U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

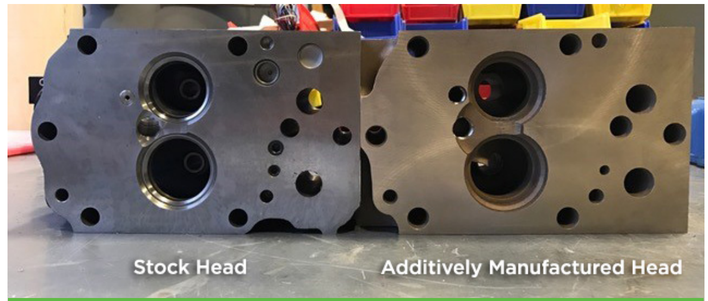
Combined Heat and Power Research and Development at the National Laboratories

Increasing Efficiency and Lowering the Entry Cost of CHP for End Users

The U.S. Department of Energy's (DOE) Combined Heat and Power (CHP) Research and Development (R&D) program is performing early-stage research on technologies to increase the electrical and thermal efficiency of CHP and reduce component costs. The CHP R&D program evolved from the highly successful DOE Advanced Reciprocating Engine Systems (ARES) program that promoted cooperation among engine manufacturers, universities, national laboratories, and engine consultants to obtain maximum engine efficiency and low emissions from natural gas reciprocating engines for power generation, and resulted in products with greater than 47% thermal efficiency from two engine manufacturers. Since 2014, the CHP R&D program has been led by two national laboratories, Argonne National Laboratory and Oak Ridge National Laboratory.

Benefits for Our Nation

The recent expansion of natural gas production in the United States has resulted in price stability that has not been seen since the 1960s. Utility-scale generation has been shifting toward natural gas from coal, and the stable gas price makes investments in distributed generation and CHP systems more attractive. A recent DOE analysis of flexible CHP support of the California power grid identified more than $1 billion in potential energy cost savings to industrial owners and more than $250 million in annual savings to the power grid for more widespread adoption of CHP at industrial sites. The Argonne and Oak Ridge teams are improving electrical efficiency of power generation and lowering manufacturing costs for CHP systems.

