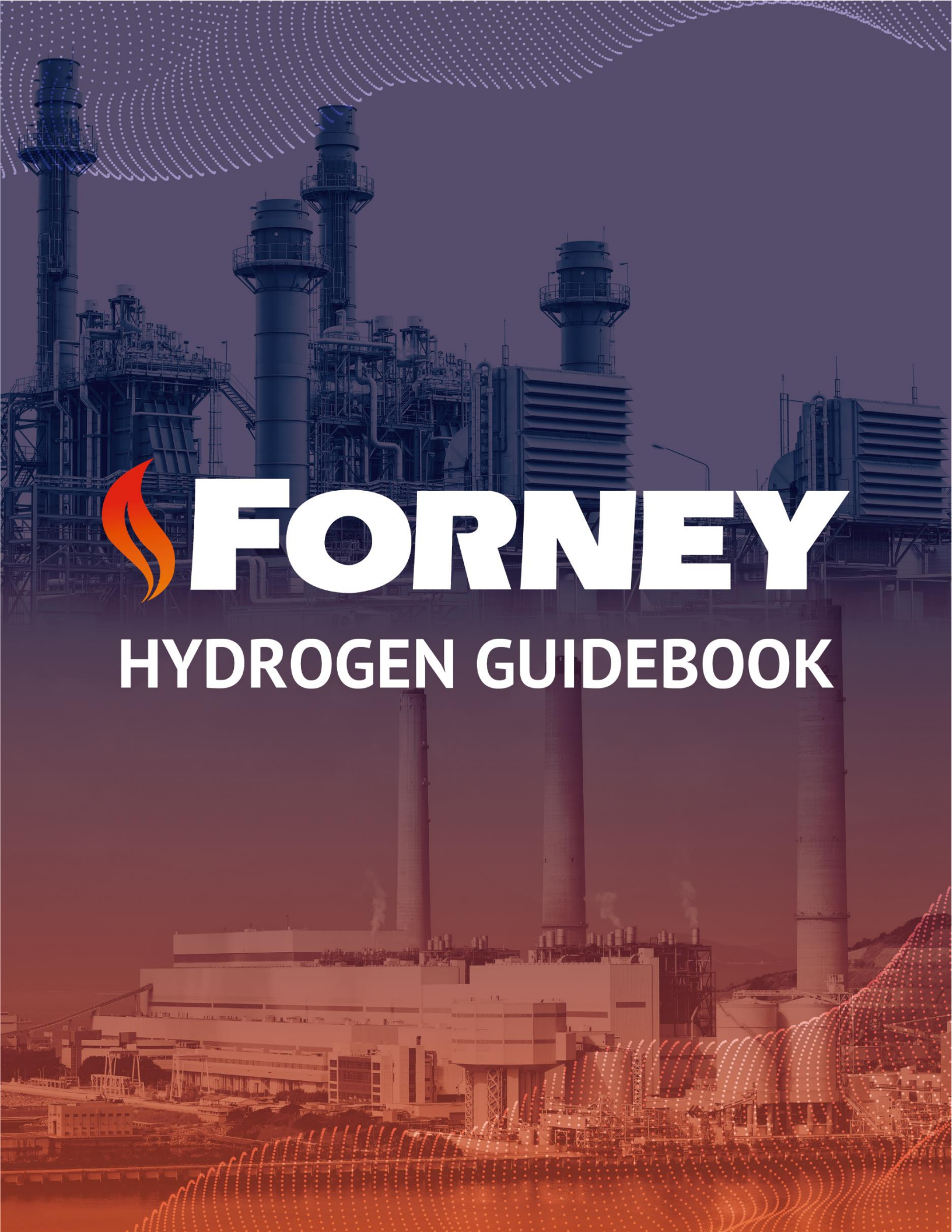


FORNEY

HYDROGEN GUIDEBOOK

CONTENTS

Introduction

Since 1927, Forney has been providing combustion solutions for coal, gas, and oil. For over a decade, we have also supplied combustion systems for hydrogen fuels. This guidebook describes the products and services Forney has available to assist end-users with starting up a new process or converting an existing one to a renewable hydrogen fuel system. It also outlines services available from our partners – REI,Tetra, and Strafire.

Background

Because of its numerous benefits, hydrogen is increasingly recognized as the ideal fuel for the future. It is non-poisonous, tasteless, colorless, odorless, and the most abundant material in the universe. The production of hydrogen has many potential sources, including wind or solar electrolysis (Green Hydrogen) or nuclear power generation (Pink Hydrogen); Steam reformation of methane without carbon capture (Grey Hydrogen) or with carbon capture (Blue Hydrogen); and even from coal (Brown Hydrogen).

