NATIONAL ENERGY TECHNOLOGY LABORATORY

AVAILABLE TECHNOLOGIES

OIL & GAS

U.S. DEPARTMENT of ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

FY 2027

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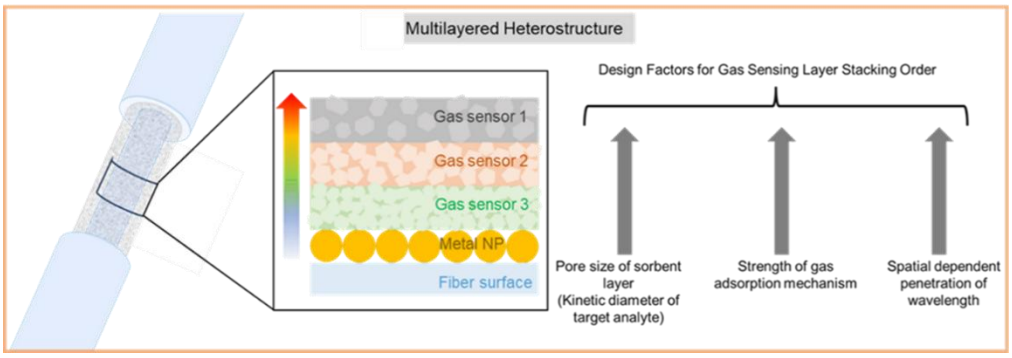
Heterostructure and Composite Coating with Edge Compatible Analytics Framework for Multiparameter Optical Fiber Point Sensing (25N-02)

Opportunity

Detecting multiple gases or chemicals simultaneously presents a significant challenge due to the inherent complexity of sensor responses and the high cost associated with current solutions. NETL and the University of Pittsburgh (Pitt) utilized an optical fiber coated with a multilayer heterostructure, where distinct sensing layers, including metal nanoparticles and various gas-sensitive materials, are vertically arranged. This design exploits wavelength-dependent penetration depths of leaky optical waveguide modes, allowing broadband light to interact selectively with different layers at varying depths, thereby enabling simultaneous detection of multiple gases and temperature through wavelength-division multiplexing. Complex spectral data generated by the sensor is then analyzed by a physics-informed machine learning algorithm, which is trained on a synthetic dataset that combines empirical measurements and physics-based simulations, to accurately discriminate and quantify multiple parameters with real-time edge inference capabilities. This technology is available for licensing and/or collaborative research from NETL and Pitt.



Multilayered heterostructure as multiparameter gas and temperature sensor using leaky mode optical penetration depth's wavelength dependence

Challenges Addressed

- Existing multimaterial sensors, such as electronic or photonic noses, often produce vast and intricate datasets that are difficult to accurately interpret

Potential Commercial Applications

- Simultaneously detects multiple gases and temperature at low cost and in real time, making it ideal for safety, leak detection, and emissions monitoring in factories
- Multiparameter, real-time sensing with physics-informed analytics enables precise monitoring of chemical reactions and material compositions

Competitive Advantages

- Multilayer heterostructure coating on optical fibers enables simultaneous detection of multiple gases and environmental parameters, surpassing traditional single-parameter sensors that require multiple devices for comprehensive monitoring
- Sensor's fabrication costs are potentially under $1 per device, offering a more affordable solution compared to existing multiparameter sensors

Intellectual Property Status

A PCT application has been filed.

Licensing/Collaboration

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Inventors

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Multiparameter Fiber-Optic Monitoring for Oil and Gas Pipelines (23N-16)

Opportunity

Monitoring the integrity of pipelines, power grids, and other critical infrastructure remains a major challenge because existing sensor systems are costly, limited in range, and typically measure only a single parameter at a time. To address this need, NETL has developed a new type of distributed optical fiber sensor that can measure multiple parameters at once, including temperature, strain, and vibration, over long distances. The system combines two complementary sensing methods with a wavelength diversity approach to improve accuracy and reduce errors, delivering reliable measurements across 25 kilometers of fiber. A specialized optical interrogation enables multiparameter monitoring and long-range performance. Unlike conventional systems that require separate fiber cables and interrogators for each type of measurement, this invention consolidates multiple sensing functions into a single platform, significantly lowering costs and complexity. Capturing several critical data streams simultaneously improves safety and decision-making for operators by providing a more complete picture of infrastructure conditions. This invention offers a comprehensive solution for monitoring energy infrastructure and is available for nonexclusive licensing and/or collaborative research from NETL.

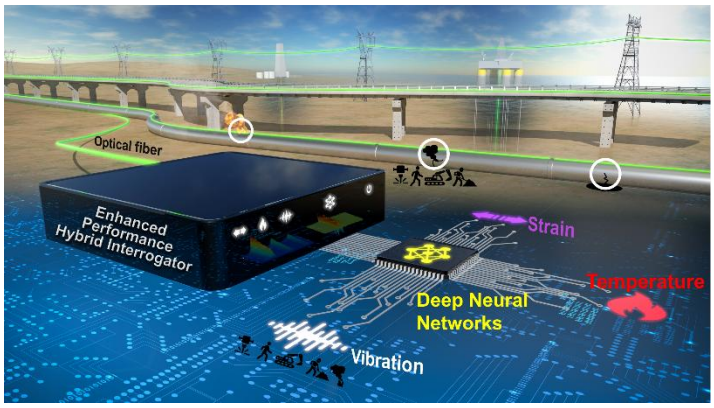

Diagram of NETL multiparameter fiber-optic monitoring

Challenges Addressed

- Most existing fiber sensors typically measure only one parameter, requiring separate interrogators and fibers for each measurand, which increases system complexity and cost
- Noise, cross-sensitivity and limited range reduce reliability and cause false alarms
- High system complexity and cost restricts widespread deployment for long-distance oil and gas pipeline monitoring

Potential Commercial Applications

- Real-time remote detection of leaks and third-party intrusion
- Continuous assessment of transmission lines and transformers to prevent outages
- Ensuring structural integrity and safety in drilling and production

Competitive Advantages

- Simultaneously measures strain, temperature, vibration, and chemical changes with one system
- Monitors up to 25 km with high accuracy, reducing false alarms and improving reliability
- Lowers installation costs and complexity by using a single fiber and interrogator unit

Intellectual Property Status

A nonprovisional patent application has been filed in the U.S.

Publications

N. Lalam, et al. Achieving Precise Multiparameter Measurements with Distributed Optical Fiber Sensor Using Wavelength Diversity and Deep Neural Networks. (2024). *Commun. Eng.* 3, 121. https://doi.org/10.1038/s44172-024-00274-5.

Licensing/Collaboration

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Inventors

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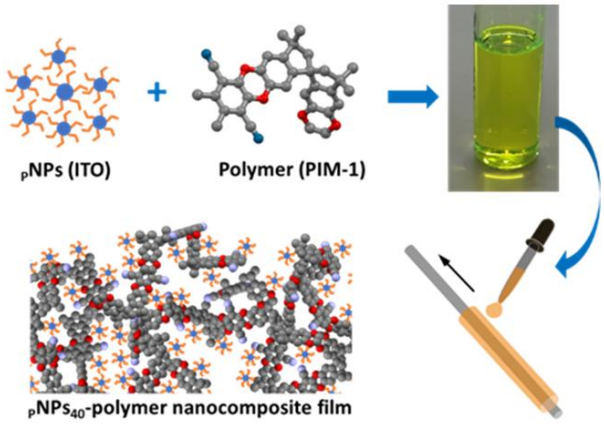
Tunable, Long-Life Fiber-Optic Sensor with Composite Coating for Industrial Gas Detection (23N-04)

Opportunity



Industrial facilities depend on gas-monitoring systems that remain accurate over long operating periods, yet many existing sensors struggle with drift, polymer degradation, or insufficient sensitivity at ambient temperatures. To address these limitations, researchers at NETL created a fiber-optic platform that uses a composite coating of tin-doped indium oxide nanocrystals and a microporous polymer to enhance refractive-index response during gas exposure. The coating embeds 1–30 nm plasmonic nanoparticles within a polymers-of-intrinsic-microporosity matrix, allowing absorbed gases such as methane or hydrogen to modulate the localized surface plasmon resonance of the film. This process produces rapid, reversible optical changes while maintaining the mechanical and chemical durability of a silica-fiber sensor. The architecture enables wavelength tuning, long operational lifetimes, and low-cost fabrication compatible with distributed fiber networks. This technology is available for nonexclusive licensing and/or collaborative research from NETL.

Challenges Addressed

- Conventional gas sensors often require high temperatures or complex nanofabrication, increasing cost and limiting scalability
- Many systems suffer from polymer aging and poor long-term stability under continuous operation
- There is a need for a durable, low-maintenance platform that operates at room temperature and delivers consistent performance over time

Potential Commercial Applications

- Industrial gas leak detection in chemical, manufacturing, and energy facilities
- Pipeline monitoring for methane or hydrogen leaks
- Safety systems for underground mines or confined industrial environments

Competitive Advantages

- Responds within seconds, outperforming electrochemical and diffusion-limited sensing technologies
- Maintains accuracy for over 40 weeks with only ~7% signal decrease
- Avoids expensive nanolithography and vacuum deposition steps common in traditional surface plasmon resonance sensor manufacturing

Intellectual Property Status

A nonprovisional patent application has been filed in the U.S.

Publications

J. Culp, et al. Sorption-Induced Tunable Fiber Optic Plasmonic Gas Sensing. (2024). *United States Patent and Trademark Office*. U.S. Patent Application Publication No. US20240272072A1.

Licensing/Collaboration

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Inventors

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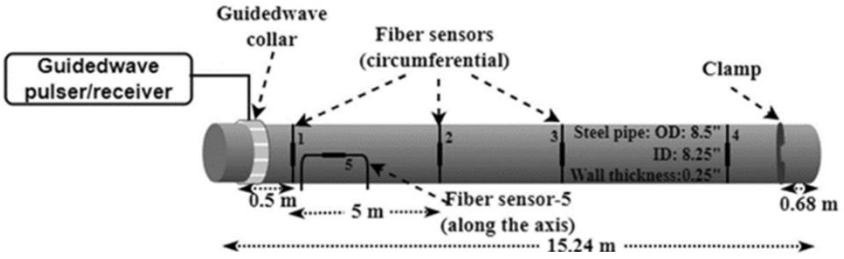
Fiber-Optic Sensor and Guided Acoustic Wave Monitoring Fusion for Pipelines (23N-01)

Opportunity



Schematic illustration of the guided wave acoustic/fiber-optic fusion system for pipeline health monitoring

Pipeline operators require monitoring systems that capture distributed structural changes rather than isolated inspection points, especially in environments where access is limited and electromagnetic interference may degrade electronic instruments. To address this need, NETL, in partnership with the University of Pittsburgh (Pitt), developed a sensing architecture that merges guided acoustic wave interrogation with multiplexed fiber-optic acoustic sensors. The system uses single-mode–multimode–single-mode (SMS) fiber structures capable of detecting vibration-induced spectral shifts from 10 Hz to 400 kHz, while guided waves generated along the pipe reveal reflections from corrosion, cracking, or third-party intrusion. Combining these modalities enables continuous, real-time localization of defects over long distances with minimal sensor footprint and straightforward fabrication. This technology is available for licensing and/or collaborative research through NETL in partnership with Pitt.

Challenges Addressed

- Point sensing and narrow bandwidth limit defect coverage in conventional guided wave systems
- Electrical sensors are bulky, susceptible to electromagnetic interference, and less practical for long runs
- Existing fiber solutions can be costly, complex to fabricate, and difficult to scale for multipoint monitoring

Potential Commercial Applications

- Continuous structural health monitoring of liquid and gas transmission pipelines
- Detection and localization of corrosion, erosion, fatigue, weld anomalies, and third-party intrusion
- Retrofit monitoring for remote or harsh environments where electromagentic interference immunity is required

Competitive Advantages

- Wide frequency response from 10 Hz to 400 kHz for high-resolution defect detection
- Quasidistributed sensing via multiplexed SMS fiber sensors for scalable coverage along the pipe
- High sensitivity with optical immunity to electromagnetic interference and suitability for harsh conditions
- Cost-effective sensor fabrication and integration with active guided wave excitation and advanced analytics

Intellectual Property Status

A PCT application has been filed in the U.S.

Publications

P. Ohodnicki, et al. Pipeline Monitoring Based on Ultrasonic Guided Acoustic Wave and Fiber Optic Sensor Fusion. (2024). *World Intellectual Property Office.* PCT Patent Application No. WO2024206298A1.

Licensing/Collaboration

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Inventors

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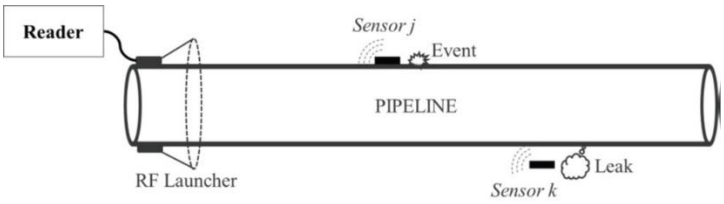
Structure-Guided Wireless Sensing Using Goubau Line (22N-15)

Opportunity

Accurate, long-range monitoring of metallic infrastructure is challenging due to signal loss, interference, and limited range in conventional wireless systems. NETL and the University of Pittsburgh (Pitt) have developed a wireless sensor platform that uses electromagnetic surface waves known as Goubau waves, which travel along a single metallic conductor rather than through open air. This design enables secure and efficient data communication over extended distances by reducing signal attenuation caused by surrounding materials such as soil, concrete, or insulation. The technology allows multiple passive sensors, including surface acoustic wave, surface spoof plasmon, and radio frequency identification devices, to be interrogated along the same structure. The reflected signals are analyzed to detect parameters such as temperature, strain, pressure, or localized material degradation. This approach provides durable, high-fidelity monitoring for pipelines and other metallic systems where traditional wireless methods are unreliable. This technology is available for licensing and/or collaborative research from NETL in partnership with Pitt.



Schematic of single-line guided surface wave-based sensing for pipeline monitoring

Challenges Addressed

- Conventional wireless sensor networks experience high signal loss and interference near metallic structures or in enclosed environments
- Limited communication range restricts monitoring of large-scale systems such as pipelines and facility infrastructure
- Free-space signal transmission can introduce data security concerns and instability under harsh environmental conditions

Potential Commercial Applications

- Structural health monitoring of pipelines, power plants, and industrial facilities
- Utility and water distribution systems
- Monitoring of nuclear waste containment and chemical process equipment
- Aerospace and manufacturing applications requiring continuous structural data

Competitive Advantages

- Extends communication range using guided surface electromagnetic waves
- Reduces signal loss and interference in harsh or confined environments
- Improves data security by limiting free-space signal propagation
- Supports multiple wireless sensor types for multiparameter monitoring
- Offers cost-effective deployment using existing metallic infrastructure

Intellectual Property Status

A nonprovisional patent application has been filed in the U.S.

Publications

P. Ohodnicki, et al. System and Method Employing Single Line Guided Surface Electromagnetic (Em) Waves for Wireless Sensing. (2024). *United States Patent and Trademark Office.* U.S. Patent Application Publication No. US20250052696A1.

Licensing/Collaboration

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Inventors

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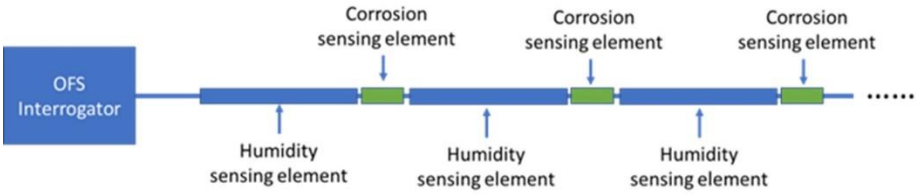
Distributed Multiparameter Sensors for Corrosion and Humidity Monitoring (22N-05)



Schematic of distributed multiparameter OFS sensor for simultaneous monitoring of corrosion and humidity

Opportunity

Corrosion and humidity are leading causes of structural degradation in pipelines, bridges, and other critical infrastructure, often going undetected until costly failures occur. NETL has developed distributed multiparameter sensor systems that simultaneously monitor corrosion and humidity in real time. Using either optical fiber sensors (OFS) or surface acoustic wave (SAW) sensors, the system enables early detection of corrosion onset, moisture accumulation, and other precursors to damage across long distances and harsh environments. The optical fiber configuration integrates metal-coated and polymer-jacketed segments interrogated by optical frequency domain reflectometry to provide spatially resolved measurements of corrosion and humidity along a single fiber. Alternatively, the passive wireless SAW sensor array uses humidity- and corrosion-sensitive coatings to detect resonant frequency shifts, enabling wired or wireless monitoring. This technology is available for licensing and/or collaborative research from NETL.

Challenges Addressed

- Conventional corrosion monitoring relies on periodic inspections and localized sensors that cannot deliver continuous or distributed data
- Existing techniques are costly, limited in coverage, and often fail to detect early signs of corrosion or humidity-induced degradation
- Current sensors may lose accuracy or fail in harsh industrial conditions due to temperature, pressure, or electromagnetic interference

Potential Commercial Applications

- Continuous corrosion and humidity monitoring in oil, gas, and water pipeline networks
- Structural integrity management for bridges, tunnels, aircraft, and industrial facilities
- Monitoring of turbines, reactors, and combustion systems exposed to extreme environments

Competitive Advantages

- Simultaneous, real-time measurement of corrosion and humidity along a single optical fiber or multielement SAW array
- Distributed sensing enables spatial mapping of conditions over extended distances
- Operable in both liquid and gaseous environments, with resilience to heat, pressure, and electromagnetic interference
- Wireless and passive operation reduces maintenance and installation costs

Intellectual Property Status

A nonprovisional patent application has been filed in the U.S.

Publications

R. Wright, et al. Distributed Multi-parameter Sensors for Simultaneous Monitoring of Corrosion and Humidity: Optical Fiber Sensors and Surface Acoustic Wave Sensors. (2023). *United States Patent and Trademark Office.* U.S. Patent Application Publication No. US20230333024A1.

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Inventors

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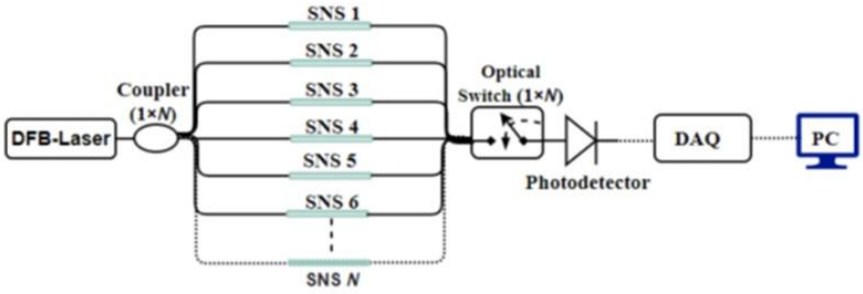
Multiplexed Sensor System (22N-02)

Opportunity

Monitoring vibrations and acoustic emissions is critical for assessing the health of energy infrastructure, transportation systems, and industrial equipment. NETL and the University of Pittsburgh (Pitt) have developed a low-cost acoustic emission monitoring system that uses multiplexed single-mode-no-core-single-mode (SNS) fiber sensors to detect vibrations through multimode interference. The system provides high sensitivity, broad frequency coverage from 1 Hz to 400 kHz, as well as simplified fabrication compared to traditional optical sensing approaches such as fiber Bragg gratings (FBG) and phase-sensitive optical time-domain reflectometry (φ-OTDR). By combining multiple SNS sensors through optical multiplexing, the technology delivers quasidistributed acoustic and vibration sensing for real-time monitoring across diverse environments. This technology is available for licensing and/or collaborative research from NETL and Pitt.



Schematic of SNS fiber sensors

Challenges Addressed

- Conventional optical sensors such as FBG and φ-OTDR systems are costly, complex, and limited in sensitivity or frequency range
- Existing systems often require expensive lasers, complex demodulation electronics, and long acquisition times that reduce responsiveness
- Current fiber-optic vibration sensors exhibit signal fading, limiting detection accuracy
- Many monitoring systems lack distributed or multiplexed sensing capabilities for extended coverage

Potential Commercial Applications

- Pipeline and energy infrastructure integrity monitoring
- Real-time acoustic emission detection in power plants, reactors, and turbines
- Vibration monitoring in transportation systems, including railways, bridges, and roadways
- Seismic, subsea, and structural health monitoring in industrial or military applications
- Automotive diagnostics, flow monitoring, and smart city sensor networks

Competitive Advantages

- Low-cost, simple fabrication compared to FBG and DAS technologies
- Broad frequency response ranges from 1 Hz to 400 kHz
- High sensitivity and improved signal-to-noise ratio for vibration and acoustic detection
- Quasidistributed sensing via multiplexed SNS fiber configuration
- Scalable and versatile system adaptable to harsh and remote environments

Intellectual Property Status

A nonprovisional patent application has been filed in the U.S.

Publications

P. Ohodnicki, et al. Monitoring System Based on Multiplexed Multimode Interferometric Sensors. (2023). *United States Patent and Trademark Office*. U.S. Patent Application Publication No. US20250207954A1.

Licensing/Collaboration

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Inventors

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Atomic Layer Deposition Sensing and Protection Layers for Optical Fiber Sensors (21N-10)

Opportunity

High-temperature reactors, fuel cells, and harsh gas environments require sensors that maintain stable performance where conventional electronic devices fail. Optical fiber sensors can withstand elevated temperatures, but their response and durability depend heavily on the functional layers applied to the fiber surface. To meet this need, researchers at NETL and the University of Pittsburgh (Pitt) have established a method for forming nanometer-scale sensing or protection layers on optical fibers using atomic layer deposition (ALD). This approach enables uniform, conformal coatings of refractory oxides such as TiO_2, ZrO_2, or Al_2O_3 as well as engineered films containing plasmonic or quantum dot nanoparticles. These layers enhance chemical selectivity, improve resistance to corrosive species, and maintain optical stability at temperatures exceeding those tolerated by typical sensing materials. The precise thickness control offered by ALD allows the coatings to be tailored for evanescent-wave–based detection schemes used in optical fiber sensing. This technology is available for licensing and/or further collaborative research from NETL in partnership with Pitt.

Challenges Addressed

- Electrical-based sensors often suffer from instability and degradation when exposed to extreme temperatures and nonambient chemical environments
- There is a need for protective layers to prevent long-term degradation of sensor materials in such harsh environments

Potential Commercial Applications

- Ability to integrate oxide-based sensing layers with optical fibers allows for accurate monitoring of gas stream chemistry at elevated temperatures
- Protective oxide layers deposited via ALD enhance the durability and stability of optical fiber sensors in nonambient gas atmospheres

Competitive Advantages

- Provides a uniform, conformal coating structure that enhances the stability of sensing responses and optical fiber transmission compared to sol-gel-based wet chemistry deposition
- ALD-coated oxides serve as protective layers, mitigating long-term degradation at high temperatures in nonambient gas atmospheres
- ALD is compatible with scalable coating of optical fiber samples, offering an advantage over other methods that may not be as easily scalable for mass production

Intellectual Property Status

A U.S. patent (US11782210B2) was issued October 10, 2023, and expires April 7, 2042.

Publications

P. R. Ohodnicki, et al. Sensing and/or Protection Layers for Optical Fiber-Based Sensors Using Atomic Layer Deposition Synthesis on Optical Fibers. (2023). *United States Patent and Trademark Office.* U.S. Patent No. 11782210.

