Thermochimica Acta, 154 (1989) 167–185
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

DESIGN AND TESTING OF A NEW ISOTHERMAL FLOW GAS CALORIMETER: THE HART FIELD-DEPLOYABLE NATURAL GAS ENERGY METER *

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(Received 4 April 1989)

ABSTRACT

The design and testing of a new isothermal flow gas calorimeter is described. The calorimeter achieves complete combustion of the natural gas at temperatures from 400 to 500 °C using a bed packed with a proprietary catalyst. The catalyst is 100% efficient for mixtures containing all of the typical natural gas components (C_1–C_6). The calorimeter assembly consists of a flow reactor that is suspended in a high temperature air bath. The temperature sensors for both reactor and shield temperature measurement or control are Pt RTDs. The gas is delivered by a cycling sample loop with constant volume and a lean gas/air mixture is supplied to the reactor. The gas sample net heating value (NHV) is determined from the gas flow rate required to maintain a constant reactor temperature. The water content in the exhaust is measured to obtain the gross heating value (GHV). All operations of the calorimeter including periodic calibration and reporting of heating values, specific gravity, and compressibility data are automated.

The calorimeter makes energy measurements with an accuracy of ±1 BTU ft^{-3} and a precision of 0.5 BTU ft^{-3} for gas samples having gross heating values ranging from 800 to 1200 BTU ft^{-3}. The calorimeter measures both the net and gross heating values. The mol. percent inerts, specific gravity, and compressibility are calculated by use of empirical correlation equations relating these properties to the net and gross heating values. The gas calorimeter has been packaged for field operation and operation in areas with potentially combustible atmospheres. The field performance of the gas calorimeter is compared with both an on-line gas chromatograph and a Cutler–Hammer calorimeter.

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* Dedicated to Professor James J. Christensen in memory of his contribution to innovation in calorimetry

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INTRODUCTION

The problem of natural gas energy measurement has become increasingly important as gas produced in many different fields (with different chemical composition and thus energy content) is mixed in large pipeline distribution networks. The gas industry has a real need to measure gas energy content at a large number of locations including sites in the production field, in processing plants, at mixing points in pipeline networks, and even at the point of delivery to large consumers. At present, the technology for BTU measurement, which includes both existing calorimeters and gas chromatographs, is too costly to install at low volume sites and/or unworkable at remote locations. In effect there is no device which is currently available for the continuous measurement of gas energy content at remote locations.

The present state of the art in gas calorimetry is somewhat archaic. The "industry standard", the Cutler–Hammer calorimeter, is an enormous piece of equipment, contains approximately 100 gallons of water and will only operate in a well-controlled thermal environment. Calorimetric measurement of gas energy content has been made in a variety of ways, e.g. by controlling the air intake to maintain a constant flame temperature or by burning a standard gas and continuously comparing the temperature difference between two flames. While the existing gas calorimeters do provide a direct energy measurement, they typically require large amounts of sample gas, yield only a gross heating value (or a net heating value, but not both), do not provide specific gravity or compressibility data, and are not readily adaptable to field installation.

Gas chromatography on the other hand is quite modern. The gas in the pipeline is sampled and analyzed for its chemical composition. The energy content (both net and gross heating values), compressibility, and specific gravity are then calculated from the composition. In order for the calculated energy values to be as accurate as the calorimetric values, the concentrations of all of the gas phase components of the sample gas must be accurately determined including the non-combustible gases N_2, O_2, CO_2, and H_2O. The principle disadvantages with the gas chromatography approach are that the measurement is indirect (requiring the use of approximate equations of state), the measurements must be made intermittently rather than continuously, the system must be calibrated frequently, the operating environment must be clean and temperature controlled, and the instruments required to make the most accurate measurements are rather expensive.

Because neither technique is ideally suited to field deployment, at least with current instrumentation, a typical practice is to collect time-averaged gas samples at field locations, e.g. wellheads, custody transfer points, metering stations, etc. The gas samples which have been collected automatically in pressurized cylinders are then removed at intervals to a laboratory for either calorimetric or GC analysis. Such sampling is labor intensive and thus can only be done at long intervals (e.g. weekly or monthly). Another less obvious problem is that the samples as analyzed may not truly represent even the time-averaged gas at the sampling point. Changes in sample composition resulting from shifting vapor–liquid equilibria may occur as changes in temperature and pressure take place during sampling. Contamination of sample cylinders with the condensed heavy hydrocarbons from previous samples can also be a significant problem. Obviously, a direct energy measurement performed continuously in the field would be preferable.

The gas calorimeter described in this paper is small, is self-calibrating, requires minimal maintenance, has been designed to operate in remote locations (e.g. production fields in west Texas or Wyoming), and measures both the net and gross heating values of a gas stream to within ±1 Btu/SCF, the mol. percent inerts to within ±0.1%, the specific gravity to within ±0.003, and the compressibility to within ±0.00005.

