and we take it seriously by meeting critical industry standards,” said Kevin Daffey, Senior Vice President of Mobile Automation.

According to Henker, on-premise data management and analytics solutions, particularly for critical infrastructure, are also upcoming trends. The creation of insights from the plant data can optimize processes, save emissions, and prevent downtime.

A couple of trends are on the horizon in the ship automation software industry. Gallagher said that the accumulation of big data from various platforms requires IPMS to interface, gather, and make this data accessible onboard marine vessels, onshore, and in the cloud. Additionally, platform issues must be identified early so dynamic analysis and fault prediction using digital-twin comparisons can be integrated into ship automation software.

As highly experienced engineers at sea become rarer, there is a growing need for tools such as machinery data insights, onboard training, and equipment documentation, which are all integrated into ship automation to enable shipboard engineers to pre-empt and prevent machinery breakdowns, apply intelligence to maintenance, and make repairs easier. ■

Digitally Transforming Compressor Inspection and Repair

Combining 3D laser scanning and generative AI automates inspection processes, enhances service quality, and expedites equipment overhauls.

BY STEVEN BAIRD

Inspiration before major compressor repairs and/or overhauls has traditionally been tedious and time-intensive. The process often entails shipping equipment to an OEM service center, where technicians can disassemble the unit to take precise measurements by hand and visually examine components, such as rotors, impellers, bearing housings, etc., for wear or damage.

Over the last decade, 3D laser scanning has gained popularity as a tool for streamlining inspections by allowing manufacturers to rapidly detect material deformities or dimensions that are out of tolerance.

As many companies take the next step in the digitalization journey, they are now leveraging these capabilities in combination with generative artificial intelligence (Gen AI) to automate the inspection process further, enhance service quality, and expedite equipment overhauls.

REAL-TIME DIGITAL INSPECTIONS

3D laser scanning reduces and, in many instances, eliminates the need for dimensional measurements to be taken manually. While this capability alone reduces the technician's workload and provides several advantages in terms of component visualization, additional steps are often needed to fully utilize the scan data being collected.

Automated inspection scripts customized for the specific type and model of machine being serviced extract key measurements from 3D scans. A scan of a first-stage impeller indicates measurements in and out of tolerance.

Measurements from the 3D scan are exported to a digital inspection platform for disposition, allowing technicians to analyze the unit directly from the shop floor in real time and eliminating the need for data processing onsite.

FIGURE 1 is a screenshot from the digital inspection platform showing how the scan results, along with data from manual procedures such as non-destructive testing (NDT), can be used to generate prescriptive repair recommendations using Gen AI. All the information is mapped to enterprise resource planning (ERP) and product lifecycle management (PLM) systems, which allows sales and repair personnel to provide faster and more accurate responses to customers on lead times and costs.

The entire process aims to reduce human error, improve repair consistency across service centers, and expedite compressor overhauls. These efforts have already yielded positive results. For many components, the time it takes to inspect, analyze, and determine necessary repairs has been reduced by more than 50%.

USING GEN AI FOR SEMANTIC SEARCH

Gen AI can also be valuable as a semantic search tool. Particularly for legacy product



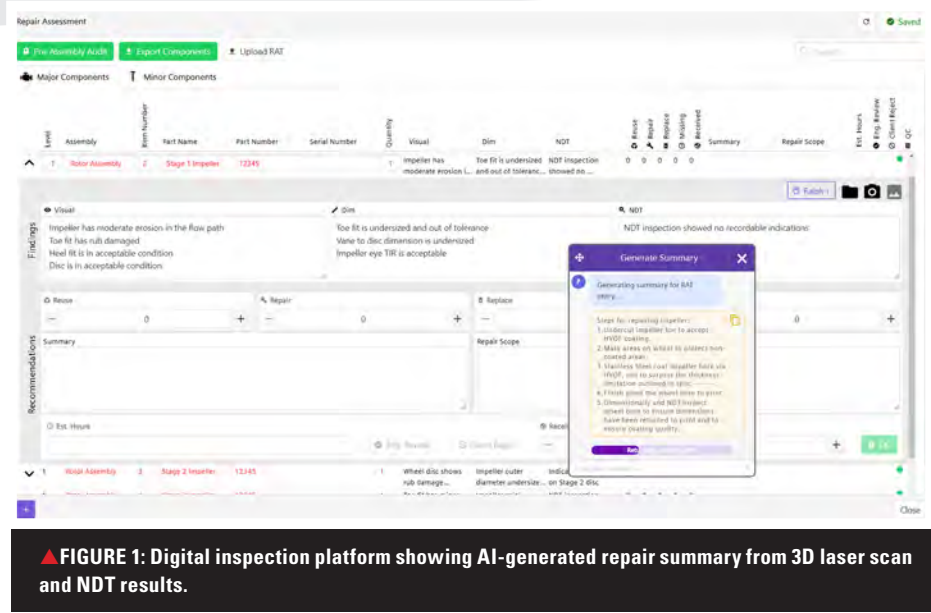
lines, it is not uncommon for personnel to spend significant time searching old documentation and databases to find answers to questions. In some cases, employees who served as subject matter experts on a particular part or product line in the past have retired, leaving knowledge gaps that can hinder the repair process.