Hydrogen burns cleanly with no CO2 and manageable levels of NOx. It's a gas at room temperature with a high gravimetric energy density but a very low volumetric density. Due to these unique physical and chemical characteristics, there are some challenges to combusting this material safely on a large scale, but overcoming these challenges allows plant operations to take advantage of a plentiful, inexpensive, and clean-burning fuel.

Operational Configurations

In order to safely and efficiently use hydrogen fuel in plant operations, the burner design and construction must be changed to combust hydrogen at higher temperatures. Additionally, the fuel distribution system into the burners must be changed to adapt to hydrogen's unique chemical characteristics. The higher flame temperatures and flows of a hydrogen system also affect some downstream system components to ensure minimal leakage and safe operations.

Transition Configurations

Sites considering adding hydrogen to their fuel mix have several options. Hydrogen can be used as a blend with other fuels or as pure hydrogen. For combustion purposes, it is important that the fuel composition remains relatively stable. Often users are evaluating blends of hydrogen and natural gas that contain up to 30% hydrogen. This can be accomplished using standard equipment, and this setup typically functions using pure natural gas.

If plants cannot reasonably expect consistent, reliable availability of hydrogen, then a dual-fuel system is preferable. In these systems, both natural gas and hydrogen are fired into two independent systems of a common vessel, keeping each fuel separated and burning safely under appropriate conditions. Below is a photo of two duct burners, one firing hydrogen (which is invisible) and another firing natural gas. This arrangement also provides flexibility to meet process requirements without restrictions on fuel availability.

Example of a dual fuel system

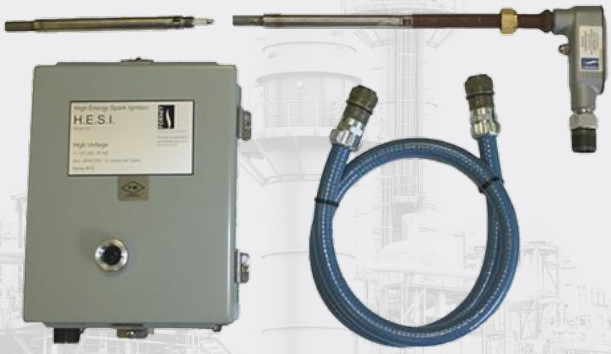
Forney Offerings

In 1927, Forney Corporation was established by a Texas utility engineer who had an idea for advancing burner designs for the combustion of fossil fuels. Since the start of Forney, the safe combustion of fossil fuels has evolved to meet market demands and environmental regulations. Over the years, Forney's product line expanded beyond traditional burners to include a variety of associated equipment, including Flame Detectors, Burner Management Safety Systems, Safety Shutoff Valves, Main Fuel Skids, and Ignition Systems designed for the robust needs of various combustion applications.

For the last 30 years, Forney has worked hard to design burners with lower emissions and higher efficiency for typical fuels such as pulverized coal, natural gas, and oil. In addition, Forney's engineers have developed combustion equipment for applications that have waste gas streams, landfill gas, biofuels, wood, and other agricultural fuels, as well as hydrogen from process plants.

As the hydrogen economy is evolving, we have been working hard to meet current market demand and supply duct burner systems for the Combined Cycle market that are capable of firing from 30-100% H2. To do this safely, our engineers consistently review existing sites with co-fired hydrogen and natural gas systems, reevaluate the longevity and durability of our equipment long after installation, and gather real customer feedback on the ease of use and maintenance efforts required to keep systems in top operational condition. Based on this research, our engineers work hard to continually develop and refine our designs and identify the safest and most cost-effective solutions for many aspects of the power generation process.

• IGNITERS



HESI IGNITER

MAXFIRE® GAS IGNITER

Forney has igniters that seamlessly integrate with main burners in many different boiler/burner combinations for the utility power generation market. The igniter design most suited for hydrogen systems is our MaxFire series. The MaxFire provides a very reliable ignition source with a heat release from 300k BTU/hr up to 40 MMBtu/hr, depending on the application.

With hydrogen systems that operate at higher temperatures, a reliable igniter is paramount for safe and efficient start-up, warm-up and support for main burner flames in boilers and gas turbines. Efficient and effective igniters are critical for line stability and help operational teams meet rigid startup times.

As we continue to develop equipment that meets the demands of operations using H2 as a primary fuel in power generation, we are developing igniter designs capable of dual fuels that can ignite either natural gas or H2. Our development process incorporates ammonia as a potential green fuel source, thus eliminating many of the transmission and storage issues typically associated with hydrogen fuel.

For additional system reliability, utilizing the Forney High Energy Spark Ignition (HESI) can extend the life of your other system components and ensure optimum operational performance. The HESI generates a spark of 12 Joules at the tip ~3 times per second. This energy cleans off build-up that can accumulate at the base of the flame envelope on the spark tip, making the HESI a self-cleaning mechanism.

