

# UCI Combustion Laboratory

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## General Capabilities

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UCI COMBUSTION  
LABORATORY

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This document summarizes the general capabilities of the UCI Combustion Laboratory. It includes facility details, test stands for both high pressure and atmospheric study and citation to references that provide additional information. For more information contact Vincent McDonell

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## UCI Combustion Laboratory

The UCI Combustion Laboratory ([www.ucicl.uci.edu](http://www.ucicl.uci.edu)) has evolved through 30 years of research ranging from basic science to practical applications. The UCICL is housed in the Engineering Laboratory Facility in the Mechanical and Aerospace Engineering Complex on the main campus. Figure 1 shows a view of the facility looking west. The tall stacks are located immediately above the combustion test cells illustrated in Figure 1b.

a) Photo Looking North



b) General Layout of the Facility (each cell, e.g., “101” is ~20’w x 25’l x15’ high)

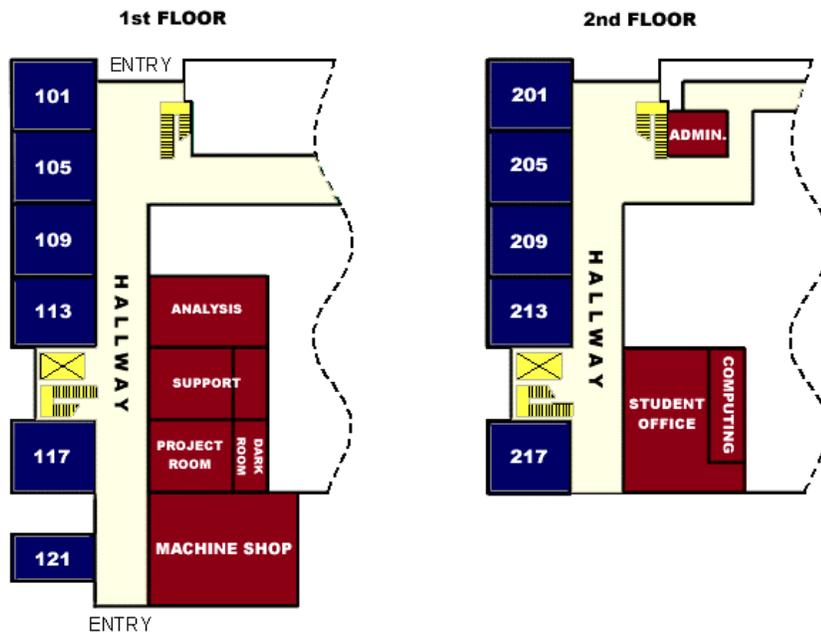


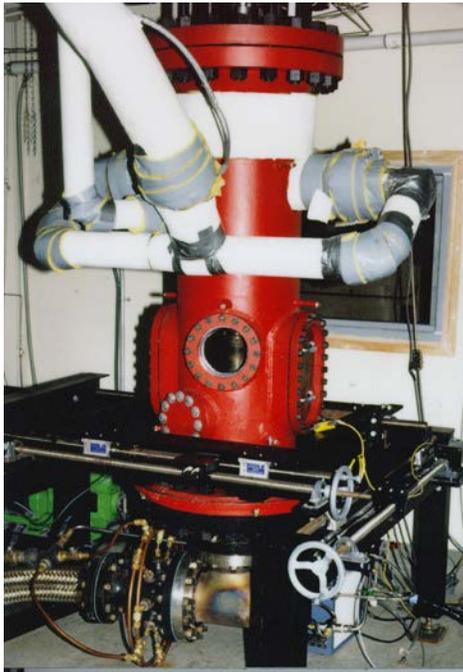
Figure 1. UCI Combustion Laboratory.

# 1 High Pressure Facilities

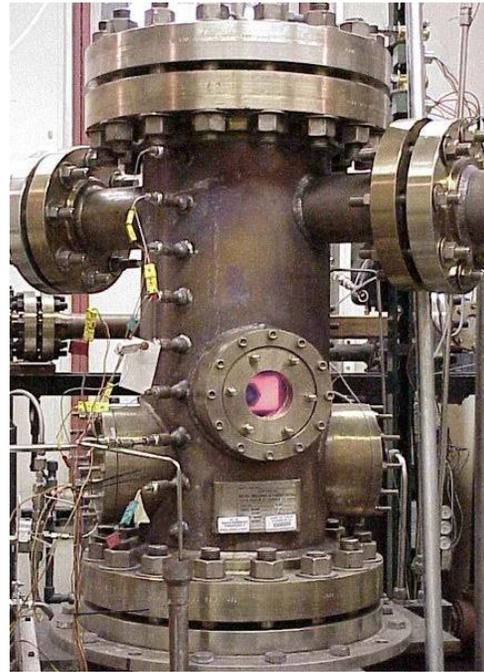
## 1.1 Elevated Pressure Vessels for General Use

Support from NASA, the U.S. Air Force, UC Irvine, and industry has enabled the UCI Combustion Laboratory (UCICL) to establish the infrastructure and operational experience necessary to explore component and system performance at elevated temperature and pressures. Two pressure vessels are available at the UCICL that feature similar capabilities. The first vessel was originally designed and built over 20 years ago in support of the NASA high speed transport program. The facility has been used for a variety of high pressure spray and combustor experiments and features significant optical access as well as full traversing, allowing detailed in-situ measurements to be obtained (e.g., 1,2,3,4). A second facility with no traversing has also been developed with the purpose of providing long duration reacting experiments for exposure testing and durability evaluations. This facility can also serve as a combustion performance test rig (e.g., emissions and stability assessment, e.g., 5). The two vessels are shown in Figure 2.

a) High Optical Access Facility



b) Operability Testing Facility



**Figure 2. Elevated pressure facilities at the UCI Combustion Laboratory.**

<sup>1</sup> RAPID LIQUID FUEL MIXING FOR LEAN BURNING COMBUSTORS: LOW POWER PERFORMANCE (2001). *ASME J. Engr. Gas Turbines And Power*, Vol 123, Pp. 574-579 (M.Y. Leong, C.S. Smugeresky, V.G. McDonell, and G.S. Samuelsen).

<sup>2</sup> EFFECT OF AMBIENT PRESSURE ON AN AIRBLAST SPRAY INJECTED INTO A CROSSFLOW (2001). *J. Prop. And Power*, Vol 17., No. 5, Pp. 1076-1084 (M.Y. Leong, V.G. McDonell, And G.S. Samuelsen).

<sup>3</sup> THE EFFECT OF LIQUID-FUEL PREPARATION ON GAS TURBINE EMISSIONS (2008). *ASME J. of Engineering for Gas Turbines and Power*. Vol. 130, Mar., pp. 021506-1 -- 021506-11 (S. Nakamura, V.G. McDonell, and G.S. Samuelsen).

<sup>4</sup> FLASHBACK AND TURBULENT FLAME SPEED MEASUREMENTS IN HYDROGEN/METHANE REACTIONS STABILIZED BY A LOW-SWIRL INJECTOR AT ELEVATED PRESSURES AND TEMPERATURES (2013). Accepted for Publication, *ASME J. Engr. Gas Turbines and Power* (D.J. Beerer, V.G. McDonell, P. Therkelsen, and R.K. Cheng)

<sup>5</sup> DEVELOPMENT OF FLASHBACK RESISTANT LOW-EMISSION MICROMIXING FUEL INJECTOR FOR 100% HYDROGEN AND SYNGAS FUELS (2009). Paper GT2009-59502, TurboEXPO 2009, Orlando, FL, June. (H.H. Lee, S. Hernandez, V.G. McDonell, A. Mansour, E. Steinthorsson, and B. Hollon).