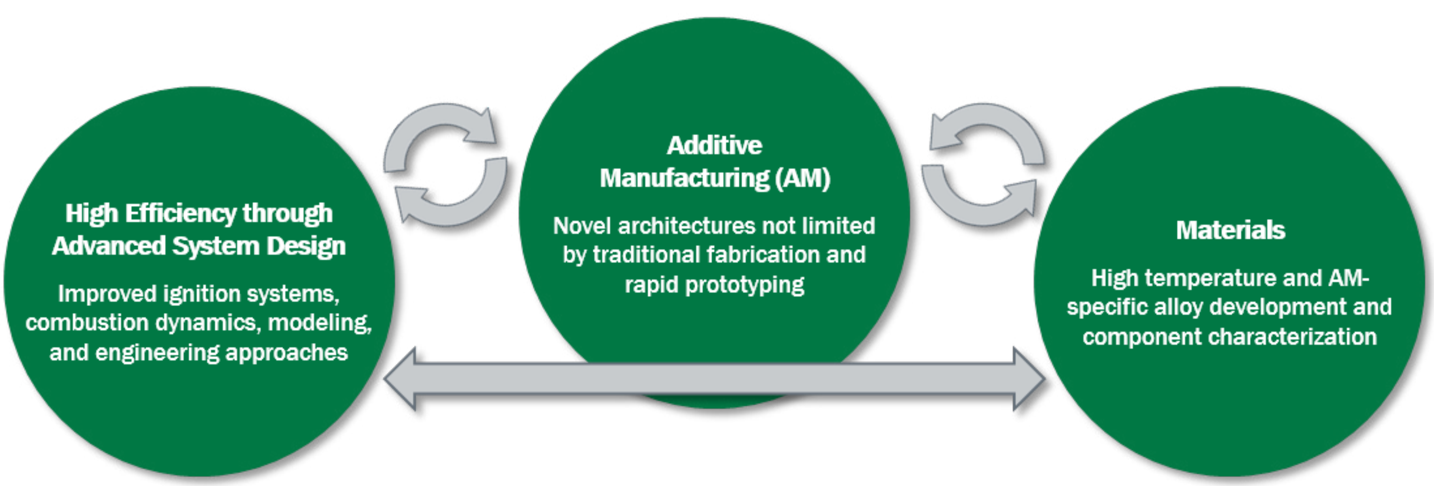


A joint project by Argonne National Laboratory and Oak Ridge National Laboratory is applying additive manufacturing to rapidly develop custom engine components that improve engine operation and efficiency. *Photo courtesy of Argonne National Laboratory.*

CHP R&D Goals

The goal of the CHP R&D Program is to improve the efficiency and viability of distributed generation systems and CHP while supporting the U.S. manufacturing base as it continues to use these technically advanced systems. Specific objectives include:

- Identification and development of turbine component materials to enable combustion temperature increase
- Utilization of additive manufacturing (AM) to improve heat transfer
- Development of a laser ignition system for reciprocating engines to improve system efficiency
- In-cylinder ignition and combustion visualization to develop advanced ignition systems
- Visualization and measurement of two-phase flow within heat exchangers to enable computational fluid dynamics (CFD) simulation



CHP Research and Development Program – Technical Approach

Argonne National Laboratory Projects

Project Partners: Argonne National Laboratory, Princeton Optronics Inc., Cummins, Inc.

Laser Ignition System for Reciprocating Engines

Laser ignition extends the operable envelope of lean-burn natural gas engines. Benefits include higher engine efficiency and the ability to meet stricter emissions regulations. Argonne has developed a viable laser igniter with a similar footprint of a standard spark plug and the ability to withstand the harsh environment of the engine. Demonstrated on a Cummins 6-cylinder natural gas engine, the igniter realized a 2.6% improvement in efficiency. A design incorporating a prechamber was found to offer even better performance by providing distributed ignition. Lens fouling mitigation strategies tested so far have allowed unhindered operation up to 666 hours. Efforts continue to further improve the ignition performance as well as longevity of the laser igniter.

Laser igniters being tested on a 6-cylinder natural gas engine. Laser ignition benefits include higher engine efficiency and the ability to meet stricter emissions regulations. *Photo courtesy of Argonne National Laboratory.*

Highlights

- Developed and demonstrated operation of a laser ignition system on a 6-cylinder engine
- Realized a 2.6% point efficiency gain with laser ignition over spark ignition system
- Prechamber laser igniter provides distributed ignition that offers higher performance

Visualization of Natural Gas Combustion in Stationary Reciprocating Engines

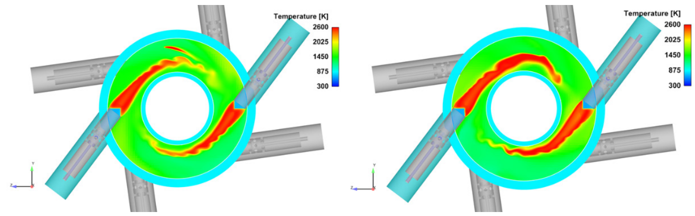
Fuel-lean or dilute combustion has been widely adopted to improve engine efficiency, but it is fraught with combustion stability issues. Advanced igniters enable expansion of the lean limits, yet the physics of the early flame development process is not well understood. In-cylinder ignition and combustion visualization enables evaluation, development, and improvement of advanced ignition systems. However, fuel-lean conditions present an extremely difficult environment to capture events during the ignition delay and subsequent combustion periods, and natural gas combustion is devoid of soot luminosity. Visualization of natural gas combustion in "real-life" engine conditions is highly desirable, but scarce in literature. A suite of optical instruments was selected to capture ignition, early flame development, ignition delay, and combustion events associated with advanced igniters, such as lasers, flame-jet, and plasma, to enable study of flame kernel influence on engine performance. Argonne's high performance computing facility was utilized to model natural gas combustion.

