Casting Emission Reduction Program

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FY 2003 Tasks

Systems Integration and Validation Laboratory Test Site

Technikon # 1410-230

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United States Environmental Protection Agency

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UNITED STATES COUNCIL FOR AUTOMOTIVE RESEARCH

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Technikon # 1410-230

This report has been reviewed for completeness and accuracy and approved for release by the following:

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EPA Test protocols may have been modified, without any consequent lowering of acceptable criteria for accuracy, precision or other measurement quality parameters. Users of this report may need to modify the measurement protocols to suit their facility/application.

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Executive Summary

The objective of this subtask was to design, develop, and install a validation site for accurately measuring emissions from foundry operations and for the verification of operation of new instrumentation for measuring foundry emissions. Such a laboratory was installed at the Technikon Research Foundry for measuring emissions from pouring, cooling and shakeout operations, representative of a typical foundry. Several other measures were adopted to improve overall productivity and data quality.

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1.0 Introduction

The Systems Integration and Validation Laboratory (SIVL) project was initiated in Task Year 2002. Its objective and purpose has been detailed in a report [1] provided Task Year 2002. In this report, the objective for Task Year 2003 was the establishment of a validation laboratory for measuring emissions from a typical foundry pouring-cooling-shakeout process. The laboratory so established would serve as a 'gold standard' for validating new technologies/instruments for use in foundry stacks.

The tasks targeted for this effort were:

1) Installation of necessary hardware to allow for efficient use of resources in the laboratory.
2) Enhancing safety aspects in the laboratory, particularly with gas handling.
3) Validation of sample handling equipment for transport of sample from the research foundry to the analyzer system.
4) Validation of parametric measurements (pressure and temperature).
5) Validation of a hydrocarbon analyzer.
6) Incorporation of and validation of analyzers for CO_2 and CO measurements.
7) Introduction of capabilities to install and validate new low cost, efficient analyzers for use in characterizing foundry emissions.

The tasks above formed a critical part of the SIVL objective in establishing a validation laboratory capable of accurately measuring VOC, CO, and CO_2 emissions from foundry operations. Successful completion of these tasks would allow for the development of a 'gold standard' against which other analyzers/technologies could be compared for accuracy and precision. This report provides introduction on the laboratory design, set-up and measurement details involved in the development of such a facility.

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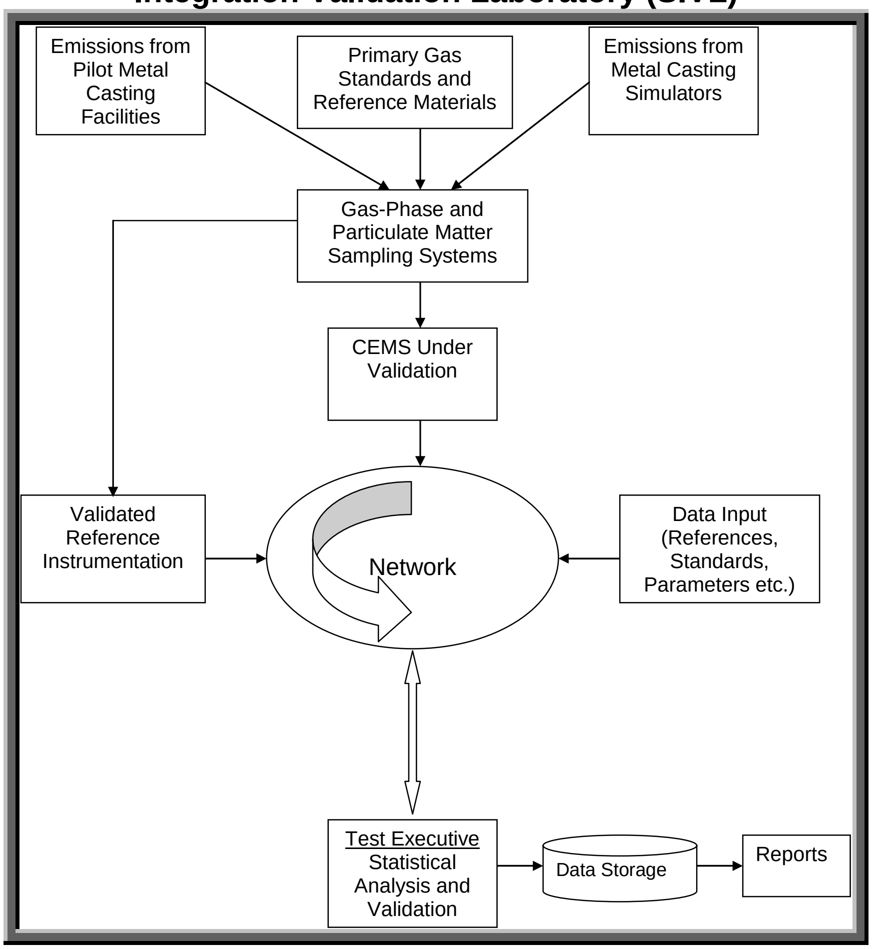
2.0 Components

The major components of SIVL are shown in Figure 1 and have been explained in detail earlier [1]. The components that were adopted/tested in the study for this report include:

1) Metal pouring, cooling and shakeout processes under controlled conditions.
2) Primary gas standards.
3) Provision for gas handling and delivery.
4) Sampling systems for gas-phase emissions.
5) Validated reference instrumentation.
6) Parametrics (pressure, temperature, etc.) validation.
7) Capabilities for testing and validation of new instruments/analyzers.