Licensing/Collaboration

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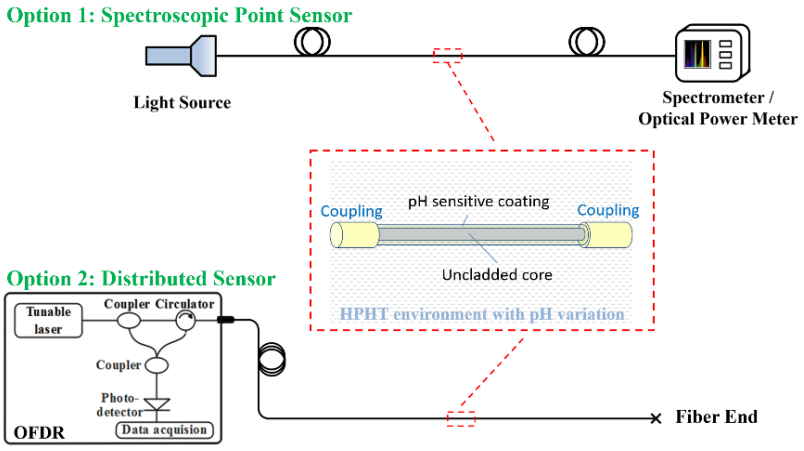
Inventors

Paul Ohodnicki, Jr., Jung-Kun Lee, Yulin Liu, Ruishu Wright, Fei Lu, and Jeffrey Wuenschell

Fiber-Optic pH Sensor for High-Temperature and High-Pressure Environments (20N-24)



Opportunity

Measuring pH in deep subsurface and industrial systems is essential for detecting corrosion, predicting cement degradation, and ensuring long-term operational safety. However, most conventional sensors fail under the high temperatures, pressures, and salinity typical of these environments. NETL has developed a fiber-optic pH sensor that uses a metal oxide-based coating to provide reversible and repeatable optical response over a broad pH range. The sensor operates without electrical components at the measurement site, enabling continuous, real-time pH monitoring in environments that exceed the limits of traditional electronic systems. This technology is available for licensing and/or collaborative research from NETL.

Challenges Addressed

- Inability of conventional electrode-based sensors to function reliably in deep or high-temperature environments
- Electrical component failure in corrosive and high-salinity wellbore conditions
- pH instability and measurement drift caused by degradation of polymer or dye-based coatings
- Difficulty monitoring cement chemistry and corrosion in real time during well operation or abandonment

Potential Commercial Applications

- Continuous pH monitoring in wellbores for early detection of corrosion and cement failure
- Subsurface sensing in oil, gas, geothermal, and underground storage systems
- Real-time monitoring of fluid chemistry in nuclear and chemical process facilities
- Corrosion detection in pipelines, wellbore plugs, and water-handling infrastructure
- Embedded or distributed sensing systems for industrial and research applications

Competitive Advantages

- Provides stable optical response to pH while resisting leaching and degradation at high temperature and pressure
- Operates without electrical wiring, preventing electromagnetic interference and hardware failure
- Lightweight design enables deployment in confined or distributed sensing networks
- Maintains accuracy and response stability over repeated cycles
- Compatible with additional optical coatings for temperature, pressure, or chemical monitoring

Intellectual Property Status

A nonprovisional patent application has been filed in the U.S.

Publications

F. Lu, et al. Metal Oxides Enabled Fiber Optic pH Sensor for High Temperature High pH Subsurface Environments. (2022). *United States Patent and Trademark Office*. U.S. Patent Application Publication No. US20220341902A1.

Licensing/Collaboration

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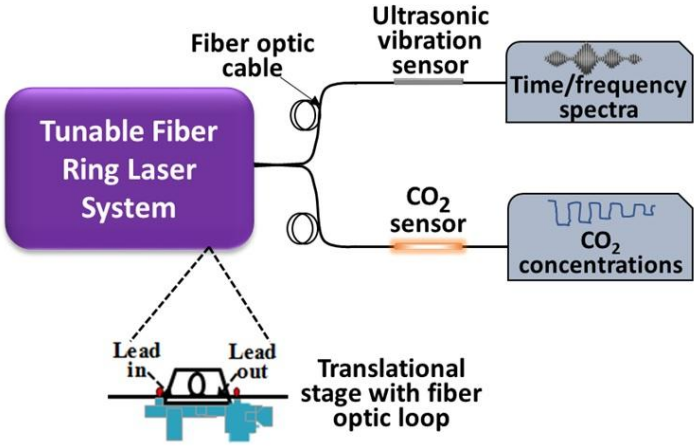
Inventors

Fei Lu, Ruishu Wright, Paul Ohodnicki Jr., and Ping Lu

Tunable Fiber Ring Laser for Dual Sensing (20N-23)

Opportunity

Real-time detection of gas composition and vibration signatures is critical for maintaining the safety and performance of pipelines, reactors, and industrial systems. NETL has developed a compact, low-cost fiber-optic sensor system that simultaneously measures both gas concentration and vibration using a single tunable fiber ring laser. This dual-function configuration simplifies traditional setups that require separate instruments, reducing system cost and complexity while improving accuracy and sensitivity. The invention integrates a vibration sensor based on a single-mode-multimode-single-mode (SMS) fiber structure with a gas detection module using a coreless optical fiber coated with a gas-sensitive film. The unified system enables continuous, high-resolution monitoring in harsh or confined environments. This technology is available for licensing and/or collaborative research from NETL.



System design for simultaneous vibration and gas sensing based on a tunable fiber ring laser

Challenges Addressed

- Conventional vibration sensors are prone to electromagnetic interference and limited frequency bandwidth
- Fiber-optic sensors using Bragg gratings or interferometers require complex fabrication and exhibit low sensitivity
- Gas and vibration parameters typically require separate systems, increasing cost and integration difficulty
- Existing sensor configurations lack compactness and real-time dual-parameter functionality

Potential Commercial Applications

- Condition monitoring of gas transmission and storage systems
- Integrity assessment of wellbores, reactors, and industrial process equipment
- Structural and vibration monitoring in turbines, transformers, and power systems
- Environmental or process gas analysis in transportation, aerospace, and manufacturing sectors

Competitive Advantages

- Dual sensing capability for gas and vibration using a single laser source
- Wide vibration frequency detection range (10 Hz to 400 kHz)
- Resistant to electromagnetic interference and extreme conditions
- Enables remote, real-time monitoring with improved sensitivity and signal quality

Intellectual Property Status

A U.S. patent was issued May 27, 2025, and expires August 26, 2043.

Publications

N. Lalam, et al. Simultaneous Ultrasonic Vibration and Gas Sensing Based on a Tunable Fiber Ring Laser. (2022). *United States Patent and Trademark Office.* U.S. Patent No. 12,313,540.

Licensing/Collaboration

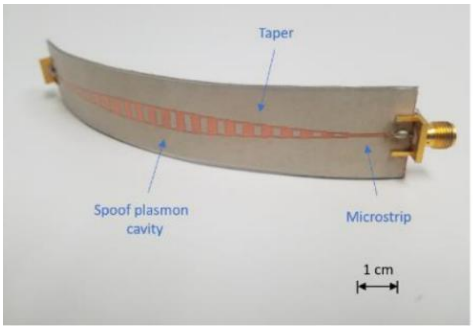
Partnerships@netl.doe.gov

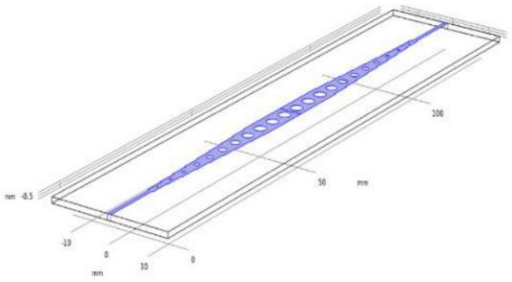
Inventors

Nageswara Lalam, Michael Buric, Ping Lu, Fei Lu,Tao Hong, and Ruishu Wright

Plasmonic Metamaterial Waveguide Sensor (20N-16)

Opportunity





(Left) Geometry of the sensor with rectangular apertures and (right) sensor with circular apertures

Detecting small changes in environmental conditions, such as trace gases or chemical contaminants, requires sensors that are highly sensitive, inexpensive to manufacture, and compatible with wireless interrogation. Conventional microwave and radio frequency sensors often struggle to detect subtle permittivity changes, limiting their usefulness in applications such as infrastructure monitoring, industrial process control, or gas detection. Researchers at NETL designed a plasmonic metamaterial waveguide sensor that enhances electromagnetic field localization to improve detection sensitivity. The device uses a spoof plasmon waveguide made from a patterned conductive layer on a substrate, forming cavities that strongly interact with the surrounding environment. When the substrate's permittivity changes upon contact with an analyte, the resonance behavior of the guided waves shifts, enabling detection through remote microwave interrogation. This planar architecture reduces fabrication complexity, supports low-cost manufacturing, and is readily integrated with wireless systems. This technology is available for licensing and/or further collaborative research from NETL.

Challenges Addressed

- Existing approaches are constrained by their reliance on resonant phenomena that typically operate within the visible and infrared spectra, limiting their compatibility with current wireless and miniaturized systems
- Conventional sensors often struggle with achieving sufficient sensitivity to detect small changes in material permittivity, and their bulky, rigid designs hinder integration onto flexible or planar substrates

Potential Commercial Applications

- Provides wireless, passive, and flexible sensors for detecting specific gases and liquids in critical industrial environments and pipelines
- Small, flexible, and wireless nature of the sensors enables their use in portable, wearable, implantable, and point-of-care devices
- Sensitive gas/liquid sensing capabilities allow for integration into smart packaging and food processing to monitor spoilage and freshness

Competitive Advantages

- Utilizing spoof surface plasmon polaritons and functional material substrates, these sensors detect small permittivity changes more effectively than traditional gas sensors
- The structure allows for easy integration into various environments, unlike rigid, bulky sensors that are less adaptable to different applications

Intellectual Property Status

A U.S. patent (US12,455,268B2) was issued October 28, 2025.

Publications

R. Shugayev, et al. Plasmonic Microwave Metamaterial Waveguide Sensing. (2023). *United States Patent and Trademark Office*. U.S. Patent Publication No. US20230243760A1.

Licensing/Collaboration

Partnerships@netl.doe.gov

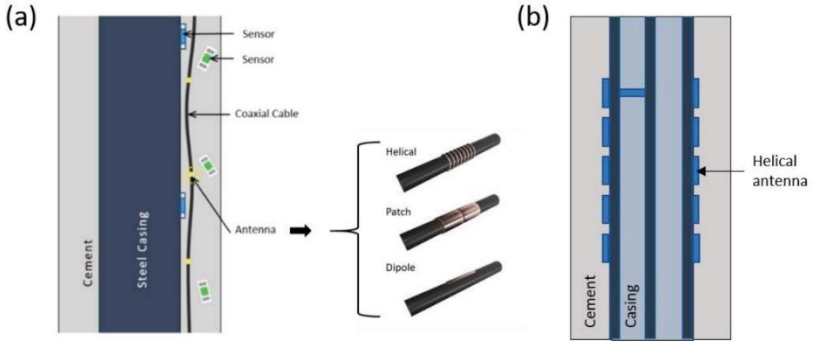
Inventors

Roman Shugayev, Jagannath Devkota, and Paul Ohodnicki

Conformal Coaxial Helical Antennas and Distributed Electromagnetic Interrogation Schemes (19N-34)

Opportunity

Monitoring subsurface environments, particularly in wellbores and geothermal settings, presents significant challenges due to the extreme conditions encountered, including high temperatures, pressures, and corrosive chemicals. To overcome these challenges, researchers at NETL utilized a distributed electromagnetic interrogation scheme employing specialized antennas integrated along a coaxial cable to enable subsurface sensing in harsh environments. The design features two primary antenna designs: conformal helical antennas, which wrap around the wellbore casing to efficiently couple to the external transverse electromagnetic propagating mode of the coaxial cable, and microstrip waveguides, which are metal-dielectric tapes attached to the casing. These antennas are designed for efficient electromagnetic radiation delivery to distributed wireless passive sensors, facilitating real-time monitoring of subsurface properties, such as rock stress states, at greater depths and higher resolution than conventional methods like ground-penetrating radar. The helical antenna design incorporates precise phase matching for optimal coupling, while the microstrip approach allows for the integration of aperture antennas with tunable radiation patterns. This technology is available for licensing and/or further collaborative research from NETL.



Wellbore sensing methodology and potential antenna designs
(a) conformal helical antenna around the (b) wellbore casing

Challenges Addressed

- Inherent electromagnetic absorption within subsurface formations, especially water-saturated ones, severely restricts the range and efficacy of conventional wireless power and signal transmission
- Ground-penetrating radar struggles with insufficient penetration depth and often compromises resolution at greater depths, making it difficult to achieve the monitoring necessary for critical applications

Potential Commercial Applications

- Continuous, high-resolution, real-time electromagnetic imaging to assess rock stress, cement integrity, fluid saturation, and other critical parameters
- Distributed, real-time electromagnetic sensing to monitor stress states, material integrity, and fluid ingress in deep underground structures

Competitive Advantages

- Allows for deeper subsurface imaging, overcoming those limitations seen in ground-penetrating radar systems
- Enables ongoing, real-time monitoring of subsurface conditions, facilitating timely decision-making and improved reservoir management

Intellectual Property Status

A U.S. patent application (US18/636,431) was filed April 16, 2024.

Publications

P. Ohodnicki, et al. Distributed Electromagnetic Interrogation System. (2025). *United States Patent and Trademark Office.* U.S. Patent Application Publication No. US20250321349A1.

Licensing/Collaboration

Partnerships@netl.doe.gov

Inventors

Paul Ohodnicki, Jagannath Devkota, Roman Shugayev, and Ruishu Wright

Metal-Organic Framework Coated Surface Acoustic Wave/Quartz Crystal Microbalance Sensors for Gas Detection (18N-19)

Opportunity

Accurate identification of complex gas mixtures requires sensing materials with predictable adsorption behavior and transducers capable of detecting extremely small mass changes. Researchers at NETL, working in partnership with the University of Pittsburgh (Pitt), created an approach that pairs metal-organic framework (MOF) coatings with mass-sensitive surface acoustic wave (SAW) or quartz crystal microbalance (QCM) devices. Each MOF layer provides a crystalline, well-defined adsorption environment whose interactions with gas molecules can be modeled and selected in advance, enabling arrays where each sensor responds to a different subset of species. When gas molecules adsorb into the MOF pores, the added mass perturbs the SAW or QCM oscillation frequency, generating a measurable signal without requiring optical or chemical labeling. The method also includes a computational workflow that screens MOFs, array sizes, and gas mixtures to identify configurations with strong discrimination capability, reducing the trial-and-error that limits traditional electronic nose designs. This integrated strategy supports broad-spectrum gas analysis using compact sensor arrays. This technology is available for licensing and/or further collaborative research from NETL in collaboration with Pitt.

Challenges Addressed

- Portable electronic noses are typically specialized for detecting specific gas mixtures or single gas species, lacking broad capabilities
- Many current gas sensor technologies, utilizing materials like polymers, metal oxides, carbon nanotubes, and zeolites, suffer from issues such as poor reproducibility, sensitivity, and selectivity

Potential Commercial Applications

- The invention can provide real-time, broad-spectrum analysis of air quality, detect pollutants, identify hazardous gas leaks, and monitor industrial processes for safety and compliance without extensive calibration
- The invention can rapidly and precisely identify unknown hazardous gases, explosives, or chemical warfare agents in real-time, providing critical information for threat assessment and emergency management without requiring prior training

Competitive Advantages

- Use of tunable MOFs on SAW or QCM sensors enables the detection of a wide range of gases without prior training
- The crystalline nature of MOFs allows for predictable gas adsorption behavior, reducing drift and enhancing long-term stability
- Existing devices typically provide concentration data for a single gas species. The invention's intelligent analytics algorithm processes responses from the sensor array to accurately determine the composition of complex gas mixtures in real-time

Intellectual Property Status

A U.S. patent (US11513100) was issued November 29, 2022, and expires August 21, 2039.

Publications

C. Wilmer, et al. Gas Sensor and Method of Optimizing an Array of Gas Sensors. (2022). *United States Patent and Trademark Office.* U.S. Patent No. 11,513,100.

Licensing/Collaboration

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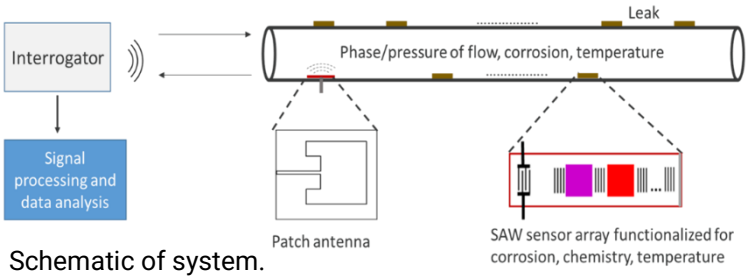
Inventors

Christopher E. Wilmer, Jenna Gustafson, Paul R. Ohodnicki, and Jagannath Devkota

Microwave Diagnostics and Passive Sensors for Metallic Tubular Infrastructure (18N-18)



Schematic of system.

Opportunity

Unplanned failures in pipelines, wellbores, and boiler tubes are costly and difficult to predict without continuous insight into internal conditions. Engineers at NETL have established a wireless monitoring approach that uses the metal tube itself as a waveguide for radio and microwave signals. Patch antennas launch and receive the guided signals, and passive surface acoustic wave sensors placed inside the structure report localized temperature, pressure, corrosion, and chemical indicators. Changes in transmitted or backscattered signals can also be analyzed without local sensors to detect faults over long distances. This technology is available for licensing and/or further collaborative research from NETL.

Challenges Addressed

- Conventional acoustic inspections provide indirect measurements that require complex modeling and can miss early degradation
- Many inline sensors need wires or batteries, adding failure points and limiting deployment in harsh environments
- Spot checks and periodic sampling do not provide real-time condition monitoring along long assets
- Existing methods struggle to localize corrosion, leaks, scaling, or changes in flow and composition inside metal tubes

Potential Commercial Applications

- Continuous health monitoring of transmission pipelines for oil, gas, carbon monoxide, steam, and water
- Boiler tube and heat recovery systems in power and industrial plants
- Wellbore integrity monitoring and completion diagnostics
- Chemical processing lines, refineries, and high-temperature process piping
- Aerospace and manufacturing systems that use metallic tubular components

Competitive Advantages

- Uses the tube as a guided medium to interrogate long sections from limited access points
- Surface acoustic wave elements require no on-board power and operate across wide temperature ranges
- Patch antennas couple efficiently to guided modes for launch, receive, and power transfer to passive sensors
- Backscatter and transmission analysis supports event detection, localization, and trending without intrusive probes

Intellectual Property Status

A U.S. patent was issued September 7, 2021, and expires September 24, 2039.

Publications

P. Ohodnicki, et al. Microwave Diagnostics and Passive Sensors for Pipeline, Well-Bore, and Boiler-Tube Monitoring. (2020). *United States Patent and Trademark Office.* U.S. Patent No. 11,113,594.

Licensing/Collaboration

Partnerships@netl.doe.gov

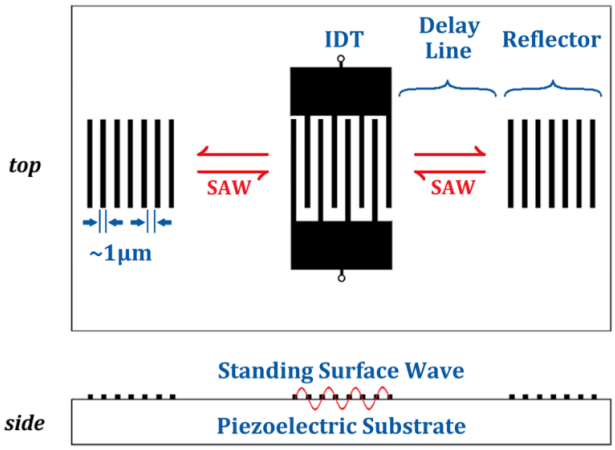
Inventors

Paul Ohodnicki, Jagannath Devkota, and David Greve

Conducting Metal Oxides Integrated with Surface Acoustic Waves Sensors for Use in Harsh Environments (18N-06)

Opportunity

Monitoring gas composition in high-temperature and chemically reactive environments is critical for maintaining process efficiency, safety, and equipment longevity. NETL has developed a method for achieving tunable gas sensitivity in surface acoustic wave (SAW) sensors through the integration of conducting metal oxides. These materials offer controllable electrical conductivity that can be optimized for specific gases and temperature ranges, enabling SAW sensors to function reliably in conditions exceeding 1,000°C. The technology allows calibration across diverse operating environments by tailoring oxide conductivity through doping or processing, producing sensors that maintain high sensitivity and stability under extreme thermal and chemical stress. This technology is available for licensing and/or further collaborative research from NETL.



Schematic of NETL surface acoustic platform wave sensor

Challenges Addressed

- Conventional SAW gas sensors exhibit limited response outside narrow conductivity ranges
- Standard metal oxide sensing films lose sensitivity at high temperatures or in reactive atmospheres
- Existing materials cannot be tuned to match varying gas compositions or temperature gradients
- Most gas sensors require wiring or external power sources, limiting their use in harsh or inaccessible locations

Potential Commercial Applications

- Gas composition monitoring in power plants, gas turbines, and combustion systems
- Process control in refining, petrochemical, and high-temperature manufacturing operations
- Aerospace and space vehicle sensor systems requiring wireless and passive operation
- Distributed sensing arrays for industrial or environmental monitoring

Competitive Advantages

- Conducting metal oxides enable adjustment of absolute film conductivity for targeted gas detection
- Operates reliably from 500°C to over 1,000°C in oxidizing or reducing atmospheres
- SAW devices require no external wiring or power sources
- Compatible with a range of piezoelectric substrates and oxide compositions
- Maintains signal stability and repeatable response across multiple sensing cycles

Intellectual Property Status

A U.S. patent was issued April 13, 2021, and expires May 22, 2039.

Publications

P. Ohodnicki. Conducting Metal Oxides Integrated with the Surface Acoustic Wave (SAW) Sensor Platform. (2019). *United States Patent and Trademark Office.* U.S. Patent Publication Application No. 10,976,287.

Licensing/Collaboration

Partnerships@netl.doe.gov

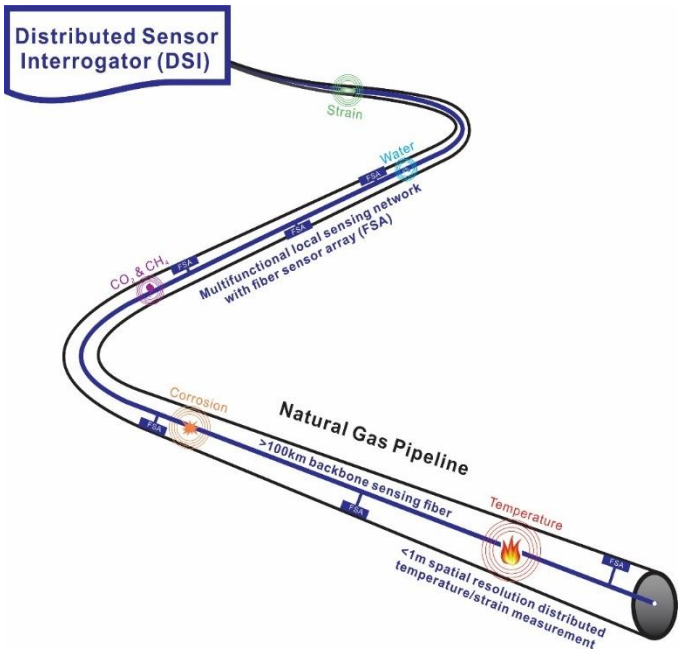
Inventors

Paul Ohodnicki, Jagannath Devkota, and Robert Fryer

Corrosion Detection Sensors for Use in Natural Gas Pipelines (17N-21)

Opportunity

Pipeline corrosion poses a major safety and economic challenge for the natural gas industry, accounting for billions of dollars in maintenance and failure-related costs each year. NETL has developed a new sensing technology that enables early detection of corrosion inside natural gas pipelines using either optical or wireless platforms. The system employs a distributed fiber-optic network or wireless sensor array capable of monitoring localized condensation and corrosion indicators along extensive pipeline systems, allowing operators to predict corrosion rates and implement preventive measures before damage occurs. This technology is available for licensing and/or further collaborative research from NETL.