The operation of both vessels is maintained by the facility control system. The control system can route fuel and/or air flows to either vessel. The resources available can provide and control air flow rates up to 1.0 kg/sec (2.2 pounds/sec), pressures of 15 atmospheres, and temperatures up to 649°C (1200°F). The facility can also provide a high-pressure supply of liquid fuel and natural gas. A data acquisition system (LabView, National Instruments) monitors and controls the flow rates and experimental settings and records measurements from thermocouples and emissions analyzers onto a resident computer. These facilities are housed in Test Cells 117 and 217 as shown in Figure 1. These vessels have been used for experimental work that has been reported in numerous papers and publications including footnotes [1-5].

One of the vessels (Figure 2a) is specifically designed to accommodate optical diagnostics. The chamber is traversed while the diagnostics remained fixed about it on optical breadboards. Some details regarding some of the key dimensions and layout of the ports are shown in Figure 3 and Figure 4.

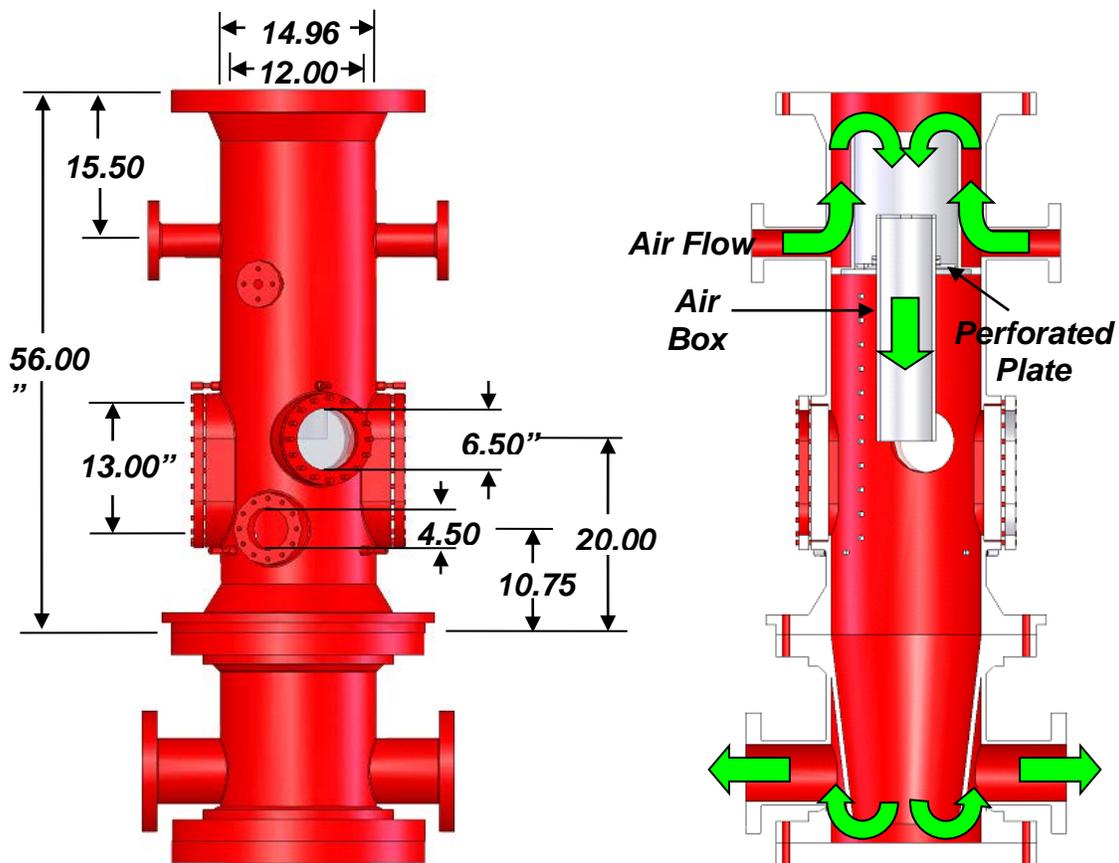


Figure 3. Side View of Pressure Vessel (top flange and Z-traverse removed).

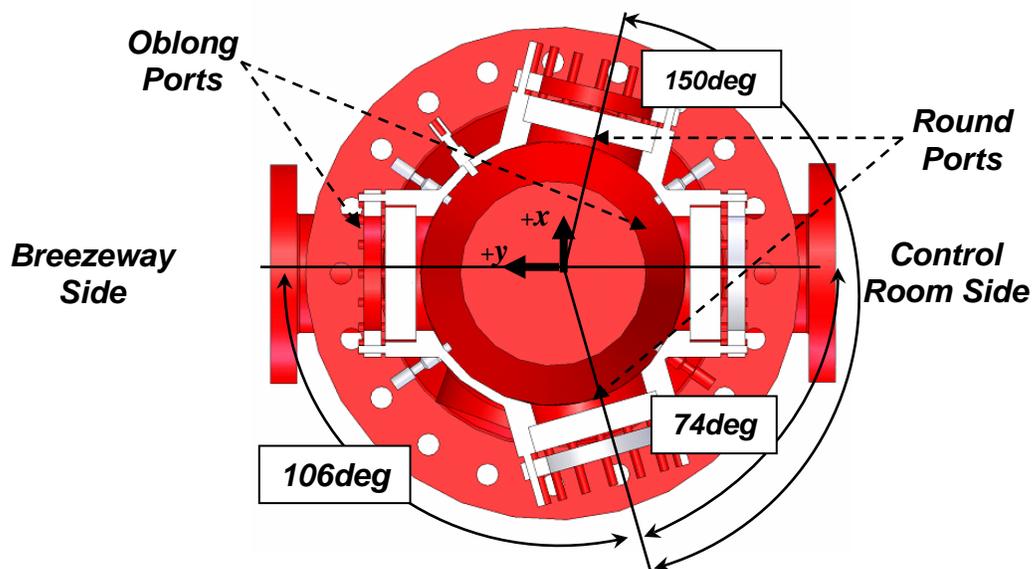


Figure 4. Cross Section of Pressure Vessel at the Optical Height

## 1.2 Flow Reactor

In addition to the pressure vessels, the UCICL maintains a flow reactor which can be used for studies of autoignition delay. The current flow reactor configuration is shown in Figure 5. This flow reactor has been used to measure ignition delay of alkanes and syngas like fuels and the results have been reported in several publications (e.g., 6,7,8). The flow reactor is setup to allow control of wall temperature. It has also been configured to measure ignition delay either directly (through the use of a IR laser extinction signal produced by the presence of an alkane coupled with an end view fiber optic/photomultiplier tube assemble that senses any chemiluminescence emission). Work has been done with hydrogen containing fuels as well as alkane mixtures.

<sup>6</sup> NEW SYNGAS/AIR IGNITION DATA AT ELEVATED PRESSURE AND COMPARISON TO CURRENT KINETICS MODELS (2007). *Combustion and Flame*, Vol. 149 (1-2), pp. 244-247. (E.L. Petersen, D.M. Kalitan, A. Barrett, S.C. Reehal, J.D. Mertens, D.J. Beerer, R.L. Hack, and V.G. McDonell).