Figure 1 Major Components of the Systems Integration Validation Laboratory (SIVL)



The Technikon Environmental Research Center has developed the capability to reproducibly generate emissions from mold production, core making, metal melting, and metal pouring, cooling and shakeout processes under controlled conditions. This center has a general purpose, non-automated metal casting plant, which has been adapted to generate, collect and measure emissions, using methodologies based on EPA protocols for pouring, casting cooling, and shakeout processes on discrete mold and core packages under tightly controlled conditions not feasible in a commercial foundry.

This research foundry utilizes cored and un-cored greensand and No-Bake® molds. In order to obtain reproducible emission samples, a number of process parameters are carefully controlled and have been provided in an earlier report [1]. Process and stack parameters include the weights of the casting, mold, seacoal additions, core and binder; loss-on-ignition (LOI) values for the mold prior to the test and at shakeout; LOI for the core; percent clays and metallurgical data. Stack parameters measured include temperature, pressure, volumetric flow rate and moisture content. The process parameters are maintained within prescribed ranges in order to ensure the reproducibility of the tests.

The most widespread chemical binder systems are organic in nature. These systems are chemically and/or thermally cured to harden the sand mold. The pouring of molten metal, in the range from 1200 ^{o}F to nearly 3000 ^{o}F, causes the organic polymer to undergo pyrolysis. During this metal pouring process, the mold is heated non-uniformly, which causes incomplete combustion of the organic polymer to produce a multitude of pyrolysis products. It also produces significant amounts of carbon monoxide and carbon dioxide as by-products of this process.

The mold is placed under a hood for pouring, cooling and shakeout so that all emissions are collected for analysis. This general purpose casting plant has been adapted and instrumented to allow the real-time and batch collection and measurement of organic emissions (Figures 2a-2b).

Figure 2a Technikon Research Foundry Emission Collection Hood

Figure 2b Metal Pouring into Test Casting Molds

3.0 Development of the SIVL Laboratory

The primary gas standards were obtained from a local gas supplier and were certified to EPA standards for calibration gases. To minimize down time for gas hook ups and also to enhance safety in the laboratory, a significant upgrade in the gas delivery system was implemented. Most of the gas cylinders were contained in a designated area outside the laboratory. A bank of 'switchable' manifolds was incorporated to provide for instantaneous switching from an empty cylinder to a completely full cylinder. Stainless steel tubing was used to deliver gases from the cylinders to a bank of quick disconnect fittings (Swagelok™). The provision of these fittings made for quick connect and disconnect of gases required for calibration/instrument use. Safety was also enhanced due to the location of cylinders outside the laboratory.

Figure 3 Emissions Bench (E-Bench)

Individual gas lines were attached to an Environics™ gas mixing unit (see Appendix A) with NIST traceable mass flow meters to provide for accurate flow rates of calibration gas mixtures. It allowed for blending of a single concentration of a calibration gas with precise amounts of diluent to provide for a wide range of gas concentration mixtures necessary to calibrate an analyzer. It also reduced the inventory of certified gas cylinders required to perform a multi-point calibration of an analyzer.

Samples drawn from the stack pass through a probe placed at the center-line of the duct. Particulates greater than 0.7 µm were filtered using a heated (130^{o}C) Unique Products filter (see Appendix A). The sample was then transported through a Teflon line enclosed in a heated constant temperature (130^{o}C) 47 ft. sheath designed by Clayborn (see Appendix A). The sampling line was connected to a heated oven in the E-Bench (Figure 3). An additional Teflon line was also provided for in the sheath to be used for transporting gases for system calibration purposes (discussed later). Four thermocouples (OMEGA™, Type J) were placed at appropriate points to provide temperature data for the system flow, input air, stack flow and ambient air. Two calibrated differential pressure sensors (Dwyer, 674-400 series) were located on the stack for calculating flow rate of gas in the stack.

The E-Bench included the housing, internal plumbing and the analyzers used in the measurement of the research foundry emissions. A schematic of the internal flow diagram of the E-Bench is shown in Appendix B. The main components included were:

1) A heated oven in which was placed a sample pump.
2) A sample conditioning unit with chiller to remove moisture and filters to remove organics.
3) Hydrocarbon and infra-red analyzers.
4) Provision for housing additional analyzers.

The total hydrocarbon (THC) analyzer was a California Analytical Instruments model 300 HFID. It consisted of a flame ionization detector with pure hydrogen as fuel and zero air as the oxidant. The hot and wet sample from the stack was directly introduced into the analyzer without any preconditioning to minimize losses of ‘organics’. Details of this instrument are provided in Appendix A.

The Infra-Red Analyzer (Model 300), also from California Analytical Instruments was designed to include 3 individuals cells, one for CO (0-1000 ppm range) and two for CO_2 (0-2000 ppm range for one and 0-5000 ppm range for the other). Part of the stack sample was pre-conditioned before it was introduced to the IR cells. Details of these instruments are provided in Appendix A.