EXPERIMENTAL

Design criteria

At a minimum, the new gas calorimeter had to provide a means for measuring (delivering) a known volume of gas, a means for combusting the gas (preferably completely), and a means for sensing the heat produced by the combustion reaction.

Gas volume measurement was initially accomplished with a constant displacement fluid metering pump and, most recently, has been accomplished by using a solenoid valve pulsed sample loop. The combustion is accomplished by passing a lean gas/air mixture through a Pt/Pd catalyst bed at high temperature. The heat sensing has been done by either measuring the temperature rise in the catalyst bed (isoperibol operation) or by controlling the catalyst bed temperature (isothermal operation). The subsystems of the gas calorimeter include: the flow control system, the catalytic reactor, the calorimeter measurement and control electronics, and the computer (for data analysis, logging, and transmission). A block diagram showing the gas calorimeter subsystems is given in Fig. 1.

The gas calorimeter design was developed in stages beginning with a very simple breadboarded unit and continuing to the current manufacturing prototype. To better understand the development of this new instrument during the last two years and the improvements in measurement performance that have resulted at each stage of development, we will briefly discuss each of the earlier models before describing the design of the production prototype calorimeter in some detail.

The laboratory prototype was actually assembled on a bench top. This first instrument demonstrated that the catalytic combustion approach was

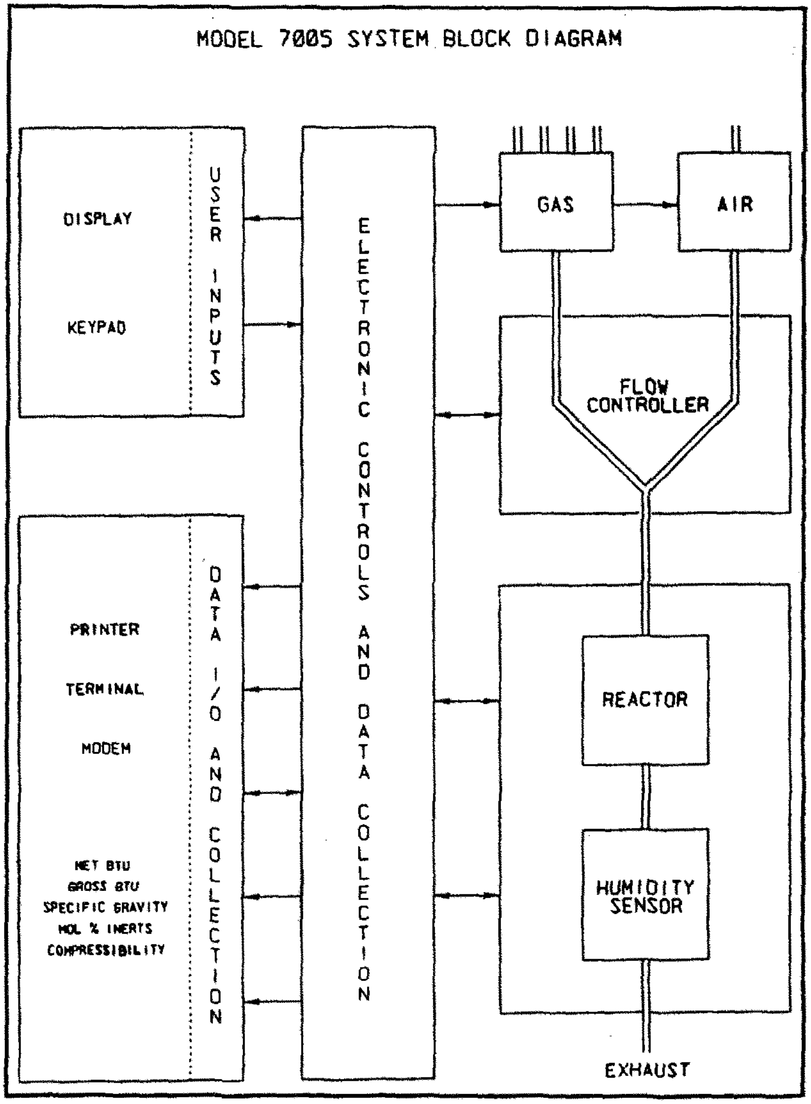

Fig. 1. Gas calorimeter block diagram showing sybsystem organization. Major subsystems include the flow controller, reactor, electronic controls, and computer.

feasible and that BTU measurements could be made by measuring the temperature of the catalyst bed in an isoperibol calorimeter approach. However, it was also obvious at this point that improvements in the temperature control of critical components, e.g. pressure regulators, pumps, electronic circuitry etc., would be required to obtain the stability required for operation in field environments. It was also apparent that an isothermal approach wherein the reactor/calorimeter temperature was controlled by either adjusting the gas flow or an auxiliary heater might prove helpful in minimizing environmental effects on the stability of the calorimeter.