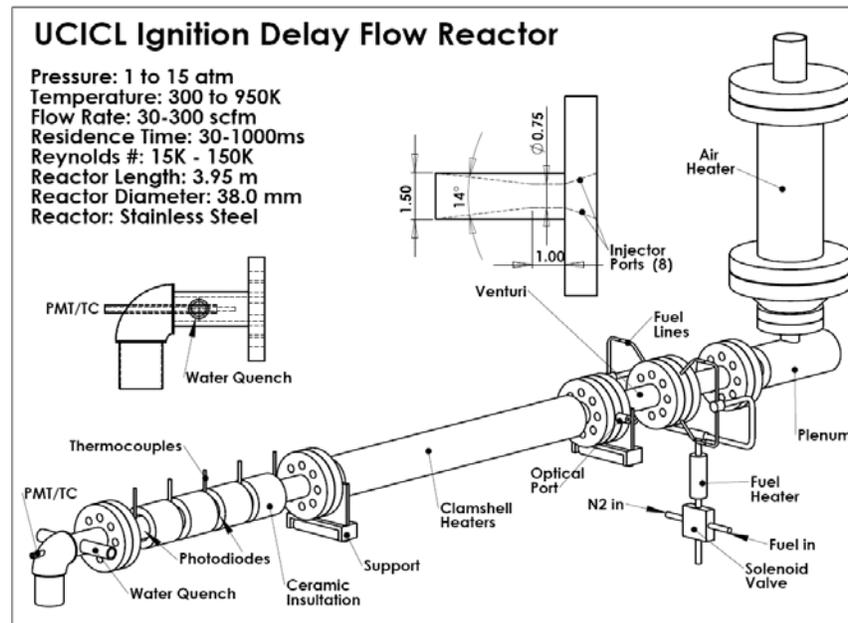
<sup>7</sup> AUTOIGNITION OF HYDROGEN AND AIR IN A CONTINUOUS FLOW REACTOR WITH APPLICATION TO LEAN PREMIXED COMBUSTION (2008). *ASME J. Engr. Gas Turbines and Power*, Vol 130, 051507-1 to 051507-9, September (D.J. Beerer and V.G. McDonell).

<sup>8</sup> AN EXPERIMENTAL AND KINETIC STUDY OF ALKANE AUTOIGNITION AT HIGH PRESSURES AND INTERMEDIATE TEMPERATURES (2011). *Proceedings of the Combustion Institute*, Vol 33, pp. 301-307 (D.J. Beerer and V.G. McDonell).

## a) Photo of Flow Reactor



## b) Schematic



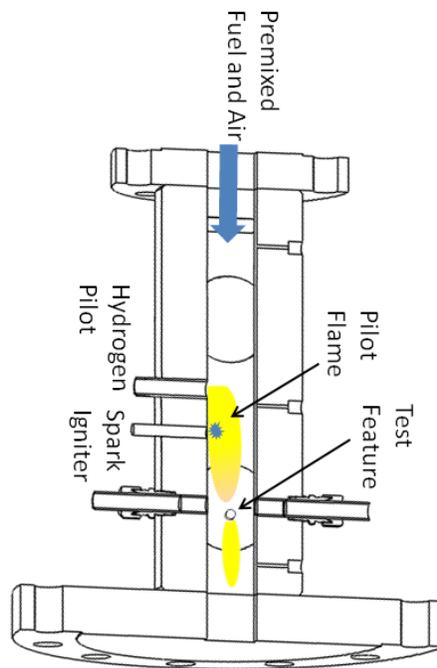
**Figure 5. Existing UCICL Flow Reactor.**

### 1.3 Flameholding Test Rig

Yet another test rig has been established with the goal of allowing flashback and flameholding studies to be carried out. The setup of this rig is shown in Figure 6. Premixed fuel and air mixtures at elevated temperature and pressures are introduced upstream of the test section as shown in Figure 7. A pilot igniter initiates reaction of the mixture which “bathes” over a test feature. The pilot is turned off and the subsequent flameholding tendencies of the feature is assessed.



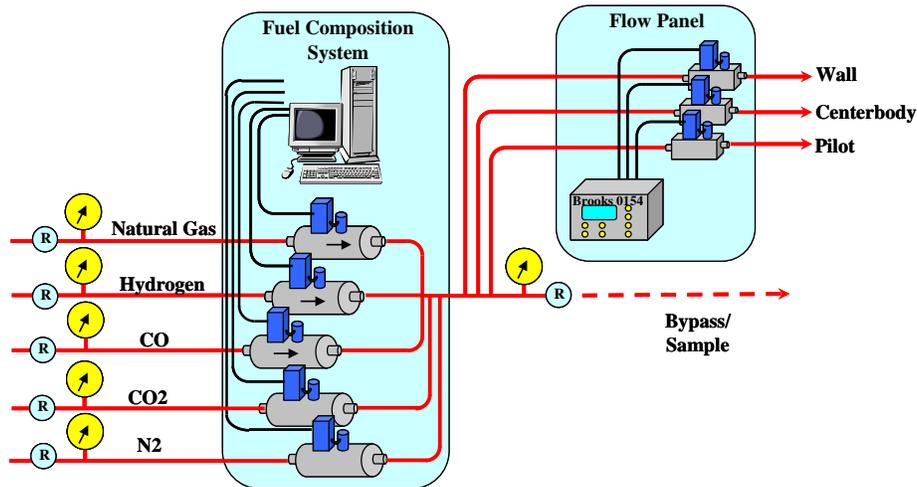
**Figure 6. Configured with Flameholding Experiment Test Section.**



**Figure 7. Flameholder Ignition System**

## 1.4 Existing UCI Fuel Blending Capability

The Fuel Composition Cart was created to accurately meter and blend a variety of gases. The cart, shown pictorially in Figure 8, can blend up to seven different gas streams to create a gas mixture for use by other external systems. This is accomplished through the use of multiple parallel flowing mass flow controllers (MFCs) to monitor and meter the flowrate of each constituent gas. As a result, with suitable calibration and flow matching, the same system can be utilized to simulate HSG fuels in an efficient manner.



**Figure 8. Laboratory Fuel Composition Control System.**

A larger scale facility is also available for which larger scale fuel flows can be established with varying composition. This system can also be used to generate simulated vitiated products. This larger scaled system is shown in Figure 16 and is discussed in the next section with emphasis on EGR simulation. The system shown in Figure 16 has been used, however, to generate mixed fuels for study in 60 kW gas turbine engines.

## 2 Atmospheric Test Facilities

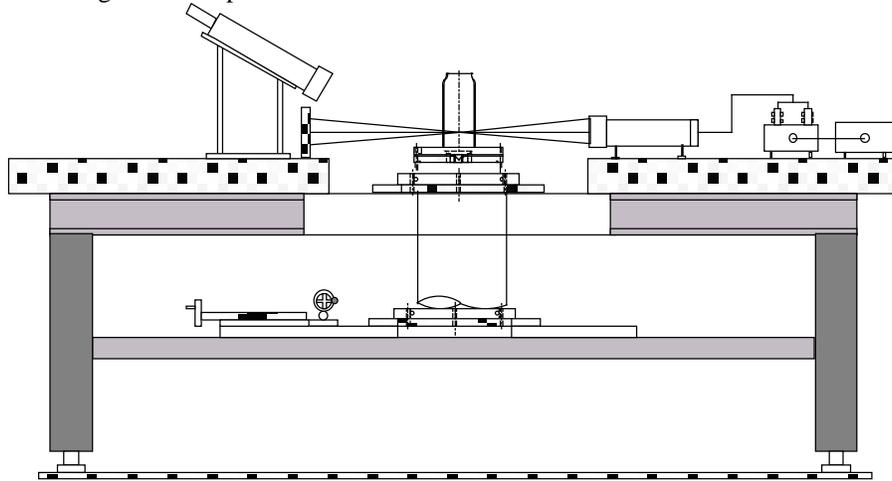
### 2.1 Combustion and Spray Characterization Stands

In addition to the two elevated pressure test cells and test rigs, the UCICL maintains 3 atmospheric test cells dedicated to gas turbine research (Test Cells 201, 113, 213 as shown in Figure 1). Each test cell has two test stands to accommodate injector hardware, combustor components, and/or full combustion systems. The stands are all designed to accommodate both conventional and laser diagnostic methods and feature traversing capability to map out parameters of interest such as fuel distribution and velocity. Each stand features flexibly configured flow metering and control as well as instrumentation for monitoring a variety of process variables such as flow rates, pressures, and temperatures. Recent papers presenting results from these stands include [9,10,11,12].

