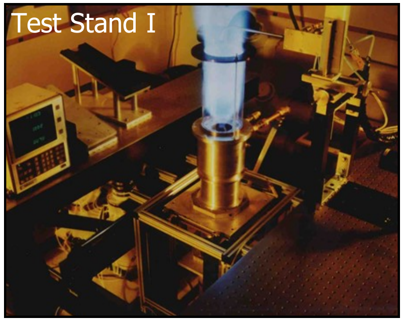

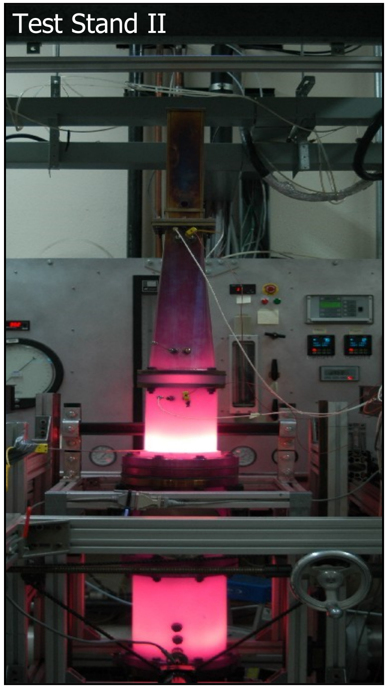

Brochure Ver June 2018

ENERGY RESEARCH CONSULTANTS

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ERC ENERGY RESEARCH CONSULTANTS

Research and Development Services

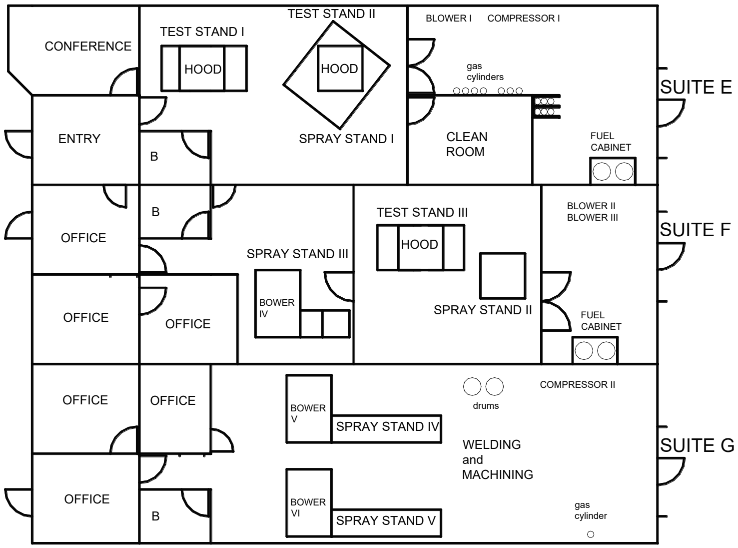
Your Expert Measurement Partner For Over 25 Years

Contents

Since 1990, Energy Research Consultants (ERC) has been providing Research and Development Services for a wide range of commercial and government customers. ERC maintains over 4,500 square feet of research space in Laguna Hills, California which houses advanced test facilities and diagnostics that are applied to wide array of spray and combustion applications.

FACILITIES

ERC has eight test stands located within flexible laboratory space as shown below. Three test stands are primarily utilized for study of gas and liquid fired combustion systems and/or components. Two are upfired and have exhausting capable of handling 6 lbs/sec of flow generated by devices fired with up to 1MW of fuel input. All facilities offer 3 axes of traversing with digital readouts for relative position. The fluid delivery systems are interchangeable between the stands.



<u>Air</u>. ERC has several independent air generation sources producing the following flows:

0.05 lbs/s (40 SCFM) at pressures up to 150 psig
0.15 lbs/s (120 SCFM) at pressures up to 125 psig
1.00 lbs/s at pressures up to 1.2 psig
2.00 lbs/s at pressures up to 3 psig
2.25 lbs/s at pressures up to 4 psig
0.80 lbs/sec at pressures up to 10 psig
37.5 lbs/sec at pressures up to 0.2 psig
1.00 lbs/sec vitiated air at 1340 F at 200 m/s

50 kW of non-vitiated preheating is available. Monitoring of air pressure, flow, temperature, and humidity is available via transducers and associated data acquisition interfaces. A specialized pressure vessel is available to study phenomena at elevated pressure.