3.1 CALIBRATION PROCEDURE

The E-Bench calibration was performed using the system calibration procedure. Gas mixtures, generated using the Environics unit, were introduced into the Teflon line that traversed the 47 ft. line from the E-bench to the stack filter. This caused an overflow of the calibration gas mixture around the vicinity of the sample probe. A sample drawn from the probe through the analyzer had to be a representative sample of the calibration gas mixture. To ensure this condition, significant excess flow than that drawn by the pump was provided. The sample transported (here the calibration gas mixture) from the stack through the Teflon line using the sample pump (termed as system calibration procedure) was then divided in two flows: one introduced into the Hydrocarbon analyzer and the other into IR analyzers.

The individual analyzers were calibrated per the protocols of the EPA methods listed below:

1) Hydrocarbon analyzer per Method 25 A [2]
2) CO_2 per Method 3A [3]
3) CO per Method 10 [4]

A beta version of a proprietary data storage and handling system developed under the SIVL program was also incorporated into the validation program. This allowed standardization of measurement parameters (and would also allow for plug-and-play capability in the future when fully implemented). Data were collected using an IOTECH Data Acquisition System (DAQ260 with its associated software (see Appendix A). The principal quantities measured included:

1) Total VOCs measured and expressed in ppm/propane
2) CO measured in ppm
3) CO_2 measured in ppm
4) Stack temperature in ^oF
5) Ambient temperature in ^oF
6) System temperature in ^oF
7) Input temperature in ^oF
8) Static pressure in inches of water
9) Venturi pressure in inches of water

The bias, calibration drift and associated parameters were kept within ±5% of span for all measurements. The instruments were calibrated before each test, in-between tests and at the end of each day after completing the tests for that day. The total sampling time for a test was 75 minutes and the averages for the hydrocarbon, infra-red analyzers, temperatures, and pressure readings were calculated upon completion of each test.

An equivalent system incorporating similar sensors/analyzers had been established previously at the Technikon facility and is referred to as the ‘legacy’ system here. The E-Bench validation process was to compare it’s equivalency with the ‘legacy’ system. The shortcomings of the previous system were:

a) Did not allow for quick incorporation of new analyzers
b) Antiquated system of calibration that required multiple certified gas mixture cylinders
c) Labor intensive due to multiple changes of cylinders
d) Bag sampling procedure for analysis of CO and CO_2 was prone to contamination

Appendix C lists the comparative values for a number of tests conducted at the Technikon foundry. Values of the different test parameters measured on the E-Bench were compared to their corresponding parameters on the ‘legacy’ system. It can be observed that for all parameters except the pressure differential values, the differences in value between the corresponding parameters are within ± 5% for most measurements. The differences appear higher for the pressure readings due to the smaller magnitude of the pressure readings (i.e. for a measurement of 0.5”, differences of 0.05 translated to differences of 10%). The actual differences in flow however, translated to only about 2%. Appendix D lists the values from additional testing for the E-Bench THC and the ‘legacy’ THC. It can be observed that here also, most differences were within ± 5%.

3.2 IMPROVEMENTS

The design, construction and validation of the SIVL laboratory was completed with two main objectives: serve as a de facto ‘gold standard’ for measurement of emissions from a foundry and also to provide cost savings with no compromise in accuracy of test results. Listed below is an analysis of cost savings realized:

1) The use of quick disconnects and the manifold system provided for fewer man-hours required to switch tanks and for connecting/disconnecting instruments. The use of the Environics mixing unit resulted in shorter times to calibrate instruments and also provided for wider calibration ranges.

2) Formerly, CO_2 and CO analysis was performed using samples collected in bags. The bags were shipped to a local testing laboratory for analysis. Sample contamination during transport to the laboratory was always possible. The on-line analysis in the SIVL has eliminated this problem.

4.0 Summary

A suitable 'gold standard' measurement system was designed, conducted and subjected to relevant criteria to validate it for measurement of foundry emissions. Results indicate that this new adaptable, reliable system performed within acceptable standards for use in the research foundry. The system now serves as a benchmark to compare other low-cost analyzers for accuracy and reliability. It also provided significant cost savings in the operation of the emissions laboratory.

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5.0 Future work

The 2004 Task year includes objectives which have been listed below:

1) Selection and validation of a low-cost, accurate flame ionization hydrocarbon analyzer to measure foundry VOCs per Method 25A.

2) Provide measurement capabilities to express VOCs both as propane and hexane (MACT for foundries [5] requires VOCs expressed as ppm/hexane).

3) Incorporate and validate NOx analyzer on the E-Bench. Its purpose is to provide estimates of any NOx production in foundry operations. It would also assist in characterizing other manufacturing emissions.

4) Include 'particulate monitoring' devices in foundry stacks and conduct reliability/performance studies.

5) Validate the data storage and handling system. Incorporate features that will allow provision for generating reports relevant to foundry operations.

6) Incorporate low-cost data acquisition 'boxes' that would provide comparable performance to the current high-cost systems.

7) Conduct preliminary searches on next generation sensors for hydrocarbon and CO, CO_2 analysis. These are expected to be dimensionally small, cheap and accurate for deployment in stacks. Nanocomposite sensor arrays [6,7], fast portable GCs [8,9] and photoionization detectors [10,11] are some of the possible candidates for adaptation in foundry stacks.

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APPENDIX A SIVL COMPONENTS AND SPECIFICATIONS

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Environics Series 4040 Diluter

*Performance**

Accuracy
Concentration:± 1.0% set point
Flow: ± 1.0% set point
Repeatability: ± 1.0% set point
Warm up time: 30 minutes

* Performance specifications are valid when all Mass Flow Controllers are operating between 10% and 100% of full scale flow.