The Forney HESI can be used in a Class 3 special (NFPA 85) to directly ignite the main fuel. This feature is even more ideal for H2 systems, since direct ignition of main burners eliminates the need for pilot fuel safety shutoff valves, piping, BMS associated logic, and other additional equipment.

• FLAME DETECTORS

FRONT VIEW

SIDE VIEW

HD FLAME DETECTOR

The Forney HD-01 Flame Detector, also referred to as the Flame Scanner, is an optical device that is utilized in the safety system to verify the presence or absence of flame when fuel is being emitted into an igniter or main burner. The Flame Detector is a critical device to protect the equipment and plant crew from potential dangers in the event that unburned fuel is released into a furnace.

The HD-01 incorporates multiple sensors that detect frequency from the ultraviolet to infrared light spectrum. Depending on the fuel being detected, the HD-01 is tuned to a specific frequency emitted from the main combustion zone.

As hydrogen combusts in the ultraviolet light spectrum, our flame detectors can identify H2 flame at two different combined cycle installations. While this research is still in development, initial tests indicate these flame detectors can be successful in a variety of applications with H2 fuel mix and dual fuel systems.

• REGISTER & DUCT BURNERS

PAF BURNER

adVantage® DUCT BURNER

Forney main burners are broken down into two basic types; our PAF register style burner and our adVantage Duct Burner. The PAF is utilized in multi-burner utility boilers that fire Natural Gas and Liquid fuels, while the adVantage Duct Burner is utilized in Combined Cycle (CC) applications. The adVantage burner has already been successfully used to burn hydrogen from process applications in combined cycle applications.

For Duct Burners, Forney has two different offerings. Our standard product, originally designed for firing 100% Natural Gas, can handle blends up to 30% Hydrogen without modification. Firing pure Hydrogen (100%) requires special materials and designs for Hydrogen's unique combustion characteristics. Forney has proven designs for firing 100% Hydrogen. We do recommend modeling of the flows and reactions using CFD tools to understand the downstream and side wall impacts from the different thermal characteristics. Both types of duct burners can be fired simultaneously in the same HRSG, as shown in the earlier graphic.

• VALVE / CONTROL FUEL SKIDS

When purchasing Forney burner units, a standard scope of supply includes fuel safety and control valves. Safety shutoff valves are required at each burner and at other key locations, such as the fuel supply line.

Firing 100% H2 will require special attention to the design of the valves and the fuel piping. Since H2 is extremely lightweight, fuel skids require valves and pipe material that can hold up over time and skids must be specially designed to avoid leakage from valve stems.

• COMBUSTION RESEARCH CENTER

Forney's state-of-the-art Combustion Research Center is specially designed to provide test environments that simulate many different igniter and burner types as well as different fuel systems. All of our equipment undergoes rigorous testing to ensure equipment safety and reliability in different plant environments and system combinations.

Our short-term goal is to secure reliable sources for ammonia (NH3) and hydrogen (H2) fuels. With minor modifications to our current combustion research center, we are currently exploring the possibility of manufacturing green hydrogen from solar power right at our facility.

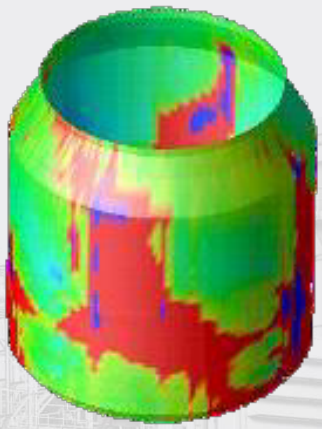
We welcome the opportunity to collaborate with you on our research activities to direct our focus on technology that will best suit your future green power production.

REI Offerings

Reaction Engineering International

- Technical focus on multiphase, chemically reacting flows
- Serving the industries since 1990
- Affiliates in Asia and Europe
- Established capabilities include advanced modeling, process evaluation and testing

REI Expertise



Gasifier Slagging Model

Modeling

Unique, Proprietary Modeling Capabilities & Tools

- Ability to develop and apply advanced chemistry to CFD and process modeling tools
- Experienced combustion modelers
- In-house tools tailored as needed

