# Combined Heat and Power (CHP) Technology Development

**Project 19864, Agreement 19128**
**Oak Ridge National Laboratory**
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# Objective of the ORNL CHP R&D program

The project objectives are to improve the efficiency and viability of Combined Heat and Power systems and high-efficiency electrical generation systems, while supporting the U.S. manufacturing base.

- Advance the state-of-the-art of CHP
- CHP offers great benefits and potential savings  but is under-utilized due to barriers including high capital costs and lack of flexibility to match the electrical and thermal loads
- Address the complications of  a wide range of demands, geography, complexity of equipment, grid interface, and utility policy

# Technical Approach – Conduct R&D along Three Main Thrusts

- High Efficiency through Advanced Thermodynamics

  Power generation and integration of CHP into the industrial sector

  - Directed toward 1 - 10 MW systems including combined modes, e.g. solid oxide fuel cell plus turbine.

- Materials development and characterization

  Investigating lower cost, high performance, high temperature materials for critical components to enable higher efficiency

  - Higher temperature heat exchangers are critical to micro-turbine efficiency and other applications

- Additive Manufacturing for CHP Components

  Removing traditional manufacturing constraints from the design of heat exchangers and engines

  - Initial focus on small-scale engines and heat pipes

# Technical Approach – Task Description

- High efficiency power generation through advanced thermodynamics
  - Modeling of high efficiency electrical generation regimes
  - Software tool that allows users to examine hourly energy usage for each industrial sub-sector to identify CHP opportunities
- Materials development and characterization
  - Higher temperature heat exchangers drive efficiency gains
  - Lower cost materials and coatings enable CHP market penetration
  - Recovery of waste heat from hostile industrial environments e.g. Electric Arc Furnaces
- Additive Manufacturing for Components
  - Fabricate and evaluate a working engine with additive manufacturing
  - Design and fabricate novel CHP components with additive manufacturing

# The technical approach connects advanced manufacturing to energy efficiency


ORNL Manufacturing Demonstration Facility

High Temperature Materials – advanced characterization

**Additive Manufacturing:** Novel devices not limited by traditional fabrication

**High Efficiency through advanced thermodynamics**: Design & evaluate new energy conversion devices & materials

**Materials:** High temperature and AM-specific alloy development & component characterization

# Transition and Deployment

- This is pre-competitive research: results being published and presented
  - 12 publications and 18 presentations since June 2012
- Working with industry in all three thrusts
- End users are equipment manufacturers, facilities
- CHP can improve the bottom line for industry through reduced energy use

**Technology Sustainment Model:**
**Applying advanced technologies to CHP from a variety of disciplines including materials, thermodynamics, and additive manufacturing**

# Impact of Existing and Future Research

- Modeling suggests electrical power generation efficiency of **> 65%** is possible using a multiple generator approach *e.g.* a solid oxide fuel cell and turbine
- IGATE-E CHP Software tool has identified the CHP potential at the manufacturing plant and locality level – e.g. the steam needs of the top 20 boiler industries represents **0.5 quad** annually. The utility of CHP on an hourly basis can be assessed.
- Low cost, high temperature **ORNL alloy deployed** to two micro-turbine manufacturers. Micro-turbine installed at ORNL for long term demonstration of alloys.
- Waste heat from existing domestic Electric Arc Furnaces represents **1/3 of a quad.**