Challenges Addressed

- Corrosion is responsible for a significant portion of natural gas pipeline failures and associated maintenance costs
- Existing inspection and monitoring systems are limited in their ability to detect early corrosion or localized pitting
- Pipeline operators need real-time, distributed sensing systems that can detect internal corrosion onset without disrupting operations

Potential Commercial Applications

- Real-time corrosion monitoring for natural gas transmission and gathering lines
- Structural health assessment for oil, gas, and chemical pipeline infrastructure
- Integration into digital pipeline management and predictive maintenance systems
- Monitoring of other metal structures exposed to moisture or corrosive environments
- Deployment in subsea, industrial, or refinery applications where internal corrosion risk is high

Competitive Advantages

- Identifies corrosion indicators such as water droplet condensation and pH changes
- Available in both optical fiber and wireless sensor configurations
- Enables precise, spatially resolved corrosion detection along pipeline segments
- Detects subtle chemical and environmental variations before visible corrosion occurs
- Provides continuous data without requiring invasive inspection procedures

Intellectual Property Status

A U.S. patent was issued August 15, 2023, and expires October 2, 2038.

Publications

P. Ohodnicki, et al. Distributed Fiber-Optic Sensor Network for Sensing the Corrosion Onset and Quantification. (2023). *United States Patent and Trademark Office.* U.S. Patent No. 11,726,047.

Licensing/Collaboration

Partnerships@netl.doe.gov

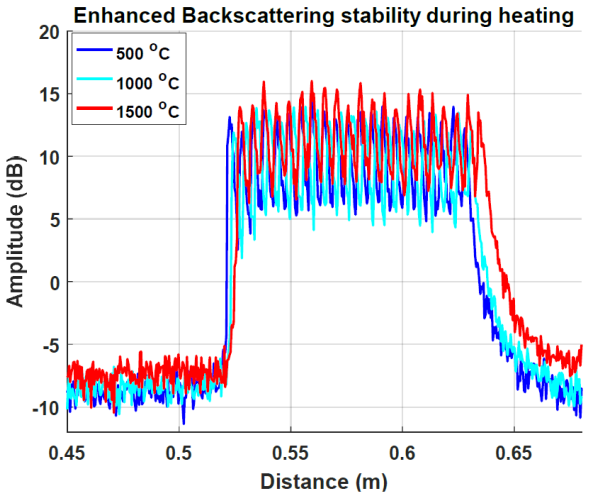
Inventors

Paul Ohodnicki, Jagannath Devkota, Ping Lu, and Ruishu Wright

Nanograting Enhanced Distributed Fiber Sensors (17N-13)

Opportunity

Reliable temperature mapping in high-temperature reactors requires optical fibers that maintain stable Rayleigh scattering profiles even after prolonged exposure to harsh thermal and chemical conditions. Rayleigh scattering arises from nanoscale refractive index variations within the fiber core, and its wavelength dependent pattern acts as a unique optical fingerprint used for distributed sensing. Researchers at NETL and the University of Pittsburgh (Pitt) established a method that uses tightly focused ultrafast laser pulses to inscribe nanograting elements directly within the fiber core. These periodic structures amplify the intrinsic Rayleigh response, improving spectral correlation for optical frequency domain reflectometry and enabling high-resolution distributed measurements. The modified fibers sustain their scattering characteristics at temperatures where standard telecommunications fibers experience structural drift, supporting long duration monitoring in systems such as solid oxide fuel cell assemblies. The fabrication process preserves the external geometry of single-mode fibers, enabling straightforward integration into existing sensing architectures. This technology is available for licensing and/or further collaborative research from NETL in partnership with Pitt.



Enhanced backscattering profile along with the central tube-furnace reading as the furnace ramped up to 1,500°C

Challenges Addressed

- Reliable distributed temperature measurements are crucial for monitoring critical infrastructure and processes, particularly in harsh environments such as solid oxide fuel cells
- Approaches involving liquids in hollow core fibers or specialized polymer fibers can be prohibitively expensive or incompatible with standard optical equipment

Potential Commercial Applications

- Enables precise, distributed temperature measurements in high-temperature and harsh industrial and energy production environments
- Provides reliable, distributed temperature sensing for critical assets and infrastructure, enhancing safety and operational integrity

Competitive Advantages

- Increases Rayleigh backscattering intensity by over 50 dB
- Remains stable up to 800°C, unlike ultraviolet-induced enhancements in hydrogen-loaded fibers, which may degrade at elevated temperatures
- Utilizes commercially available silica fibers, avoiding the need for specialized fibers like hollow-core or polymer fibers

Intellectual Property Status

A U.S. patent (US10670802) was issued June 2, 2020, and expires August 30, 2038.

Publications

P. Chen, et al. Method of Making a Distributed Optical Fiber Sensor Having Enhanced Rayleigh Scattering and Enhanced Temperature Stability, and Monitoring Systems Employing Same. (2020). *United States Patent and Trademark Office.* U.S. Patent No. 10,670,802.

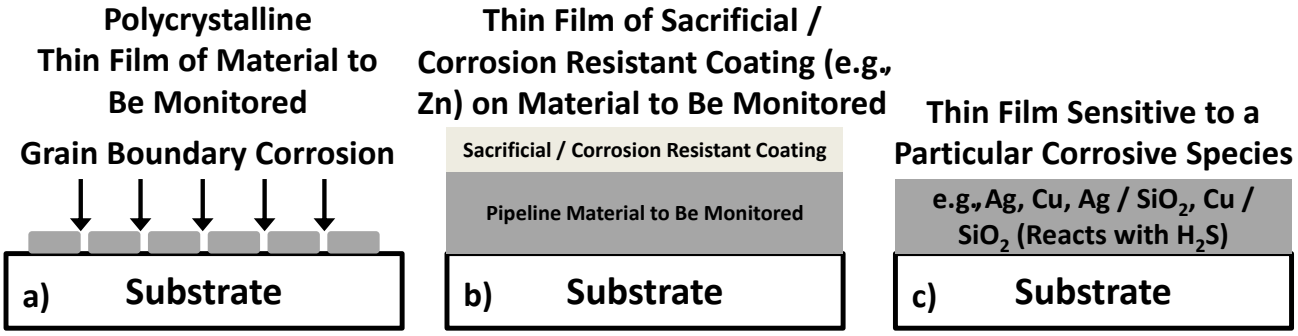
Licensing/Collaboration

Partnerships@netl.doe.gov

Inventors

Peng Kevin Chen, Aidong Yan, Michael Buric, Paul Ohodnicki, and Sheng Huang

Sensors for Corrosion Monitoring in Harsh Environments (15N-22)



Opportunity

Critical infrastructure in the subsurface and other harsh environments is routinely exposed to high temperatures, high pressures, salinity, and chemically aggressive species that accelerate corrosion. Conventional electrochemical probes require electrical contacts at the measurement point, limiting their usefulness for wide-area or distributed monitoring and increasing the likelihood of sensor failure. NETL has developed corrosion proxy material integrated sensor devices that provide early detection of corrosion onset using optical or passive wireless sensor platforms. By incorporating a thin film that corrodes faster than the underlying structural material, the system detects characteristic changes in optical, electrical, or mass-related properties before significant degradation occurs in the host component. This approach enables remote, embedded, and distributed corrosion monitoring in extreme environments without the need for electrical wiring at the sensing location. This technology is available for licensing and/or further collaborative research from NETL.

Challenges Addressed

- Conventional electrochemical sensors require electrical connections that are unreliable in harsh environments
- Existing corrosion sensors are not well suited for wide-area or distributed monitoring
- Early-stage corrosion is difficult to detect before significant structural damage occurs

Potential Commercial Applications

- Corrosion monitoring in natural gas pipelines, wellbores, and subsurface infrastructure
- Integrity assessment for offshore systems, geological formations, and high-salinity environments
- Monitoring of turbines, combustion chambers, boilers, and other high-temperature systems
- Condition-based maintenance for bridges, water pipelines, industrial assets, and critical facilities

Competitive Advantages

- Enables remote, wireless detection of early corrosion onset
- Operates under extreme temperature and pressure conditions
- Compatible with optical fiber and surface acoustic wave sensor platforms
- Facilitates wide-area, distributed monitoring without electrical connections
- Utilizes corrosion proxy films that provide measurable signals before bulk material degradation

Intellectual Property Status

A U.S. patent was issued March 1, 2022, and expires December 30, 2036.

Publications

P. Ohodnicki, et al. Corrosion Proxy Material Integrated Sensor Devices for Distributed Sensing of Early Corrosion Onset and Corrosion Quantification. (2022). *United States Patent and Trademark Office.* U.S. Patent No. 11,262,289.

Licensing/Collaboration

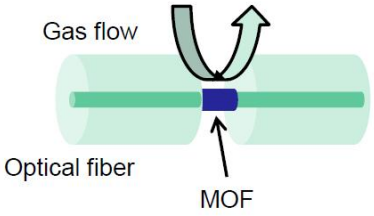
Partnerships@netl.doe.gov

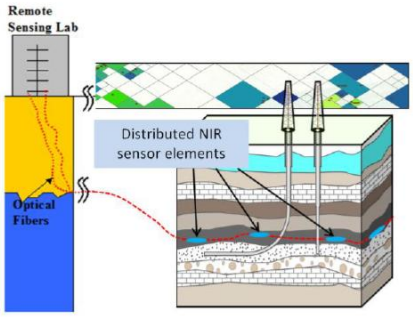
Inventors

Paul Ohodnicki and Malgorzata Ziomek-Moroz

Metal-Organic Framework and Plasmonic Nanomaterial Fiber-Optic Gas Sensor (15N-04)

Opportunity





Gas sensing platforms used in industrial environments must be compact and stable while still offering strong analyte selectivity and high signal strength at low concentrations. Engineered in collaboration between NETL and Oregon State University (OSU), this fiber-optic sensor combines a metal-organic framework (MOF) coating with a plasmonic nanostructure to strengthen analyte–light interactions and amplify near-infrared absorption signals. The MOF layer functions as a selective preconcentrator that draws target molecules into the optical field, while the plasmonic material provides localized electromagnetic enhancement that produces measurable transmission shifts at low gas concentrations. The architecture supports rapid response times, compatibility with standard fiber components, and tuning for specific analytes through MOF chemistry selection. This technology is available for licensing and/or further collaborative research from NETL in partnership with OSU.

Challenges Addressed

- Mid-infrared absorption spectroscopy offers high sensitivity and reliability for identifying various gases; however, these systems are typically bulky, expensive, and require specialized equipment
- Near-infrared (NIR) systems have inherently low sensitivity for most gases, as molecular absorption bands in the NIR region are generally weak

Potential Commercial Applications

- Rapid response, high sensitivity for trace gases, and robustness make it suitable for real-time monitoring of industrial processes
- The sensor can precisely monitor critical gas levels in greenhouses for optimal crop growth or in food storage facilities to detect spoilage and extend shelf life

Competitive Advantages

- Use of MOF coatings significantly increases local gas concentration at the fiber surface, amplifying the weak NIR absorption signals
- By operating in the NIR region and utilizing fiber-optic technology, the invention offers a compact and robust sensor suitable for distributed and remote sensing applications
- Ultrathin MOF films provide high surface area and rapid adsorption/desorption kinetics, resulting in faster response times for real-time monitoring

Intellectual Property Status

A U.S. patent (US9983124) was issued May 29, 2018, and expires February 9, 2036.

Publications

A. Wang, et al. Sensor Device Comprising a Substrate Coupled to a Sensing Component Comprising a Metal-Organic Framework and a Plasmonic Nanomaterial. (2018). *United States Patent and Trademark Office*. U.S. Patent No. 9,983,124.

Licensing/Collaboration

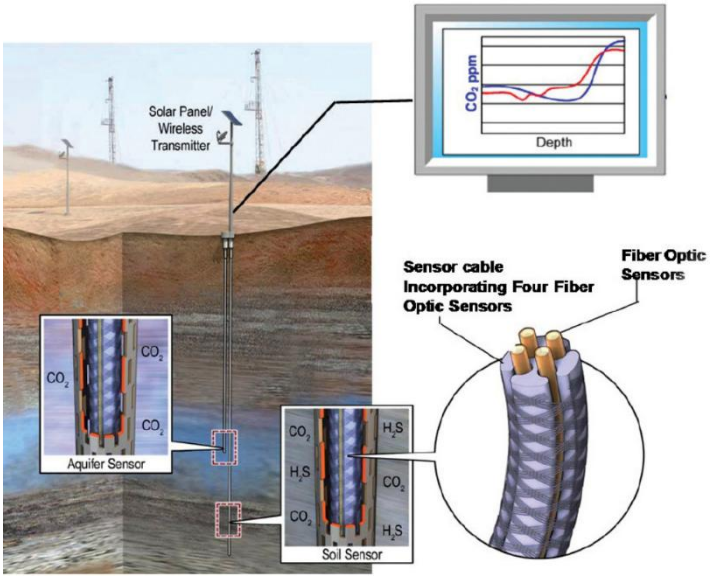
Partnerships@netl.doe.gov

Inventors

Alan X. Wang, Chih-Hung Chang, Ki-Joong Kim, Xinyuan Chong, and Paul R. Ohodnicki

Fiber-Optic Nanoparticle pH Sensors for Harsh Environments (15N-02 and 14N-19)

Opportunity



Accurate, real-time pH measurement in downhole, subsea, and other harsh environments is difficult because conventional electrode and dye-based sensors drift, leach, or fail under high temperature, high pressure, high salinity, and corrosive conditions. NETL has developed complementary optical pH sensing approaches that transduce pH-dependent changes in optical properties using nanoparticles integrated with fiber-optic platforms. One method embeds electronically conductive or plasmonic metal nanoparticles in a stable matrix that modulates optical response with surface charge changes over pH 2 to 12. A second method fixes inorganic-oxide nanoparticles directly on a substrate or optical fiber to achieve localized refractive index modulation without requiring a responsive host matrix. Together, these approaches enable robust, reversible, and fast pH sensing suitable for distributed or embedded monitoring. This technology is available for licensing and/or further collaborative research from NETL.

Challenges Addressed

- Conventional pH probes lack stability at elevated temperature and pressure
- Electrical sensors require local wiring and packaging that fail in aggressive media
- Prior sol-gel coatings often need bent fibers and offer limited long-term stability
- Lack of real-time, distributed pH data limits process control and materials selection

Potential Commercial Applications

- Downhole and subsea pH monitoring for resource extraction and well integrity
- pH mapping in geological formations and test wells
- Industrial process monitoring in hot, corrosive, or saline aqueous systems

Competitive Advantages

- High-stability sensing layers for harsh environments with reversible response
- Compatibility with silica fiber platforms for remote and distributed measurements
- Tunable response via nanoparticle composition, size, and morphology

Intellectual Property Status

U.S. Patent No. 11,408,827 issued August 9, 2022, with anticipated expiration on April 24, 2035.
U.S. Patent No. 10,274,431 issued April 30, 2019, with adjusted expiration on February 10, 2037.

Publications

- P. Ohodnicki, et al. Method of Evaluating pH Using a Metallic Nanoparticle Incorporated Nanocomposite-Based Optical pH Sensor. (2022). *United States Patent and Trademark Office.* U.S. Patent No. 11,408,827.
- D. Kauffman, et al. Method of Evaluating pH Using an Inorganic-Oxide Nanoparticle-Based Optical pH Sensor. (2019). *United States Patent and Trademark Office.* U.S. Patent No. 10,274,431.

Licensing/Collaboration

Partnerships@netl.doe.gov

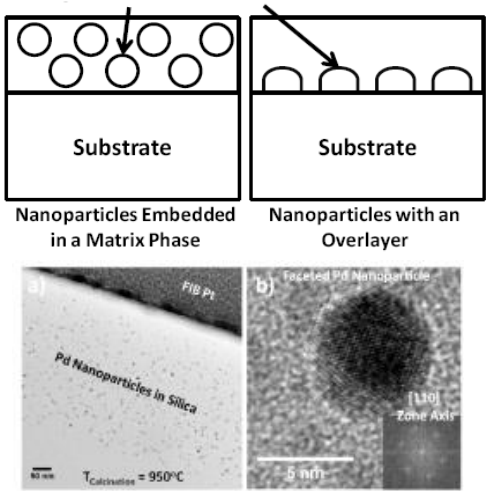
Inventors

Paul Ohodnicki, Jr., Congjun Wang, Thomas Brown, Barbara Kutchko, Douglas Kauffman, Christopher Matranga, and Xin Su

Palladium and Platinum Nanocomposite Sensors for Selective Hydrogen Detection (15N-01)

Opportunity

Accurate detection of hydrogen in complex gas environments is critical for safety and performance in energy, aerospace, and industrial systems. NETL has developed an optical hydrogen sensor that uses palladium- and platinum-based nanoparticles dispersed in an inert matrix to detect hydrogen through shifts in optical signals. The sensor structure can include engineered filter layers that enhance selectivity by allowing hydrogen to diffuse through while blocking other gases such as carbon monoxide or methane. This optical approach eliminates the need for electrical wiring at the sensing point, improving safety and reliability in high-temperature or explosive environments. This technology is available for licensing and/or further collaborative research from NETL.



Schematic and images of Pd nanoparticles embedded (left) or coating silica substrate (right)

Challenges Addressed

- Conventional hydrogen sensors often suffer from poor selectivity in mixed gas environments
- Electrical contact-based sensors present ignition and corrosion risks in explosive or high-temperature conditions
- Existing systems require frequent calibration and are limited in their response range and sensitivity
- Many sensing materials degrade under repeated hydrogen cycling or long-term operation

Potential Commercial Applications

- Hydrogen leak detection and safety monitoring for industrial and energy systems
- Real-time hydrogen sensing in gas turbines, fuel cells, and reformers
- Condition-based monitoring of dissolved hydrogen in transformer oil
- Aerospace and defense applications where lightweight, wireless sensors are preferred
- Metallurgical and process monitoring at elevated temperatures

Competitive Advantages

- Engineered filter layers improve discrimination against interfering gases
- Nanoparticle-based films maintain structural integrity and responsiveness at high temperatures
- Eliminates electrical wiring and contacts at the sensing point, reducing explosion risk
- Applicable as single-layer nanocomposites, multilayer thin films, or integrated optical coatings

Intellectual Property Status

A U.S. patent was issued December 26, 2023, and expires August 10, 2041.

Publications

P. Ohodnicki, et al. Palladium and Platinum-Based Nanoparticle Functional Sensor Layers and Integration with Engineered Filter Layers for Selective H2 Sensing. (2019). *United States Patent and Trademark Office.* U.S. Patent No. 10,345,279.

Licensing/Collaboration

Partnerships@netl.doe.gov

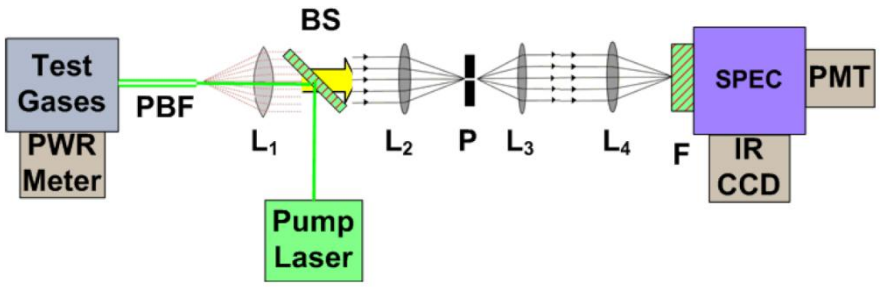
Inventors

Paul Ohodnicki, Chenhu Sun, John Baltrus, and Thomas Brown

Gas Sensing System Employing Raman Scattering (10N-26)

Opportunity

Accurate, real-time measurement of gas composition is essential for industrial systems that rely on natural gas, synthesis gas, biogas, or mixed fuel streams, yet existing analytical methods such as mass spectrometry and gas chromatography are too slow or complex for continuous control. NETL , in collaboration with the University of Pittsburgh (Pitt), has developed a Raman-based gas sensing system that rapidly identifies and quantifies all major components in a gas mixture. Raman scattering generates only a small number of useful photons during each laser–gas interaction, limiting sensitivity and demanding high-end optics. By guiding the laser through a hollow waveguide and optimizing the coupling of the Stokes-shifted photons to the detector, this design increases Raman signal strength and allows continuous measurement of gas composition in one second or less. The system enables real-time fuel characterization that can dramatically improve combustion efficiency and process control. This technology is available for licensing and/or further collaborative research from NETL and Pitt.



Challenges Addressed

- Conventional gas analyzers lack the speed needed for real-time process control
- High-accuracy measurements require large instruments and laboratory workflows
- Natural gas composition varies by source, reducing combustion efficiency without active adjustment
- Existing sensors cannot simultaneously quantify all major fuel-gas components at high speed

Potential Commercial Applications

- Real-time characterization of natural gas composition for turbine and pipeline operations
- Process monitoring for gasifiers, reformers, and industrial reactors
- Analysis of biogas, landfill gas, and other variable-quality fuel streams
- Inline fuel-air ratio control for combustion optimization

Competitive Advantages

- Measures major gas components with better than 0.1% accuracy in one second or less
- Uses low laser power and low-resolution spectrometers to reduce system cost
- Operates at pressures from 10 to 800 psi and gas temperatures up to 200°C
- Hollow waveguide design increases Raman signal strength and sensitivity
- Enables continuous, high-speed monitoring for improved process efficiency

Intellectual Property Status

A U.S. patent was issued March 18, 2014, and expires February 4, 2032.

Publications

J. Falk, et al. Gas Sensing System Employing Raman Scattering. (2014). *United States Patent and Trademark Office.* U.S. Patent No. 8,674,306.

Licensing/Collaboration

Partnerships@netl.doe.gov

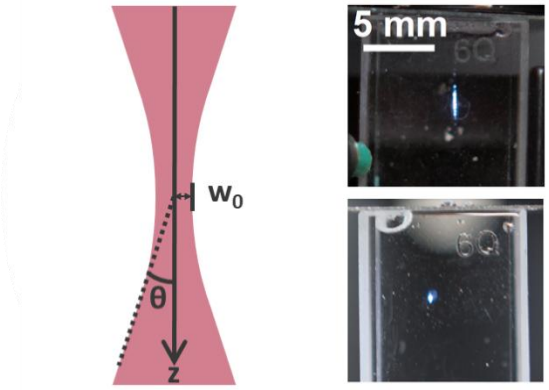
Inventors

Joel Falk, Peng Chen, Michael Buric, and Steven Woodruff

Downhole Laser System with Improved Laser Output Production and Data Collection (19N-22)

Opportunity

Monitoring chemical and physical conditions deep underground remains a major challenge due to extreme temperature and pressure, as well as accessibility limitations. NETL has designed a laser-induced breakdown spectroscopy (LIBS) system that enables real-time, in-situ chemical analysis in harsh downhole environments. The system combines lens, beam, and spectral emission controls to enhance output stability, spark efficiency, and data quality. These optical design improvements allow for accurate trace element detection and continuous monitoring without the need to transport and retrieve samples to the surface. This technology is available for licensing and/or further collaborative research from NETL.



Schematic and example of beam expansion control using the LIBS system

Challenges Addressed

- Traditional downhole monitoring systems can only measure bulk parameters such as pH and conductivity, requiring samples to be extracted for trace analysis
- Current diode-pumped solid-state laser systems suffer from instability under temperature and pressure fluctuations common in downhole environments
- Existing LIBS systems produce elongated, filamentary sparks that result in weak or inconsistent spectral signals
- Conventional optical setups lose significant light during emission collection, limiting data quality and sensitivity

Potential Commercial Applications

- Real-time elemental analysis of fluids in oil, gas, and geothermal wells
- Continuous leak detection and integrity monitoring for injection and production wells
- Environmental and subsurface monitoring in energy and resource extraction industries
- Portable or remote LIBS-based sensor systems for harsh environments

Competitive Advantages

- Beam overlap control provides adjustable and stable laser output characteristics
- Beam expansion control enables efficient spark generation using lower pulse energy
- Spectral emission control improves light collection and reduces signal loss
- Minimizes sensitivity to temperature and pressure variations during operation
- Provides more consistent and accurate trace element measurements than existing systems

Intellectual Property Status

A U.S. nonprovisional and divisional patent were issued and expire November 11, 2040 and October 19, 2040, respectively.