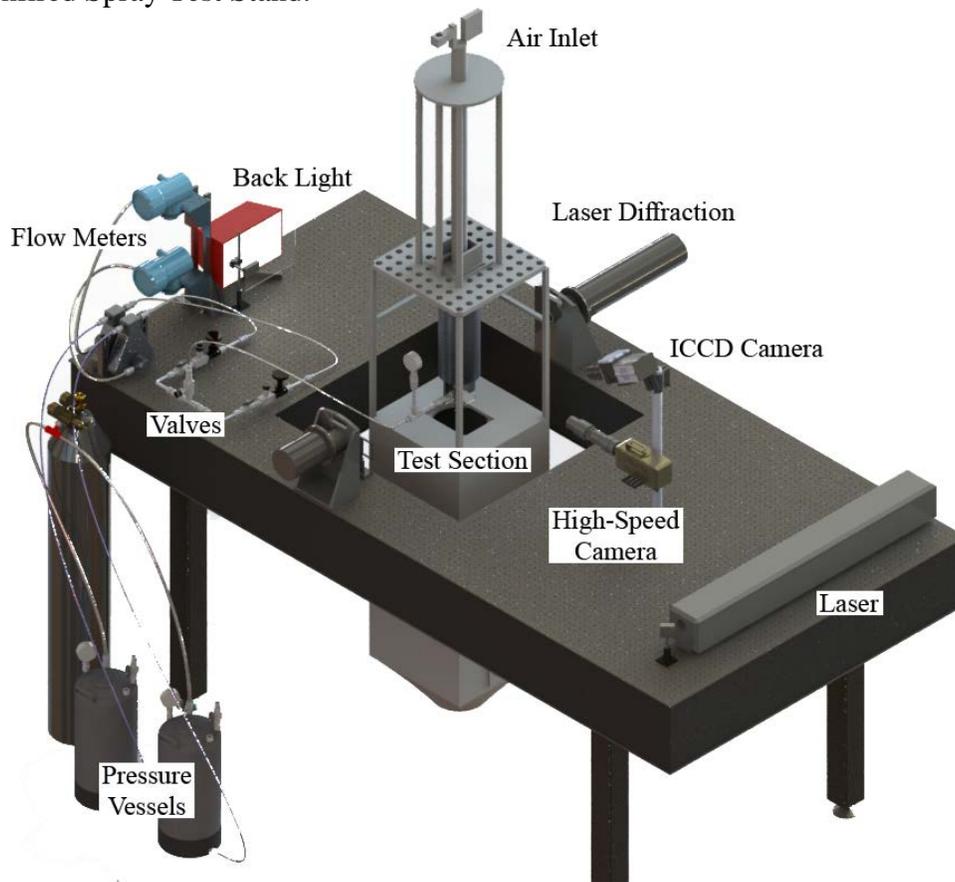
<sup>9</sup> STUDY OF FUEL COMPOSITION EFFECTS ON FLASHBACK USING A CONFINED JET FLAME BURNER (2013). *ASME J. Engr Gas Turbines and Power*, Vol 135, pp. 011502-1:9 (B.Shaffer, Z. Duan, and V.G. McDonell)

<sup>10</sup> COMPARISON OF WATER-IN-OIL EMULSION ATOMIZATION CHARACTERISTICS FOR LOW AND HIGH CAPACITY PRESSURE-SWIRL NOZZLES (2011). *Atomization and Sprays*, Vol 12, pp 391-410 (A.A. Narvaez, C.D. Bolszo, V.G. McDonell, D.Dunn-Rankin, and W.A. Sirignano)

a) Upfired Reacting Flow Setup



b) Downfired Spray Test Stand.

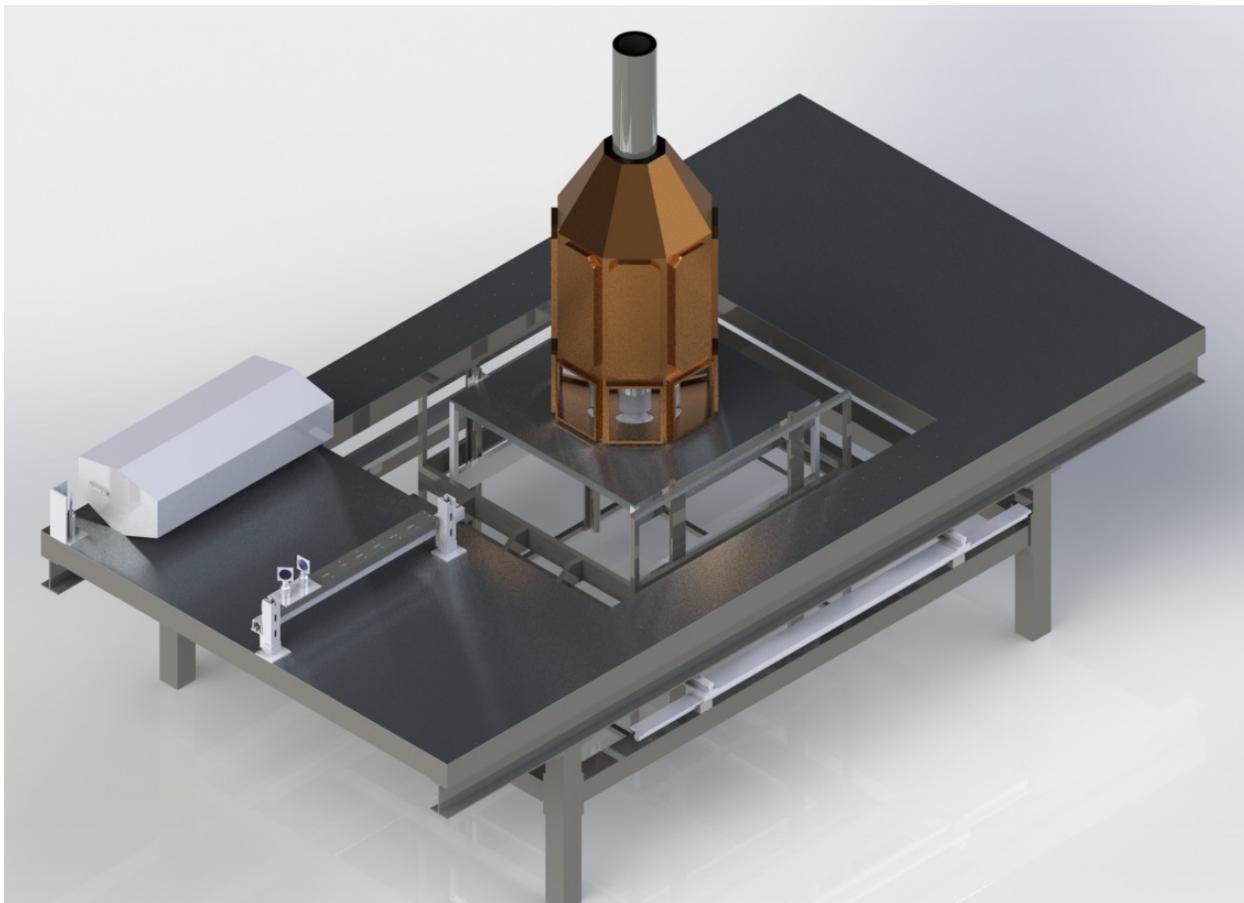
**Figure 6. Typical Atmospheric Test Stands.**

<sup>11</sup> EXPERIMENTAL AND COMPUTATIONAL ANALYSES OF METHANE AND HYDROGEN MIXING IN A MODEL PREMIXER (2011). *ASME J. Engr. Gas Turbines and Power* Vol 133, pp. 101503-1 – 101503-11, Oct 2011 (A.Akbari, S.Hill, V.G.McDonell, and G.S. Samuelsen).