Mass flow controllers are calibrated using a NIST traceable Primary Flow Standard, using a Reference Temperature of 0°C (32°F) and a Reference Pressure of 760 mm Hg (29.92 in. Hg)

Mechanical

Gas connections
1/4" Swagelok (or compatible fitting)

Operating Pressures
Minimum: 10 psig (0.67 Bar)
Recommended: 25 psig (1.68 Bar)
Maximum: 75 psig (5.04 Bar)

Wetted Surfaces
Tubing: Electro-polished 316 Stainless Steel
MFCs: Stainless Steel
Seals: Viton®
(Optional: Kalrez®, Buna-N, Neoprene, Metal)

Operating temperatures
32° - 104° F (0° - 40° C)

Weight
23 lbs.

Dimensions (w x h x d)
17" x 4.25" x 20"

Electrical
110 to 240 VAC, 50/60 Hz

Electronics
12 Bit A/D and D/A Conversion - RS232 Serial interface

Software
Environics Instrument Control Software - (supplied on 3-1/2" floppy disks)

PC Requirements

IBM PC or compatible (486-33 or higher)	Microsoft Windows 3.1 (or higher)
8 MB RAM	10 MB Hard Disk Space
3-1/2" floppy drive	RS-232 Communication port

Unique Products Heated Filter # 1069

SII-1069-B-B-6-A-AJ/K-000

The standard 1069 filter operates on 120 V at 2.82 amps (338.8 W, 42.5Ω). The filter has a 0.5 c_v factor, approximately 250 cm^3 volume and can handle an operating temperature of up to 200°C. The outside diameter is 4.5" with an overall height of 13.5" with handle installed. The 1069 can be controlled with J or K type thermocouples as well as RTDs or a combination of the three. Fitting sizes are 1/4 or 3/8 inch swage or NPT. The filter element for the 1069 is 1" x 7". They are a glass micro fiber filter element with Teflon binder, rated at 95% efficient retention at .03 μm.

Clayborn 47 Foot Heated Hose Specifications

Length:	47’
Tubing:	¾”Dia x .062 wall thickness FEP Teflon
Insulation:	Two layers of ¼” thickness Nomex
Braid:	PET Nylon braid to bind insulation in place
Exterior jacket:	Silicone jacket
Electrical heating circuit:	Resistance: 5.5 ohms Voltage: 120VAC Wattage: 2618 Current: 21.8 Amps
Temperature protection:	Two 200C creep action thermostats
Temperature control:	‘J’ type thermocouple
Additional power circuits:	Three power leads 18 gauge (black, white, and green)

California Analytical Model 300 HFID Hydrocarbon Analyzer

DESCRIPTION

The CAI Heated Total Hydrocarbon Analyzer Model 300 HFID is designed to continuously measure the total concentration of hydrocarbons within a gaseous sample. All components in contact with the sample are maintained at the oven set temperature preventing condensation.

METHOD OF OPERATION

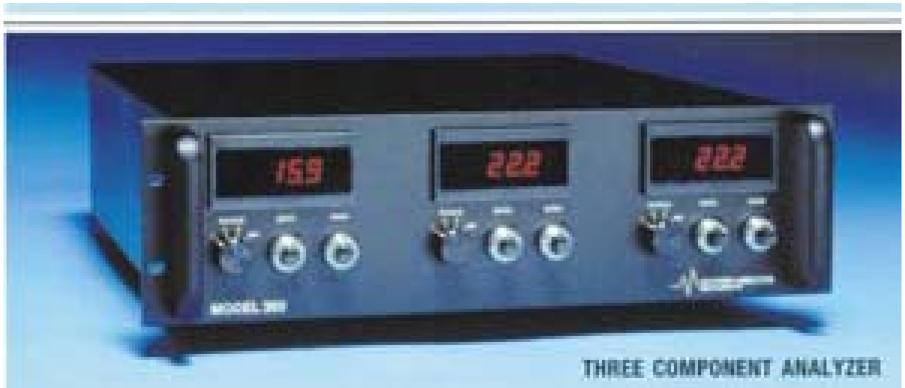
The Model 300 HFID uses the Flame Ionization Detection (FID) method to determine the total hydrocarbon concentration within a gaseous sample. The analyzer has an adjustable heated oven (60 TO 200°C) which contains a heated pump and a burner in which a small flame is elevated and sustained by regulated flows of air and pure hydrogen. The burner jet is used as an electrode and is connected to the negative side of a precision power supply. An additional electrode, known as the "collector," is connected to a high impedance, low noise electronic amplifier. The two electrodes establish an electrostatic field. When a gaseous sample is introduced to the burner, it is ionized in the flame and the electrostatic field causes the charged particles (ions) to migrate to their respective electrodes. The migration creates a small current between the electrodes. This current is measured by the precision electrometer amplifier and is directly proportional to the hydrocarbon concentration of the sample.