## Example: High-Efficiency Electrical Generation at the 1-10 MW scale

| | |
|---|---|
| **Fuel-To-Electricity Efficiency (FTEE)** | Maximum practical limit **65-70%** on a Higher Heating Value **(HHV)** basis using natural gas<br>• Literature studies allow ~65% Combined Cycle **in theory**<br>• Modeling at ORNL showed up to **70%** possible in theory<br>• Larger (>200 MW) systems more likely to approach limit<br>• Systems at 1-10 MW this efficient not market-feasible |
| **Known Technical Challenges to Achieve 65-70% FTEE at the 1-10 MW Scale** | |
| **Materials** | - Existing, in-use metal alloys, ceramics lack corrosion, temperature resistance to operate at highest efficiency<br>- Exotic materials may be better, but can have durability issues; value of 1-10 MW systems doesn't support cost |
| **Friction, viscous flow, external heat losses** | - The smaller volume/surface area ratio (more fluid-wall interaction) of 1-10 MW systems. increases the importance of friction and viscous flow losses, as well as external heat losses |
| **Control Science** | - Precise control of air-fuel ratio in combustion and fuel cell chemical processes is critical to achieving high efficiency and may be enabled by model-based controls that are more common to higher value systems<br>- High-speed sensors and feedback algorithms may facilitate rapid response to changes in system dynamics and promote the most efficient output; not common on lower value systems |
| **Optimization** | - Optimizing individual cycles in a combined system will not result in optimized output<br>- Co-optimization of all of the components is necessary for the highest possible efficiency and particularly important for a 1-10 MW system due to the lower system flows and potential losses between components |
| **Heat Exchanger Design** | - Efficient heat transfer between fluids is crucial, particularly in 1-10 MW systems which have lower volume flows than larger systems.<br>- Typical commercial heat exchangers are designed for ease of manufacturing and known materials. Novel processes, such as additive manufacturing, may overcome current limitations in heat exchanger design. |

# Future Measures of Success

- 10% improvement in engine efficiency for advanced reciprocating and turbine systems
- Adoption of an Electric Arc Furnace waste heat recovery system
- Utilization of one or more advanced alloys or additive manufacturing techniques by an equipment manufacturer
- Software tool in use by industry and regional application centers to identify new opportunities for industrial CHP
- Build CHP system component not currently manufactured using Additive Manufacturing as a final or prototyping step

# Project Management & Budget

- Project is ongoing: June 2014 – May 2015 being reviewed
- Thrust 1: High Efficiency through Advanced Thermodynamics

  Milestone: IGATE-CHP: Completion of Geospatial Representation aligned with Regional CHP Centers Technical Assistance Partnerships (TAPs) *due 3/31/2015, complete*
- Thrust 2: Materials development and characterization

  Milestone: Complete characterization of alumina-forming austenitic (AFA) steel air cells after 3,000h microturbine test and compare to performance of current commercial alloy *due 9/30/2015, complete ahead of schedule*

  Milestone: Energy and mass balance analysis on actual EAF off-gas data acquired from a steel mill for the stationary regenerator heat recovery system and the fluidized bed concept *due 3/31/2015, complete.*
- Thrust 3: Additive Manufacturing for Components

  Milestone: Manufacture and demonstrate the operation of a complete miniature engine with embedded sensors *due 6/30/2015, complete.*

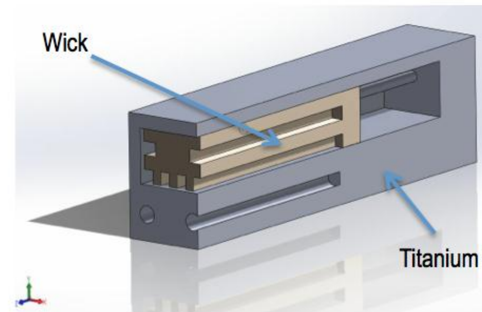
| Total Project Budget | |
|---|---|
| **DOE Investment** | $1,200 |
| **Cost Share** | This a pre-competitive program |
| **Project Total** | $1,200K |