The next stage in the development was attained by placing the loose components of the laboratory prototype into a temperature-controlled enclosure. This instrument could be operated in either an isoperibol or an isothermal mode, and tests were run in both modes. Although this second version of the gas calorimeter was in principle field-deployable, it was quite large and had high electrical power requirements.

The gas calorimeter was next modified in the following ways: (1) the constant temperature enclosure was operated at elevated temperature so that the refrigeration system could be avoided; (2) the computer employed was a small single-board computer designed in house; (3) the catalytic reactor was redesigned to be smaller, to require less power to reach light-off temperature, and to have a passive rather than an actively controlled outer adiabatic shield; (4) the temperature-sensitive flow components were mounted on a heat sink for passive isolation from ambient fluctuations; and (5) the enclosure was designed to comply with National Electrical Code regulations for Class I/Division II/Group D environments. This instrument was operated successfully in both laboratory and field environments.

The most recent version of the gas calorimeter, the production prototype, is quite similar to the previous model. There are however at least two significant features that have been added: (1) the measurement of exhaust gas water content allowing calculation of the correction to obtain gross heating values (required in most gas purchase contracts) from the calorimetrically measured net heating value; and (2) the calculation of mol% inerts, specific gravity, and compressibility of the sample gas by use of empirical correlation equations relating these properties to the NHV and GHV. In addition, the catalytic reactor has been redesigned to operate more efficiently, the temperature control of the enclosure has been improved, and the Hart Gas Energy Meter has been packaged more attractively. The computer has been programmed to calculate all relevant data (NHV, GHV, mol% inerts, specific gravity, and compressibility) and to store both individual data points as well as time-averaged data for either onsite retrieval or transmission to a host computer.

The design of the production prototype isothermal flow gas calorimeter is illustrated in several figures. Figure 2 is a block diagram which shows all of the components required in the present design of the catalytic combustion gas calorimeter. The components shown in the upper right quadrant comprise the flow control system while the components of the calorimeter catalytic reactor are shown in the lower right quadrant. The calorimeter measurement and control electronics are represented by the line of rectangular boxes down the center of the figure and the computer with its associated I/O functions is shown on the left side of the figure. Figure 3 shows the location of the component subassemblies in the environmental enclosure.

The flow system components have been mounted on an aluminum plate for temperature control. The thick aluminum plate effectively buffers the