SPECIFICATIONS

ANALYSIS METHOD:	Flame Ionization Detector
MULTIPLE RANGE CAPABILITY:	Eight operation ranges - 10, 30, 100, 300, 1000, 3000, 10,000, 30,000 ppm carbon
RESOLUTION:	0.01 ppm Carbon (lowest range)
REPEATABILITY:	Better than ± 0.5% of full scale
LINEARITY:	Better than 1% of full scale
O2 EFFECT:	Less than 2% of full scale
CH4 EFFECT:	Less than 1.3 times Propane
RESPONSE TIME:	90% of full scale in 1.5 seconds
SAMPLE FLOW RATE:	With pump: 3.0 liter/min. ±1.5 liter/min.

INTERNAL SAMPLE FILTER:	0.1 micron replaceable filter provided
NOISE:	Less than ± 0.5% of full scale
ZERO & SPAN DRIFT:	Less than 1% of full scale per 24 hours
FLOW CONTROL:	Electronic Proportional Pressure Controller
FUEL REQUIREMENTS:	40% H_2/60% He (100cc/min.) or 100% H_2 (30cc/min.) (specify at time of order) Fuel inlet pressure 25 psig
READOUT:	As ppm CH_4 or C_3H_8 (specify at time of order)
AIR REQUIREMENTS:	Less than 1 ppm Carbon - Purified or synthetic air (200cc/min.) Air Inlet Pressure 25psig
DISPLAY:	3-1/2 Digit Panel Meter
DIAGNOSTICS:	31/2 Digit Panel Meter with 8 Position Switch
COLLECTOR VOLTAGE:	15 VDC
ANALOG OUTPUT:	0-10 VDC & 4-20 mA DC/0-20 mA DC
FUEL/AIR CONTROL:	Forward Pressure Regulator
IGNITION:	Momentary push-button with Flame-On Indicator (manual or remote control)
AMBIENT TEMPERATURE:	5-45°C
WARM-UP TIME:	1 hour
FITTINGS:	1/4" tube
POWER REQUIREMENTS:	115/230 (±10%)VAC@50/60Hz, 750watt
DIMENSIONS:	5-1/4"H x 19"W x 23"D (133mm x 483mm x 508mm)
RELATIVE HUMIDITY:	Less than 90%

CAI Infra-red Analyzer Model 300



METHOD OF OPERATION

Non Dispersive Infrared (NDIR)

The CAI NDIR analyzer section is based on the infrared absorption characteristics of gases. Using a single infrared beam to measure gas concentrations, this analyzer produces highly stable and reliable results.

A single infrared light beam is modulated by a chopper system and passed through a sample cell of predetermined length containing the gas sample to be analyzed. As the beam passes through the cell, the sample gas absorbs some of its energy. The attenuated beam (transmittance) emerges from the cell and is introduced to the front chamber of a two-chamber infrared Microflow detector. The detector is filled with the gas component of interest and, consequently, the beam experiences further energy absorption. This absorption process increases the pressure in both chambers. The differential pressure between the front and rear chambers of the detector causes a slight gas flow between the two chambers. This flow is detected by a mass-flow sensor and is converted into an AC signal. The AC signal is amplified and rectified into a DC voltage signal and ultimately supplied to the output terminal and digital panel meter. The electrical output signal is directly proportional to the concentration of the sample gas.

Specifications:

Detector	Microflow
Sample contact	Stainless steel and Tygon disposable gold plated cell liner. Window material CaF_2
Linearity	Better than 1% full scale
Repeatability	Better than 1% full scale
Response time	90% of full scale in less than 1 s
Sample flow rate	0.5 to 2 L/min
Noise	Less than 1% of full scale
Zero and Span drift	Less than 1% of full scale in 24 h
Outputs	0-10 V DC, 4-20 mA or 0-20 mA
Ambient Temperature	-5 to 45 C
Sample Temperature	0 to 50 C
Sample condition	Clean, non-condensing
Fittings	¼” tube
Power	115/220/240 VAC, 50/60 Hz, 70 W per channel
Relative humidity	Less than 90 % R. H.

IOTECH Daqbook 260 with DBK cards

Specifications

Enhanced parallel port (EPP) interface

100 kHz channel-to-channel scan

512 location sequence

Ability to handle 8 differential or 16 single-ended signal inputs

3 expansion slots for DBK cards

16 bit, 2 analog output, 620mA @12 V

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APPENDIX B FLOW DIAGRAM FOR THE E-BENCH