Publications

D. McIntyre and D. Hartzler. Downhole Laser System with an Improved Laser Output Production and Data Collection. (2022). *United States Patent and Trademark Office.* U.S. Patent No. 11,451,004.

Licensing/Collaboration

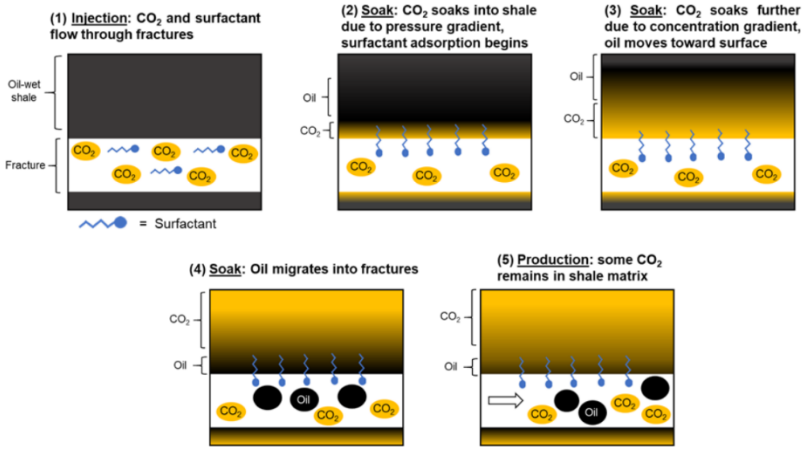
Partnerships@netl.doe.gov

Inventors

Dustin McIntyre and Daniel Hartzler

Carbon Dioxide-Soluble Additives for Wettability Modification in Oil Recovery (19N-02)

Opportunity



Enhancing hydrocarbon production from low-permeability and unconventional formations often requires modifying how reservoir surfaces interact with injected fluids. Researchers at NETL and the University of Pittsburgh (Pitt) established a method that uses carbon dioxide (CO_2) as a carrier fluid for specialized CO_2-soluble compounds that diffuse into and adsorb onto mineral surfaces. These additives include surfactants, amphiphilic polymers, and low-molecular-weight ketones that remain soluble under injection pressures near their cloud points. Once adsorbed, the compounds decrease oil-wettability or increase water wettability or CO_2-philicity, shifting the interfacial balance that controls fluid displacement. Because the additives are delivered in CO_2 rather than water, they penetrate tight formations more effectively and avoid the viscosity and mass-transfer limitations associated with aqueous surfactant treatments. The method can also incorporate controlled soak periods to maximize diffusion and adsorption before production resumes, supporting improved recovery in formations where conventional foams and water-based enhanced oil recovery (EOR) agents underperform. This technology is available for licensing and/or further collaborative research from NETL in collaboration with Pitt.

Challenges Addressed

- Recovering oil from unconventional shale formations presents a significant challenge due to the complex nature of these reservoirs
- While CO_2-soluble surfactants have been investigated, their primary application has been in generating foams within conventional formations to improve CO_2 mobility, rather than directly addressing wettability alteration in unconventional shale

Potential Commercial Applications

- Novel process enables oilfield service companies and operators to increase oil recovery from shale formations
- Chemical manufacturers can develop, produce, and supply the specialized CO_2-soluble surfactants required for EOR

Competitive Advantages

- CO_2-surfactant solution directly alters wettability, improving oil displacement efficiency
- Combined solvent and surfactant action enhances oil recovery by simultaneously reducing viscosity and modifying wettability

Intellectual Property Status

A U.S. patent was issued April 29, 2025, and expires September 6, 2041.

Publications

R. Enick, et al. Method of Oil Recovery Using Compositions of Carbon Dioxide and Compounds to Increase Carbon Dioxide Wettability of Formations. (2025). *United States Patent and Trademark Office.* U.S. Patent No. 12,286,589.

Licensing/Collaboration

Partnerships@netl.doe.gov

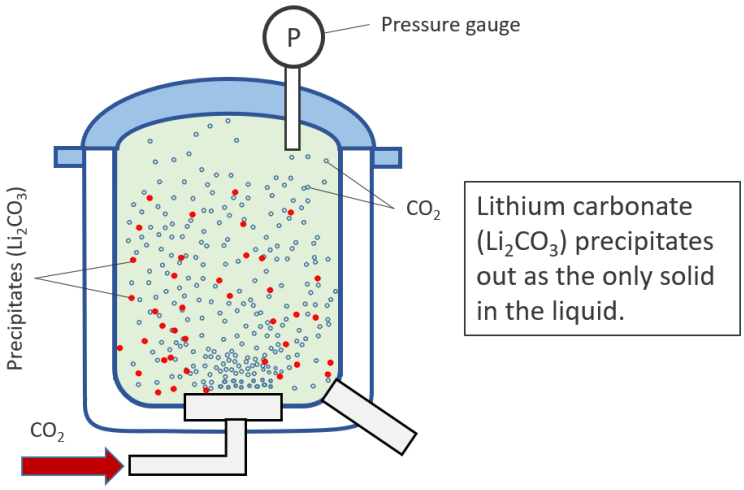
Inventors

Robert M. Enick, Deepak Tapriyal, Angela Goodman Hanson, and Dustin Crandall

Selective Material Recovery from Natural Brines (17N-07)

Opportunity

Efficient extraction of high-value materials from natural and industrial brines requires a process that can separate impurities and concentrate target species without extensive evaporation ponds or large chemical inputs. Researchers at NETL designed a carbon dioxide (CO_2)-driven precipitation method that relies on controlled adjustments of temperature and the CO_2-to-pressure ratio (CO_2/P) within a reaction vessel. When CO_2 is introduced into heated brine at a predetermined CO_2/P value, impurities preferentially precipitate and can be removed, leaving a second brine enriched in the desired material. A subsequent heating step followed by a second CO_2 injection at a different CO_2/P value induces selective precipitation of the target compound itself. This staged approach provides a tunable way to separate impurities from valuable species using only CO_2, temperature control, and residence time. The method reduces reliance on large reagent quantities and eliminates time-consuming evaporation steps. This technology is available for licensing and/or further collaborative research from NETL.



Challenges Addressed

- There is an escalating global demand for lithium
- Brines represent a vast and promising resource, but conventional extraction techniques, predominantly solar evaporation ponds, are notoriously slow

Potential Commercial Applications

- Efficiently extracts lithium from various natural brine sources by selectively precipitating impurities and then lithium carbonate
- Directly produces lithium carbonate, a key chemical precursor for battery materials and various industrial applications, from brine solutions

Competitive Advantages

- Traditional lithium extraction from brines via solar evaporation can take 12-24 months, whereas this method achieves lithium precipitation in under an hour
- Conventional methods often yield lithium recovery rates between 30% and 50%, whereas the new approach's controlled CO_2 injection and heating processes achieve higher recovery rates
- Operates effectively regardless of weather, enabling consistent lithium extraction in diverse environments

Intellectual Property Status

A U.S. patent was issued July 25, 2023, and expires September 20, 2041.

Publications

J. Nakano, et al. Selective Material Recovery from Solution. (2023). *United States Patent and Trademark Office.* U.S. Patent No. 11,708,279.

Licensing/Collaboration

Partnerships@netl.doe.gov

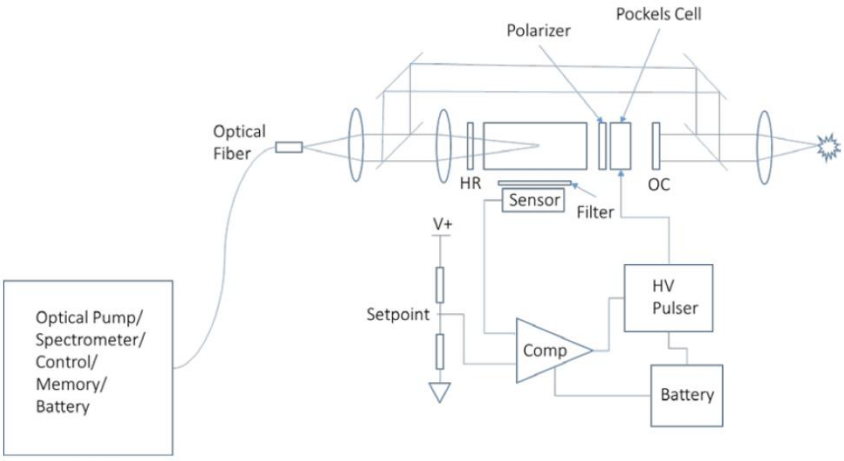
Inventors

Jinichiro Nakano, Anna Nakano, and James Bennett

High Power Q-Switched Downhole Laser-Induced Breakdown Spectroscopy Systems (16N-18)

Opportunity

Accurate subsurface chemical measurements require laser outputs that can generate stable plasmas in water and rock environments, but most downhole laser-induced breakdown spectroscopy (LIBS) probes cannot reach the pulse energies needed for reliable elemental excitation. Engineers at NETL designed an actively Q-switched LIBS architecture that overcomes these limitations while maintaining conventional probe geometry. The system routes a pump beam through an optical fiber to a coupler and collimating lens that feed an internally mounted Q-switched laser equipped with a Pockels cell for controlled high voltage triggering. This configuration enables the laser to store energy and release it in short, high-power bursts that exceed typical downhole thresholds and produce a robust plasma for elemental or molecular analysis. A second lens focuses the outgoing pulse, and the return emission is captured and transmitted back to topside instrumentation. This approach supports high-energy operation without enlarging the probe, which expands LIBS deployment into deeper, higher pressure and more varied monitoring environments. This technology is available for licensing and/or further collaborative research from NETL.



NETL downhole system using an active Q-switch

Challenges Addressed

- Monitoring of gas storage in geological formations is essential to prevent gas leakage
- Energy constraints seen in other systems severely hampers their ability to detect and identify a comprehensive range of elemental species

Potential Commercial Applications

- Robust, in-situ chemical analysis in wells and boreholes, allowing for the detection and tracking of groundwater contaminants and waste leakage
- High-energy, downhole LIBS/Raman capabilities offer real-time, detailed chemical characterization of rock formations, fluids, and minerals

Competitive Advantages

- Actively Q-switched laser system achieves output pulse energies approaching or exceeding 100 mJ, significantly surpassing the 25-30 mJ typical of passively Q-switched systems
- Allows for exact control over pulse timing and repetition rates, facilitating synchronization with external devices

Intellectual Property Status

A U.S. patent (US11953443) was issued April 9, 2024, and expires October 19, 2041.

Publications

D. McIntyre and D. Hartzler. High Power Actively Q-Switched Downhole LIBS Analysis Systems. (2024). *United States Patent and Trademark Office.* U.S. Patent No. 11,953,443.

Licensing/Collaboration

Partnerships@netl.doe.gov

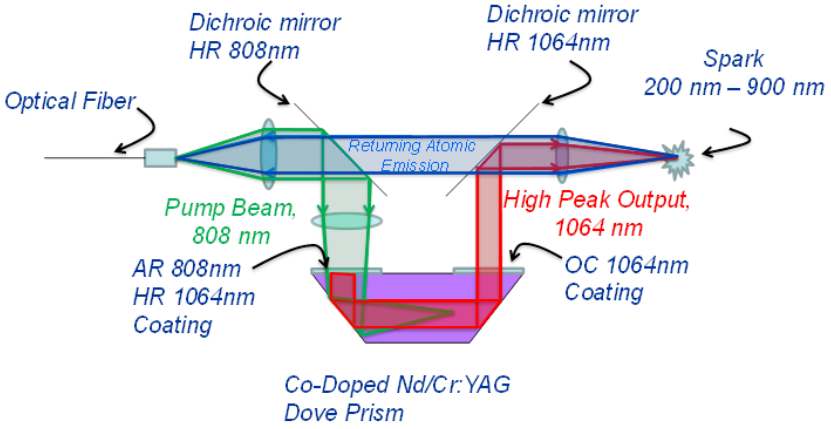
Inventors

Dustin McIntyre and Daniel Hartzler

LIBS Probe for Simplified Light Collection and Laser Operation (15N-05)

Opportunity

NETL has developed an improved laser-induced breakdown spectroscopy (LIBS) probe that simplifies the optical layout and reduces the number of required mirrors. Traditional LIBS systems rely on complex mirror assemblies, including dichroic mirrors that require costly chemical vapor deposition and precision alignment. NETL's design replaces two of these mirrors with a dove prism laser medium that performs both beam reflection and transmission within a compact optical path. This configuration enhances signal strength, minimizes optical losses, and significantly lowers fabrication and alignment complexity. The simplified probe enables high-quality spectral analysis of solids, liquids, and gases while maintaining ruggedness and cost efficiency. This technology is available for licensing and/or further collaborative research from NETL.



Challenges Addressed

- Conventional LIBS probes require multiple mirrors and precise alignments that increase system cost and fragility
- Dichroic mirrors introduce optical losses and can interfere with accurate light collection
- Complex assembly and alignment processes increase calibration time and limit field deployment
- Existing probes are less suitable for confined or harsh environments requiring compact, durable instrumentation

Potential Commercial Applications

- Elemental and molecular analysis in geological, environmental, and industrial monitoring
- Field-deployable spectroscopic analysis for mining, water quality, and pollution detection
- Real-time compositional monitoring of combustion and plasma processes
- Laser ignition systems with integrated diagnostics for engines and turbines

Competitive Advantages

- Simplified optical layout using a dove prism reduces mirror count from four to two
- Enhanced light return improves spectral quality and signal-to-noise ratio
- Lower fabrication and alignment costs enable affordable, scalable deployment
- Compact and robust probe design suitable for challenging environments
- Compatible with existing LIBS spectrometers and fiber-optic collection systems

Intellectual Property Status

A U.S. patent was issued December 4, 2018, and expires October 26, 2037.

Publications

D. McIntyre. Laser Induced Breakdown Spectroscopy (LIBS) Probe for Simplified Light Collection and Laser Operation. (2018). *United States Patent and Trademark Office.* U.S. Patent Publication Application No. 10,145,737.

Licensing/Collaboration

Partnerships@netl.doe.gov

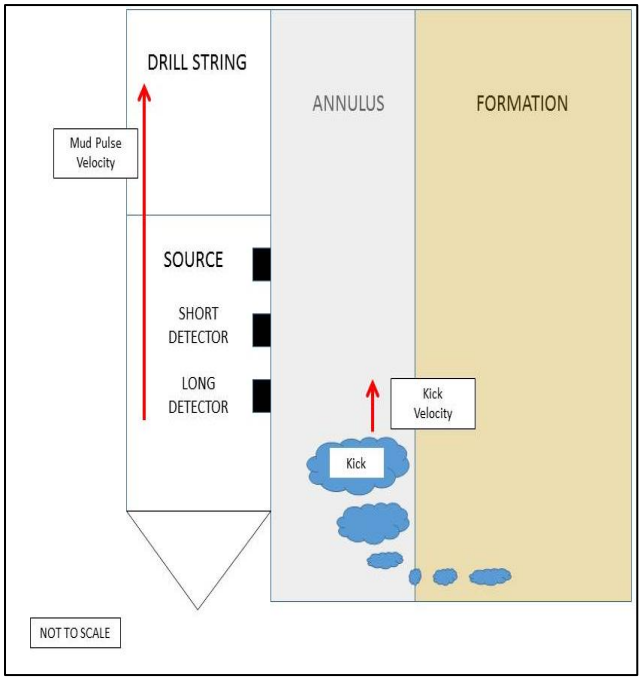
Inventors

Dustin McIntyre

Real-Time Wellbore Monitoring for Kick Detection (13N-32)

Opportunity

Early identification of formation fluid influxes remains one of the most difficult safety challenges in subsurface drilling. Traditional kick detection relies on mud returns at the rig floor, which can delay awareness until the influx has already progressed. NETL has built a real-time kick detection system that analyzes compensated geophysical measurements around the drill bit to identify subtle changes in the drilling fluid column. By tracking standoff-related corrections in logging-while-drilling (LWD) and measurement-while-drilling (MWD) signals, the system provides an earlier warning of abnormal wellbore conditions. This technology is available for licensing and/or further collaborative research from NETL.



Challenges Addressed

- Conventional kick detection methods provide delayed alerts
- Influxes of gas, water, or oil may not be recognized until reaching the surface
- Current LWD and MWD logs ignore standoff behavior and treat it as noise
- Delayed kick response increases the likelihood of loss of well control

Potential Commercial Applications

- Onshore and offshore drilling operations
- Managed pressure drilling
- Real-time wellbore geophysics and automated drilling systems
- Enhanced well control monitoring for high-risk formations

Competitive Advantages

- Uses existing LWD and MWD tools without hardware modification
- Identifies fluid property changes at or near the bit in real time
- Converts standoff corrections into actionable drilling intelligence
- Reduces risk of uncontrolled influxes and associated downtime
- Supports integration into automated or semi-automated drilling workflows

Intellectual Property Status

A U.S. patent was issued April 9, 2019, and expires September 14, 2035.

Publications

K. Rose, et al. Kick Detection at the Bit Using Wellbore Geophysics. (2019). *United States Patent and Trademark Office.* U.S. Patent No. 10,253,620.

Licensing/Collaboration

Partnerships@netl.doe.gov

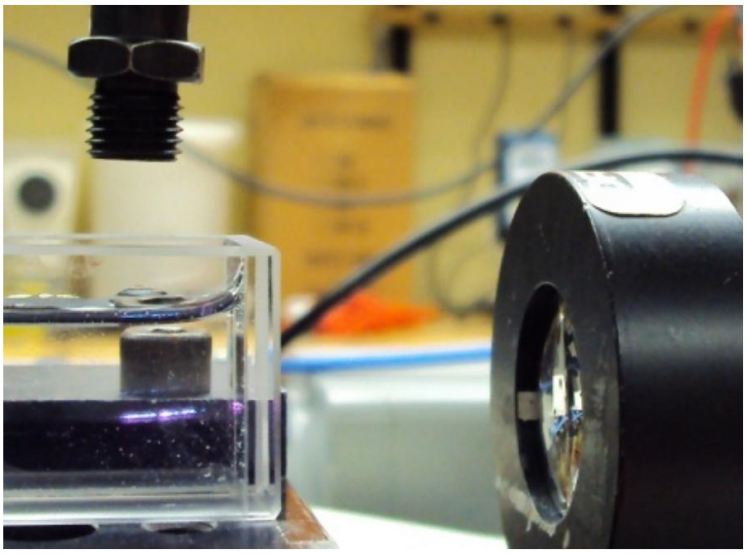
Inventors

Kelly Rose, Brian Tost, and Fred Aminzadeh

Split Laser Systems for Remote Environmental Monitoring (13N-10)

Opportunity

Accurate environmental monitoring in extreme or remote settings such as subsurface storage, downhole drilling, and offshore exploration requires compact and durable optical systems capable of real-time measurements under high-temperature and -pressure conditions. NETL has developed a family of split laser systems that enable in-situ sensing using low peak power optical pumps and fiber-coupled solid-state lasers. These passively Q-switched systems perform laser-induced breakdown spectroscopy (LIBS) and Raman analysis directly at the monitoring site, allowing sensitive detection of gases, liquids, and solids without high-power transmission through optical fibers. The technology is available for licensing and/or further collaborative research from NETL.



Challenges Addressed

- Conventional laser monitoring systems are bulky, complex, and unsafe for remote or high-pressure use
- High peak power delivery through optical fibers can damage cables and limit deployment distance
- Real-time fluid chemistry monitoring during drilling or sequestration remains challenging

Potential Commercial Applications

- Long-term sequestration and leakage detection
- Downhole and offshore oil and gas monitoring
- Groundwater and municipal water quality analysis
- Real-time pollution assessment

Competitive Advantages

- Performs LIBS and Raman spectroscopy at remote sites using low-power optical pumping
- Compact, low-cost design with no moving parts or active electrical components
- Operates reliably in harsh environments such as boreholes or subsea wells
- Enables multipoint, fiber-linked sensing networks for distributed environmental monitoring

Intellectual Property Status

A U.S. patent was issued July 22, 2014, and expires June 2, 2032. Related patents include U.S. Patent No. 9,297,696 (Laser Based Analysis Using a Passively Q-Switched Laser, issued March 29, 2016) and U.S. Patent No. 9,548,585 (Multi-Point Laser Ignition Device, issued January 17, 2017). Related NETL Ref. Nos.: 12N-02 and 11N-06

Publications

- S. Woodruff, et al. Multi-Point Laser Ignition Device. (2017). *United States Patent and Trademark Office.* U.S. Patent No. 9,548,585.
- D. McIntyre, et al. Laser Based Analysis Using a Passively Q-Switched Laser. (2016). *United States Patent and Trademark Office.* U.S. Patent No. 9,297,696.

Licensing/Collaboration

Partnerships@netl.doe.gov

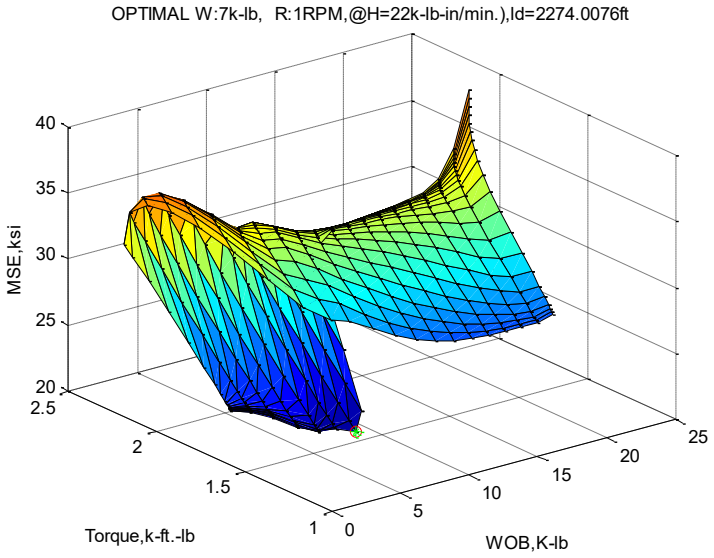
Inventors

Steven Woodruff, Dustin McIntyre, and Jinesh Jain

Computational and Simulation-Based Tools for Drilling Optimization (12N-20)

Opportunity

Efficient drilling becomes increasingly difficult as wells deepen and rock strength, temperature, and pressure increase. Conventional drilling practices rely on operator judgment, drill-off tests, and rule-of-thumb parameter ranges that do not capture the complex, nonlinear relationship between weight-on-bit (WOB), rotational speed (RPM), hydraulic power (H), rate of penetration (ROP), and specific energy (SE). NETL has designed a computational method that uses real-time measurement-while-drilling (MWD) data and artificial neural networks to directly relate controllable drilling parameters to performance indicators such as mechanical specific energy and ROP. The system predicts drilling behavior at probable operating points and recommends parameter combinations that achieve the lowest SE or highest ROP/SE ratio. This technology is available for licensing and/or further collaborative research from NETL.



Mechanical specific energy, the mechanical energy consumed in removing unit volume of rock, as a function of controlled drilling parameters

Challenges Addressed

- Drilling parameters (WOB, RPM, H) are adjusted through trial-and-error rather than optimized relationships
- Current practices do not directly link controllable parameters to SE or ROP
- Empirical models fail under changing subsurface conditions
- Inefficient drilling leads to slower penetration and reduced operational effectiveness

Potential Commercial Applications

- Onshore and offshore oil and gas drilling
- Geothermal drilling operations
- Real-time drilling automation systems
- Digital drilling platforms requiring predictive control models

Competitive Advantages

- Direct prediction of torque, SE, and ROP from controllable inputs
- Continuously updated models that adapt to changing drilling conditions
- Supports safer, more consistent drilling performance
- Requires no specialized hardware and leverages existing MWD data streams

Intellectual Property Status

A U.S. patent was issued March 5, 2019, and expires July 22, 2037.