Testing

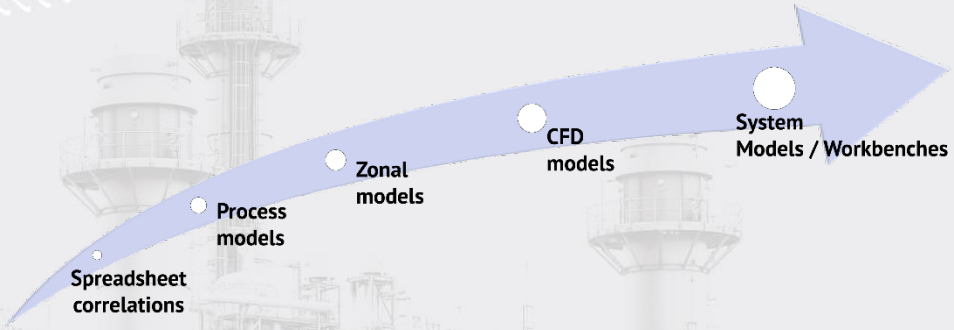
R&D Testing Expertise

- Bench-scale & pilot-scale facilities
- Field demonstrations

Specialized Equipment and Control

- Customized software development
- Corrosion monitoring

REI Modeling Options

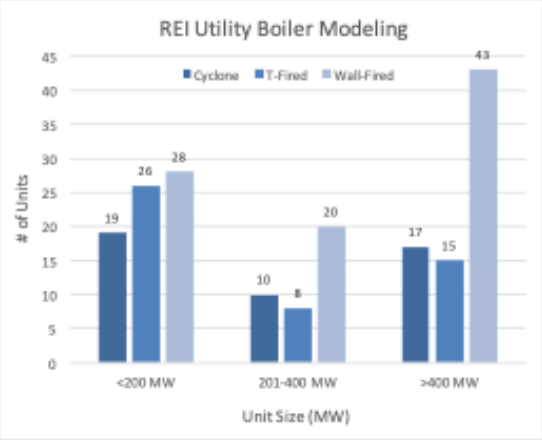


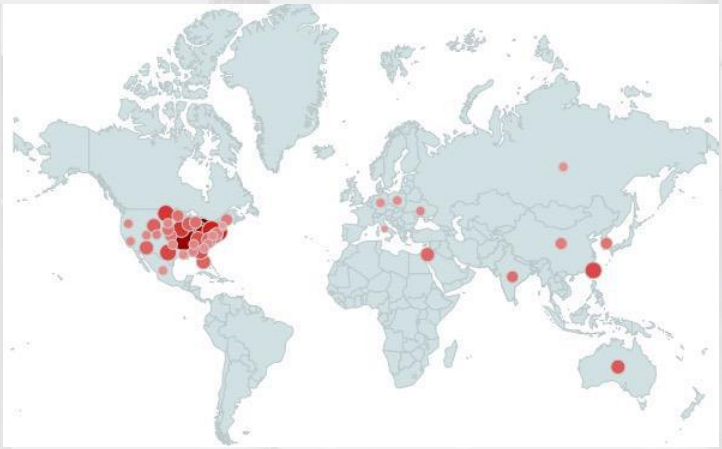
Increasing Process Knowledge and Computer Resources

Many types of simulation tools; each serves a different purpose. Model development and use are correlated with:

- Process Knowledge
- Modeling techniques
- Computational resources
- Value to market

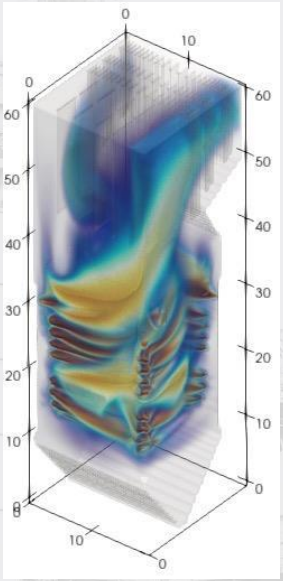
REI Utility Boiler Modeling

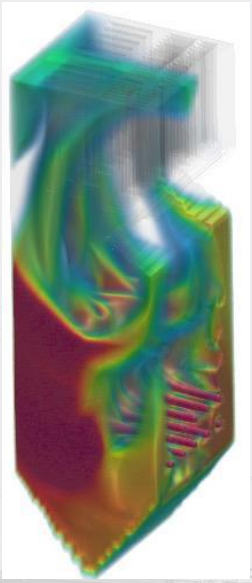




- >200 Utility Boiler Modeled
- >70,000 MW of Capacity
- Cyclone, Wall, Turbo & T-fired
- Firing Coal, Oil, Gas, Biomass, Petcoke, TDF, Blends, Oxygen
- Stokers, OTSGs, Fluidized Beds, Emission Reduction Strategies
- Operational Impacts