<sup>12</sup> ATOMIZATION AND COMBUSTION PERFORMANCE OF RENEWABLE LIQUID FUELS IN A SWIRL-STABILIZED RESEARCH COMBUSTOR (2012). 24<sup>th</sup> ILASS-Americas Conference, San Antonio, TX, May (J.M. Legg, A.A. Narvaez, and V.G. McDonell)

## 2.2 Boiler Combustion Facility

In addition to atmospheric combustion test stands focused on gas turbine combustion, the UCICL maintains a boiler combustion test facility (Test Cell 101 in Figure 1). The boiler combustion facility has water-cooled walls to simulate the unique conditions of steam boilers and features modular burner mounting hardware that allows burners of different dimensions to be installed for evaluation (See Figure 9). This facility is extractive sampling capable and is also optically accessible to allow for imaging and laser diagnostics. Like the majority of the UCICL combustion test stands, the apparatus is capable of traversing to measure features of interest that vary spatially. In addition to air metering capabilities, this facility also has the capability to meter multiple gas fuel streams to use with burners with multiple fuel circuits. Firing rates of up to 5 MBTU/hour can be accommodated. Recent papers presenting results from this facility include [13,14].



**Figure 9. Boiler Combustion Facility**

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<sup>13</sup> AN EXPERIMENTAL STUDY OF THE STABILITY LIMITS AND EMISSIONS OF A SURFACE-STABILIZED COMBUSTION BURNER USING BIOGAS AND NATURAL GAS (2015). 9th U.S. Nation Combustion Meeting, Cincinnati, OH, May (A. Colorado, D. Avila, V.G. McDonell)

<sup>14</sup> FUEL INTERCHANGEABILITY EFFECTS ON A SCALED INDUSTRIAL BOILER (2013). 8th U.S. Nation Combustion Meeting, Salt Lake City, UT, May (A. Jordan, V.G. McDonell, G.S. Samuelsen)

### 2.3 Emulsion Generation Fuels

In conjunction with either high pressure or atmospheric facilities, the UCICL has developed significant infrastructure for the study of oil-water emulsions.

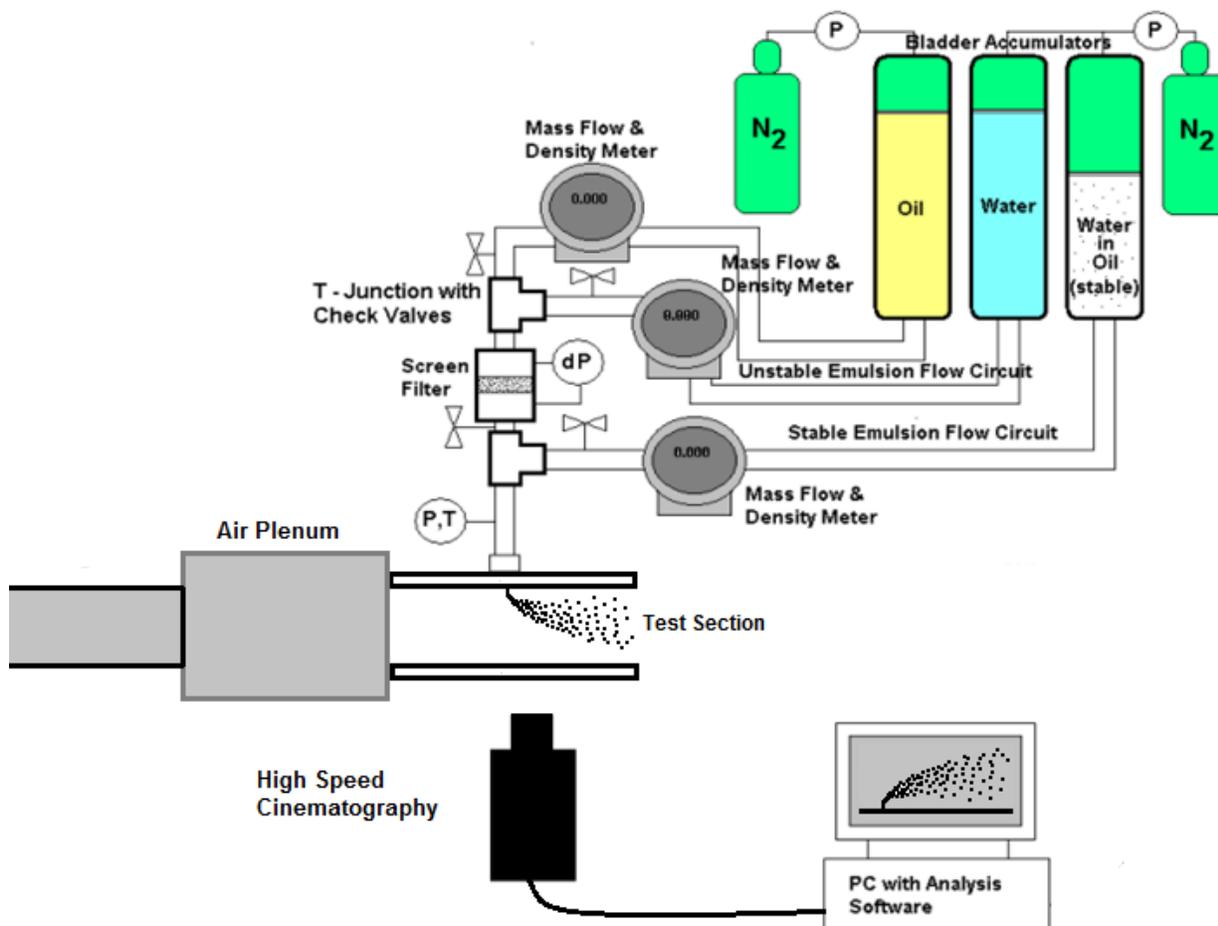
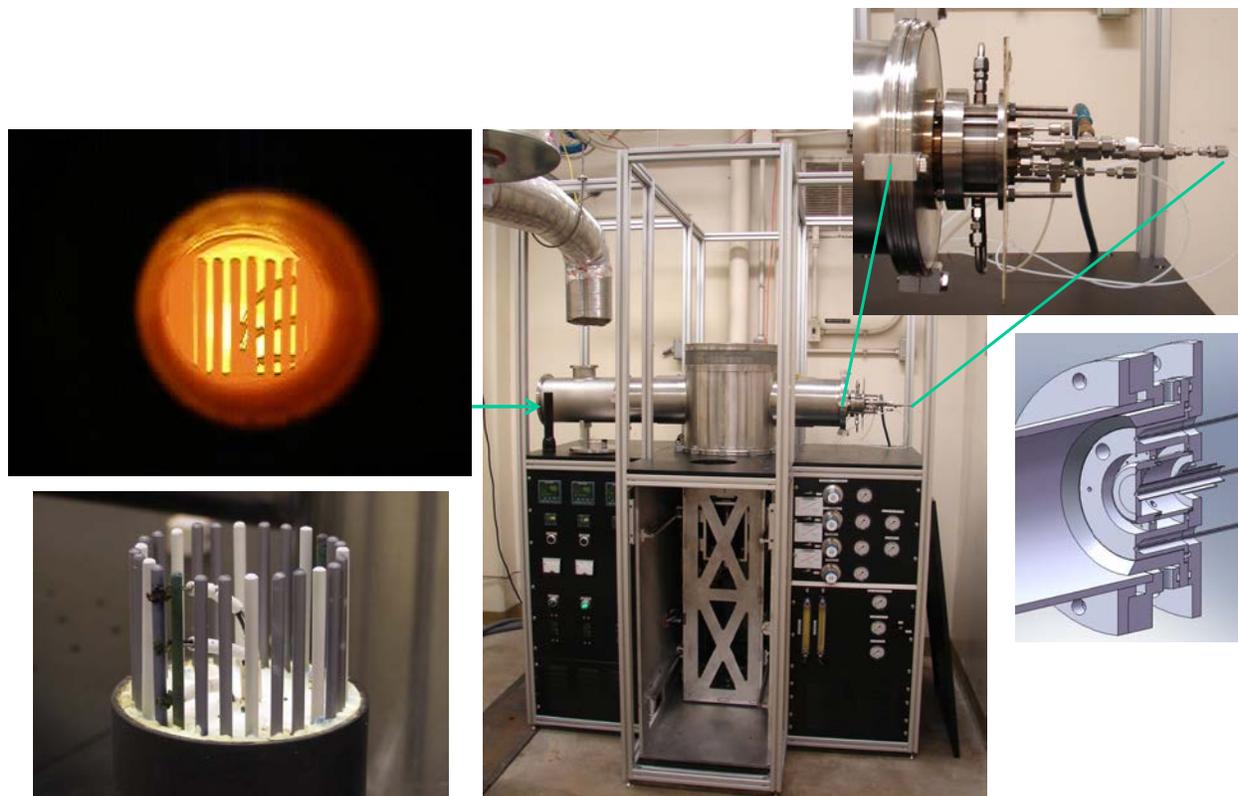