Publications

W. Zhang, et al. MSE-Based Drilling Optimization Using Neural Network Simulation. (2019). *United States Patent and Trademark Office.* U.S. Patent No. 10,221,671.

Licensing/Collaboration

Partnerships@netl.doe.gov

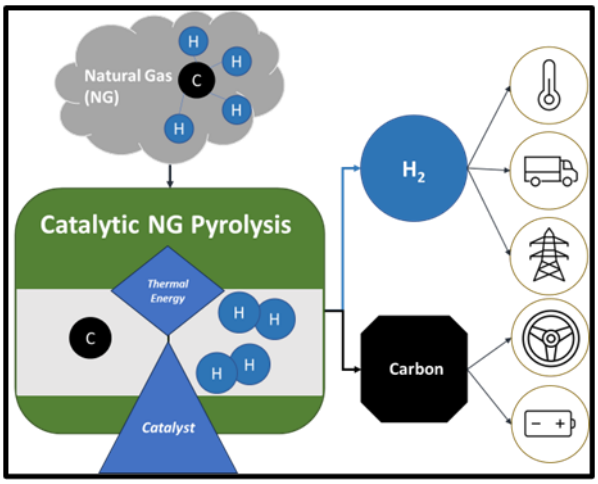
Inventors

Wu Zhang

Improved Methane Pyrolysis Catalysts for Hydrogen and Carbon Production (24N-01 and 23N-15)

Opportunity

Hydrogen is an important chemical mainly used in production of ammonia for fertilizers. In the United States, more than 95% of hydrogen generated is produced by steam methane reforming of natural gas, which is energetically expensive. To address this problem, NETL has developed advanced catalysts for methane pyrolysis, which are aimed at producing hydrogen more efficiently. The catalysts are composed of transition metal (i.e., nickel, cobalt, molybdenum, manganese, and/or zinc) substitutions within iron-alumina formulations and calcined at temperatures exceeding 1,150°C. These catalysts demonstrate improved performance over previous formulations, achieving methane to hydrogen conversion rates close to 100% in both fixed- and fluidized-bed reactor tests. Further, these new catalysts reduce the need for methane/hydrogen separation units, thereby lowering production costs. This invention is available for licensing and/or further collaborative research from NETL.



Schematic showing NETL catalyst's role in converting methane to carbon and hydrogen

Challenges Addressed

- Existing catalysts often suffer from deactivation and low methane conversion rates, preventing economic viability and scalability of methane pyrolysis
- Other catalysts typically require lower calcination temperatures, which limit their performance and longevity
- Achieving consistently high performance across different reactor configurations remains difficult

Potential Commercial Applications

- Enables on-site hydrogen production for fueling stations or industrial sites
- Carbon nanomaterials produced by methane pyrolysis have unique structures, which could be sold as high-value materials for electronics, composites, and energy storage applications

Competitive Advantages

- The novel catalyst achieves methane conversion rates of 92%-100%, significantly outperforming prior catalysts.
- The process operates at 700°C, significantly lower than plasma-based pyrolysis that requires 1,500-2,000°C, reducing energy consumption and operational costs
- The invention produces valuable carbon nanostructures, offsetting hydrogen production costs

Intellectual Property Status

A nonprovisional patent application has been filed in the U.S.

Publications

R. Siriwardane and J. Riley. Process for Production of Hydrogen with Transport from Chemical Looping using Mixture of Partial Oxidation Oxygen Carriers and Combustion Oxygen Carriers. (2025). *United States Patent and Trademark Office.* U.S. Patent No. 12,319,575.

Licensing/Collaboration

Partnerships@netl.doe.gov

Inventors

Ranjani Siriwardane and Jarrett Riley

Enriched Microbial Biocatalyst for Conversion of Carbon Dioxide and Carbon Monoxide into Acetate and Other Products (22N-09)

Opportunity

Industrial processes generate significant carbon-containing gas streams that often remain underutilized. NETL has created an enriched microbial biocatalyst capable of converting carbon dioxide, carbon monoxide, and other one-carbon compounds into acetic acid and short-chain fatty acids. The biocatalyst operates efficiently at ambient temperature and pressure, tolerates variable gas compositions, and provides a reliable method for producing valuable organic acids. This technology is available for licensing and/or collaborative research from NETL.



Challenges Addressed

- Conventional gas-to-liquid conversion processes require high temperatures and pressures, increasing cost and energy use
- Pure microbial cultures used in gas fermentation are often sensitive to feedstock variations
- Existing systems depend on purified gas feeds, limiting use of mixed industrial streams
- Many biological conversion platforms rely on genetically engineered organisms that raise stability and regulatory concerns

Potential Commercial Applications

- Production of acetic acid and other short-chain fatty acids from industrial gas or synthesis gas streams
- Conversion of formate, methanol, or mixed one-carbon feedstocks into valuable organic acids
- Integration into industrial fermentation or waste gas utilization systems
- Platform for biomanufacturing of specialty chemicals such as butyrate and phenylacetic acid

Competitive Advantages

- Operates under mild conditions without extensive process control
- Mixed microbial community resists contamination and adapts to feed variability
- Converts unpurified gas mixtures directly into desired products
- Nongenetically modified system with consistent and stable performance
- Near-complete carbon conversion to organic acids at low energy input

Intellectual Property Status

A nonprovisional patent application has been filed in the U.S.

Publications

D. Gulliver, et al. Enriched Microbial Biocatalyst for Conversion of CO2 into Acetate. (2024). *United States Patent and Trademark Office.* U.S. Patent Application Publication No. US20240409968A1.

Licensing/Collaboration

Partnerships@netl.doe.gov

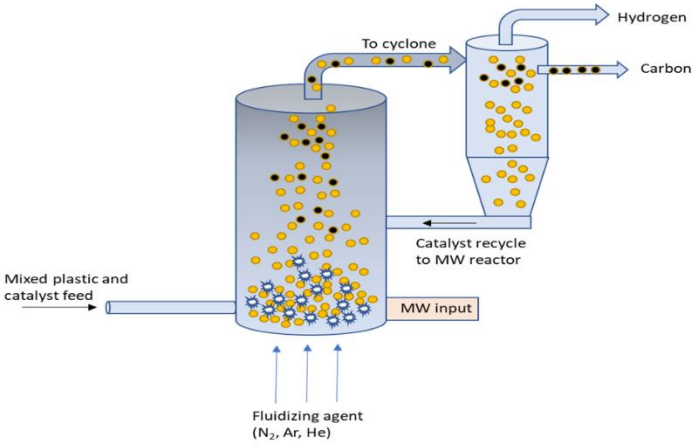
Inventors

Djuna Gulliver, Daniel Ross, and Samuel Flett

Microwave-Assisted Conversion of Plastics to Hydrogen and Carbon (22N-17)

Opportunity

Plastic waste is accumulating worldwide at a rate that far exceeds recycling capacity, with billions of tons projected to require disposal by mid-century. NETL and Cecilia Energy Inc. have developed a microwave-assisted catalytic process that converts mixed plastic waste directly into hydrogen and solid carbon. The method uses an earth-abundant catalyst in a fluidized bed microwave reactor to selectively heat the catalyst rather than the plastic itself, enabling complete decomposition without melting or producing liquid byproducts. This single-vessel design integrates catalyst reuse and carbon separation, simplifying operation while achieving high hydrogen recovery and minimal emissions. The process demonstrated greater than 70% efficiency for hydrogen recovery and over 60% overall conversion efficiency in laboratory testing. This technology is available for additional collaborative research with NETL.



Schematic of a microwave fluidized bed reactor for plastic conversion to hydrogen and carbon

Challenges Addressed

- Most plastics are landfilled or incinerated, as conventional recycling is limited to a few thermoplastics
- Existing thermal conversion methods such as pyrolysis and gasification require high energy input and produce complex product mixtures
- Batch microwave systems used for similar reactions are energy intensive and not suited for continuous operation

Potential Commercial Applications

- Conversion of municipal or industrial plastic waste into hydrogen and solid carbon
- On-site hydrogen generation from mixed or contaminated waste streams
- Decentralized waste-to-fuel systems for industrial or community energy production

Competitive Advantages

- High hydrogen yield exceeding 70% with minimal byproducts
- Continuous operation using a single-stage microwave reactor with catalyst recirculation
- Lower energy requirements than pyrolysis or gasification through selective microwave heating
- Ability to process mixed and contaminated plastics using inexpensive, reusable magnetite-based catalysts

Intellectual Property Status

A nonprovisional patent application has been filed in the U.S.

Publications

C. Wildfire, et al. Methods and Apparatuses for Producing Hydrogen. (2023). *United States Patent and Trademark Office.* U.S. Patent Application Publication No. US20230242825A1.

Licensing/Collaboration

Partnerships@netl.doe.gov

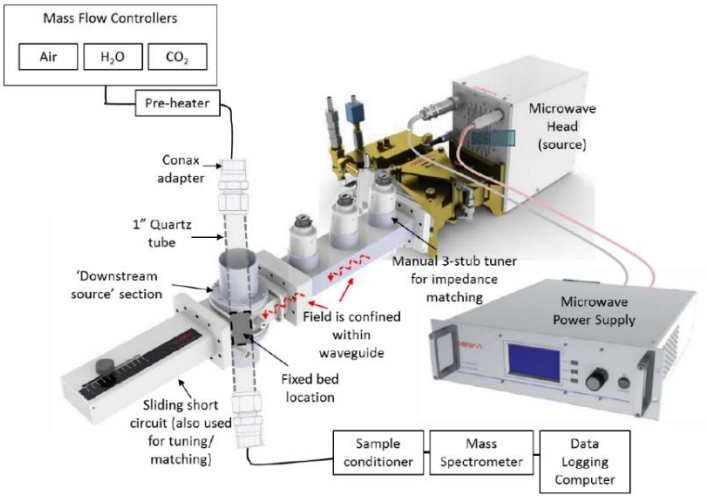
Inventors

Christina Wildfire, Pranjali Muley, Ashraf Abedin, and Kathryn Carpenter

Microwave-Assisted Solid Oxide Electrolysis Cells for Hydrogen Production (21N-05)

Opportunity

Efficient and cost-effective hydrogen production from water electrolysis remains a significant challenge. NETL has enhanced hydrogen production in solid oxide electrolysis cells (SOECs) by applying microwave (MW) radiation. The MWs provide targeted, direct heating to the electrolyzer, efficiently supplying the thermal energy required for the endothermic water electrolysis reaction. Simultaneously, specific MW frequencies are utilized to lower the activation energy of the electrolysis reaction, thereby improving reaction kinetics and increasing hydrogen production rates. The system is designed to operate optimally at half the thermal neutral current, where maximum MW heat addition, highest efficiency, and desired hydrogen production rates are achieved. The MW system consists of a generator, waveguide, and deflectors to direct MWs to the SOEC, which operates at high temperatures (e.g., 750-850°C) with simultaneous direct current power. This technology is available for licensing and/or further collaborative research from NETL.



Schematic of MW reactor system

Challenges Addressed

- Existing heating methods typically involve indirect heat transfer, where the reactor is heated and then transfers energy to the reaction medium, leading to inefficiencies
- Improving the kinetics of the water electrolysis reaction to achieve higher production rates and lower operational costs is a persistent hurdle

Potential Commercial Applications

- Enables more efficient and cost-effective production of hydrogen for various industrial processes, energy storage, and fuel applications
- Can be commercially applied to coelectrolysis of water and carbon dioxide, efficiently converting them into valuable synthetic fuels and chemicals like methanol or methane

Competitive Advantages

- MW heating delivers energy directly to the reaction medium, reducing heat losses associated with conventional methods that rely on conduction and convection
- MW irradiation can lower the activation energy of electrolysis reactions, resulting in faster reaction rates

Intellectual Property Status

A U.S. patent (US18/617,295) was filed March 26, 2024.

Publications

R. Gemmen, et al. Microwave-Assisted Solid Oxide Electrolysis Cell (SOEC), Proton Conducting Solid Oxide Electrolysis Cell (H-SOEC), Reversible Proton Conducting Solid Oxide Electrolysis Cell (rH-SOEC) or Reversible Solid Oxide Electrolysis Cell (rSOEC) for Hydrogen Production. (2025). *United States Patent and Trademark Office*. U.S. Patent Application Publication No. US20250305156A1.

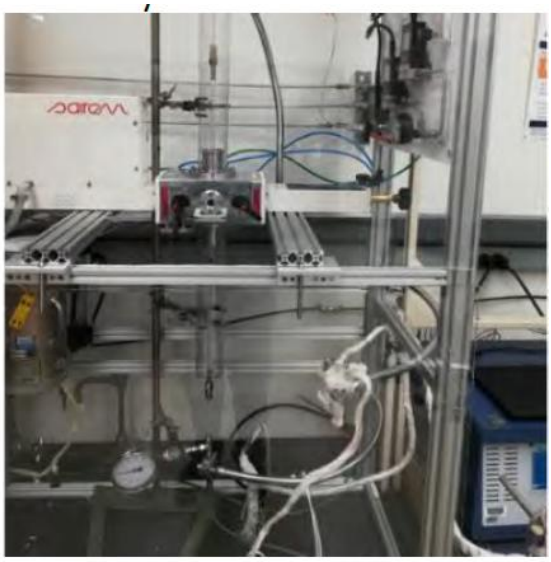
Licensing/Collaboration

Partnerships@netl.doe.gov

Inventors

Randall Gemmen, Dushyant Shekhawat, Alfred Unione, and Mark Williams

Improved Methods and Compositions for Microwave Catalytic Ammonia Synthesis (20N-31)



Microwave reaction system

Opportunity

Ammonia is a globally essential chemical, serving as a critical raw material for fertilizers, polymers, and explosives. To reduce the high level of energy required to synthesize ammonia, NETL , working in collaboration with West Virginia University (WVU), has employed a high-pressure microwave-assisted process for ammonia synthesis, integrating heterogeneous catalysis with microwave reaction chemistry. It utilizes specially formulated ruthenium-based catalysts, typically supported on cerium oxide and promoted by cesium, prepared through an incipient wetness method. These catalysts are designed for efficient and selective microwave energy absorption, operating within a high-pressure microwave reactor system capable of up to 200 PSI and using microwave frequencies such as 2.450 GHz. This configuration enables direct heating of the catalyst, achieving high ammonia formation rates at moderate reaction temperatures (e.g., 533-593K) and pressures, thereby reducing overall energy consumption compared to conventional methods. This technology is available for licensing and/or further collaborative research from NETL in partnership with WVU.

Challenges Addressed

- Current production predominantly relies on the Haber-Bosch process, which operates under extreme conditions of high temperatures (673-873K) and pressures (20-40MPa)
- The conventional synthesis method is highly energy-intensive, consuming 1%-2% of the world's total energy while also requiring substantial capital investment

Potential Commercial Applications

- Provides an energy-efficient and lower-cost method for producing ammonia, which is a critical raw material for fertilizers, polymers, and other industrial chemicals
- Enables smaller-scale, localized ammonia synthesis with lower capital investment and moderate operating conditions

Competitive Advantages

- Microwave-assisted ammonia synthesis process operates at near ambient pressures and moderate temperatures, significantly reducing energy consumption
- The process can be rapidly started and stopped, making it well-suited for integration with intermittent energy sources, unlike the Haber-Bosch process, which requires a constant energy supply

Intellectual Property Status

A U.S. patent (US18/284,525) was filed March 27, 2022.

Publications

J. Hu, et al. Compositions, Methods, and Systems for Microwave Catalytic Ammonia Synthesis. (2024). *United States Patent and Trademark Office.* US Patent Application Publication No. US20240174526A1.

Licensing/Collaboration

Partnerships@netl.doe.gov

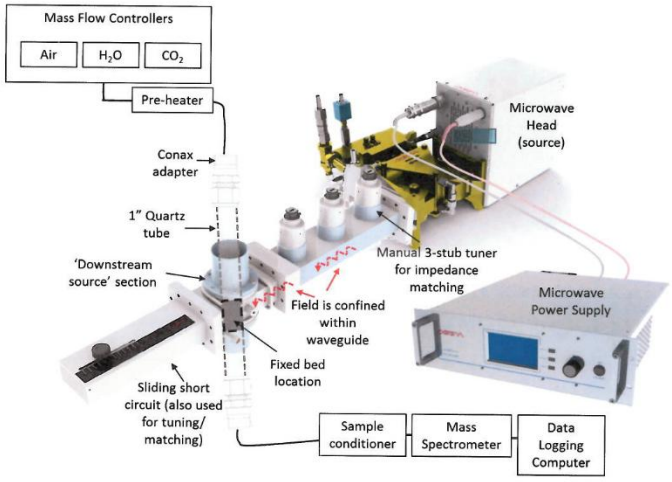
Inventors

Jianli Hu, Yuxin Wang, Dushyant Shekhawat, Christina Wildfire, Alexander Welsh, and Robert Weiss

Microwave-Assisted Catalysis for Direct Methane Conversion (17N-19)

Opportunity

Natural gas is an abundant, low-cost source of methane that can be upgraded into higher-value products such as hydrogen and ethylene. NETL has developed a microwave-assisted catalytic process that enables direct, one-step conversion of methane into hydrogen and ethylene without forming synthesis gas. By using targeted electromagnetic energy to selectively activate catalyst sites, the process improves conversion efficiency and product selectivity while reducing overall energy consumption and equipment complexity. This technology is available for licensing and/or further collaborative research from NETL.



Challenges Addressed

- Traditional methane conversion requires an intermediate synthesis gas step that adds cost and complexity
- Existing thermal reforming processes are energy-intensive and yield a wide range of byproducts
- Methane's chemical stability makes it difficult to activate under conventional catalytic conditions
- Uniform bulk heating in standard reactors leads to inefficient energy use and lower selectivity

Potential Commercial Applications

- Direct production of hydrogen and ethylene from natural gas or biogas
- Modular conversion systems for remote or small-scale gas utilization
- Integration with petrochemical and refining operations for feedstock generation
- Application to other endothermic catalytic processes requiring selective energy input
- Electromagnetic regeneration of industrial sorbents and catalysts

Competitive Advantages

- Produces hydrogen and ethylene directly from methane in a single-step conversion
- Microwave-assisted heating activates specific catalytic sites, minimizing waste heat
- Faster reactions and higher yields compared to conventional thermal methods
- Promotes desired reaction pathways and suppresses byproduct formation
- Adaptable for distributed or centralized chemical production systems

Intellectual Property Status

A U.S. patent was issued May 7, 2024, and expires April 19, 2041.

Publications

D. Shekhawat, et al. Electromagnetic Field-Assisted Method for Chemical Conversion. (2019). *United States Patent and Trademark Office.* U.S. Patent No. 11,975,303.

Licensing/Collaboration

Partnerships@netl.doe.gov

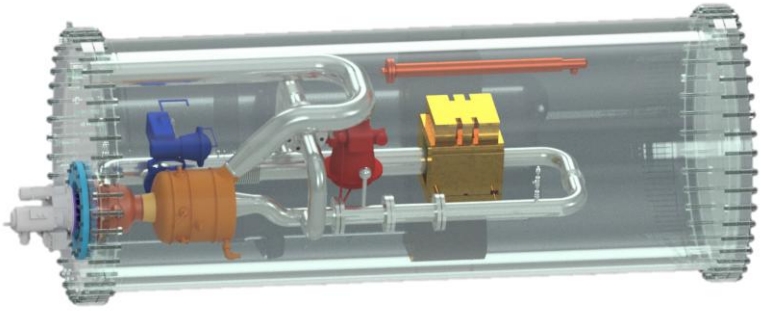
Inventors

Dushyant Shekhawat, David Berry, Mark Smith, Christina Wildfire, and Victor Abdelsayed

Hybrid Solid Oxide Fuel Cell-Gas Turbine for Efficient and Flexible Power Generation (25N-17)

Opportunity

NETL has developed a recuperated gas turbine (GT) cycle, augmented with a solid oxide fuel cell (SOFC) capable of operating at ultralow fuel utilization (10%-30%). This capability is achieved through specific thermal and chemical management strategies, including a hot air bypass around the SOFC to the combustor for rapid load transitions and temperature control, as well as a cold air bypass around the recuperator directly to the turbine inlet for surge margin and temperature control. Chemically, anode exhaust is recycled to a reformer, which is thermally coupled to the exhaust stream, improving fuel use and mitigating carbon deposition. The SOFC itself incorporates larger flow passages to accommodate high air flow rates, contributing to high overall efficiency, especially at part-load, and extended SOFC operational life. This invention is available for licensing and/or further collaborative research from NETL.



A compact (truck scale) design of a scalable SOFC-GT integrated reformer system

Challenges Addressed

- Traditional GTs suffer from significant efficiency losses and increased emissions during part-load operation and dynamic load changes
- SOFCs offer high efficiency but are limited in their operational flexibility and lifespan
- Existing hybrid systems combining fuel cells with GTs often operate with high fuel utilization, which increases fuel cell degradation risk

Potential Commercial Applications

- Supporting modern grids with variable demand
- Acting as a potential off-grid power solution
- Producing electricity and useful heat with superior load following for industrial and commercial facilities

Competitive Advantages

- Offers high efficiency during part-load operations, addressing the efficiency drop observed in traditional GTs
- Mitigates degradation issues common in conventional SOFC-GT hybrids
- Is well-suited for distributed energy applications and linkage to variable generators, providing an advantage over larger, centralized power systems

Intellectual Property Status

A provisional patent application has been filed.

Publications

B. Zhang, et al. Rapid Load Transition for Integrated Solid Oxide Fuel Cell–Gas Turbine (SOFC-GT) Energy Systems: A Demonstration of the Potential for Grid Response. (2022). *Energy Convers and Management* 258, 115544. https://doi.org/10.1016/j.enconman.2022.115544.

Licensing/Collaboration

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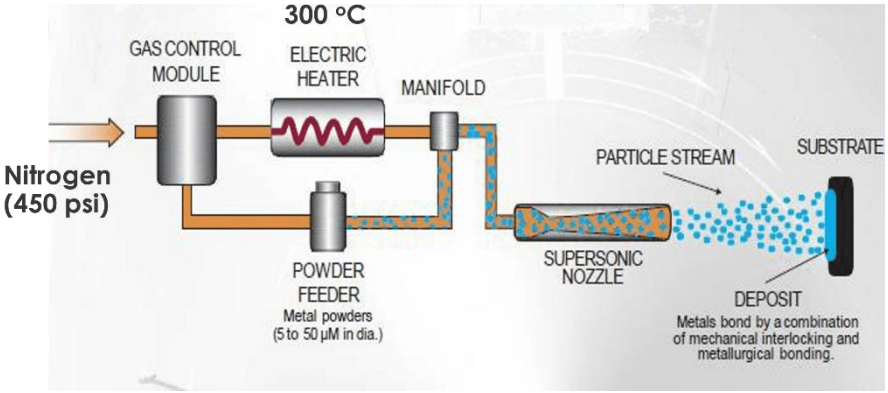
Inventors

David Tucker, Dan Oryshchyn, Nor Farida Harun, Nana Zhou, and Biao Zhang

Self-Healing Cold Spray Coating for Internal Corrosion Protection of Natural Gas Pipelines (23N-12)



Opportunity

Internal corrosion poses a significant threat to the integrity of pipelines transporting natural gas, hydrogen blends, and carbon dioxide (CO_2), primarily driven by the presence of water, CO_2, and hydrogen sulfide within the fluid stream. To mitigate challenges caused by corrosion, NETL and Battelle Memorial Institute have designed a cold-sprayed coating composed of zinc (Zn) and 2-12 wt% titanium (Ti). This coating is applied to steel substrates using a high-pressure nitrogen gas process that mechanically mixes and supersonically deposits Zn and Ti powders. It provides cathodic protection through galvanic coupling between Zn and Ti, which accelerates hydrogen evolution and increases local pH, thereby promoting the formation of a stable, passivating zinc carbonate ($ZnCO_3$) layer. This $ZnCO_3$ layer acts as a corrosion barrier, significantly reducing the corrosion rate over time, even in acidic and CO_2-rich environments. A key feature is its self-healing capability, where $ZnCO_3$ and zinc oxide form within defect sites, restoring protective integrity. This technology is available for licensing and/or further collaborative research from NETL and Battelle.