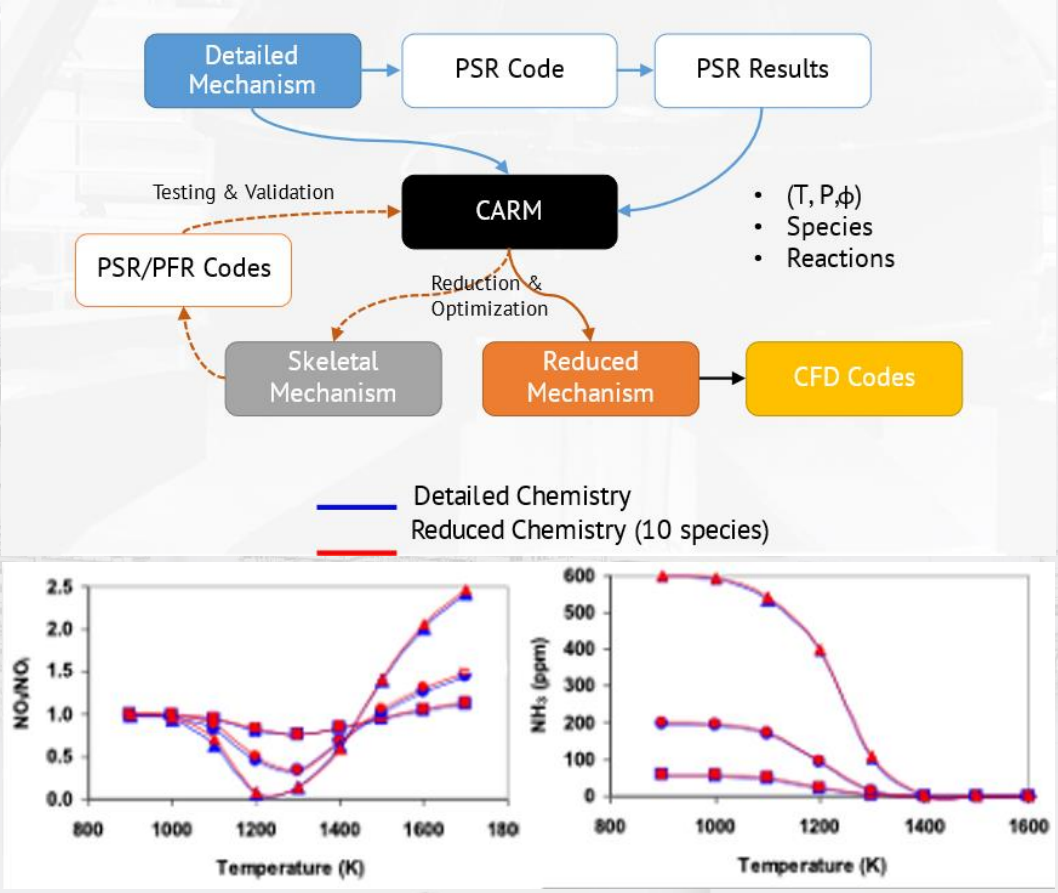
REI CFI Modeling





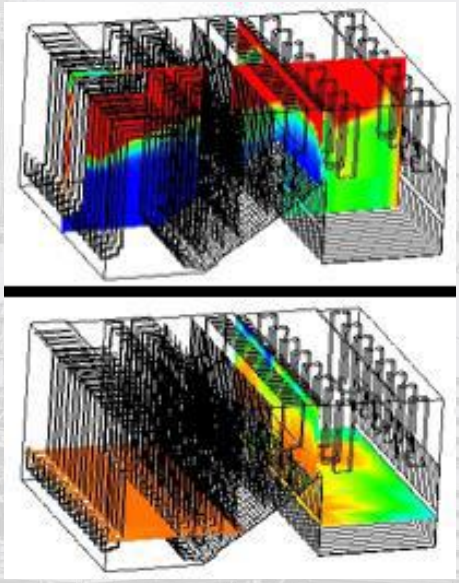
- Pioneers in the development of Computational Fluid Dynamics software for fossil fuel boilers:
- Independent internally developed tools
    - GLACIER multi-phase reacting flows
    - ADAPT - adaptive mesh refinement and advanced turbulence chemistry interactions
- Tools developed/c- developed by affiliates or collaborators:
    - SIMIT (with Univ. at Buffalo) and Uintah -MPM (with Univ. of Utah) - reacting, compressible, unsteady flows, highly parallelized, multi physics
    - AIOLOS (with Univ. of Stuttgart) - reacting, multi-phase, unsteady flows, highly parallelized
- Commercial or open-source tools, for which REI has active licenses and has participated in development
    - ANSYS FLUENT
    - CPFD Barracuda
    - NETL MFIX