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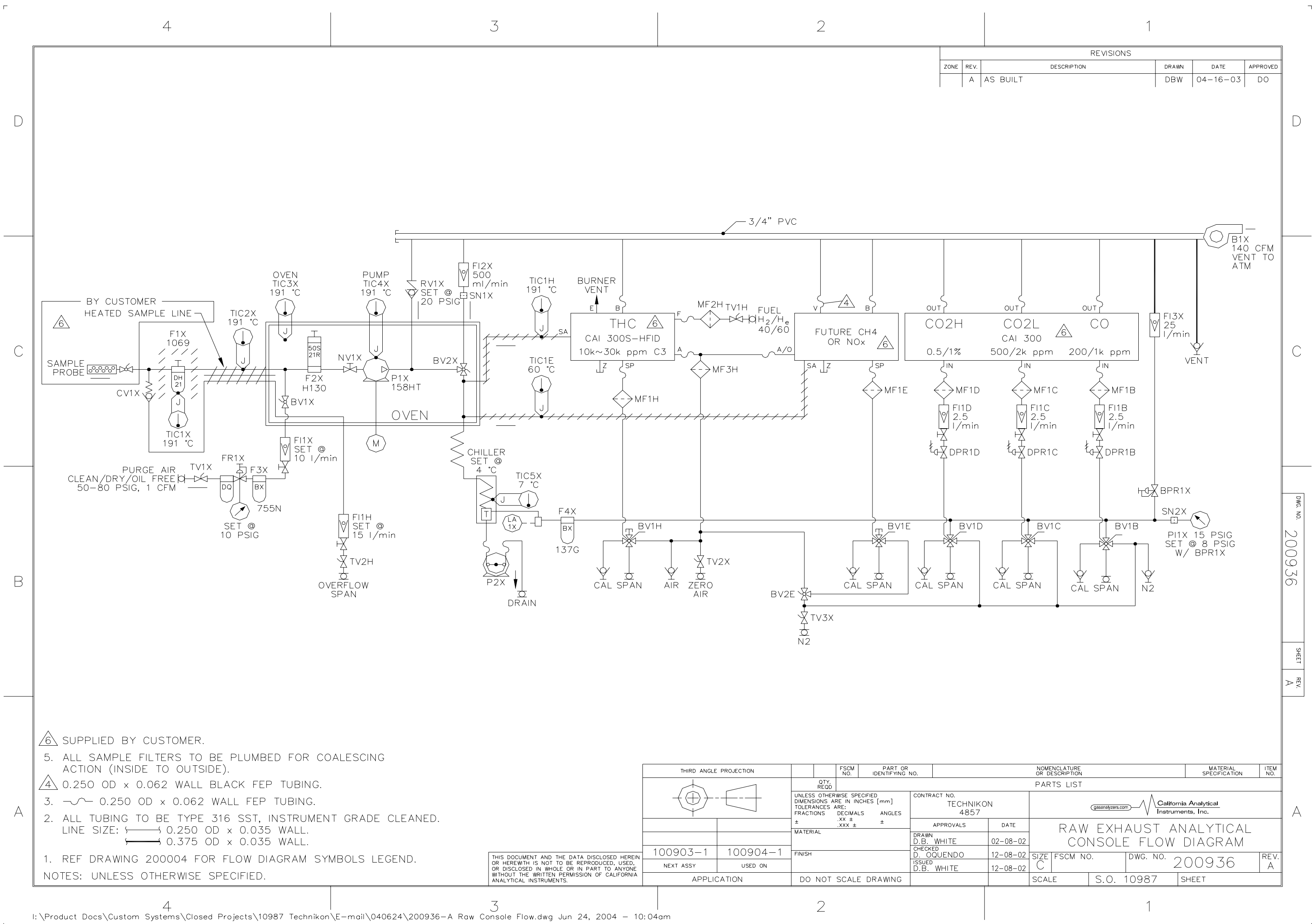
Flow Diagram for the E-Bench



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APPENDIX C COMPARISON OF E-BENCH WITH 'LEGACY' SYSTEM

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Comparison of E-Bench with 'Legacy' system

	Legacy system	E-Bench	Difference
Data Set 1			
THC	12.57	11.94	5.01%
Stack Temp.	117.63	118.60	-0.82%
Ambient Temp.	60.97	61.79	-1.34%
Input Temp.	96.15	96.61	-0.48%
Syst Temp.	90.20	90.83	-0.70%
Static Pressure	0.54	0.65	-20.37%
Venturi Pressure	1.26	1.34	-6.35%
Data Set 2			
THC	8.01	8.56	-6.87%
Stack Temp.	99.53	100.53	-1.00%
Ambient Temp.	63.07	63.98	-1.44%
Input Temp.	112.48	112.93	-0.40%
Syst Temp.	84.03	84.94	-1.08%
Static Pressure	2.05	2.15	-4.88%
Venturi Pressure	5.37	5.42	-0.93%
Data Set 3			
THC	7.72	8.34	-8.03%
Stack Temp.	97.27	98.15	-0.90%
Ambient Temp.	61.94	62.68	-1.19%
Input Temp.	110.56	110.97	-0.37%
Syst Temp.	90.89	91.62	-0.80%
Static Pressure	2.04	2.14	-4.90%
Venturi Pressure	5.32	5.37	-0.94%

All temperatures are in ^{o}F
All pressures are in inches of water
THC is in ppm

Comparison of E-Bench with 'Legacy' system

	Legacy system	E-Bench	Difference
Data Set 4			
THC	15.78	14.43	8.56%
Stack Temp.	116.63	117.64	-0.86%
Ambient Temp.	63.05	63.95	-1.43%
Input Temp.	110.73	111.22	-0.44%
Syst Temp.	93.76	94.80	-1.11%
Static Pressure	0.53	0.64	-20.19%
Venturi Pressure	1.25	1.32	-5.84%
Data Set 5			
THC	15.25	15.46	-1.38%
Stack Temp.	117.49	118.39	-0.77%
Ambient Temp.	62.06	62.84	-1.26%
Input Temp.	102.74	103.23	-0.48%
Syst Temp.	92.50	93.12	-0.67%
Static Pressure	0.53	0.64	-20.75%
Venturi Pressure	1.24	1.32	-6.45%
Data Set 6			
THC	14.60	13.95	4.45%
Stack Temp.	110.78	111.77	-0.89%
Ambient Temp.	63.57	64.41	-1.32%
Input Temp.	83.12	83.62	-0.61%
Syst Temp.	87.46	88.30	-0.96%
Static Pressure	0.52	0.63	-20.96%
Venturi Pressure	1.23	1.32	-6.58%