Virtual repair engineers, i.e., chatbots built using Gen AI, can help solve this problem by quickly retrieving and contextualizing information from internal service and product documentation. Large language models (LLMs) can return much more accurate and relevant results to user queries than a traditional keyword search.

When a virtual repair engineer is presented with a query about the type of coating that can be used to repair a damaged journal bearing, the chatbot returns the relevant inspection requirements, coating restrictions, repair options, and even recommended next steps.



Using laser scanning to inspect a large open-faced impeller.



EXTENDING DIGITALIZATION TO THE FIELD

Extending digital inspection activities like 3D laser scanning to the field also benefits customers by enabling granular data collection and providing greater flexibility and adaptability in project execution. It may be possible to perform all work onsite for certain inspection activities, avoiding the need to ship machines or components to service centers.

Field scanning can even help address problems beyond the scope of compressor repair. In one example, a plant operator evaluated the drain line redesign during a compressor removal. Technicians scanned the existing configuration and quickly created a new piping isometric that eliminated the need to perform tack welds onsite.

In a separate field application, the operator was concerned about the bedplate leveling of their motor-driven compressor. Onsite scanning revealed that the motor, gearbox, and compressor pedestals were out of tolerance. Measurements from the scan were then provided to the customer to remedy the issue.

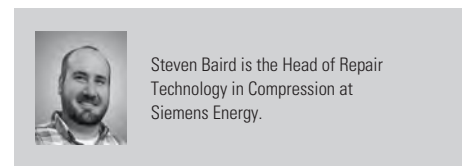
Laser scanning can be used to virtually assemble compressor components before physical assembly. Piecing digital scans together ensures that any potential fitment or interference issues are identified early on. Precision machining can occur before reassembly so that delays during the compressor overhaul or plant turnaround are avoided.

For example, digital preassembly and reassembly of a steam turbine spare rotor allowed a service center to ship components to an offsite machine shop on Day 2 of the turnaround. Had scanning not been used, this likely would have occurred on Day 7 or 8.

CHANGING THE STATUS QUO

Minimizing the duration of planned and unplanned outages remains a priority for process plant operators as they seek to improve margins and extend the useful life of their facilities. 3D laser scanning supports these goals by enhancing the speed and efficiency of inspections. Now, with Gen AI, compressor OEMs can take the next step by further automating the repair process and unlocking new capabilities that have previously not been possible.

As these technologies continue to advance, they will eventually become the standard for inspection and repair, generating tangible value for both manufacturers and their customers through lower costs, improved repair consistency, and shorter equipment overhauls. ■



Myth: Compressor Transient Surge Analysis is Really Accurate

Most transient surge analysis software relies on significant assumptions about one- versus three-dimensional effects and presumes steady-state compressor maps.

BY KLAUS BRUN & RAINER KURZ

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The transient behavior of most physical systems is often fundamentally different from their static behavior. This principle ties back to Newton's second law, which incorporates acceleration as a second derivative term. For example, the movement of a race car accelerating through a curve cannot be analyzed by superimposing its stationary positions over time. This approach neglects the 3D inertial forces acting on the vehicle. However, for the sake of simplicity, quasi-static analysis is typically employed in engineering tools. Such an approach simplifies complex problems by treating transient phenomena as a series of steady-state conditions. This method is sufficient for many slow-moving physical processes, as transient effects can often be disregarded when inertial forces are minimal. Unfortunately, this simplification can lead to the misapplication of analysis methods when transient problems are analyzed using tools or software designed for steady-state scenarios.

For example, the characteristics of centrifugal or axial compressors are usually described with a head-flow map that assumes all operating points are stable and that thermal transfer is negligible; however, unless a compressor operates under a single condition for an extended period, allowing all heat-soaking effects to reach equilibrium, most real operating points are inherently transient. This is particularly true during startup and shutdown phases, especially in emergency-related fast shutdowns.

We previously discussed the phenomenon of surge in our Myth Busters column: Surge is a violent physical occurrence in centrifugal compressors that can potentially cause significant damage. It occurs when a compressor operates at the low-flow end of its range, where the impellers' aerodynamic capability falls below the threshold needed to produce sufficient head to overcome the pressure differential between high discharge and low suction pressure. This imbalance reverses flow, temporarily rebalancing the

pressures until the compressor generates forward flow and head.

Surge is a periodic and cyclic phenomenon that occurs at characteristic frequencies of the compressor and piping system, independent of the running speed. The full-flow reversals inherent to surge create significant forces that can severely damage various internal components. While the phenomenon has been thoroughly documented in existing literature and will not be explained here, it is essential to recognize that all compression systems are susceptible to surge. Correspondingly, surge control systems are designed to ensure compressors operate away from the surge line, avoiding the dynamically unstable region.