# Results and Accomplishments

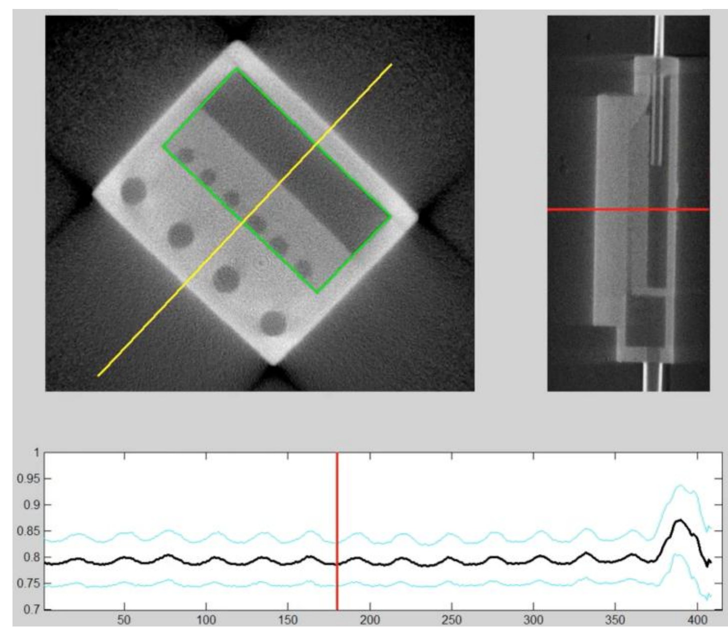
- Project tasks on schedule
- Milestones on schedule or have been met for June 30
- Results: High Efficiency through Advanced Thermodynamics
  - Incorporated geography, thermal base loads, and electrical base loads *by 4-digit SIC code* into validated IGATE-E software tool to assess CHP potential across industry subsectors.
- Results: Materials Development and Characterization
  - Measured temperature of EAF off-gases at a commercial steel mill
  - Lower-cost, ORNL-developed stainless steel deployed in turbine
  - Patent being submitted on new high temperature alloy
- Results: Additive Manufacturing for Components
  - Fabricated and evaluated complete miniature engine with embedded sensors
  - Designed, manufactured, and characterized a novel heat pipe for heat exchanger applications

# Example: Heat Exchanger Enhancement using Additive Manufacturing to Embed Heat Pipes

- Heat pipes significantly increase the heat transfer rate versus conventional heat exchangers
- No external pumping of a heat exchanger fluid
    - Wicking drives the capillary flow
- Successful implementation in Titanium and Cobalt-Chromium based powder machines, now working with mesh and groove structures
- X-rays and thermal images accelerated R&D by characterizing the wick structure in terms of porosity, a critical design variable.
- Demonstrated superior thermal management potential of AM heat pipes –
- 100-1000X improvement in heat conductance over base material




Loop Heat Pipe Evaporator Section



# Example: Additive Manufacturing used to fabricate working engine


- Additive manufacturing (AM) enabled the incorporation of titanium as an engine material thereby improving efficiency
  - Printed titanium head was successfully operated over 20 hours
  - Titanium head provided 7% increase in efficiency for low speed conditions (compared to stock aluminum head).
  - Titanium has a much lower thermal conductivity which translated into higher in-cylinder heat retention, thereby improving combustion efficiency.
- AM also enabled in-cylinder pressure measurement, leading to a first-order analysis of the energy balance for small-scale engines.
  - Full printed engine (shown at left) is currently being evaluated. To date engines have been printed out of titanium and inconel alloys.
- Bearings composed of bronze were also printed and are being evaluated.