Highlights

- Successfully captured flame growth during ignition delay period
- Model-based and image-based flame matched qualitatively
- Advanced ignition systems offered significant benefit in extending lean limit

Natural Gas/Hydrogen Blends for Microturbines

Fuels from various processes, such as gasification syngas or byproduct gas from industrial processes, have a higher hydrogen content than conventional gaseous fuels. Shale-derived natural gas exploration, harvesting, and refinement process requires a combustion system capable of handling such fuels. Hydrogen poses flashback issues due to its extremely high flame speed. While natural gas-hydrogen blends allow leaner fuel/air ratios (resulting in higher efficiency), combustion boundaries to avoid lean blowout or flashback have not been fully established. This project is developing novel fuel injectors and combustion liners for microturbines utilizing natural gas-hydrogen blends and other high flame-speed fuel compositions. Argonne's gas blending system is being utilized to achieve natural gas-hydrogen compositions to fuel a Capstone C65 microturbine. The potential economic impact of hydrogen use is significant due to its availability from crude oil exploration, lignite, and other unused resources, as well as waste and byproduct hydrogen from industrial processes. Economic and regulatory considerations warrant utilizing these fuels for electricity and to meet heating and cooling needs in CHP applications.



Transition from flame structure of 50/50 H_2/CH_4 blend (left) to a 70/30 H_2/CH_4 blend (right) did not exhibit flashback. *Photo courtesy of Argonne National Laboratory.*

Highlights

- Model with finite rate chemistry and detailed chemical kinetics implemented for the Capstone C65
- Cold start was modeled for the low-load condition with 50/50 fuel mix for two-injector operation
- Transition from 50/50 to 70/30 blend of H_2/CH_4 did not exhibit flashback for the current design

Oak Ridge National Laboratory Projects

Project Partners: Oak Ridge National Laboratory, Solar Turbines Inc., Capstone Turbine Corporation, Purdue University, ThermalCentric Corporation

Advanced Materials Research

Materials challenges for CHP applications include developing new lower-cost materials, identifying materials with improved durability to improve system performance and increase efficiency, and reducing materials and maintenance costs. Oak Ridge has developed a new oxidation resistant alloy for turbine combustor liners at 1100°C-1150°C that is in the final stages of patent approval. An additional alloy, an alumina-forming austenitic (AFA) steel commercialized by Carpenter Technologies, has completed more than 15,000 hours of high temperature operation (690°C) in a microturbine recuperator. Standard static corrosion testing cannot adequately determine if current and new coatings are sufficiently durable for the demands of the next generation of industrial gas turbines. Oak Ridge is collaborating with Germany's Jülich Research Center to develop better lifetime models for predicting the long-term behavior of high performance alloys as a function of component thickness and operating temperature. An industrial team is working to evaluate the mechanical properties of candidate coatings that resist type II hot corrosion at ~700°C.

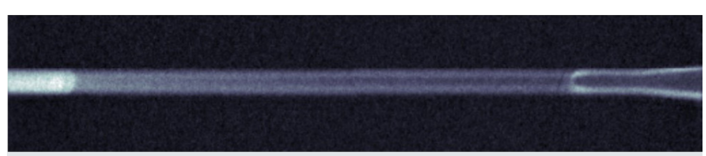
Exposure of turbine recuperator materials to high temperature exhaust for 15,000 hours in a Capstone 65 kW microturbine yielded no decrease of power output due to material degradation. *Photo courtesy of Oak Ridge National Laboratory.*

Highlights

- Exposure of turbine recuperator materials to high temperature (690°C) exhaust for 15,000 hours yielded no decrease of power output due to material degradation
- Less expensive, high temperature alumina-forming austenitic (AFA) foils exhibited lower corrosion than current stainless steel alloys under combustion conditions