When assessing the operating stability of centrifugal compressors within complex plant piping systems—particularly their ability to avoid surge—transient surge analysis is often conducted. This analysis involves a detailed, one-dimensional evaluation of the compressor and its associated components, including valves, pipes, vessels, and the control system behavior. The goal is to evaluate the system's capability to prevent surge under four transient scenarios: startup, process control, controlled shutdown, and emergency shutdown. Emergency shutdowns present the greatest challenge, as they lead to notable process change orders faster than any other situation. Failure of a compression train in a station—with multiple trains in operation—is another situation with rapid changes in operating conditions. Therefore, the surge control system must respond rapidly, opening the recycle valve to prevent the compressor from crossing the surge line as it decelerates quickly under a high-pressure differential.

Two key factors determine how close a system can operate to the surge line during an emergency shutdown:

- the system's response, including surge control capabilities
- the physical impact of surge on the compressor

The latter is often overlooked. Many robust low-energy compressors could theoretically operate in surge indefinitely without sustaining damage, as long as the temperatures stay reasonable. Extending the normal operating range closer to the surge line is acceptable for such machines. Conversely, more sensitive or process-critical compressors require a safe surge margin to ensure, through a properly conducted dynamic analysis, that the system remains out of surge.

Unfortunately, many fixed and variable operating parameters and fluid properties are unknown before a machine begins operation. The analysis itself is complicated, requiring fluid dynamics modeling across the entire system under rapidly changing boundary conditions. Factors such as driver shutdown dynamics—involving electric motors, steam turbines, or gas turbines—are seldom modeled accurately. Even the compressor's mechanical behavior and performance map pose challenges, as these models are based on steady-state assumptions. For example, standard compressor head-flow performance maps derive from measurements taken under steady conditions with the compressor in thermal equilibrium. During quickly changing process conditions, thermal equilibrium doesn't exist.

The ability to prevent surge during an emergency shutdown is typically determined using simplified estimation tools. Two primary methods are employed: experience-based non-dimensional numbers—which consider piping volumes, inertia, and compressor power—and low-fidelity dynamic simulations. The latter combines lumped representations of the system's physics with experimental data, and generally, the speed decay of the compressor must be estimated.

When the shutdown behavior of the driver, train inertia, system volumes, or valve-opening characteristics are known, these simplified tools can offer insights into dynamic system behavior and aid in

conceptual decisions, such as determining the necessary number of valves early on in a project. However, non-dimensional number models lack sufficient accuracy for these analyses. Most compressor manufacturers mandate that surge control systems prevent short transient surges during rapid emergency shutdowns. This is prudent for the operator since repeat surges may degrade compressor performance. Increasing compression ratios and demanding operating conditions have made using hot-gas bypass valves and the surge control valve to mitigate compressor surges during emergency shutdowns more common.

Achieving satisfactory performance requires a carefully designed and optimized surge control system, which depends on detailed and accurate engineering analysis. Simplified rules-of-thumb, non-dimensional models, or basic lumped volume models cannot accomplish this. A well-implemented, full-time-domain numerical one-dimensional dynamic compressor analysis, calibrated with real test data, can achieve modeling uncertainties as low as 10 - 20%. This assumes that the driver behavior, heat transfer, dynamic compressor behavior, and control system behavior are correctly implemented. It also assumes that the instrumentation that feeds data into the control system is calibrated correctly and accurately.

The industry's transient one-dimensional dynamic analysis tools have significantly improved over the past five to 10 years and have been repeatedly validated with test data. However, any engineering tools with uncertainty over 10% cannot be used to reduce design safety margins (such as head rise to surge or turndown) that are lower than that or, as an alternative, require increasingly expensive valves. Thus, even with these advancements, analysis results must be interpreted conservatively to facilitate sound surge control system design decisions. When analysis tools with significant inherent uncertainties are used,

achieving a reasonable design is impossible when critical parameters demand accuracy within a few percent.

Clearly, the physics of compressor shutdowns is highly complex, leaving many real-world effects unaccounted for. The accuracy of any complex analysis is contingent on the quality of its assumptions and boundary conditions. In transient surge analysis, these assumptions and boundary conditions are often poorly understood, leading to inaccurate results. Most commercially available transient surge analysis software relies on significant assumptions about one-dimensional versus 3D effects and presumes steady-state compressor maps.

Additionally, these tools frequently fail to accurately model driver dynamics, transient pressure waves, and surge control system behavior, which can lead to substantial errors. In many cases, transient surge analysis results have such high uncertainties that overly conservative surge margins, restricting a compressor's operating range, are required.

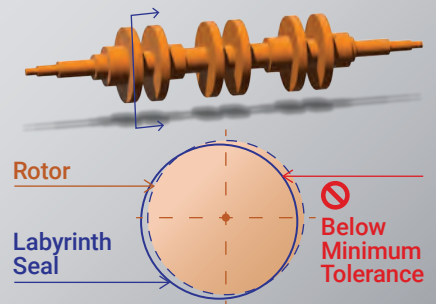
An engineering analysis is only as good as its assumptions. This is especially true for transient surge analysis where physical modeling is challenging, boundary conditions are often gross estimates, and required design margins for safe operation are very tight. Consequently, transient surge analysis outcomes are often so generic that they lack practical value or drive cost for the yard valves. ■



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