Reduced Chemistry by CARM

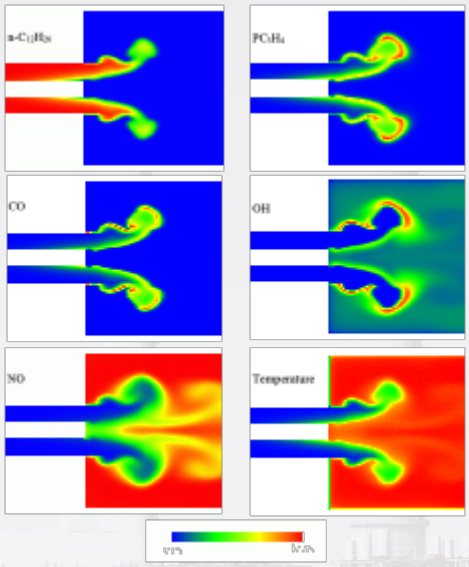


- CARM (Computer Assisted Reduction Method) – J.Y. Chen
  - Conventional RM method
  - Steady state assumption
  - Automated
- User chooses species to treat kinetically based on error analysis
- Subroutine calculates rates based on composition and temperature

Reduced Chemistry Application Examples

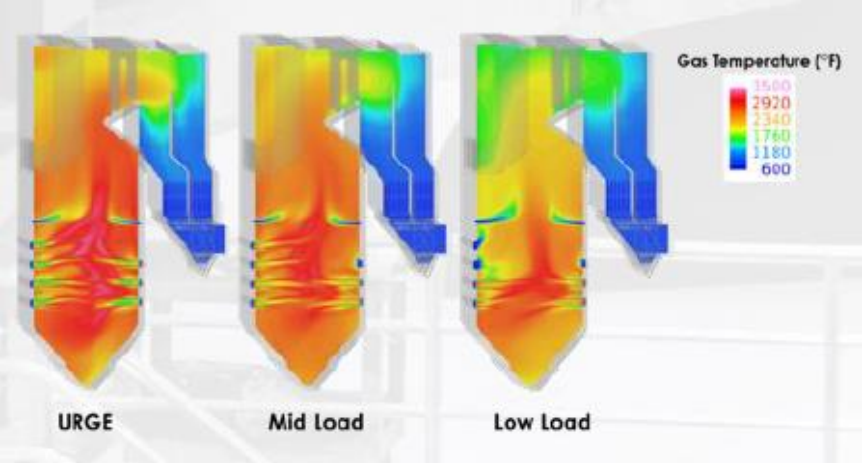


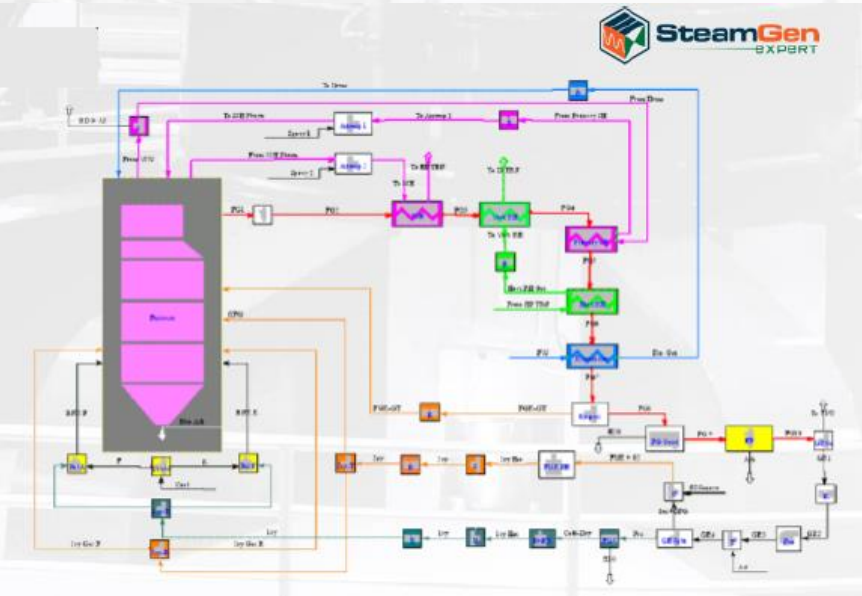
SCNR in a Coalfired Boiler



LES of Gas Turbine Combustor Burning P-8

Integrated CFD-Process Modeling

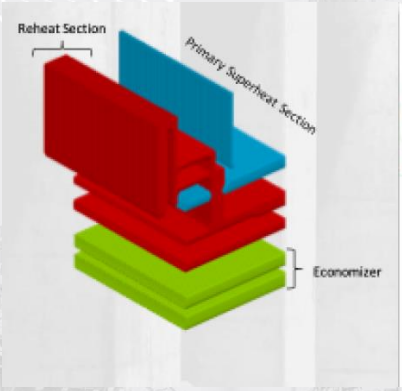