Challenges Addressed

- Organic coatings often suffer from poor abrasion resistance, making them vulnerable to mechanical damage and difficult to maintain effectively
- Sacrificial metallic coatings, while offering protection, are rapidly consumed, particularly in acidic or CO_2-rich environments, leading to a short protective lifespan and requiring frequent replacement or reapplication

Potential Commercial Applications

- Self-healing, durable coating for the interior of new and existing pipelines transporting natural gas, hydrogen, CO_2, oil, and water
- Protects a wide range of industrial equipment and public infrastructure components exposed to harsh, corrosive environments

Competitive Advantages

- ZnTi cold spray coating forms protective $ZnCO_3$ layers at defect sites, restoring corrosion protection without external intervention
- Galvanic coupling accelerates hydrogen evolution, increasing local pH and promoting stable $ZnCO_3$ formation, effectively protecting pipelines in CO_2-rich conditions
- Applied via high-pressure cold spray, the coating achieves strong adhesion and resistance to mechanical cleaning processes like pigging

Intellectual Property Status

A U.S. nonprovisional application has been filed.

Licensing/Collaboration

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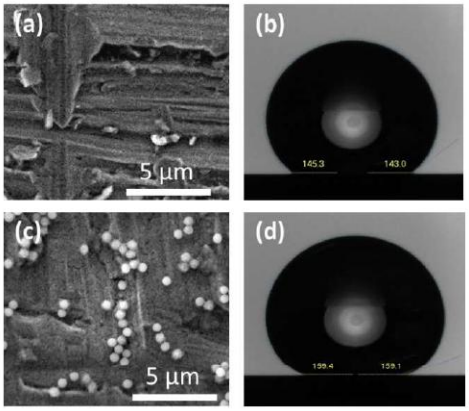
Inventors

Zineb Belarbi, Omer Dogan, Joseph Tylczak, and Margaret Ziomek-Moroz

Superhydrophobic Multilayer Anticorrosion Coating (23N-10)

Opportunity

Internal corrosion poses a significant and ongoing challenge for the extensive and aging natural gas pipeline infrastructure, leading to incidents, leaks, substantial monetary losses, and potential explosions. Engineers at NETL have created an asymmetric multilayer anticorrosion coating designed for internal natural gas pipelines, addressing corrosion from water, salt, and carbon dioxide (CO_2). The coating is composed of three distinct portions: a superhydrophobic top portion, a middle primer portion, and a bottom portion containing corrosion inhibitors. The superhydrophobic top, formed by alternating 60 nm and 600 nm silica nanoparticles and treated with fluorinated silane, creates a rough surface that minimizes contact with corrosive liquids by trapping air pockets. The middle primer portion uses 60 nm silica nanoparticles for a smooth foundation, and the bottom portion incorporates tannic acid as a corrosion inhibitor to manage permeated water vapor. This design reduces the corrosion rate of carbon steel by 18 times in CO_2-saturated salt water and is available for licensing and/or further collaborative research from NETL.



Surface morphology and contact angle of carbon steel surface coated by (a, b) PDDA/SiNP-60BLs, and (c, d) PDDA/SiNP-60/PDDA/SiNP-600 QLs

Challenges Addressed

- Existing internal coatings, often epoxy-based, are largely designed for drag reduction and are insufficient to withstand complex and highly corrosive environments
- Conventional solutions typically offer inadequate protection, being single-composition and unable to effectively address the combined corrosive effects of multiple species

Potential Commercial Applications

- Provides exceptional, long-lasting internal corrosion protection for diverse fluid transport and storage systems, including natural gas, hydrogen, oil, and chemical pipelines and tanks
- Offers superior protection for industrial and marine assets such as offshore structures, marine equipment, or chemical processing equipment

Competitive Advantages

- The asymmetric multilayer coating reduces the corrosion rate of carbon steel in CO_2-saturated salt water from 1.12 mm/year to 0.06 mm/year, an eighteen-fold improvement
- The modular design allows for tailoring to specific applications by adjusting the composition and sequence of each layer
- With a total thickness of approximately 16 µm, the coating is significantly thinner and lighter than traditional coatings, potentially reducing material and transportation costs

Intellectual Property Status

A U.S. nonprovisional application has been filed.

Publications

F. Xiang and D. Hopkinson. Simple, Tough, and Effective Porous Coating for Anti-Corrosion Application. (2025). *OSTI.GOV* DOI: https://doi.org/10.2172/2997208.

Licensing/Collaboration

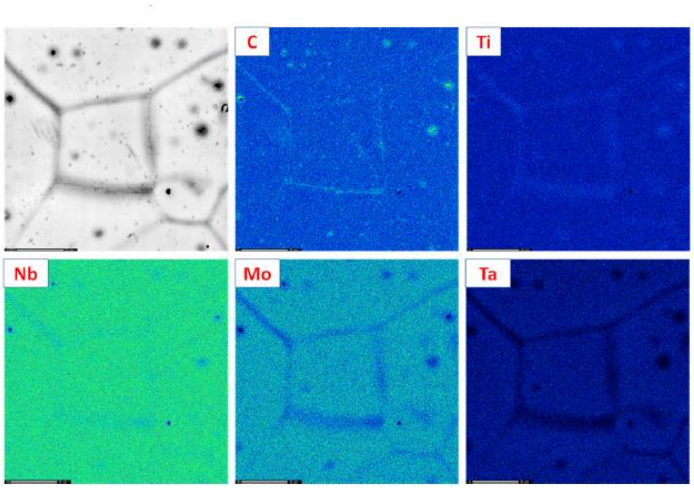
Partnerships@netl.doe.gov

Inventors

David Hopkinson and Fangming Xiang

Low-Cost, High-Performance Alloys for Gas Turbine Blades (21N-18)

Opportunity



Backscatter electron micrograph of NETL superalloy in the as-cast state

Developing materials for ultrahigh-temperature applications, particularly turbine blades operating above 1300°C, presents significant challenges, as existing nickel (Ni)-based superalloys are insufficient for these extreme conditions. NETL has engineered lightweight, cost-effective, precipitation-strengthened refractory high-entropy alloys (RHEAs) designed for turbine blade applications above 1300°C. These alloys, based on niobium, molybdenum, tantalum, zirconium, hafnium, vanadium, carbon and/or other elements, consist of a ductile high-entropy solid solution matrix strengthened by fine precipitates of high-entropy MC carbides (M = Nb, Ta, Ti, Zr, Hf). The MC carbides are expected to enhance high-temperature strength, improve creep performance by hindering dislocation gliding and grain boundary sliding, and reduce thermal expansion. The alloys are additively manufactured, with rapid solidification processing facilitating carbide precipitation, and their design utilizes high-throughput multiscale computer modeling and machine learning for property optimization. This technology is available for licensing and/or further collaborative research from NETL.

Challenges Addressed

- Existing Ni-based superalloys are inadequate for extreme, high-temperature conditions
- Other refractory alloys struggle to achieve a harmonious balance of essential properties, such as room-temperature ductility, fracture toughness, high-temperature creep and fatigue resistance

Potential Commercial Applications

- These alloys are superior to Ni-based superalloys, specifically designed for turbine blades in power generation, commercial, and military aircraft engines operating above 1300°C
- Lightweight, high-temperature strength, ductility, and oxidation resistance make it ideal for components in rocket engines, hypersonic vehicles, and spacecraft re-entry shields

Competitive Advantages

- The precipitation-strengthened RHEAs exhibit superior strength at temperatures exceeding 1300°C, surpassing traditional Ni-based superalloys like Inconel 718, which typically operate effectively up to around 700°C
- The fine MC carbide precipitates in the RHEAs hinder dislocation movement and grain boundary sliding, enhancing creep resistance at elevated temperatures

Intellectual Property Status

A U.S. nonprovisional application was filed January 30, 2024.

Publications

M. Gao, et al. Low-Cost High-Performance Refractory High Entropy Alloys for Gas Turbine Blade Applications Above 1300 Celsius. (2024). *United States Patent and Trademark Office.* U.S. Patent Application Publication No. US20250243568A1.

Licensing/Collaboration

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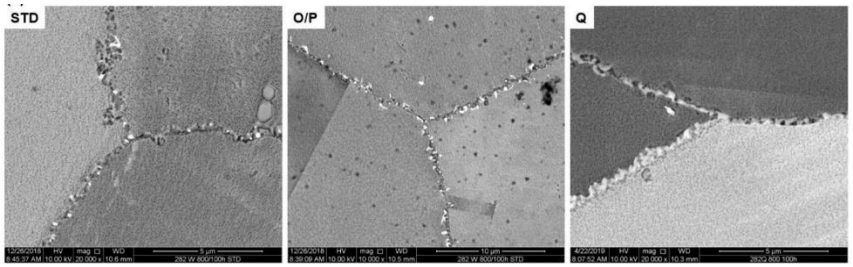
Inventors

Michael Gao, David Alman, Michael Kirka, Michael Widom, and Saket Thapliyal

NiCrCoMoW Age-Hardenable Alloy for Creep-Resistant, High-Temperature Applications (21N-08)



Microstructure of NETL alloys following 100 h exposure at 800°C

Opportunity

Advanced energy conversion systems, such as those in ultra-supercritical and supercritical carbon dioxide power (CO_2) plants, demand materials that maintain high yield strength and exceptional creep resistance well above 800°C. NETL and Battelle have designed an alloy for high-temperature applications. The alloy is a nickel-based superalloy with a modified composition, including adjusted levels of chromium, cobalt, molybdenum, tungsten, titanium (Ti), and aluminum (Al), that maintains high yield strength and creep resistance above 800°C. It is produced via a controlled process involving vacuum induction melting with minimal carbon pickup, followed by a series of homogenization, hot working, and dual-stage heat treatments. This process optimizes the formation of ordered γ' ($Ni_3(Al,Ti)$) precipitates in a matrix, along with the formation of $M_{23}C_6$ carbides along grain boundaries while suppressing topologically close-packed phases. This technology is available for licensing and/or further collaborative research from NETL in partnership with Battelle.

Challenges Addressed

- Existing high-temperature alloys, while effective up to certain thermal thresholds, suffer from rapid degradation, reduced creep life, and formation of destabilizing phases when pushed beyond their design limits
- Conventional materials often lack the necessary balance between mechanical performance and manufacturability, particularly regarding phase stability and long-term microstructural integrity under prolonged high-temperature exposure

Potential Commercial Applications

- Exceptional creep resistance and phase stability make it ideal for critical structural parts such as turbine blades, discs, and boiler tubes in advanced ultra-supercritical and supercritical CO_2 power plants, as well as in traditional steam and gas turbine systems
- Suited for manufacturing high-performance aero engine components, where durability and reliability are paramount

Competitive Advantages

- Demonstrates up to a 130% increase in creep life at 760°C and maintains performance at 780°C, significantly outperforming Haynes 282 in high-temperature applications
- Offers improvements of 7%-14% in ultimate tensile strength and yield stress at both room temperature and 800°C compared to traditional nickel-based superalloys
- The modified composition and specialized heat treatment markedly reduce the formation of detrimental topologically close-packed phases over prolonged exposure at 800°C and 900°C

Intellectual Property Status

A U.S. nonprovisional application (US18/194,447) was filed March 31, 2023.

Publications

P. Jablonski, et al. NiCrCoMoW Age Hardenable Alloy for Creep-Resistant High Temperature Applications, and Methods of Making. (2023). *United States Patent and Trademark Office.* U.S. Patent Application Publication No. US20230383382A1.

Licensing/Collaboration

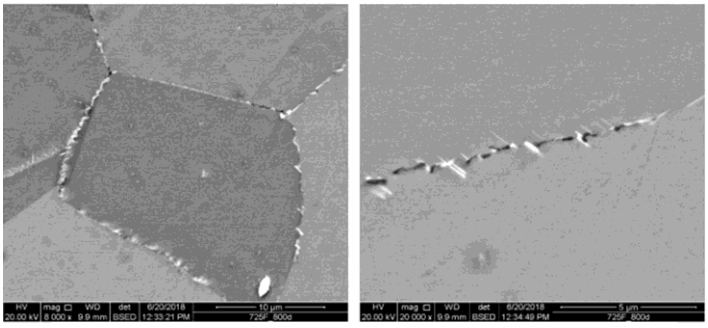
Partnerships@netl.doe.gov

Inventors

Paul Jablonski, Martin Detrois, and Jeffrey Hawk

Creep-Resistant NiCrMoNb Alloy for High-Temperature Components (20N-15)

Opportunity



δ phase precipitates located at the grain boundaries of NETL alloy

Power generation systems are moving toward higher operating temperatures, which places increasing mechanical stress on components such as turbine blades, valves, and heat exchangers. Traditional steels lose strength and creep resistance under these conditions, creating a need for alloys that can maintain performance at temperatures approaching 750°C. NETL and Battelle Memorial Institute have engineered an advanced nickel-chromium-molybdenum-niobium (NiCrMoNb) alloy that provides high yield strength, improved creep life, and stable microstructural behavior at elevated temperatures. The alloy's chemistry is tailored to promote strengthening precipitates within the grains and controlled phase formation at grain boundaries, while heat treatment methods further enhance high-temperature stability. Together, these features enable the alloy to outperform existing commercial Ni-based alloys used in energy, aerospace, and industrial applications. This technology is available for licensing and/or further collaborative research from NETL in partnership with Battelle.

Challenges Addressed

- High-temperature applications in energy and aerospace sectors demand materials that resist creep, oxidation, and corrosion under extreme conditions
- Many conventional alloys struggle to balance strength and long-term durability
- Grain boundary instability and nonuniform precipitate distribution

Potential Commercial Applications

- Superior creep resistance, yield strength, and oxidation/corrosion stability make the alloy ideal for gas turbine disks, blades, and spacers operating at elevated temperatures
- Enhanced high-temperature performance and microstructural stability, suited for next-generation power plants components

Competitive Advantages

- Delivers a 40%-370% increase in creep life and a 53%-550% improvement in creep ductility at 700°C compared to INCONEL 725
- With an average 16% boost in ultimate tensile strength and 21% increase in yield strength at 750°C, this alloy outperforms standard Ni-based alloys
- The use of a computationally optimized homogenization cycle and a dual-step high-temperature aging treatment yields a uniform microstructure

Intellectual Property Status

A U.S. patent (US11827955) was issued November 28, 2023, and expires October 27, 2041.

Publications

M. Detrois, et al. NiCrMoNb Age Hardenable Alloy for Creep-Resistant High Temperature Applications, and Methods of Making. (2023). *United States Patent and Trademark Office.* U.S. Patent No. 11,827,955.

Licensing/Collaboration

Partnerships@netl.doe.gov

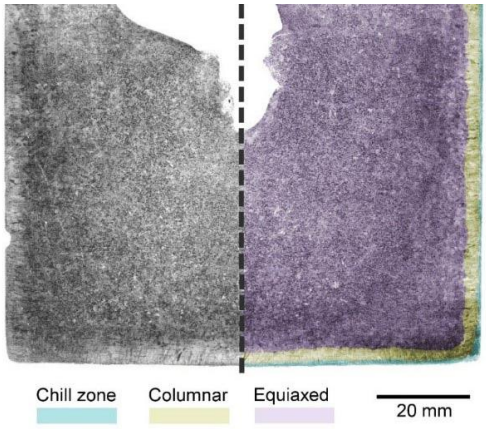
Inventors

Martin Detrois, Paul Jablonski, and Jeffrey Hawk

Creep-Resistant Nickel-Based Superalloy Casting and Manufacturing (20N-13)

Opportunity

Raising the efficiency and durability of high-temperature energy systems depends on materials that can withstand long-term stress without deforming or degrading. The U.S. Department of Energy 's National Energy Technology Laboratory (NETL) has created a refined casting and heat-treatment process for a nickel-based superalloy derived from Inconel 740H that maintains the creep strength of wrought material while offering the versatility of casting. The fine grain homogenized process combines low-temperature pouring with preheated molds and a precisely timed homogenization sequence to create a uniform, fine-grained microstructure with consistent chemical distribution. This advancement enables reliable performance above 760°C in turbine housings, valves, and heat exchangers used in next-generation power systems. The technology is available for licensing and collaborative research from NETL.



Superalloy derived from NETL process

Challenges Addressed

- Conventional cast Inconel 740H exhibits poor creep resistance compared to wrought forms
- Large or complex superalloy components remain expensive to manufacture through traditional methods
- Nonuniform grain structure and elemental segregation reduce long-term material stability
- Existing ferritic and austenitic steels fail to meet strength requirements at high temperature and pressure

Potential Commercial Applications

- Advanced ultra-supercritical and supercritical carbon dioxide power plant components
- Steam turbine, boiler, and heat exchanger fabrication
- Aerospace and industrial gas turbine hardware
- Any high-temperature system requiring long-term creep resistance and oxidation stability

Competitive Advantages

- Produces uniform microstructure with improved creep and tensile strength
- Performs consistently at sustained operating temperatures above 760°C
- Increased resistance to cracking and environmental degradation
- Enables cost-effective casting of large or complex geometries
- Compatible with existing IN740H supply chains and manufacturing infrastructure

Intellectual Property Status

A U.S. patent (US11453051) was issued September 27, 2022, and expires February 24, 2041.

Publications

P. Jablonski, et al. Creep Resistant Ni-Based Superalloy Casting and Method of Manufacture for Advanced High-Temperature Applications. (2022). *United States Patent and Trademark Office.* U.S. Patent No. 11,453,051.

Licensing/Collaboration

Partnerships@netl.doe.gov

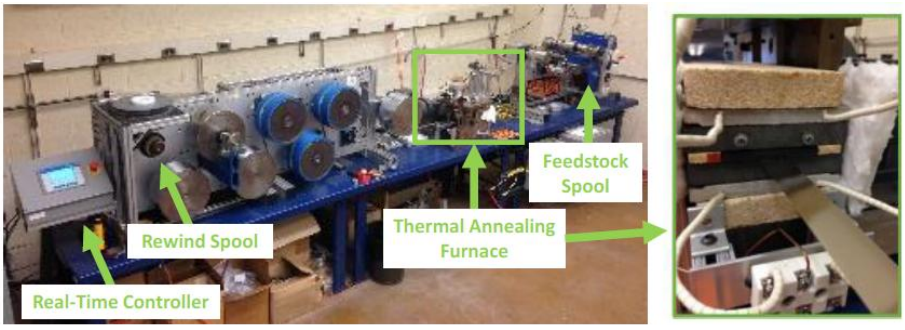
Inventors

Paul Jablonski, Jeffrey Hawk, and Martin Detrois

Microwave Annealing Systems for Alloy Processing (18N-29)

Opportunity

Producing soft magnetic alloys with tightly controlled properties requires heat treatments that can tune microstructure without introducing large thermal gradients or slow furnace cycles. Engineers at NETL and Pennsylvania State University (Penn State), designed a single mode microwave processing system that creates spatially distinct regions of pure magnetic and pure electric fields inside the same chamber. Amorphous alloy segments are automatically positioned in one of these field regions, where microwave energy couples directly into the material to generate internal heating between 400°C and 700°C. Because the chamber geometry separates electric and magnetic field maxima, operators can select annealing conditions that influence permeability, microstructural evolution, or stress relief with high spatial precision. Automated loading and unloading support continuous, in-line treatment of short alloy sections, enabling consistent production of tape-wound cores and other magnetic components. This approach provides a controllable alternative to conventional furnace annealing while allowing real-time adjustment of stress, temperature, and processing speed. This technology is available for licensing and/or further collaborative research from NETL in partnership with Penn State.



In-line processing facility for applied tension annealing using a conventional furnace set-up for high-temperature thermal processing

Challenges Addressed

- Traditional thermal annealing methods involve large heating zones and slow processing, which severely limit spatial control over material properties and reduce production speed
- Existing in-line annealing techniques, such as strain annealing furnaces, lack the fine spatial resolution needed to easily produce localized variations in properties like permeability

Potential Commercial Applications

- High-throughput, in-line production of improved soft magnetic components like inductors, transformers, motors, and sensors
- Efficient, in-line production of electromagnetic interference and general electromagnetic shielding materials

Competitive Advantages

- Microwave and radio frequency (RF) annealing provide fine spatial control over heating, enabling localized treatment of amorphous and nanocrystalline alloy ribbons
- The rapid heating and cooling cycles of microwave and RF annealing significantly reduce processing time compared to traditional thermal annealing methods

Intellectual Property Status

A U.S. patent (US12349262) was issued July 1, 2025, and expires January 16, 2042.

Publications

P. Ohodnicki, et al. In-line Microwave Processing of Alloys. (2025). *United States Patent and Trademark Office.* U.S. Patent No. 12,349,262.

Licensing/Collaboration

Partnerships@netl.doe.gov

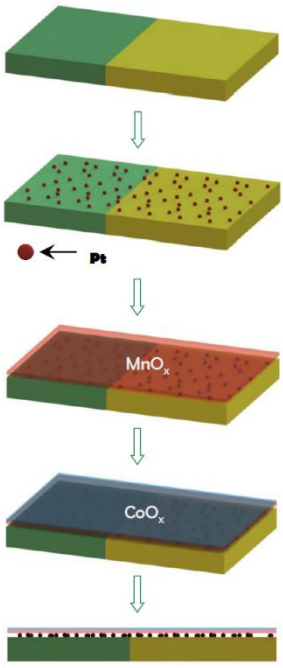
Inventors

Paul Ohodnicki, Jr., Kevin Byerly, Dinesh Agrawal, and Michael Lanagan

Atomic Layer Deposition-Formed Multilayer Electrocatalyst Structures (18N-25)

Opportunity

Improving the activity and durability of solid oxide fuel cell (SOFC) electrodes requires electrocatalyst architectures that remain nanoscale, uniformly distributed, and resistant to coarsening under high-temperature operation. Researchers at NETL and West Virginia University (WVU) established an atomic layer deposition (ALD) method that forms a controlled multilayer electrocatalyst structure directly on porous electrode backbones. The process begins with an ALD layer of discrete nanoparticles of the first electrocatalyst, followed by one or more ALD layers containing the second electrocatalyst. These stacked layers create a composite nanostructure that stabilizes catalyst particle size and increases active site density during oxygen reduction. Because ALD provides conformal coating throughout the porous network, electrocatalyst loading can be minimized while preserving accessibility to gas pathways and ionic transport. The resulting electrodes maintain performance at temperatures above 650°C, where conventional infiltrated catalysts typically agglomerate. This technology is available for licensing and/or further collaborative research from NETL in collaboration with WVU.



Schematic of ALD deposition procedure

Challenges Addressed

- SOFCs are significantly limited by the performance of their porous cathodes, where the oxygen reduction reaction dominates device efficiency
- Traditional chemical solution-based infiltration methods face substantial challenges in depositing uniform films onto the complex, three-dimensional porous structures of cathodes

Potential Commercial Applications

- Enables the production of SOFCs with significantly higher power density, improved durability, and the potential for lower operating temperatures

Competitive Advantages

- ALD provides highly uniform and conformal coatings on complex three-dimensional porous structures, ensuring consistent catalyst distribution throughout the cathode
- ALD-deposited nanostructured coatings exhibit enhanced thermal and chemical stability, reducing degradation over time
- The ALD process is automated, time-efficient, scalable, and capable of processing multiple SOFCs simultaneously

Intellectual Property Status

A U.S. patent (US11316169) was issued April 26, 2022, and expires March 11, 2040.

Publications

X. Song, et al. Methods for Forming Electrocatalyst Structures and Electrodes Comprising Same. (2022). *United States Patent and Trademark Office.* U.S. Patent No. 11,316,169.