Additive Manufacturing (AM) for CHP Systems

Through extensive exploration of new materials and additive manufacturing, Oak Ridge is developing improved waste heat recovery systems, including more effective heat exchangers and chillers with smaller footprints. Oak Ridge has additively manufactured both macro and microchannel heat exchangers and has been able to quantify the exchangers' effectiveness through neutron imaging by utilizing the Spallation Neutron Source and High Flux Isotope Reactor at ORNL. This non-invasive flow



Neutron image of coolant flow in a metal microchannel heat exchanger. The image illustrates the attachment of the liquid to the walls and enables high-fidelity modelling of the transition of the coolant from liquid to gas phase. *Image courtesy of Oak Ridge National Laboratory.*

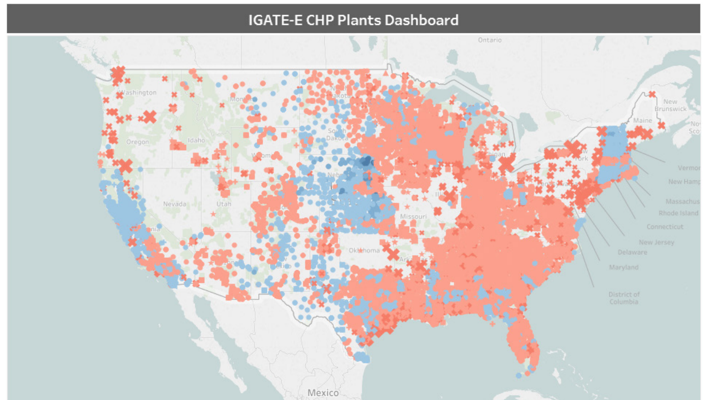
visualization technique "sees through" the metal and finds contrast in the working fluid of an Organic Rankine Cycle system to enable smaller footprints and lower cost through compact designs.

Highlights

- Development of novel heat exchanger designs with additive manufacturing
- Additive manufacturing enables neutron imaging, a non-invasive flow visualization technique

Advanced Geospatial Modeling of CHP System Installations and Web-Based Tool for Energy Evaluation (IGATE-E CHP)

A major barrier to distributed generation and CHP utilization in the manufacturing and commercial buildings sectors is the ability to match thermal demands with the facility and local electrical loads. Matching demand with load on a geographical basis (zip code, county, state, and region) enables facilities the option to provide distributed generation for local and regional grid utilization. Geospatial analysis also helps identify the need for waste heat in nearby facilities to increase overall CHP efficiency as well as financial returns. Oak Ridge has developed the Industrial Geospatial Analysis Tool for Energy Evaluation (IGATE-E) for evaluating CHP feasibility at the facility level and projecting the CHP penetration potential and energy impacts across the manufacturing sector in the United States. Oak Ridge is currently expanding this tool to include commercial and institutional buildings.



Manufacturing plant locations with average spark spread and CHP potential. *Image courtesy of Oak Ridge National Laboratory.*

Highlights

- IGATE-CHP geospatial modeling tool identifies spark spread and thermal-to-electric ratio for manufacturing facilities at the zip code level
- Estimation of CHP capacity for individual (or groups) of sites for a region or whole country is enabled through an easy-to-use web interface with filtering capabilities

Joint National Laboratory Project

Project Partners: Argonne National Laboratory, Oak Ridge National Laboratory

Using Additive Manufacturing to Advance the Efficiency and Performance of Natural Gas Engines Used in CHP Applications

Argonne and Oak Ridge are working together to use additive manufacturing (AM) to create engines out of non-traditional materials and designs that can enable more efficient combustion and heat recovery. The labs are demonstrating AM as a viable rapid prototyping method to manufacture custom engine components that improve engine efficiency. The innovation lies in making AM engine components that include complex geometries (such as cooling passages, ports, and igniter location) and multiple materials. Oak Ridge has used the AM capabilities at the Manufacturing Demonstration Facility to rapidly manufacture a complex bimetallic engine head for use on the single cylinder natural gas engine at Argonne for testing. The AM head was successfully printed with steel (60%) and bronze (40%) and matched very closely with the stock head. The material properties are expected to improve heat transfer for better thermal availability.

For additional information, please contact

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