# Example: National-level, Web-based CHP Potential Analysis using the IGATE-E CHP Tool

**IGATE-E**
IAC, ESA, and MNI Databases

↓

**Database Schema****
45 tables-MySQL

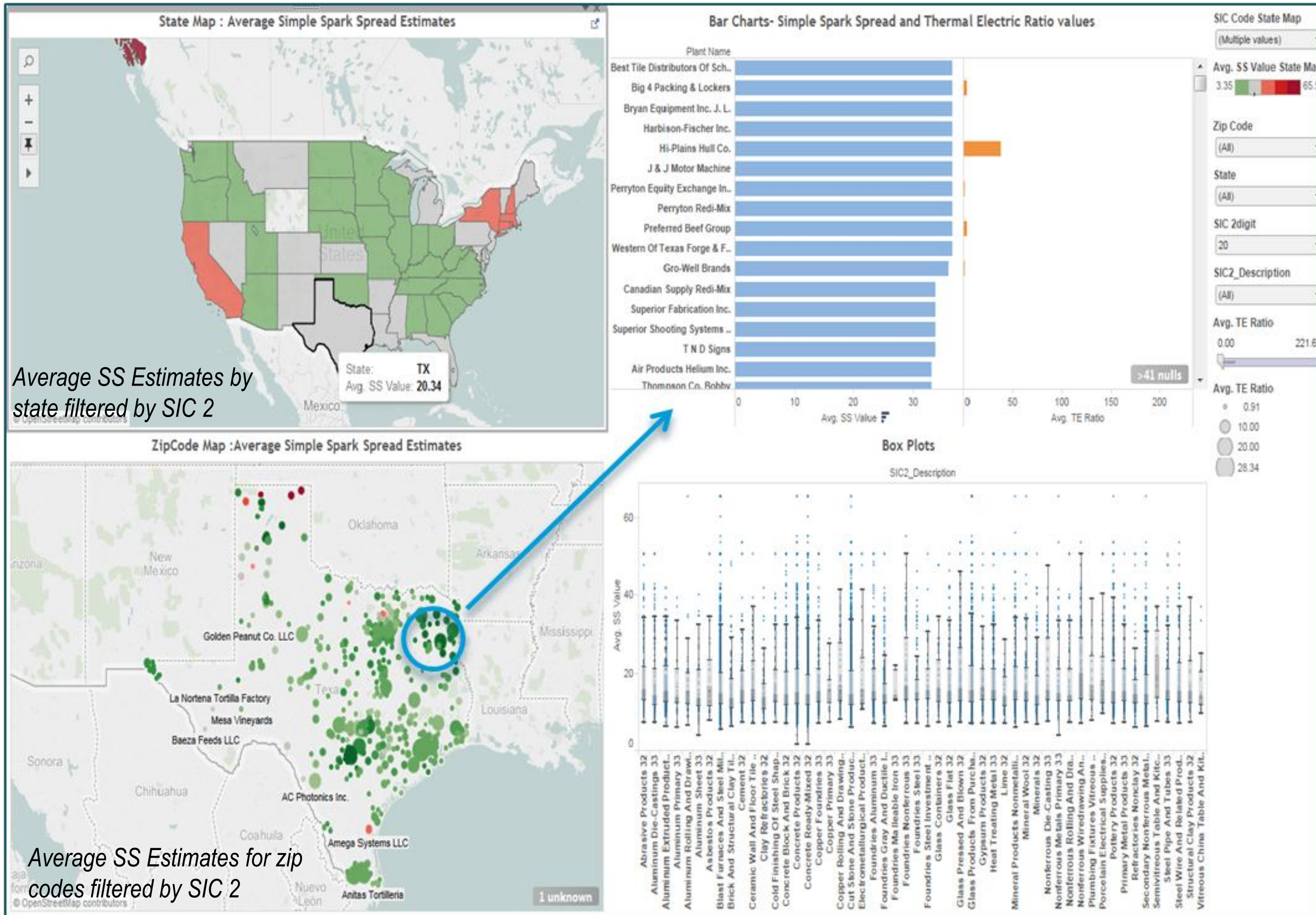
↓

**Interactive Visual Analytic Dashboard**

Manufacturing Plants and their Simple Spark Spread estimates, Thermal- Electric ratios *at SIC, state, and zip code levels*