All temperatures are in ^{o}F
All pressures are in inches of water
THC is in ppm

Comparison of E-Bench with 'Legacy' system

	Legacy system	E-Bench	Difference
Data Set 7			
THC	19.41	20.43	5.22%
Stack Temp.	115.22	116.04	0.71%
Ambient Temp.	58.30	58.95	1.12%
Input Temp.	103.31	103.67	0.35%
Syst Temp.	92.10	92.51	0.45%
Static Pressure	0.57	0.60	6.04%
Venturi Pressure	1.26	1.38	9.26%
Data Set 8			
THC	19.83	19.97	0.68%
Stack Temp.	118.34	119.25	0.77%
Ambient Temp.	62.44	63.17	1.18%
Input Temp.	107.62	108.04	0.39%
Syst Temp.	94.68	95.50	0.87%
Static Pressure	0.55	0.59	6.29%
Venturi Pressure	1.26	1.37	8.49%
Data Set 9			
THC	19.20	19.74	2.85%
Stack Temp.	115.69	116.58	0.77%
Ambient Temp.	60.08	60.77	1.15%
Input Temp.	105.59	105.99	0.37%
Syst Temp.	91.78	92.28	0.55%
Static Pressure	0.57	0.60	5.77%
Venturi Pressure	1.28	1.38	7.86%

All temperatures are in ^{o}F
All pressures are in inches of water
THC is in ppm

Comparison of E-Bench with 'Legacy' system

	Legacy system	E-Bench	Difference
Data Set 10			
THC	18.40	19.48	5.90%
Stack Temp.	115.23	116.17	0.82%
Ambient Temp.	62.87	63.66	1.26%
Input Temp.	99.31	99.70	0.39%
Syst Temp.	91.56	92.27	0.77%
Static Pressure	0.55	0.58	5.67%
Venturi Pressure	1.25	1.35	7.28%
Data Set 11			
THC	22.05	22.52	2.15%
Stack Temp.	108.73	109.55	0.75%
Ambient Temp.	60.72	61.36	1.05%
Input Temp.	83.81	84.14	0.39%
Syst Temp.	85.42	86.07	0.77%
Static Pressure	0.55	0.58	5.26%
Venturi Pressure	1.22	1.35	10.12%
Data Set 12			
THC	20.15	20.89	3.67%
Stack Temp.	117.15	118.02	0.75%
Ambient Temp.	59.83	60.48	1.08%
Input Temp.	104.82	105.16	0.32%
Syst Temp.	92.23	92.76	0.57%
Static Pressure	0.55	0.58	5.04%
Venturi Pressure	1.23	1.36	10.28%

All temperatures are in ^oF
All pressures are in inches of water
THC is in ppm

Comparison of E-Bench with 'Legacy' system

	Legacy system	E-Bench	Difference
Data Set 13			
THC	16.25	16.75	3.07%
Stack Temp.	112.17	113.32	1.03%
Ambient Temp.	75.15	76.17	1.35%
Input Temp.	103.74	104.42	0.66%
Syst Temp.	88.19	89.15	1.10%
Static Pressure	1.13	1.15	1.88%
Venturi Pressure	2.89	2.94	1.38%
Data Set 14			
THC	13.15	13.53	2.89%
Stack Temp.	102.00	103.17	1.14%
Ambient Temp.	77.92	78.99	1.37%
Input Temp.	85.99	86.59	0.70%
Syst Temp.	83.60	84.86	1.50%
Static Pressure	1.13	1.15	1.85%
Venturi Pressure	2.88	2.92	1.17%
Data Set 15			
THC	16.41	17.30	-5.45%
Stack Temp.	111.24	112.16	-0.83%
Ambient Temp.	61.48	62.25	-1.26%
Input Temp.	88.17	88.62	-0.51%
Syst Temp.	87.84	88.54	-0.80%
Static Pressure	0.51	0.62	-21.02%
Venturi Pressure	1.19	1.31	-10.08%

All temperatures are in ^oF
All pressures are in inches of water
THC is in ppm

Comparison of E-Bench with 'Legacy' system

	Legacy system	E-Bench	Difference
Data Set 16			
THC	17.26	17.67	-2.39%
Stack Temp.	116.85	117.82	-0.83%
Ambient Temp.	63.92	64.72	-1.26%
Input Temp.	100.25	100.75	-0.49%
Syst Temp.	93.08	93.75	-0.72%
Static Pressure	0.51	0.62	-21.08%
Venturi Pressure	1.17	1.28	-9.94%
Data Set 17			
THC	18.03	18.32	-1.63%
Stack Temp.	114.28	115.10	-0.71%
Ambient Temp.	64.27	65.21	-1.47%
Input Temp.	91.46	91.96	-0.54%
Syst Temp.	90.38	91.24	-0.95%
Static Pressure	0.50	0.61	-21.49%
Venturi Pressure	1.16	1.27	-9.71%
Data Set 18			
THC	19.28	18.40	-4.59%
Stack Temp.	118.67	119.57	0.77%
Ambient Temp.	61.85	62.60	1.20%
Input Temp.	103.69	104.02	0.32%
Syst Temp.	90.59	91.46	0.95%
Static Pressure	0.55	0.58	5.29%
Venturi Pressure	1.26	1.38	9.59%