<u>Liquid</u>. ERC has experience running the following distillate and non-distillate liquids (others available upon request):

—Gasoline
—Diesel
—Calibration Fluid (Mil-PRF-7024)
—Water/Glycerin Mixtures
—Viscor
—Heptane
—Acetone
—Water
—Jet-A/JP-8/Biofuels
—Emulsions/Slurries

KEY PERSONNEL

L to R:
Ulises Mondragon, Principal Research Engineer; Facilities Manager
Leonel Blanco, Research Engineer
Jonathan Bastiaans, Sr. Research Engineer
Christopher Brown, Co-Owner; Research and Business Manager
Dr. Vincent McDonell, Co-Owner; Sr. Scientist
Brendan Hickey, Research Engineer

NEXT STEPS

Working with ERC is very straight forward. With over 25 years of experience, a short phone conversation and answers to a few simple questions will generally be sufficient to let us give you a sense of what can be accomplished, how long it might take and what the cost will be. ERC maintains a number of example reports and project profiles that can be used to give you a clear idea of what you can expect. Please direct inquiries to:

Christopher Brown, Manager of Research, 949 583 1197 x101, Brown@ERC-Ltd.com.

EXAMPLE PAPERS

Liquid Fuel Injection Strategy to Reduce Sensitivity to Liquid Physical Properties (2017). Paper AIAA-2017, Grapevine TX (C.T. Brown, B.Hickey, V.G. McDonell, E. Baldwin, and D.P. Schmidt

Velocity and Flame Wrinkling Characteristics of a Transversely Forced Bluff-Body Stabilized Flame, Parts 1&2 (2013). Combustion Science and Technology, Vol. 185, pp. 1056-1097. (V. Acharya, B. Emerson, U. Mondragon, D-H. Shin, C. Brown, V. McDonell, T. Lieuwen)

Characterization of Trajectory, Breakpoint, and Breakpoint Dynamics of a Plain Liquid Jet in Crossflow (2011). Atomization and Sprays, Vol 21(3), pp 203-219 (Q. Wang, U.M. Mondragon, C.T. Brown, and V.G. McDonell).

Coal Slurry Atomization: Applications, Scaling, and Unanswered Questions (2011). ILASS-Americas 2011, Ventura, CA, May (B. Steinhaus, E. Yilmaz, K. Venkatesan, A. Ergut, C.T. Brown, U.M. Mondragon, and V.G. McDonell).

Characterization of a Superheated Fuel Jet in a Crossflow (2011). J. Eng. Gas Turbines Power, Vol 133 (1) 011501 (M. Corn, J. Cohen, J. Lee, D. Hautman, S. Thawley, C. Brown, and V. McDonell).

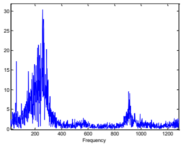
Dynamics of a Longitudinally Forced, Bluff Body Stabilized Flame (2011). J. Prop Power, Vol 27(1) pp 105-116. (D.-H. Shin. D.V. Plaks, T. Lieuwen, U.M. Mondragon, C.T. Brown, V.G. McDonell)

Investigation of the Effect of Injector Discharge Coefficients on Penetration of a Plain Liquid Jet into a Subsonic Crossflow (2007). ILASS-Americas, Chicago, IL (C.T. Brown, U.M. Mondragon, and V.G. McDonell)

Characteristics of High Capacity Cone Sprays Injected into a Crossflow (2004). ILASS Americas, Arlington, VA (C.T. Brown, V.G. McDonell, and S. Sherikar).

Accounting for Laser Extinction, Signal Attenuation, and Secondary Emission While Performing Optical Paternation in a Single Plane (2002). ILASS Americas, Madison, WI (C.T. Brown, V.G. McDonell, D.G. Talley).

ERC has optical arrangements to facilitate measurement of fine particles (1.2 microns) to those approaching 2 mm in diameter. ERC personnel have extensive experience in optimizing optical setups, dealing with potential issues such as beam steering, sample clipping, correction for laser extinction, and presentation and interpretation of results obtained using LD.

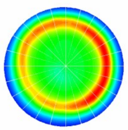


Combustion Dynamics. High sensitivity dynamic pressure probes are available to quantify the frequency and magnitude of combustion oscillations. Combined with chemiluminescence, these probes can provide insight into the coupling between pressure and heat release.

Temperature. A variety of thermocouples and optical diagnostics are utilized to obtain in-situ temperature measurements.

Planar Liquid Laser Induced Fluorescence (PLLIF). A technique related to PELSI is planar liquid laser induced fluorescence (PLLIF). In this case, rather than obtaining qualitative images, fluorescence is utilized to provide quantitative characterization of the spatial distribution of the liquid material.