Figure 10. Emulsion Generation Systems (Jet In Crossflow Setup Illustrated).

### 2.4 Materials Exposure Rig

In collaboration with the Material Department, the UCICL has developed an autonomous materials exposure rig under support of the Office of Naval Research and the US Department of Energy. This test rig features the ability to carry out 1000 hour continuous tests with automated cycling and test conditions. The rig is designed to generate Type I and Type II hot corrosion conditions. A rotary block can be outfitted with 27 pins that can be made of various materials and different coatings. The carousel is rotated continuously as it is exposed to the combustion products generated by a small burner. The system is designed to work with small quantities of fuel (e.g, 55 gallons will suffice for a 1000 hour test). In addition, the burner head can introduce contaminants of interest into the combustion zone (e.g, salt or sulfurous compounds) in order to study their effects on the material degradation. The materials department maintains an array of advanced materials analysis equipment that can be used to quantify the behavior of the materials.



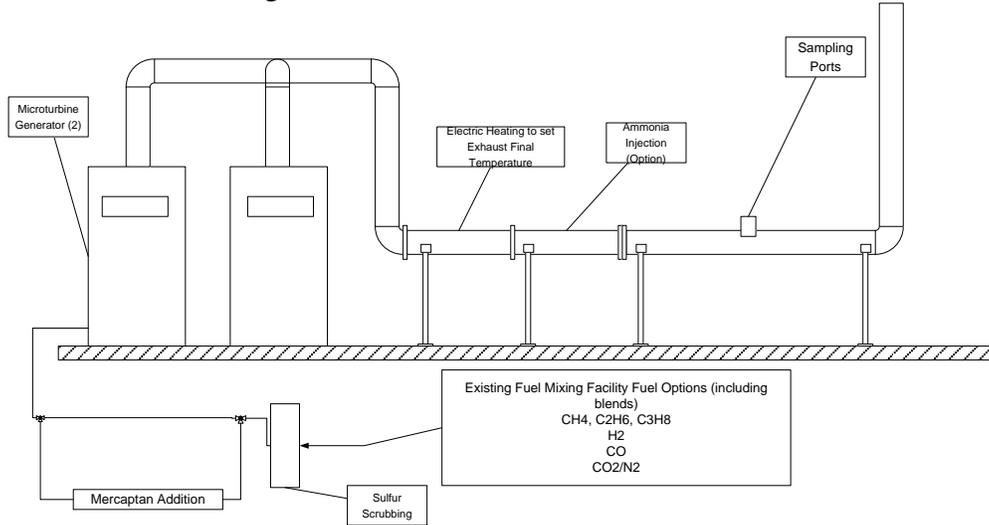
**Figure 11. Low Velocity Burner Rig for Materials Exposure Studies.**

### **2.5 Fine Particulate Test Facility.**

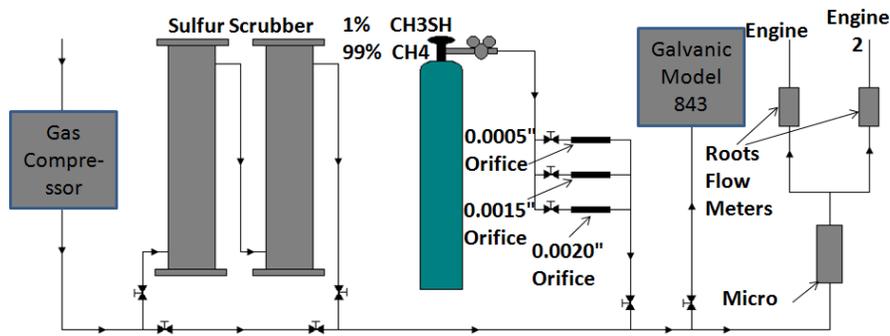
A test bed has been developed at the UCI Combustion Laboratory to study gaseous and particulate emissions from gas fired gas turbines. A photograph of the overall facility is shown in Figure 12. The facility consists of a pair of Capstone 60 kW microturbine generators designed to operate on natural gas. These engines can be ganged together to produce higher volumes of exhaust gas flow (up to 2 lb/sec). The nominal exhaust temperature of these engines is 550 deg F. The facility incorporates external heating to allow the temperature of the exhaust to be varied up to 900 deg F to study the temperature window effect. The engines are fed with fuels generated from an existing fuel blending station. These fuels can be conditioned so as to remove any sulfur present and can also be doped with controlled amounts of mercaptan to allow systematic study. The load of the engines can be varied to induce different combustion stoichiometries for the nominally fully premixed fuel and air mixture. This allows different combustion temperatures to be achieved and therefore studied.

To remove the fuel sulfur from the incoming natural gas, a packed bed reactor was designed and built which used a specially designed sorbent called TDA Research SulfaTrap R6. This sorbent is designed to remove fuel sulfur from natural gas for fuel cell applications. Using this system, total sulfur concentrations in the test gas were lower than the detection limits ( $>0.1$  ppm) of the gas analysis equipment. To introduce mercaptan systematically, a sonic orifice injection system is used to inject controlled amounts of sulfur odorant into the previously scrubbed gas (Figure 13). This allowed for testing numerous fuel sulfur concentrations and

numerous sulfur compounds. For this purpose, a sonic orifice injection system was designed and constructed as illustrated in Figure 13.

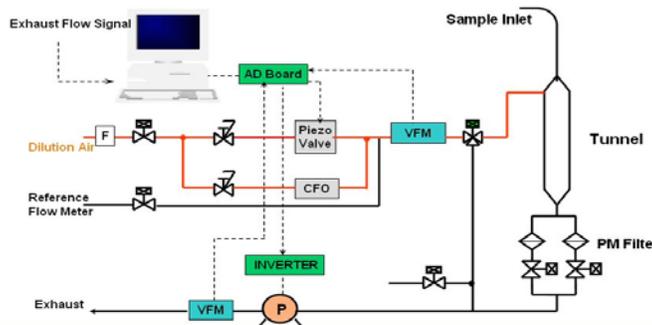


**Figure 12. Schematic of Test Bed.**



**Figure 13. Fuel Sulfur Management.**

Sampling equipment immediately available consists of a Horiba MDLT-1302TA constant volume micro dilution tunnel system and a Horiba MEXA-1370PM particulate analyzer. A schematic is shown in Figure 14.