All temperatures are in ^{o}F
All pressures are in inches of water
THC is in ppm

Comparison of E-Bench with 'Legacy' system

	Legacy system	E-Bench	Difference

Data Set 19

THC	20.14	19.20	-4.66%
Stack Temp.	115.78	116.72	0.81%
Ambient Temp.	62.26	63.03	1.23%
Input Temp.	96.66	96.99	0.34%
Syst Temp.	89.96	91.02	1.18%
Static Pressure	0.54	0.57	5.46%
Venturi Pressure	1.24	1.36	9.64%

Data Set 20

THC	21.85	20.01	-8.44%
Stack Temp.	117.57	118.52	0.80%
Ambient Temp.	62.88	63.68	1.27%
Input Temp.	93.55	93.97	0.44%
Syst Temp.	89.44	90.20	0.85%
Static Pressure	0.54	0.57	5.64%
Venturi Pressure	1.22	1.34	9.71%

Data Set 21

THC	19.73	21.54	9.19%
Stack Temp.	114.82	115.78	0.84%
Ambient Temp.	60.54	61.27	1.20%
Input Temp.	96.51	96.90	0.41%
Syst Temp.	90.75	91.33	0.63%
Static Pressure	0.56	0.58	4.97%
Venturi Pressure	1.26	1.37	8.78%

All temperatures are in ^{o}F
All pressures are in inches of water
THC is in ppm

Comparison of E-Bench with 'Legacy' system

	Legacy system	E-Bench	Difference
Data Set 22			
THC	20.27	20.87	2.93%
Stack Temp.	113.96	114.87	0.79%
Ambient Temp.	61.05	61.80	1.22%
Input Temp.	95.14	95.53	0.41%
Syst Temp.	89.97	90.66	0.76%
Static Pressure	0.55	0.58	4.97%
Venturi Pressure	1.24	1.35	8.93%
Data Set 23			
THC	21.50	21.89	1.82%
Stack Temp.	116.70	117.68	0.84%
Ambient Temp.	61.66	62.46	1.30%
Input Temp.	96.54	96.94	0.42%
Syst Temp.	90.71	91.47	0.83%
Static Pressure	0.54	0.57	4.83%
Venturi Pressure	1.22	1.34	9.23%
Data Set 24			
THC	21.34	22.58	5.83%
Stack Temp.	113.87	114.75	0.78%
Ambient Temp.	59.15	59.83	1.16%
Input Temp.	95.79	96.10	0.32%
Syst Temp.	90.10	90.63	0.59%
Static Pressure	0.55	0.58	4.83%
Venturi Pressure	1.24	1.36	10.22%

All temperatures are in ^{o}F
All pressures are in inches of water
THC is in ppm

Comparison of E-Bench with 'Legacy' system

	Legacy system	E-Bench	Difference
Data Set 25			
THC	25.61	27.23	6.29%
Stack Temp.	114.61	115.49	0.77%
Ambient Temp.	61.74	62.44	1.14%
Input Temp.	95.98	96.30	0.33%
Syst Temp.	90.15	90.84	0.76%
Static Pressure	0.54	0.57	5.00%
Venturi Pressure	1.21	1.33	9.93%
Data Set 26			
THC	11.41	10.32	-9.54%
Stack Temp.	112.53	113.65	1.00%
Ambient Temp.	71.86	72.82	1.33%
Input Temp.	105.29	105.83	0.51%
Syst Temp.	88.31	89.27	1.09%
Static Pressure	1.15	1.17	1.99%
Venturi Pressure	2.92	2.97	1.74%
Data Set 27			
THC	12.97	13.56	4.52%
Stack Temp.	106.48	107.68	1.12%
Ambient Temp.	80.42	81.55	1.40%
Input Temp.	84.97	85.63	0.77%
Syst Temp.	85.80	86.83	1.20%
Static Pressure	1.13	1.15	1.88%
Venturi Pressure	2.90	2.93	1.02%

All temperatures are in ^{o}F
All pressures are in inches of water
THC is in ppm

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APPENDIX D ADDITIONAL THC TESTS

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Additional THC tests

Legacy System (in ppm)	E-Bench (in ppm)	Difference
14.20	15.06	-5.71%
15.90	15.37	3.45%
16.69	16.96	-1.59%
14.84	15.10	-1.72%
16.20	16.23	-0.18%
19.44	19.88	-2.21%
22.34	22.80	-2.02%
22.58	22.26	1.44%
20.21	20.56	-1.70%
21.41	21.67	-1.20%
18.15	18.25	-0.55%
22.41	22.91	-2.18%

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APPENDIX E GLOSSARY

CO	Carbon Monoxide
CO_2	Carbon Dioxide
E-Bench	Emissions Bench
EPA	Environmental Protection Agency
GCs	Gas Chromatographs
IR	Infrared
LOI	Loss On Ignition
MACT	Maximum Achievable Control Technology
MFCs	Mass Flow Controller
NIST	National Institute of Standards and Technology
NO_x	Nitric Oxides
SIVL	Systems Integration and Validation Laboratory
THC	Total Hydrocarbon
VOC	Volatile Organic Compound
Zero Air	Hydrocarbon & Moisture Free Air

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APPENDIX F REFERENCES

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