Optical Patternation. Extending the PLLIF technique, ERC developed a quantitative approach (under a Phase II SBIR) to characterize the spatial and temporal distribution of sprays (optical patternation). The technique corrects for both the attenuation of the incident light as it travels through the spray and the signal as it travels from the spray to the camera. An En'Urga optical patternation system is also available.



High Speed Visualization. High speed video (up to 100,000 frames per sec with 1 microsecond exposure), combined with various lighting techniques, provides unique insight into system behavior.

Tunable Diode Laser Absorption Spectroscopy (TDLAS). A number of tunable diode lasers are available as part of a spectroscopy systems that can be used to determine select species concentration and temperature in-situ

Film Thickness Measurements. Spatially and temporally resolved liquid film thickness.

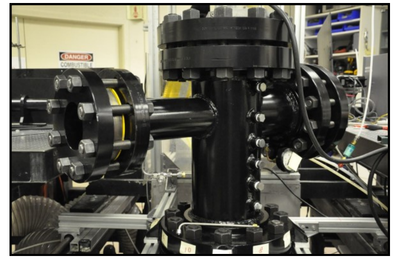
Calibration Devices. ERC has a wide variety of calibration devices, methods, and experience for quality control of all diagnostics and instrumentation.

MODELING

ERC applies Fluent and OpenFOAM for Computational Fluid Dynamics modeling of reacting and non-reacting, single and two phase systems. ERC also applies statistically design test matrices to efficiently identify key factors impacting processes of interest which can produce empirical correlations that can be very useful for engineering design.

Several pumps are available:

- 1 gpm distillate fuel @ 300 psig
- 3 gpm water @3000 psig
- 10 gpm water @ 300 psig
- 100 gpm water @ 150 psig
- 1.4 gpm distillate fuel @ 600 psig



Optically Accessible Pressure Vessel

Low pressure, low flow rate (to below 1 g/s) operation can be accomplished with precision syringe pumps. A hydraulic accumulator can drive liquids with an inert gas pressure head (gas and liqud are separated by a membrane) at up to 3000 psig. In all cases, computer based monitoring of liquid flow rate, temperature and pressure is available via transducers and associated data acquisition interfaces. Multiple liquid circuits can be operated and monitored simultaneously (e.g., pilot and main stages).

Gaseous Fuel. ERC can flow up to 1MW of natural gas. In addition, fuel handling to provide higher hydrocarbons such as ethane, propane and butane is available. Also, hydrogen and diluents such as carbon dioxide and nitrogen can be accommodated.

Diagnostics. ERC maintains a wide array of conventional and advanced diagnostics that are described on Pages 4-6.

PRODUCTS

ERC has developed several products including a high temperature inspection camera, and a turn key calibration flame system. Software products include Automated Feature Extraction and Analysis Tool (AFEAT) which extracts features from high resolution videos and has been packaged as a stand-alone tool. The Advanced Spray Injection Phenomenon Simulator (ASIPS), predicts the spray droplet and vapor characteristics downstream of an injector. Currently, ERC is developing a software tool to assess sensitivity of bluff body stabilized flames to acoustic fields called Flame Response Sensitivity Tool (FRST). Learn more about these products at our website, www.ERC-Ltd.com.

OTHER SERVICES

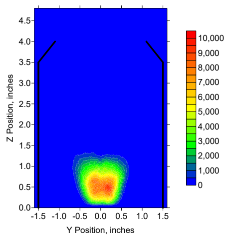
In addition to characterization of combustion systems and/or components, ERC can also provide assistance in development of test facilities, including design and fabrication of test stands, traverse systems, sampling systems, and specification, installation, and guidance on various diagnostics such as those outlined herein. ERC can also assemble and program data acquisition systems. ERC also has experience in the development, application, and interpretation of statistically designed evaluation methods which are being utilized in leading companies today for quality assurance. These methods, when applied to complex devices, can provide an efficient cost effective means to identify the key factors that control performance of the devices. ERC can also provide analysis of results and provide interpretation of phenomena associated with combustion systems.

We are happy to discuss your application and explore ways in which we can work with you.

DIAGNOSTICS

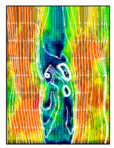
ERC personnel have extensive experience with a wide range of diagnostics as applied to a variety of applications.

Fuel/Air Mixing Probes. For the characterization of fuel/air mixing in gaseous systems, ERC employs both intrusive and non-intrusive methods. Extractive probes can be used to pull a sample out of the flow and conveyed to an emissions analyzer package where a doped constituent (e.g., natural gas, carbon dioxide) can be monitored. This approach offers high accuracy and relatively high efficiency.