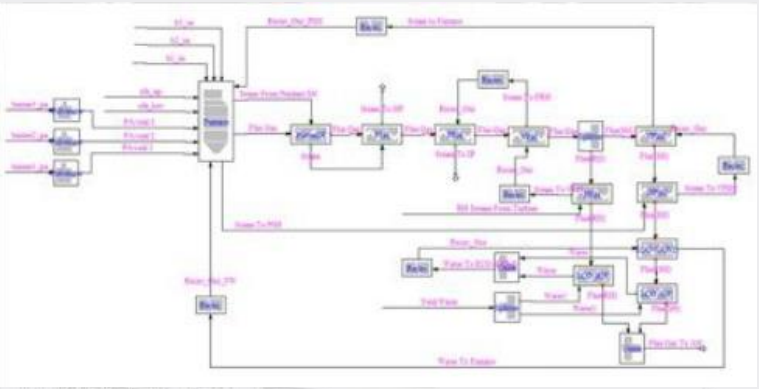


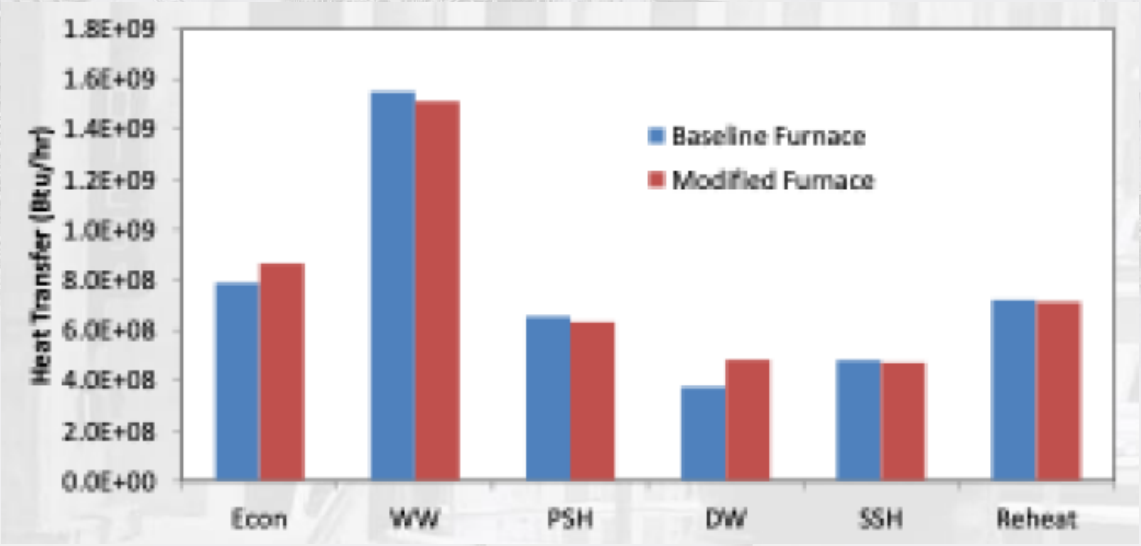
REIs extensive experience in boiler CFD modeling, is combined with steamside process simulation (Steam Gen Expert) to guide:

- Coal to gas conversion
- Heat transfer surface modification
- Heat balance
- Fuel quality impacts

Boiler Thermal Analysis







Based on CFD and Process model

- Evaluation of existing steam circuit
- Impact analysis of operation change
- Optimization of heat distribution

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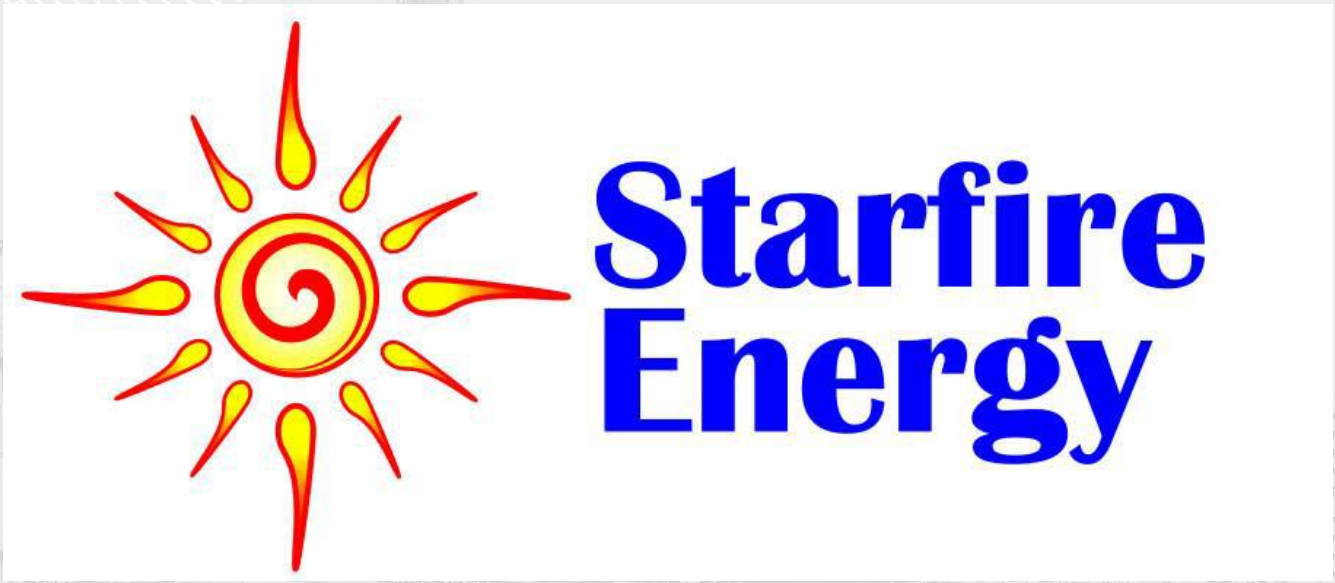
Tetra Engineering Offerings