**State or Regional-level Overview**

**Plant Specific TE* ratios and SS* estimates**




**State, County, and Zip Code-level Filter/Zoom Capability**

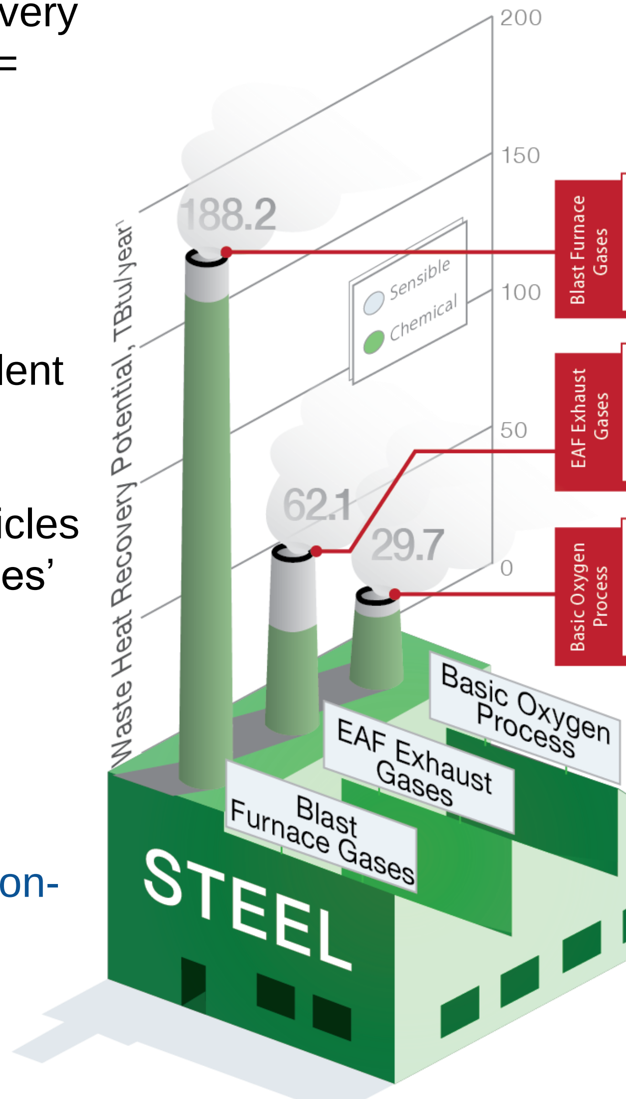
**TE and SS Box Plots & Outliers by Industry Sub-sector**

**TE – Thermal to Electric ratio and SS – Simple spark spread, as defined in the CHP Resource Guide by Midwest CHP TAP.*
***A database schema of a database system is its structure described in a formal language supported by the database management system (DBMS) and refers to the organization of data as a blueprint of how a database is constructed (Source – Wiki).*

# Example: Significant Waste Heat Recovery opportunity in Electric Arc Furnace exhaust gases/other metals processing

- Total waste heat recovery potential (TBtu/year) = 280
- Total avoided $CO_2$ emissions (Million MT/year) = 18.3
- Avoided annual $CO_2$ emissions are equivalent to:
  - 3.8 million passenger vehicles
  - 1.7 million homes' energy use
  - 4.8 coal-fired power plants

- Challenges: Temperatures and non-continuous process




| | Characteristics | WHR technology/ system status | Exhaust gas flow | Production[2] (MM tons/year) | Temp. range (°C) |
|---|---|---|---|---|---|
| Blast Furnace Gases | Contain combustibles, particulates, etc. | Available and widely used–partial WHR | Constant | 30 | 400 to 600 |
| EAF Exhaust Gases | Contain combustibles, particulates, etc. | Available, not widely used–partial WHR | Varying | 64.32 | 1500 to 1600 |
| Basic Oxygen Process | Contain combustibles, particulates, etc. | Available, not widely used–partial WHR | Varying | 31.68 | 1250 to 1700 |

[1] For few waste heat sources (particularly in steel, aluminum, and glass industry), a small quantity of waste heat is already being recovered using the existing WHR technologies.

[2] Production data for steel industry is from 2013, glass industry 2002, aluminum industry 2012, and for cement and lime industry production data is from 2013.