Licensing/Collaboration

Partnerships@netl.doe.gov

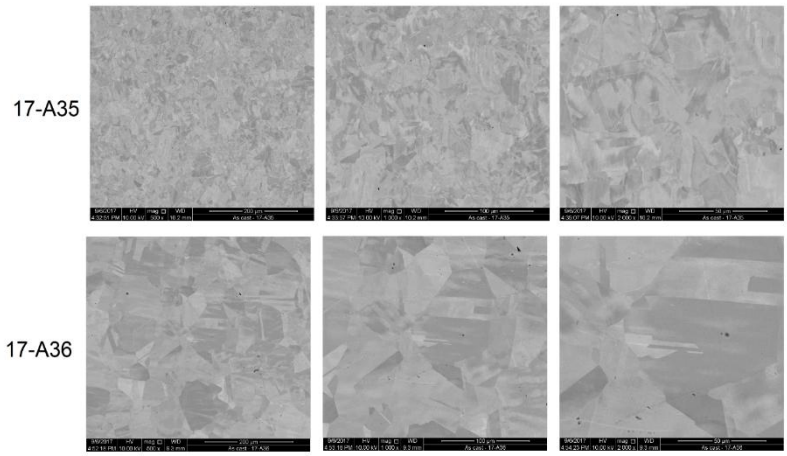
Inventors

Xueyan Song, Yun Chen, and Kirk Gerdes

High-Performance Corrosion-Resistant High-Entropy Alloys (18N-09)

Opportunity

Corrosion is a persistent challenge for metals exposed to seawater, acidic environments, and other harsh industrial conditions. NETL has established a new class of high-performance, corrosion-resistant high-entropy alloys that combines exceptional durability with reduced material costs. These alloys, designed using advanced thermodynamic modeling, provide superior resistance to pitting and crevice corrosion compared to conventional nickel-based superalloys such as Hastelloy® C276. They can be manufactured as protective coatings or bulk components for long-lasting service in aggressive environments. This technology is available for licensing and/or further collaborative research from NETL.



Scanning electron micrograph of the as-processed A35 and A36 high-entropy alloys

Challenges Addressed

- Conventional nickel-based superalloys such as Hastelloy® C276 are highly effective but costly
- Metals operating in seawater or acidic environments are prone to localized corrosion that can lead to cracking and structural failure
- Existing materials often exhibit limited ductility or poor chemical stability over long-term service
- Industry lacks a cost-effective alloy with both high corrosion resistance and mechanical strength for extreme conditions

Potential Commercial Applications

- Protective coatings for marine, offshore, and subsea infrastructure
- Structural components for chemical processing and desalination equipment
- Heat exchangers and pressure vessels operating in corrosive or high-temperature environments
- Industrial systems exposed to brines, acids, or aggressive chemical streams
- Replacement for high-cost nickel superalloys in energy and manufacturing applications

Competitive Advantages

- Demonstrates strong resistance to pitting and crevice corrosion in seawater and acidic conditions
- Iron-rich composition lowers reliance on expensive nickel and cobalt
- Maintains mechanical performance in demanding environments
- Suitable for use as both bulk alloys and protective coatings

Intellectual Property Status

A U.S. patent (US11466344) was issued October 11, 2022, and expires July 10, 2040.

Publications

J. Hawk, et al. High-Performance Corrosion-Resistant High-Entropy Alloys. (2020). *United States Patent and Trademark Office*. U.S. Patent No. 11,466,344.

Licensing/Collaboration

Partnerships@netl.doe.gov

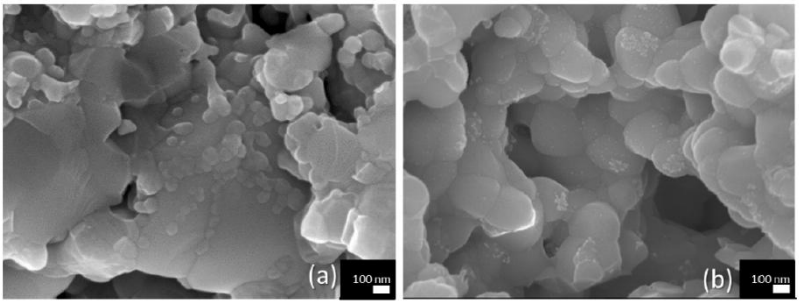
Inventors

Jeffrey Hawk, Paul Jablonski, Malgorzata Ziomek-Moroz, Joseph Tylczak, Michael Gao, and Alvaro Rodriguez

Fast Polymerized Catechol-Based Surfactant Assisted Infiltration of Solid Oxide Electrochemical Cell Infiltration Using Spraying Method (18N-02)

Opportunity

Solid oxide electrochemical cells (SOECs) offer significant potential for high-temperature power generation, but their performance is often limited by ohmic losses, catalytic deactivation, and mass transport inefficiencies. NETL and West Virginia University (WVU) have established a protocol for uniformly depositing inorganic oxide nanocatalysts within porous SOEC electrodes. It employs a computer-controlled spraying system to apply a rapid-polymerizable catechol-based biosurfactant and a weak halogen-based oxidant, either mixed at the nozzle or sequentially. This rapid polymerization forms an adhesive biotemplate within the electrode's pores, which enhances wettability and pins subsequently sprayed nanocatalyst precursors. The process culminates in a single firing step, resulting in smaller, uniformly dispersed catalyst particles (e.g., sub-10 nm) and improved electrochemical performance. This technology is available for licensing and/or further collaborative research from NETL.



Scanning electron microscope images of nanocatalyst infiltrated cathode microstructure (a) without treatment and (b) with treatment

Challenges Addressed

- Enhancing the triple phase boundary or double phase boundary within the electrode microstructure by introducing catalytically active nanomaterials is critical to improve SOECs
- Existing methods for incorporating nanomaterials face considerable challenges. Standard infiltration techniques are often labor intensive and require multiple infiltration and firing steps

Potential Commercial Applications

- Directly enhances the performance, durability, and specialized functionalities of SOEC/solid oxide fuel cell electrodes by enabling rapid, uniform nanocatalyst deposition with a single firing step

Competitive Advantages

- Use of a catechol-based biosurfactant enables rapid polymerization within seconds, significantly reducing processing time compared to traditional infiltration methods
- Spraying method employed allows for uniform deposition of nanocatalysts, resulting in smaller particle sizes (sub-10 nm) and higher surface area
- Requires only a single thermal treatment at temperatures below 900°C, simplifying the manufacturing process and reducing energy consumption

Intellectual Property Status

A nonprovisional patent application has been filed in the U.S.

Publications

O. Ozmen, et al. Rapid Polymerized Catechol Based Surfactant Assisted Infiltration of Solid Oxide Electrochemical Cell Infiltration Using Spraying Method. (2021). *United States Patent and Trademark Office.* U.S. Patent Application Publication No. US20230105993A1.

Licensing/Collaboration

Partnerships@netl.doe.gov

Inventors

Ozcan Ozmen, Shiwoo Lee, and Edward Sabolsky

High-Temperature Sensors for Monitoring and Control of Solid Oxide Fuel Cells (14N-28)

Opportunity

Reliable control of solid oxide fuel cells (SOFCs) requires real-time measurements inside high-temperature, chemically reactive environments. NETL and the University of Pittsburgh (Pitt) have developed embedded optical fiber-based sensors and high-temperature stable distributed interrogation methods that measure the absolute value and spatial gradient of gas composition and temperature along an SOFC anode or cathode stream. The approach enables localized monitoring for process optimization, degradation mitigation, and fault detection during operation. This technology is available for licensing and/or further collaborative research from NETL in partnership with Pitt.

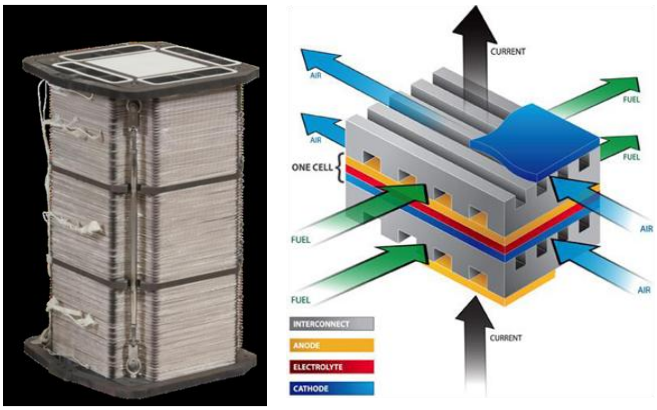


Image of a planar SOFC stack (left), a schematic of a single cell within the stack for a cross-flow configuration of fuel and air gas streams (right)

Challenges Addressed

- Conventional sensors are limited by wiring, power requirements, and material instability at SOFC operating temperatures
- Lack of spatially resolved measurements obscures local hot spots, fuel utilization imbalances, and degradation drivers
- External measurements provide delayed or indirect indicators that hinder active control
- Packaging and survivability challenges limit long-term embedded sensing in harsh gas environments

Potential Commercial Applications

- SOFC stacks and balance-of-plant controls
- Gasification reactors, gas turbines, boilers, and oxyfuel combustion systems
- Nuclear and high-temperature industrial processes requiring in-situ monitoring
- Aviation and aerospace propulsion testbeds and ground support systems

Competitive Advantages

- Measures composition and temperature with spatial resolution at multiple points within operating SOFCs
- Sensor materials and packaging are designed for stable performance in harsh oxidizing or reducing atmospheres
- Supports fuel-utilization optimization, efficiency improvements, and mitigation of degradation mechanisms

Intellectual Property Status

A U.S. patent was issued July 5, 2022, and expires May 16, 2036.

Publications

P. Chen, et al. System and Method for Monitoring a Reactor System Using Optical Fiber Based Sensors. (2017). *United States Patent and Trademark Office*. U.S. Patent No. 11,380,918.

Licensing/Collaboration

Partnerships@netl.doe.gov

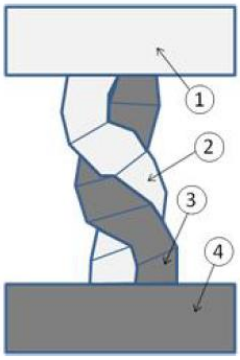
Inventors

Peng Chen, Jacob Poole, Paul Ohodnicki, Thomas Brown, Kirk Gerdes, and Michael Buric

Atomic Layer Deposition-Engineered Nanoscale Electrodes for Solid Oxide Fuel Cells (14N-26)

Opportunity

Electrode performance in solid oxide fuel cells (SOFCs) depends heavily on the nanoscale structure where gas adsorption, electrochemical reaction, and ion transport converge, yet traditional fabrication methods provide limited control over how these active regions form. Researchers at NETL , in collaboration with West Virginia University (WVU), developed an atomic layer deposition (ALD) strategy that introduces finely tuned surface-modifying phases directly into porous SOFC electrodes. The infiltration process allows subnanometer control of composition and crystallinity, generating catalytic nanoparticles, conformal ionic coatings or hybrid nanostructures that enhance triple-phase boundary density without disrupting the original scaffold. This engineered interface improves oxygen reduction kinetics, stabilizes long-term operation, and enables adaptation of the electrode to different temperature or fuel environments. This technology is available for licensing and/or further collaborative research from NETL in partnership with WVU.



1. Cathode current collecting layer (primary electronic conductor)
2. Primary electronic conductor
3. Primary ionic conductor
4. Electrolyte (ionic conductor)

Diagram depicting composite structure of cathode functional layer

Challenges Addressed

- SOFCs encounter significant performance and durability challenges, particularly at the cathode where the oxygen reduction reaction occurs
- This reaction exhibits a high activation energy, especially at temperatures below 800°C, leading to substantial overpotential and performance degradation

Potential Commercial Applications

- Enhances the power density and durability of both solid oxide and fuel cell electrodes by precisely engineering their nanoscale architecture and stabilizing catalysts
- Improves the efficiency and longevity of SOEC electrodes for hydrogen production by increasing reaction site density
- Enhances the performance and stability of electrodes in various battery types, including flow batteries

Competitive Advantages

- ALD enables the creation of conformal, porous nanoscale networks within the cathode, leading to a 1.3-1.5× increase in power density compared to baseline cells
- ALD-stabilized nanocomposite cathodes exhibit enhanced long-term stability
- The ALD process is scalable and compatible with commercial SOFC manufacturing, enabling cost-effective, batch processing of large numbers of cells

Intellectual Property Status

A U.S. patent (10529975) was issued January 7, 2020, and expires April 6, 2038.

Publications

X. Song, et al. Nanoscale SOFC Electrode Architecture Engineered Using Atomic Layer Deposition. (2020). *United States Patent and Trademark Office*. U.S. Patent No. 10,529,975.

Licensing/Collaboration

Partnerships@netl.doe.gov

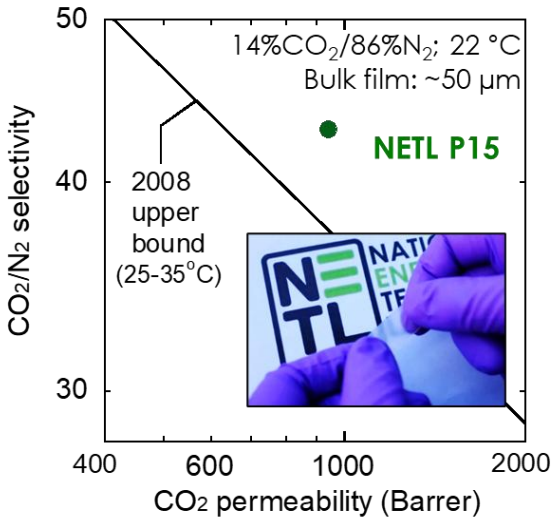
Inventors

Xueyan Song, Yun Chen, Kirk Gerdes, and Shiwoo Lee

Blended Rubbery Polymer for Gas Separation (23N-05)

Opportunity

NETL has developed a method for creating advanced polymer membranes to efficiently separate carbon dioxide (CO_2) from nitrogen (N_2). These membranes combine excellent CO_2 permeability, selectivity, and stability, even in humid conditions, making them ideal for industrial applications like CO_2 extraction from flue gas. NETL's rubbery blend membrane resists aging and humidity and exceeds Robeson's 2008 upper bound for CO_2/N_2 separation. By exhibiting high CO_2 permeance (up to 4,500 GPU), moderate CO_2/N_2 selectivity and long-term stability, it can efficiently separate CO_2 from flue gas in power plants and industrial facilities, providing a more stable and cost-effective alternative to traditional amine-based capture systems. High molecular weight facilitates thin-film coating, enabling defect-free membranes as thin as 120 nm. It is a versatile platform for CO_2 separation, medical devices, and other applications requiring robust, high-performance membranes. This invention is available for licensing and/or further collaborative research from NETL.



Gas separation properties of NETL's blended rubbery polymer membrane (green dot)

Challenges Addressed

- Industrial processes that require CO_2/N_2 separation often depend on membranes that can provide high permeability and selectivity. However, these materials have poor mechanical integrity and aging resistance
- Other solutions lack robustness and performance when exposed to humidity or prolonged use
- Complex fabrication steps and difficulties in achieving thin, defect-free films that do not degrade in the presence of water vapor or fluctuating temperatures further complicate efforts, underscoring the need for more reliable, high-performance membrane materials

Potential Commercial Applications

- Efficiently removing CO_2 from flue gas and other industrial gas streams
- For processes designed to convert or utilize CO_2
- Wound dressings, tissue engineering, and drug delivery

Competitive Advantages

- Features higher CO_2 permeability compared to cellulose acetate
- Balances permeability and selectivity at levels surpassing established performance limits
- Maintains adaptability for diverse industrial applications

Intellectual Property Status

A provisional patent application has been filed.

Licensing/Collaboration

Partnerships@netl.doe.gov

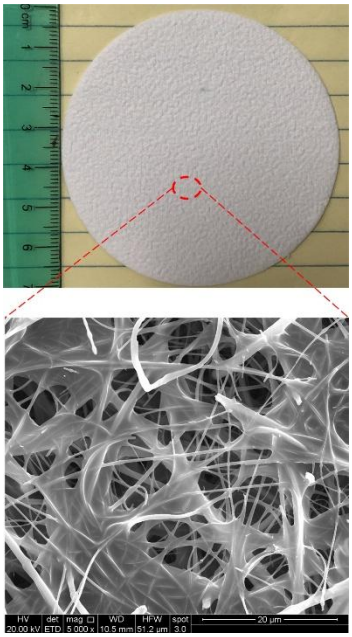
Inventors

David Hopkinson, Lingxiang Zhu, and Victor Kusuma

Fibrous Amine-Functionalized Matrix Flat Sheet Sorbent (22N-08)

Opportunity

Effective removal of dilute gases from air and selective recovery of metals from water require materials that load quickly, regenerate with low energy, and are simple to handle in flow systems. NETL and Battelle Memorial Institute have designed a fibrous amine functionalized matrix (FAM) flat sheet sorbent that applies a crosslinked polyamine coating to a glass microfiber mat, delivering high uptake, fast kinetics, and clean operation without free particles. The sheet format supports rapid microwave regeneration near room temperature for gas service and maintains performance across a wide pH range for metal recovery. This technology is available for licensing and/or further collaborative research from NETL in partnership with Battelle.



Scanning electron microscope image of the FAM

Challenges Addressed

- Particle sorbents are difficult to manage in flow systems and prone to dispersion or clogging
- Existing gas and liquid sorbents often require high regeneration temperatures and slow cycling times
- Many current sorbents have limited capacity or selectivity for low-concentration targets
- Conventional metal and contaminant removal systems can generate secondary waste or require complex chemical handling

Potential Commercial Applications

- Direct removal of trace gases from air and confined environments
- Purification of gas streams from industrial or well operations
- Wastewater treatment and polishing for lead, heavy metals, and rare earth elements
- Recovery of critical minerals from mine drainage or process leachates
- Integration into laminate or modular reactors for gas and liquid purification

Competitive Advantages

- Microwave-assisted regeneration at near-room temperature reduces operational costs and time
- Operates without free particles, minimizing maintenance and enabling direct integration in flow systems
- Maintains strong performance for metal recovery across pH 3-12 with reusable acid or buffer elution
- Adjustable coating chemistry allows performance customization and easy scaling

Intellectual Property Status

A nonprovisional patent application has been filed in the U.S.

Publications

M. Gray, et al. Fibrous Amine-Functionalized Matrix (Fam) For Contaminant Removal from Gaseous and Liquid Sources, Methods of Making and Use. (2024). *United States Patent and Trademark Office.* PCT Application Publication No. WO2024137851A1.

Licensing/Collaboration

Partnerships@netl.doe.gov

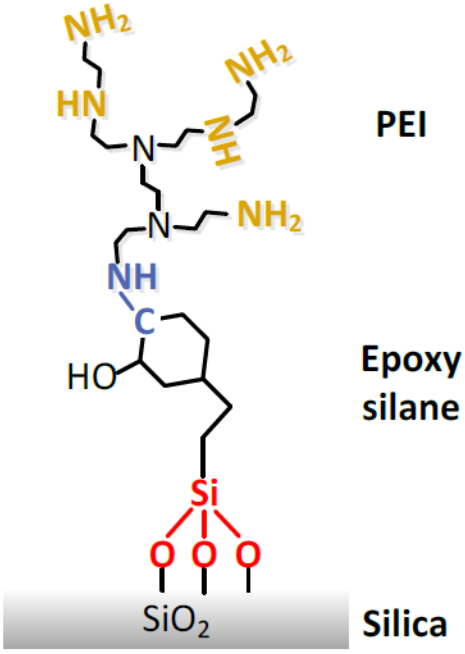
Inventors

McMahan Gray, Qiuming Wang, Walter Wilfong, and Fan Shi

Stable Immobilized Amine Sorbents for the Decoloration of Wastewaters (21N-17 and 17N-18)

Opportunity

Industrial and municipal systems frequently struggle to remove organic colorants and similar pollutants from wastewater streams without incurring high costs or media loss. NETL has developed basic immobilized amine sorbents that covalently attach polyamines to porous silica or alumina supports using epoxysilane or polyepoxide linkers. This creates a durable, water-stable network capable of capturing a broad range of organic contaminants, including dyes and structurally related compounds, while maintaining performance in variable pH and high-salinity conditions. Laboratory studies show these sorbents can retain more than 90% of their active content after extended water exposure and remove up to 99% of target dyes under continuous flow. This technology is available for licensing and/or further collaborative research from NETL.



Schematic of 181D chemical structure

Challenges Addressed

- Organic dyes and similar contaminants persist through conventional treatment and foul membranes
- Many adsorbents leach active species or lose capacity across variable pH and salinity
- Existing solutions can be costly to regenerate and sensitive to co-ions such as sodium and calcium
- Media often lack mechanical stability under continuous flow

Potential Commercial Applications

- Textile, food processing, and coffee wastewater treatment
- Point-of-use and point-of-entry polishing for drinking water systems
- Polishing of ponds, lakes, rivers, seawater, and groundwater
- Adsorption of structurally similar organic pollutants, including selected phenols, pesticides, and perfluoro compounds

Competitive Advantages

- Covalently immobilized polyamines resist leaching in flow
- High capture across diverse dye classes and selected organics in the presence of salts
- Recyclable over multiple adsorption–desorption cycles with retained capacity
- Simple, scalable synthesis from low-cost raw materials
- Demonstrated structural stability and high organic content retention after accelerated water exposure

Intellectual Property Status

A U.S. patent was issued November 17, 2020, and expires January 19, 2039.

Publications

M. Gray, et al. Stable Immobilized Amine Sorbents for Removal of an Organic Contaminate From Wastewater. (2020). *United States Patent and Trademark Office.* U.S. Patent No. 10,836,654.

Licensing/Collaboration

Partnerships@netl.doe.gov

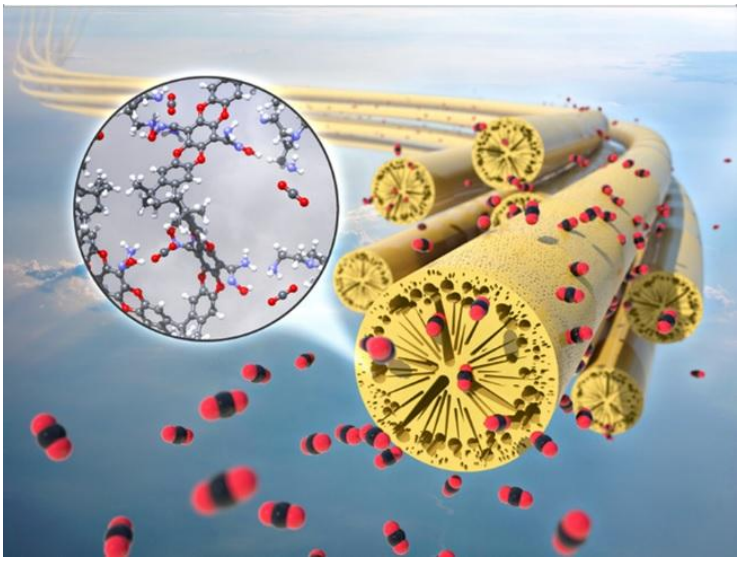
Inventors

McMahan Gray, Brian Kail, Qiuming Wang, and Walter C. Wilfong

Bifunctionalized Polymeric Sorbents (21N-14)

Opportunity

Efficient separation of acidic gases and trace contaminants from industrial or natural gas streams is often limited by slow adsorption rates, high energy requirements, and poor material stability. NETL and Battelle Memorial Institute created a bifunctionalized polymeric sorbent that combines high selectivity, rapid uptake, and low-temperature regeneration. The material integrates polymers of intrinsic microporosity functionalized with amidoximes and tethered molecular amines to achieve strong, reversible adsorption of targeted gas species while maintaining excellent stability in humid or mixed-gas environments. The material can be processed as fibers, sheets, powders, or monoliths for broad applicability in gas separation, purification, and recovery processes. This technology is available for licensing and/or collaborative research from NETL and Battelle.



Polymer fiber sorbent

Challenges Addressed

- Slow adsorption kinetics and low efficiency in existing polymeric sorbents
- Complex material synthesis and limited scalability for industrial systems
- Instability and leaching of active amine components during extended use
- High thermal demand for regeneration or desorption cycles

Potential Commercial Applications

- Separation and purification of industrial or process gas streams
- Upgrading of natural gas, synthesis gas, or biogas feedstocks
- Removal of acidic or corrosive gases from chemical and refining processes
- Gas filtration, membrane support, or storage applications
- Recovery of trace or valuable components from mixed gas or liquid streams

Competitive Advantages

- Cost-effective, scalable production using abundant polymer precursors
- High selectivity and capacity for targeted acidic gases at low concentrations
- Rapid uptake with mild regeneration conditions and low energy use
- Excellent stability under humid or contaminated operating environments
- Versatile fabrication into multiple geometries for modular system integration

Intellectual Property Status

A nonprovisional patent application has been filed in the U.S.