**Figure 14. Flow diagram for the Horiba MDLT-1302TA.**

Once particulate is captured on a quartz fiber filter, a Horiba MEXA-1370PM is used to analyze the filter for organic carbon, elemental carbon, and sulfate. The filter is placed in the MEXA furnace at 980°C in an N<sub>2</sub> environment. The particulate captured on the filter is vaporized in the furnace. The vaporized sulfate particulate is de-oxidized due to the heat to SO<sub>2</sub>. The SO<sub>2</sub> is then measured using an NDIR detector. Vaporized solid organic particulate is determined using a CO<sub>2</sub> NDIR detector while N<sub>2</sub> is flowing. Elemental carbon particulate is determined using the same method with O<sub>2</sub> replacing N<sub>2</sub>. The signals are integrated and a calibration factor is used to determine the original sample mass. The calibration factor is determined using calibration gases containing precisely known concentrations of SO<sub>2</sub> and CO<sub>2</sub>. Using this method, masses as low as 0.2µg can be measured in 4 minutes. This system is specifically designed ultra low particulate mass applications. It has been shown that the collection efficiency on the quartz filters used in this study is comparable to that of Teflon filters. This method shows strong correlation with traditional gravimetric methods.

This test rig has been recently used to generate detailed information regarding effects of fuel sulfur on fine particulate (15, 16).

## 2.6 EGR Blending System

The UCICL maintains stored gas capability for CO<sub>2</sub> (14 tons) and N<sub>2</sub> (3000 gal) as illustrated in Figure 1a. These stored gases can be blended into the compressed air stream produced by the air compressors at the facility which can provide up to 4 lb/s of continuous flow at pressures up to 150 psig.

The current maximum flows of CO<sub>2</sub> and N<sub>2</sub> is 400 lb/hr and 225 lb/hr, respectively. The gases can be mixed in the high capacity mixing station illustrated in Figure 15. This strategy has been used previously to study evaporation of DF2 at 800 deg-K without combustion in the UCICL high pressure facility. In this case N<sub>2</sub> was blended with air to drop the availability of O<sub>2</sub>. The same strategy will be incorporated in the present work with emphasis on use of CO<sub>2</sub> to dilute the O<sub>2</sub> level. CO<sub>2</sub> has also been used to study density ratios with hydrogen injection into air and CO<sub>2</sub> under atmospheric conditions. As a result of these experiences, the gas blending system to create arbitrary blends of diluted oxidizer is ready to be used.

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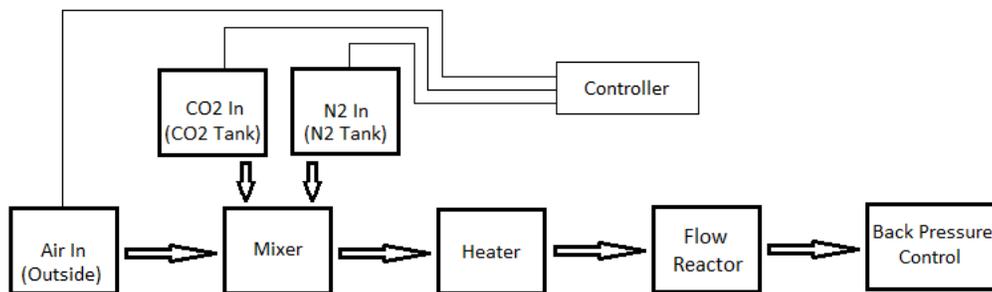
<sup>15</sup> EVALUATION OF THE LEVEL OF GASEOUS FUEL-BOUND SULFUR ON FINE PARTICULATE EMISSION FROM A LOW EMISSION GAS TURBINE ENGINE (2013). *ASME J. Engr Gas Turbines and Power* Vol. 135, pp 031501-1: 8. (B. Spang, S. Yoshimura, R. Hack, V.G. McDonell, and G.S. Samuelsen)

<sup>16</sup> EVALUATION OF THE EFFECTS OF CARBON TO HYDROGEN RATIO AND FUEL SULFUR LEVELS ON PARTICULATE EMISSIONS FROM A MICROTURBINE GENERATOR (2013). Accepted for Publication, *ASME J. Engr Gas Turbines and Power* (T. Akamatsu, R. Hack, V. McDonell, and S. Samuelsen)



**Figure 15. Gas Mixing Station.**

The overall plan for blending the oxidizer stream is shown in Figure 16. As shown, this approach has been used in a several prior projects and thus experience with the controls and flow limits are well understood.



**Figure 16. EGR control system approach.**

To provide perspective on the capability of the existing diluents flows, Figure 17 summarizes the flow of pure CO<sub>2</sub> required to achieve a given velocity at O<sub>2</sub> levels of 10% (vs 20.9% nominal in air) and pressures. As shown in Figure 17, 100 m/s velocities can be achieved up to nearly 20 atm with the current capability using the test hardware shown in Figure 6. In summary, the existing facilities should allow operation to 15 atm without any problems for the hardware planned for use.