Laser Induced Fluorescence (LIF). For non-intrusive measurements of fuel/air mixing or reaction species, either point or planar laser induced fluorescence (PLIF) can be utilized in both reacting and non-reacting flows. The specific species and methods employed will vary depending upon the type of information desired. Both continuous and pulsed lasers are available. For point measurements, a photomultiplier is used. For planar methods, scientific 16-bit intensified CCD cameras are available.

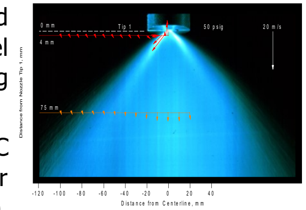
Laser Anemometry. To characterize the flowfield in reacting and non-reacting systems, a two-component laser anemometry system is available that features frequency domain processing. This method is used to provide a measure of a single component or of the total velocity at various points throughout the domain. This information is useful in defining the extent and strength of aerodynamic features such as recirculation zones and separation regions. Time resolved information can also be obtained and analyzed to search for periodic flow behavior that might be associated with shedding off a bluff body or some other instability in the system.



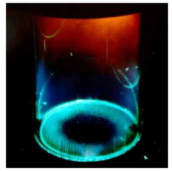
Particle Image Velocimetry (PIV). Measurements of particle velocity are obtained by tracking particle displacement with double pulsed laser and imaging. LaVision timing units and software are used to process images. It is also possible to obtain time resolved PIV results using different lighting and a Phantom high speed video camera.

Phase Doppler Interferometry (PDI). Phase Doppler interferometry systems with frequency domain processing (TSI FSA3500) are available which can be applied to reacting or non-reacting sprays. While primarily utilized to measure the joint distribution of particle size and two components of velocity at a point, it can also be utilized to measure continuous flow field velocities in the absence or presence of droplets. PDI provides considerable information regarding the spray behavior and characteristics. In particular, it can provide the inlet conditions for accurate computation fluid dynamics calculations. ERC personnel regularly apply PDI to

sprays and have extensive software codes and experience in reducing and tabulating data for model validation and/or further interpretation, including time resolved details and frequency analysis.



Planar Elastic Light Scattering Imaging (PELSI). ERC maintains a variety of optics to produce sheets or beams of laser light from either cw (e.g., Ar^+), pulsed (e.g., Nd:YAG) or diode lasers. Such lighting, when scattered by droplets or particles, can be imaged onto a digital camera. The camera can operate as both a video recorder or as a digital still camera with full user control over exposure (aperture and shutter speed). Close-up adapters are available to provide up to 30X magnification. In addition, ERC has the capability to extract frames from the video to conduct analysis (e.g., line profiles, comparison of images, etc.) as well as produce high quality video presentation of phenomena of interest. Various filters are utilized to isolate laser wavelengths and fluorescence from species of interest. The Nd:YAG laser can generate 4 ns pulses with energy levels sufficient to freeze the spray structure even with extreme magnification. This is useful in characterizing the highly complex breakup region.



Infrared Extinction/Scattering (IRES) Fuel Vapor Measurement. ERC has the capability to measure the time-averaged concentration of vapor present within hydrocarbon sprays using a two-wavelength extinction technique. While a line-of-sight technique, spatially resolved information can be obtained for arbitrary fields by topographically deconvolving a series of scans. This technique has been utilized to obtain time-resolved information as well, and can also be used in single phase situations to monitor fuel concentration.

Chemiluminescence Imaging. ERC has a variety of filters and cameras that can be used to image species such as OH*, CH*, CO_2*, or C_2* which are helpful in determining the location of reaction zones. In addition to full field imaging, point measurements of radical species can also be useful in identifying dynamics associated with heat release and/or stability monitoring.

Emissions. ERC can measure emissions including unburned hydrocarbons, oxygen, carbon monoxide, carbon dioxide, and oxides of nitrogen. In-situ samples are obtained using water-cooled extractive probes. ERC has implemented sophisticated data reduction tools for quality assurance, analysis, interpretation, and presentation of results. The spatial distribution of gaseous fuel can be determined through the use of microprobes and a flame ionization detector.

Laser Diffraction (LD). Both Malvern 2600C and Spraytec laser diffraction particle sizers are available to provide line-of-sight measurement of particle size distributions and particle concentration. This well established method of characterizing sprays provides a relatively rapid and consistent measurement.