Publications

D. Hopkinson, et al. Amidoxime Functionalized Polymers Loaded with Alkyl Amines, Methods of Making, and CO2 Capture Using Same. (2022). *United States Patent and Trademark Office.* U.S. Patent Application Publication No. US20230056553A1.

Licensing/Collaboration

Partnerships@netl.doe.gov

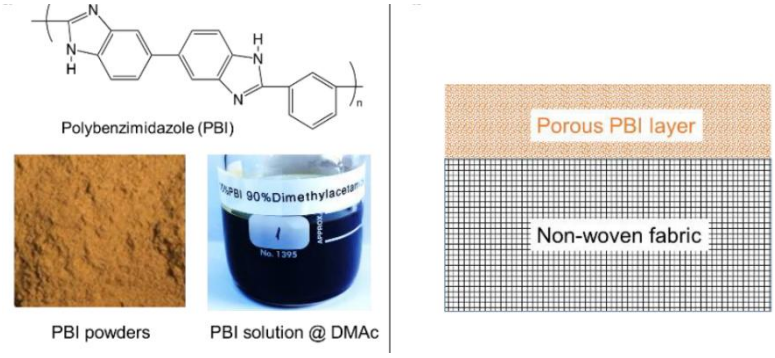
Inventors

David Hopkinson, James Hoffman, Ali Sekizkardes, Victor Kusuma, Shouliang Yi

Porous Polybenzimidazole Membrane Supports for Composite Membranes (20N-26)

Opportunity

Gas separation membranes need supports that are both highly permeable and mechanically robust, yet many commercial supports add significant resistance to gas transport and cannot tolerate harsh solvents or high temperatures used in membrane fabrication. To address this limitation, researchers at NETL and Battelle Memorial Institute have developed porous polybenzimidazole (PBI) membrane supports tailored for high-performance composite gas separation membranes. The technology uses a PBI layer bonded to a fabric substrate and produced by a controlled phase inversion process that avoids pore-forming additives. This method yields supports with nanoscale surface pores, high surface porosity, and very high gas permeance while preserving the excellent thermal and chemical stability of PBI. The resulting membranes provide a smooth, stable platform for thin selective, gutter, or protective layers and help maintain high permeance and selectivity in composite carbon dioxide, hydrogen, or other gas separation systems. The process is compatible with roll-to-roll manufacturing for large-scale production. This technology is available for licensing and/or further collaborative research from NETL in partnership with Battelle.



(Left) Chemical structure of Celazole® PBI along with its commercial products, (right) Illustration of a porous PBI membrane comprising a porous PBI layer and a nonwoven fabric substrate

Challenges Addressed

- Gas separation substrates generally lack sufficient chemical resistance against the organic solvents employed during membrane fabrication and suffer from inadequate thermal stability
- Balancing the need for high porosity and controlled nanoscale pore dimensions with robust chemical and thermal durability remains a key challenge

Potential Commercial Applications

- High surface porosity, nanosized pores, and robust chemical/thermal stability provide an ideal support structure for thin film composite membranes
- The porous PBI membrane is well-suited for separation processes under extreme conditions

Competitive Advantages

- Exhibits high surface porosity (up to 20%) and nanosized pores (15-42 nm), which significantly improve carbon dioxide permeance compared to conventional supports
- PBI membranes maintain their gas permeance when challenged with hexane, ethanol, chloroform, and acetone, enhancing durability and reducing maintenance costs
- Demonstrates remarkable thermal endurance by retaining high carbon dioxide permeance up to 200°C

Intellectual Property Status

A U.S. patent (US12138599B2) was issued November 12, 2024, and expires September 6, 2042.

Publications

D. P. Hopkinson and L. Zhu. Porous Polybenzimidazole Membrane Supports for Composite Membranes. (2024). *United States Patent and Trademark Office.* U.S. Patent No. 12138599.

Licensing/Collaboration

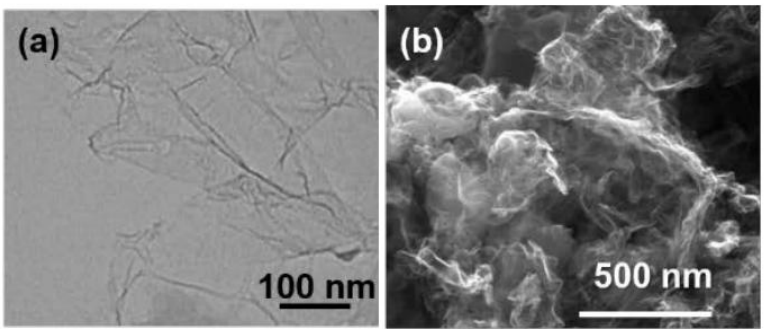
Partnerships@netl.doe.gov

Inventors

David Hopkinson and Lingxiang Zhu

MARGA Aqueous Solution for Gas Separation (19N-30)

Opportunity



(a) Scanning electron microscopy and (b) transmission electron microscopy of coal-based graphene

Gas separation technologies, particularly those employing amine-based absorption, face substantial challenges, including being energy-intensive and having slow regeneration of the amine solution. As an alternative approach, NETL has employed a microwave-accelerated regeneration of a graphene-amine (MARGA) aqueous solution for gas separation. It utilizes microwave heating to rapidly and volumetrically heat a carbon dioxide (CO_2)-rich amine solution, typically 30% aqueous monoethanolamine. The addition of coal-based graphene to the solution significantly enhances microwave absorption, creating localized hot spots that accelerate CO_2 desorption. This method achieves CO_2 desorption rates over two orders of magnitude faster than conventional thermal heating and lowers the activation energy for desorption to 25.6 kJ/mol, enabling regeneration at lower temperatures. This technology is available for licensing and/or further collaborative research from NETL.

Challenges Addressed

- Conventional thermal regeneration processes demand significant energy input, typically in the form of steam, to heat the solution to high temperatures, resulting in high operating costs and substantial capital investment for the necessary equipment
- Slow kinetics of CO_2 desorption under these conditions further contributes to large equipment footprints and considerable water usage, ultimately hindering economic viability

Potential Commercial Applications

- Significantly reduces energy consumption and equipment size for CO_2 separation from large industrial and power plant emissions, making the process more cost-effective and efficient
- Offers a highly efficient and lower-cost method for removing CO_2, hydrogen sulfide, and sulfur dioxide from natural gas, biogas, refinery streams, and flue gases, improving product quality

Competitive Advantages

- The MARGA process utilizes microwave heating combined with graphene-enhanced amine solutions, significantly lowering the energy required for CO_2 desorption
- The MARGA method achieves effective CO_2 desorption at reduced temperatures, decreasing water evaporation and solvent degradation

Intellectual Property Status

A U.S. patent (U.S. App. No: 18/420,481) was filed January 23, 2024.

Publications

F. Shi, et al. Microwave-Accelerated Aqueous Solvent Regeneration Using Microwave Absorbers for Carbon Capture. (2025) *United States Patent and Trademark Office.* U.S. Patent Application Publication No. US20250235851A1.

Licensing/Collaboration

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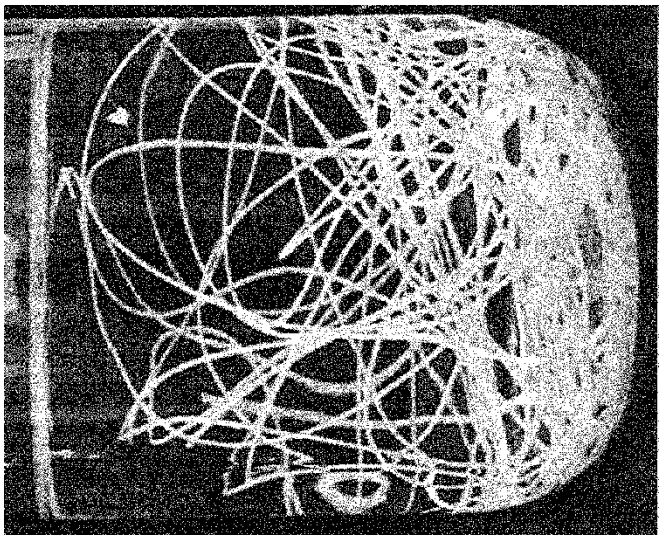
Inventors

Fan Shi, McMahan Gray, Yee Soong, Yuhua Duan, and Tuo Ji

Single-Step Synthesis of Chemisorption Fiber Sorbents for Gas Stream Purification (19N-24)

Opportunity

Many industrial gas purification systems rely on multistage sorbent processes that are costly, energy-intensive, and slow to regenerate. NETL has developed a method for fabricating chemisorption fiber sorbents through a single-step spinning process. The invention incorporates crosslinked, amine-based basic immobilized amine sorbents (BIAS) within a porous polymer fiber network to enable rapid and efficient separation of target gases from high-volume process streams. The resulting fibers combine the high sorption capacity of amine sorbents with the fast kinetics and heat management of a fiber structure, reducing cost, complexity, and energy use compared to traditional pellet or membrane systems. This technology is available for licensing and/or collaborative research from NETL.



Photograph of NETL chemisorption fiber sorbents

Challenges Addressed

- Multi-step fabrication of conventional fiber sorbents increases cost and limits scalability
- Sorbent degradation from high-temperature regeneration cycles
- Slow adsorption and desorption rates in packed-bed systems
- High energy penalties from inefficient heat transfer during adsorption

Potential Commercial Applications

- Gas purification and selective removal of acidic or reactive species from industrial exhaust streams
- Conditioning and upgrading biogas and process gas streams
- Integration with temperature- or pressure-swing adsorption systems for gas recovery or separation
- Chemical and petrochemical plant gas processing and emissions control

Competitive Advantages

- Direct spinning process reduces cost and enables large-scale production
- Up to 85% BIAS content uniformly distributed within fibers
- Porous fiber architecture allows rapid gas diffusion and efficient sorption
- Reduced thermal degradation and longer operational life
- Fiber structure promotes uniform temperature control and stable cycling

Intellectual Property Status

A U.S. patent was issued August 29, 2023, and expires September 16, 2041.

Publications

M. Gray, et al. Single-Step Synthesis of CHEmisorption Fiber Sorbents (CHEFS) for the Capture of CO2 and Removal of Water Contaminants. (2022). *United States Patent and Trademark Office.* U.S. Patent Application Publication No. US20220347654A1.

Licensing/Collaboration

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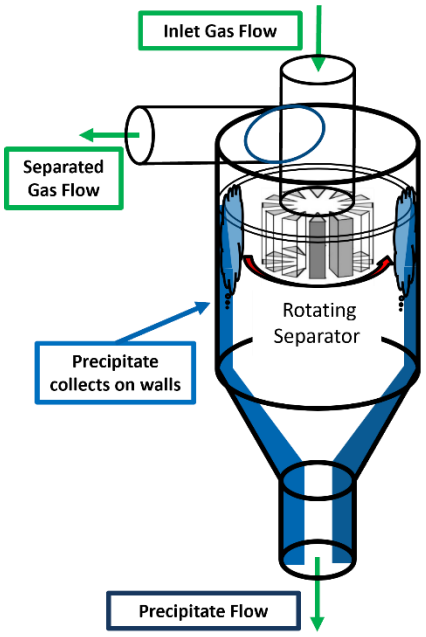
Inventors

McMahan Gray, Fan Shi, Shouliang Yi, Walter Wilfong, and Qiuming Wang

Rotational Mechanical Gas Separator (16N-07)

Opportunity

Industrial systems often require the efficient separation of specific gas components or particulates without relying on chemicals, sorbents, or complex materials. NETL has developed a compact mechanical separator that simultaneously combines supersonic expansion, oblique shock compression, and rotational flow to remove condensed liquid or solid components from a gas stream. By merging the expansion, compression, and separation stages into a single integrated unit, this system minimizes equipment footprint and enables efficient phase separation under continuous flow conditions. This technology is available for licensing and/or further collaborative research from NETL.



Schematic of a rotational mechanical gas separator

Challenges Addressed

- Conventional gas separation methods rely on adsorbents, membranes, or cryogenic processes that are costly and require extensive maintenance
- Centrifugal or stratification-based systems suffer from revaporization of condensed phases due to viscous heating
- Traditional setups require multiple stages for gas expansion, compression, and mechanical separation
- Compact, low-cost mechanical alternatives capable of continuous operation are limited

Potential Commercial Applications

- Gas purification and recovery in power generation, petrochemical, and industrial systems
- Separation of moisture or gases from mixed gas streams
- Compact, modular separation units for on-site or mobile gas processing
- Integration with turbines, compressors, or exhaust handling systems
- Pretreatment or posttreatment for downstream chemical or mechanical processes

Competitive Advantages

- Combines expansion, compression, and mechanical separation within a single device
- Is compact and modular, reducing footprint and complexity
- Eliminates need for adsorbents, membranes, or cryogenic coolants via chemical-free operation
- Maintains low thermal losses and minimizes revaporization of separated phases
- Is applicable to a range of gases and adaptable to varying process conditions

Intellectual Property Status

A U.S. patent was issued November 30, 2021, and expires November 9, 2039.

Publications

J. VanOsdol, et al. Rotational Mechanical Gas Separator. (2021). *United States Patent and Trademark Office.* U.S. Patent No. 11,185,811.

Licensing/Collaboration

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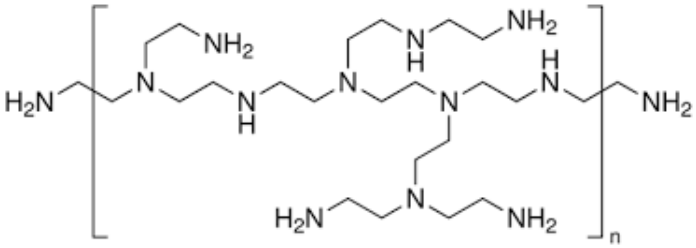
Inventors

John VanOsdol and Danylo Oryshchyn

Regenerable Nonaqueous Sorbent Slurries for Gas Separation (16N-02)

Opportunity

Efficiently separating target gases from process streams remains a persistent challenge for industries seeking durable, low-energy separation technologies. NETL has developed a regenerable sorbent slurry that uses basic immobilized amine sorbent (BIAS) particles suspended in a nonaqueous silicone oil carrier. This system combines the benefits of solid sorbents with the flow properties of a liquid medium, offering high gas absorption capacity, reduced corrosion, and simpler regeneration compared to conventional aqueous amine systems. The composition can be readily integrated into existing industrial gas treatment systems using standard scrubber or reactor designs. This technology is available for licensing and/or further collaborative research from NETL.



Chemical structure of polyethyleneimine, a component of BIAS particles

Challenges Addressed

- Conventional aqueous amine systems are energy-intensive and prone to corrosion and degradation
- Solid sorbents used in dry systems can be difficult to handle and lose effectiveness through particle attrition or aerosolization
- Many gas separation technologies require large infrastructure modifications or complex regeneration processes
- Industries need cost-effective, regenerable materials that maintain stability under continuous operation

Potential Commercial Applications

- Gas purification and separation in power generation and industrial processing
- Treatment of natural gas and synthesis gas streams to remove target contaminants
- Adaptable for use in chemical manufacturing, gas sweetening, and refining operations
- Retrofitting existing scrubber systems with nonaqueous sorbent slurries
- Regenerable solvent systems for continuous gas absorption and release

Competitive Advantages

- Nonaqueous silicone oil carrier reduces heating requirements during gas release
- Immobilized amines minimize chemical breakdown and equipment wear
- Provides strong gas absorption without the limitations of liquid-only systems
- Compatible with existing reactor types such as scrubbers, packed beds, and bubble columns
- Maintains sorbent integrity through multiple absorption-regeneration cycles

Intellectual Property Status

A U.S. patent was issued September 8, 2020, and expires August 23, 2038.

Publications

F. Shi, et al. Regenerable Non-Aqueous Basic Immobilized Amine Slurries for Removal of CO2 from a Gaseous Mixture and a Method of Use Thereof. (2020). *United States Patent and Trademark Office.* U.S. Patent No. 10,765,997.

Licensing/Collaboration

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Inventors

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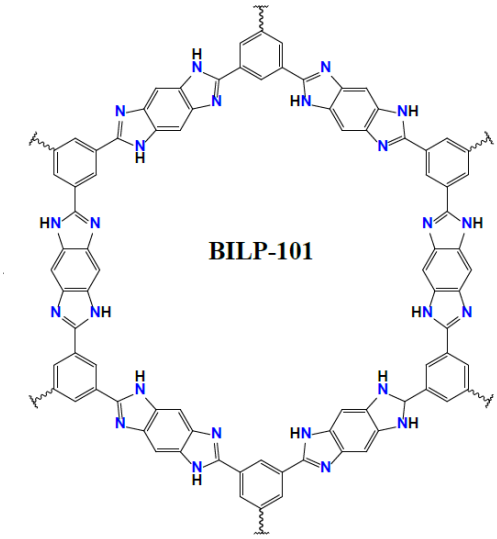
Polymeric Sorbent for Use in Gas Separation (15N-23)

Opportunity

Many gas-separation operations require materials that combine high capacity, selectivity, and stability under realistic process conditions. NETL has developed a benzimidazole-linked polymer sorbent (BILP-101) synthesized from commercially available monomers that provides high uptake, strong carbon dioxide (CO_2) selectivity within mixed streams, and exceptional thermal and chemical stability. The material can function as a physical sorbent in its neat form or be tailored for stronger interactions through postfunctionalization, enabling use across separation and drying applications. This technology is available for licensing and/or further collaborative research from NETL.



Chemical structure of the NETL sorbent

Challenges Addressed

- Limited stability of conventional sorbents under humidity, acids, and bases
- High regeneration energy for many capture materials at realistic partial pressures
- Insufficient selectivity over copresent gases such as nitrogen, methane, or hydrogen
- Complex or costly syntheses that hinder scale-up and increase material cost

Potential Commercial Applications

- Gas separation and purification in pre- and postcombustion process streams
- Natural gas sweetening and biogas upgrading
- Cabin-air and enclosed-environment gas control
- Water removal in drying and dehydration steps
- Mixed-matrix membranes and advanced separations in chemical manufacturing

Competitive Advantages

- Neat BILP-101 reaches about 4 wt% CO_2 uptake at 0.15 bar and 298 K with high CO_2 over N_2 selectivity — functionalization can approximately double uptake
- Narrow pore size distribution near 0.54 nm concentrates interaction sites for efficient separation
- Sorbent maintains performance after exposure to humidity, acids, bases, and temperatures up to about 500°C
- Physical adsorption within optimal interaction energies supports low-energy desorption and repeated cycling
- Template-free polycondensation from widely available monomers

Intellectual Property Status

A U.S. patent was issued July 18, 2019, and expires December 15, 2037.

Publications

D. Hopkinson, et al. Polymer for Carbon Dioxide Capture and Separation. (2019). *United States Patent and Trademark Office.* U.S. Patent No. 10,323,125.

Licensing/Collaboration

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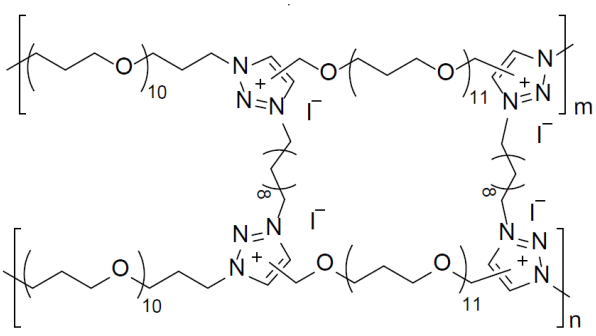
Inventors

David Hopkinson and Ali Sekizkardes

Ionically Cross-Linked Polymer Films for Gas Separation (14N-30)

Opportunity

Polymer membranes designed for gas separation often struggle to balance mechanical robustness with the segmental mobility required for selective gas transport. Rigid networks suppress permeability, while highly flexible systems can deform or lose selectivity under operating pressures. Researchers at NETL developed an ionically cross-linked membrane platform that integrates an ether-based polymer backbone with triazolium cross-linking sites to create a mechanically stable yet highly carbon dioxide-permeable material. The ionic junctions generate controlled free volume and tailored polymer dynamics, while counter-anion selection enables fine adjustment of transport pathways and thermal behavior. A single-step, solvent-free thermal process produces uniform, free-standing films and is compatible with ambient oxygen, supporting scalable manufacturing. This technology is available for licensing and/or further collaborative research from NETL.



Chemical diagram of ionically cross-linked polytriazolium membrane

Challenges Addressed

- Effective gas separation is critical for industrial applications, with membrane technology offering advantages like a small footprint, low capital cost, and the absence of a regeneration process
- Existing membrane materials, particularly those based on poly(ethylene oxide) (PEO), face significant challenges such as high crystallinity and poor mechanical strength

Potential Commercial Applications

- Material is highly suited for separating specific gases from mixtures, from flue gas, natural gas, or hydrogen streams, due to its high permeability, selectivity, and mechanical strength
- Material's film-forming capabilities, mechanical strength, and potentially tacky nature make it suitable for creating protective or functional surface layers

Competitive Advantages

- Cross-linked, free-standing membranes exhibit superior mechanical properties compared to PEO-based membranes
- Material is produced through a solvent- and catalyst-free process, simplifying manufacturing
- Fabrication process is not sensitive to oxygen and can be performed in air, unlike some poly(ionic liquid) membranes

Intellectual Property Status

A U.S. patent (US10300438) was issued May 28, 2019, and expires December 31, 2035.

Publications

H. B. Nulwala, et al. Ionic Cross-Linked Polymeric Films for Gas Separation. (2019). *United States Patent and Trademark Office*. U.S. Patent No. 10,300,438.

Licensing/Collaboration

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Inventors

Hunaid B. Nulwala, David Luebke, and Xu Zhou

Separation of Carbon Dioxide From Multicomponent Gas Streams (10N-06)

Opportunity

Efficient gas separation remains a core challenge for industrial and energy applications that process mixed gas streams. Conventional methods for isolating carbon dioxide, such as cryogenic refrigeration or multistage compression, are energy-intensive and require complex, high-maintenance equipment. NETL has developed a patented aerodynamic process that separates CO_2 and other gases through supersonic expansion and oblique-wave compression. By accelerating a gas stream through a converging–diverging nozzle, the process rapidly cools the mixture to induce the phase change of CO_2 from a vapor to a solid, eliminating the need for refrigeration. The resulting flow is then decelerated by a series of oblique shocks that gently raise pressure while maintaining CO_2 in its solid phase for mechanical separation. This technology is available for licensing and/or further collaborative research from NETL.

Challenges Addressed

- Existing CO_2 separation methods require costly compression and refrigeration cycles
- Conventional systems increase process complexity and energy consumption
- Gas separation often depends on slow or inefficient condensation steps

Potential Commercial Applications

- Removal of CO_2 from exhaust or flue gas in power generation systems
- Separation of multicomponent industrial gas streams
- Pretreatment of gases for storage, transport, or reuse
- Use in modular or mobile CO_2 recovery units

Competitive Advantages

- Enables phase change of CO_2 through aerodynamic cooling rather than refrigeration
- Maintains solid CO_2 during pressure recovery for efficient mechanical separation
- Reduces overall energy use and system complexity
- Is compatible with existing subsonic separation devices
- Eliminates the need for swirl flow or moving parts in the supersonic section

Intellectual Property Status

A U.S. patent was issued July 8, 2014, and expires April 16, 2032.

Publications

J. VanOsdol. Apparatus and Process for the Separation of Gases Using Supersonic Expansion and Oblique Wave Compression. (2014). *United States Patent and Trademark Office.* U.S. Patent No. 8,771,401.

Licensing/Collaboration

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Inventors

John VanOsdol

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