		Pressure (atm)																																						
		1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12	12.5	13	13.5	14	14.5	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20
V, m/s	5	0.937	1.405	1.873	2.342	2.81	3.278	3.746	4.215	4.683	5.151	5.62	6.088	6.556	7.025	7.493	7.961	8.429	8.898	9.366	9.834	10.3	10.77	11.24	11.71	12.18	12.64	13.11	13.58	14.05	14.52	14.99	15.45	15.92	16.39	16.86	17.33	17.8	18.26	18.73
	10	1.873	2.81	3.746	4.683	5.62	6.556	7.493	8.429	9.366	10.3	11.24	12.18	13.11	14.05	14.99	15.92	16.86	17.8	18.73	19.67	20.61	21.54	22.48	23.42	24.35	25.29	26.23	27.16	28.1	29.03	29.97	30.91	31.84	32.78	33.72	34.65	35.59	36.53	37.46
	15	2.81	4.215	5.62	7.025	8.429	9.834	11.24	12.64	14.05	15.45	16.86	18.26	19.67	21.07	22.48	23.88	25.29	26.69	28.1	29.5	30.91	32.31	33.72	35.12	36.53	37.93	39.34	40.74	42.15	43.55	44.96	46.36	47.77	49.17	50.58	51.98	53.39	54.79	56.2
	20	3.746	5.62	7.493	9.366	11.24	13.11	14.99	16.86	18.73	20.61	22.48	24.35	26.23	28.1	29.97	31.84	33.72	35.59	37.46	39.34	41.21	43.08	44.96	46.83	48.7	50.58	52.45	54.32	56.2	58.07	59.94	61.82	63.69	65.56	67.44	69.31	71.18	73.06	74.93
	25	4.683	7.025	9.366	11.71	14.05	16.39	18.73	21.07	23.42	25.76	28.1	30.44	32.78	35.12	37.46	39.81	42.15	44.49	46.83	49.17	51.51	53.86	56.2	58.54	60.88	63.22	65.56	67.9	70.25	72.59	74.93	77.27	79.61	81.95	84.29	86.64	88.98	91.32	93.66
	30	5.62	8.429	11.24	14.05	16.86	19.67	22.48	25.29	28.1	30.91	33.72	36.53	39.34	42.15	44.96	47.77	50.58	53.39	56.2	59.01	61.82	64.63	67.44	70.25	73.06	75.87	78.68	81.49	84.29	87.1	89.91	92.72	95.53	98.34	101.2	104	106.8	109.6	112.4
	35	6.556	9.834	13.11	16.39	19.67	22.95	26.23	29.5	32.78	36.06	39.34	42.62	45.89	49.17	52.45	55.73	59.01	62.28	65.56	68.84	72.12	75.4	78.68	81.96	85.23	88.51	91.79	95.07	98.34	101.6	104.9	108.2	111.5	114.7	118	121.3	124.6	127.8	131.1
	40	7.493	11.24	14.99	18.73	22.48	26.23	29.97	33.72	37.46	41.21	44.96	48.7	52.45	56.2	59.94	63.69	67.44	71.18	74.93	78.68	82.42	86.17	89.91	93.66	97.41	101.2	104.9	108.6	112.4	116.1	119.9	123.6	127.4	131.1	134.9	138.6	142.4	146.1	149.9
	45	8.429	12.64	16.86	21.07	25.29	29.5	33.72	37.93	42.15	46.36	50.58	54.79	59.01	63.22	67.44	71.65	75.87	80.08	84.29	88.51	92.72	96.94	101.2	105.4	109.6	113.8	118	122.2	126.4	130.7	134.9	139.1	143.3	147.5	151.7	155.9	160.2	164.4	168.6
	50	9.366	14.05	18.73	23.42	28.1	32.78	37.46	42.15	46.83	51.51	56.2	60.88	65.56	70.25	74.93	79.61	84.29	88.98	93.66	98.34	103	107.7	112.4	117.1	121.8	126.4	131.1	135.8	140.5	145.2	149.9	154.5	159.2	163.9	168.6	173.3	178	182.6	187.3
	55	10.3	15.45	20.61	25.76	30.91	36.06	41.21	46.36	51.51	56.66	61.82	66.97	72.12	77.27	82.42	87.57	92.72	97.88	103	108.2	113.3	118.5	123.6	128.8	133.9	139.1	144.2	149.4	154.5	159.7	164.8	170	175.1	180.3	185.4	190.6	195.8	200.9	206.1
	60	11.24	16.86	22.48	28.1	33.72	39.34	44.96	50.58	56.2	61.82	67.44	73.06	78.68	84.29	89.91	95.53	101.2	106.8	112.4	118	123.6	129.3	134.9	140.5	146.1	151.7	157.4	163	168.6	174.2	179.8	185.4	191.1	196.7	202.3	207.9	213.5	219.2	224.8
	65	12.18	18.26	24.35	30.44	36.53	42.62	48.7	54.79	60.88	66.97	73.06	79.14	85.23	91.32	97.41	103.5	109.6	115.7	121.8	127.8	133.9	140	146.1	152.2	158.3	164.4	170.5	176.6	182.6	188.7	194.8	200.9	207	213.1	219.2	225.3	231.3	237.4	243.5
	70	13.11	19.67	26.23	32.78	39.34	45.89	52.45	59.01	65.56	72.12	78.68	85.23	91.79	98.34	104.9	111.5	118	124.6	131.1	137.7	144.2	150.8	157.4	163.9	170.5	177	183.6	190.1	196.7	203.2	209.8	216.4	222.9	229.5	236	242.6	249.1	255.7	262.3
	75	14.05	21.07	28.1	35.12	42.15	49.17	56.2	63.22	70.25	77.27	84.29	91.32	98.34	105.4	112.4	119.4	126.4	133.5	140.5	147.5	154.5	161.6	168.6	175.6	182.6	189.7	196.7	203.7	210.7	217.8	224.8	231.8	238.8	245.9	252.9	259.9	266.9	274	281
	80	14.99	22.48	29.97	37.46	44.96	52.45	59.94	67.44	74.93	82.42	89.91	97.41	104.9	112.4	119.9	127.4	134.9	142.4	149.9	157.4	164.8	172.3	179.8	187.3	194.8	202.3	209.8	217.3	224.8	232.3	239.8	247.3	254.8	262.3	269.7	277.2	284.7	292.2	299.7
	85	15.92	23.88	31.84	39.81	47.77	55.73	63.69	71.65	79.61	87.57	95.53	103.5	111.5	119.4	127.4	135.3	143.3	151.3	159.2	167.2	175.1	183.1	191.1	199	207	215	222.9	230.9	238.8	246.8	254.8	262.7	270.7	278.6	286.6	294.6	302.5	310.5	318.4
	90	16.86	25.29	33.72	42.15	50.58	59.01	67.44	75.87	84.29	92.72	101.2	109.6	118	126.4	134.9	143.3	151.7	160.2	168.6	177	185.4	193.9	202.3	210.7	219.2	227.6	236	244.5	252.9	261.3	269.7	278.2	286.6	295	303.5	311.9	320.3	328.8	337.2
	95	17.8	26.69	35.59	44.49	53.39	62.28	71.18	80.08	88.98	97.88	106.8	115.7	124.6	133.5	142.4	151.3	160.2	169.1	178	186.9	195.8	204.6	213.5	222.4	231.3	240.2	249.1	258	266.9	275.8	284.7	293.6	302.5	311.4	320.3	329.2	338.1	347	355.9
	100	18.73	28.1	37.46	46.83	56.2	65.56	74.93	84.29	93.66	103	112.4	121.8	131.1	140.5	149.9	159.2	168.6	178	187.3	196.7	206.1	215.4	224.8	234.2	243.5	252.9	262.3	271.6	281	290.3	299.7	309.1	318.4	327.8	337.2	346.5	355.9	365.3	374.6
	105	19.67	29.5	39.34	49.17	59.01	68.84	78.68	88.51	98.34	108.2	118	127.8	137.7	147.5	157.4	167.2	177	186.9	196.7	206.5	216.4	226.2	236	245.9	255.7	265.5	275.4	285.2	295	304.9	314.7	324.5	334.4	344.2	354	363.9	373.7	383.5	393.4
	110	20.61	30.91	41.21	51.51	61.82	72.12	82.42	92.72	103	113.3	123.6	133.9	144.2	154.5	164.8	175.1	185.4	195.8	206.1	216.4	226.7	237	247.3	257.6	267.9	278.2	288.5	298.8	309.1	319.4	329.7	340	350.3	360.6	370.9	381.2	391.5	401.8	412.1

Figure 17. Flow Constraint for CO<sub>2</sub> (lb/hr) (Max CO<sub>2</sub> flow is 400 lb/hr)

Table 1 summarizes the general capabilities available at the UCICL.

**Table 1. Summary of UCICL Capabilities/Resources.**

<p><b>Air Factory:</b>  4 lbs/sec up to 8 ATM,  0.6 lb/sec at up to 22 ATM</p>	<p><b>“Conventional” Diagnostics:</b>  Extractive Emissions (3 rack systems for criteria pollutants)  Air Toxics system (per EPA TO-5, TO-14)  Temperature, Soot, GC/MS  High Speed Video (w/intensifier)  Acoustic Sampling</p>
<p><b>Gaseous Fuels:</b>  Natural Gas to 0.2 lb/sec, 500 psia  Hydrogen and Hydrogen/Nitrogen mix flows  Fuel Variation Simulation Facility      natural gas      biomass gases      landfill gas      digester gas      process gases</p>	<p><b>Laser Diagnostics:</b>  Laser Anemometry (2 2D systems)  Digital Particle Image Velocimetry (1 system)  Coherent Anti-Stokes Raman Scattering (1)  Planar Laser Induced Fluorescence (2 systems)  Laser Rayleigh  Laser Diffraction  Phase Doppler Interferometry (2 systems)  Optical Patternation  Chemiluminescence (point, imaging)  Differential Absorption for fuel vapor Imaging</p>
<p><b>Modeling:</b>  Power System Computer Simulation Program  GateCycle  Computational Fluid Dynamics (Fluent, Star CCM)  Chemical Kinetics (Chemkin, DARS)  Empirical/Statistical      Thermodynamic and Cycle Analyses      Dynamic Systems Modeling</p>	<p><b>Liquid Fuels:</b>  High Pressure System (400 lb/hr, 800 psia)  Mid Pressure System (100 lb/hr, 400 psia)      DF-2      Jet-A      Mil-C-7024E-Type II Calibration Fluid      Water      Single Component Hydrocarbons (Heptane, Isooctane, dodecane, etc.)</p>