Tetra Engineering Group, Inc is an international consulting engineering firm with subsidiaries in France and Dubai. Tetra provides support for design, procurement, installation, operation, troubleshooting and disputes for owners and developers of all types of thermal power systems. Established in 1989 in Hartford Connecticut, Tetra's first combined cycle projects were in 1992 and have continuously grown. A specialty of Tetra is advanced thermal-hydraulic and system modeling of power systems. Tetra is partnered with KED, GmbH of Munich Germany to provide this advanced analysis using the PPSD Power Plant Simulator and Design Software. This allows us to model the entire plant both steady state and dynamic response while addressing detailed conditions at all parts of the power plant. For hydrogen applications PPSD can model fuel changes in GT and Duct Burners with regard to exhaust gas compositions and thermal performance. Increases in H2O content with hydrogen firing change thermal capacity of the exhaust as well as heat transfer. More H2O also impacts the corrosion potential of exhaust gasses. Tetra has been working with renewable integration studies in the Middle East for combined cycle power and water plants over the last several years. These studies include solar thermal power as well has hydrogen production and use.

Starfire Engineering Offerings



Starfire Energy is a collaborative partner of Forney that provides modular plants for the production of carbon-free gree ammonia as well as systems for the downstream cracking of ammonnia into hydrogen when ammonia is used as the transport mechanism for hydrogen.

Starfire Energy's Rapid Ramp green ammonia plants represent a direct replacement for the legacy Haber-Bosch process for synthesizing ammonia. Unlike Haber-Bosch, Rapid Ramp uses no fossil fuel feedstocks and produces no carbon. The only inputs are water, air and renewable energy allowing you to produce documentably carbon-free ammonia. Rapid Ramp is able to be directly coupled to variable power renewable energy sources such as wind, solar, hydro, etc. These unique capabilities are the result of patented technologies in the areas of catalysts, monolith structures, adsorption materials, adsorption process design, reactor design and others.

Green ammonia also represents a long term multi-TwH storage solution for utilities. Ammonia's low cost and low cost of storage allow for seasonal scale storage of renewable power sources. These plants are modular in design and mass produced in a factory environment. Plants arrive in the form of ten different functional modules that are built in 40 foot shipping containers that arrive pre-wired and pre-plumbed. A qualified EPC firm commissions the plant on-site. Approximately 80% of the plant construction occurs at the factory with the balance performed by the EPC. This reduces commissioning time from years to months and allows for capacity to added incrementally as needed and located in proximity to the point of use.

Starfire Energy's Prometheus cracker systems operate at 500C versus the 900C of traditional crackers. This allows for the use of ammonia as a cost effective storage and transport vector for hydrogen while allowing energy efficient conversion at industrial points of use or at regional storage depots in a gas distribution network.

Power Generation – Replacing natural gas in existing turbines

Starfire Energy is also working with some of the largest manufacturers of gas turbines to allow existing gas turbines to be converted to dual fuel use. The turbines are then fed carbon-free ammonia in place of natural gas. Some of the ammonia is cracked into hydrogen and nitrogen using the residual heat in the exhaust stream of the turbine. A blend of approximately 70% green ammonia and 30% cracked green ammonia is fed into the turbine. This blend replicates the combustion characteristics of natural gas but represents a 100% carbon-free alternative E-fuel.

Starfire and Forney are working together to bring carbon-free E-fuels to the marketplace as integrated industrial scale solutions.

We're Here to Help!

If you're on the fence about how hydrogen research and product development can help you meet future goals and power generation needs, we welcome a conversation with your team. Forney has over 20 years of experience in the Hydrogen combustion research and 50+ years in the power generation equipment industry, and we look forward to helping organizations like yours accomplish their goals more efficiently through partnership.

Providing 50+ years of safe combustion at more than 1000 sites