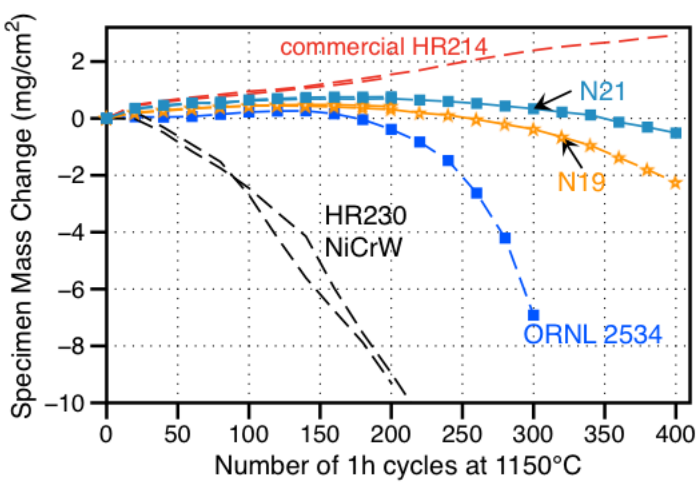
[3] WHR technologies currently not available/used for oxy-fuel fired systems.

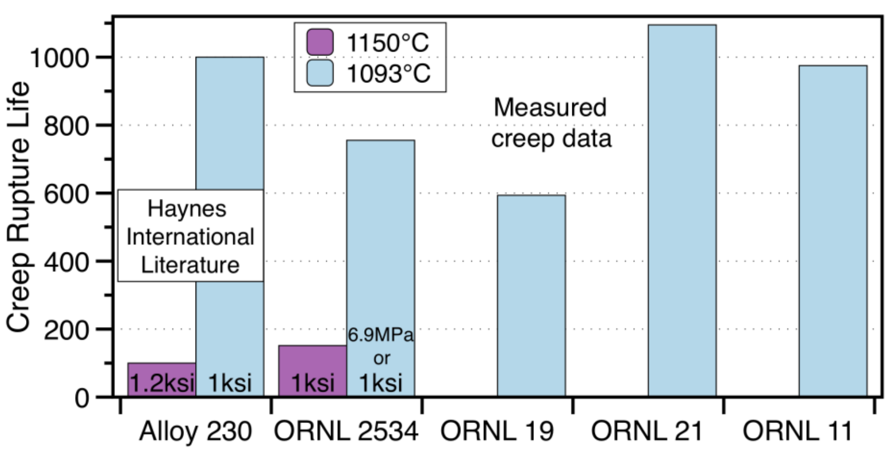
**EAF off gases offer the highest potential for waste heat recovery in the iron and steel industry**

*Oak Ridge National Laboratory (ORNL) and E3M Inc., Technologies and Materials for Recovering Waste Heat in Harsh Environments, Sachin Nimbalkar, Arvind Thekdi, et.al., ORNL/TM-2014/619.*

## Example: Computationally-designed high-temperature Ni-base alloy for gas turbines

- Objective: develop new wrought Ni-base combustor liner alloy with improved oxidation and creep resistance
- Impact: improve gas micro-turbine durability/efficiency/cost
  - 1% point efficiency gain = 20 TWh/year in U.S. electricity
- 2015: alloy patent application drafted for submission
  - Oxidation: 1150°C 1h cycles in air+10%$H_2O$ (simulate exhaust)
  - Strength: 1093-1150°C creep life matches commercial Haynes alloy 230



# Example Result: Turbine Manufacturers evaluating High Temperature Recuperator Materials in engines

- Impact: Higher efficiency turbines for less cost
  - Increased market penetration of high efficiency CHP
- Alumina-forming austenitic (AFA) steel invented by ORNL – licensed by Carpenter Technology
  - Commercial foils tested in humid environments at 650-800°C for 15000h exhibit excellent oxidation resistance
  - First Capstone C65 micro-turbine tests with AFA air cells exhibited very limited oxidation degradation after 3000h
  - New C65 micro-turbine test with a rainbow (AFA, 310 and 120) recuperator starting in May 2015 at ORNL
    - 8000h engine durability test
    - integrated into ORNL microgrid

*C65 micro-turbine test at ORNL*