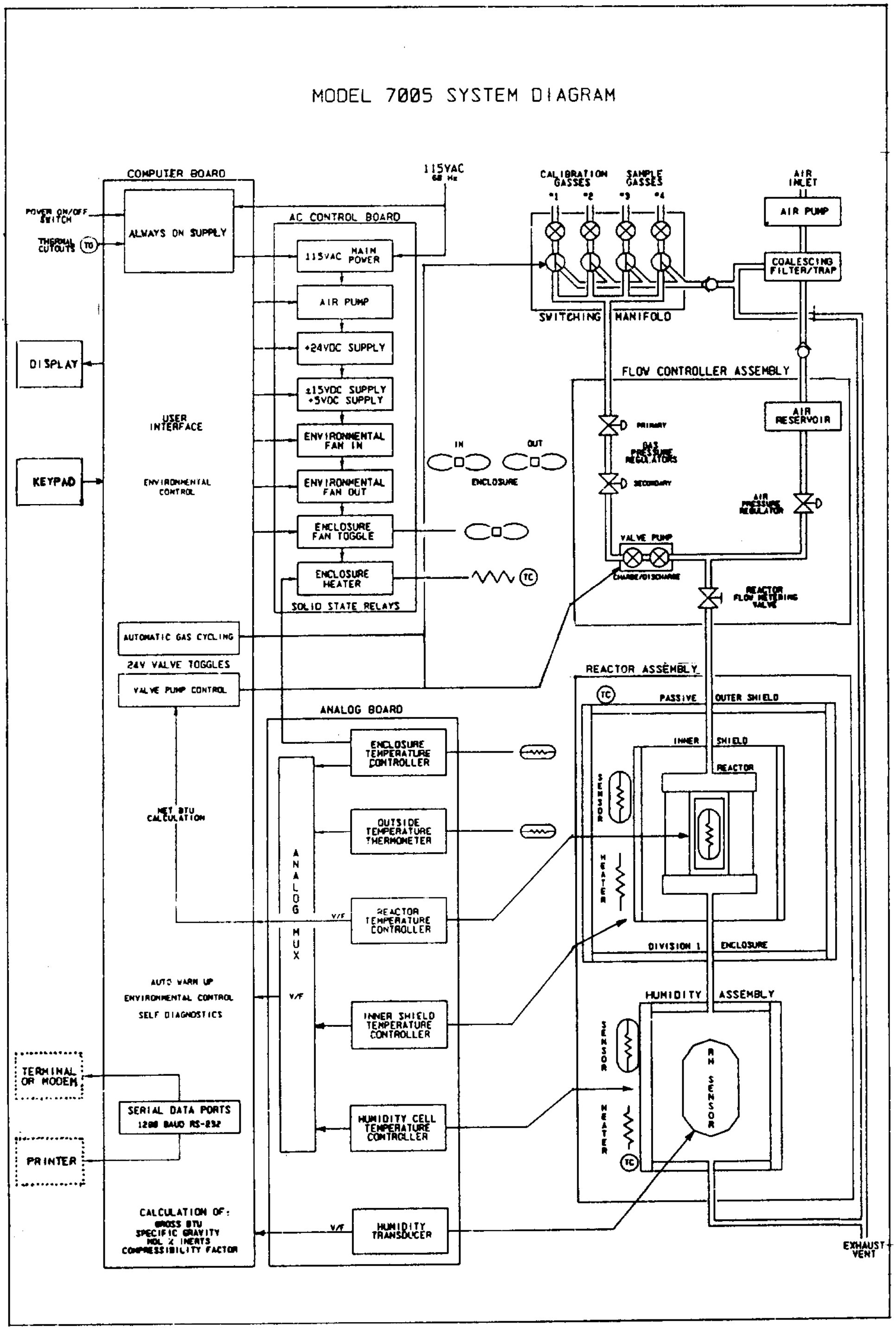

Fig. 2. Gas calorimeter system diagram showing all major components.

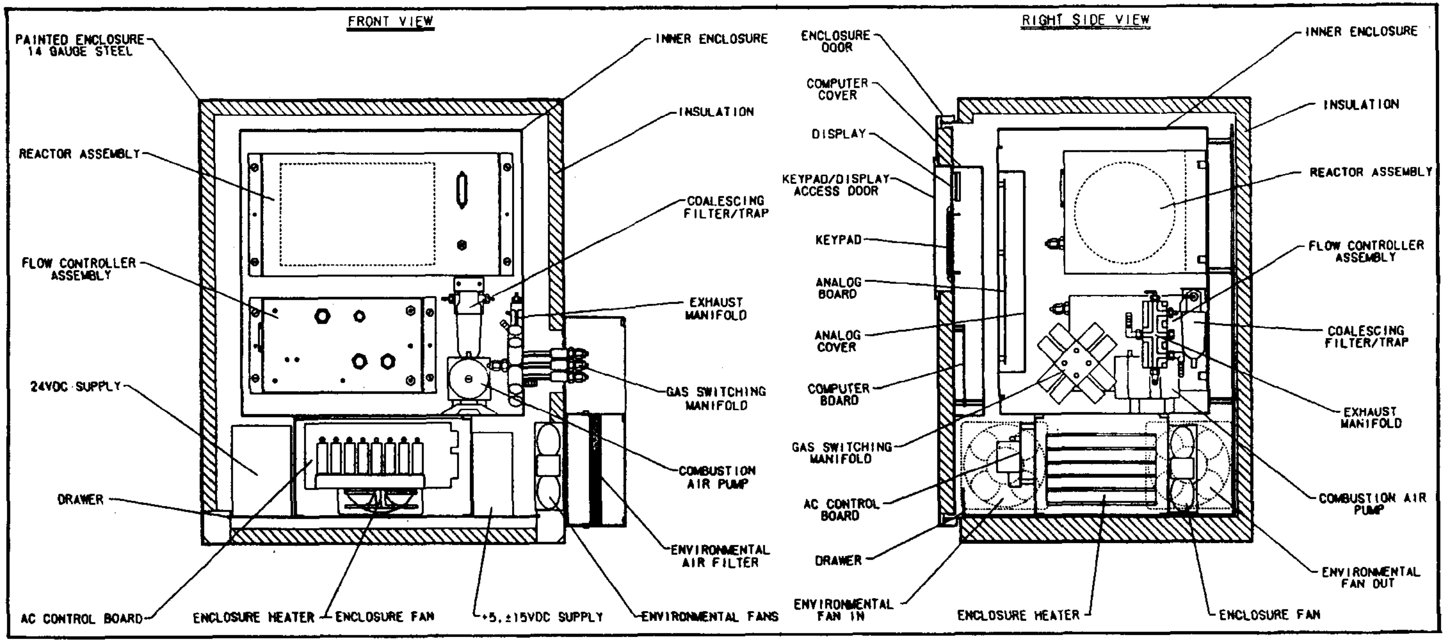

Fig. 3. Gas calorimeter enclosure diagram showing location of major subsystems within the enclosure.

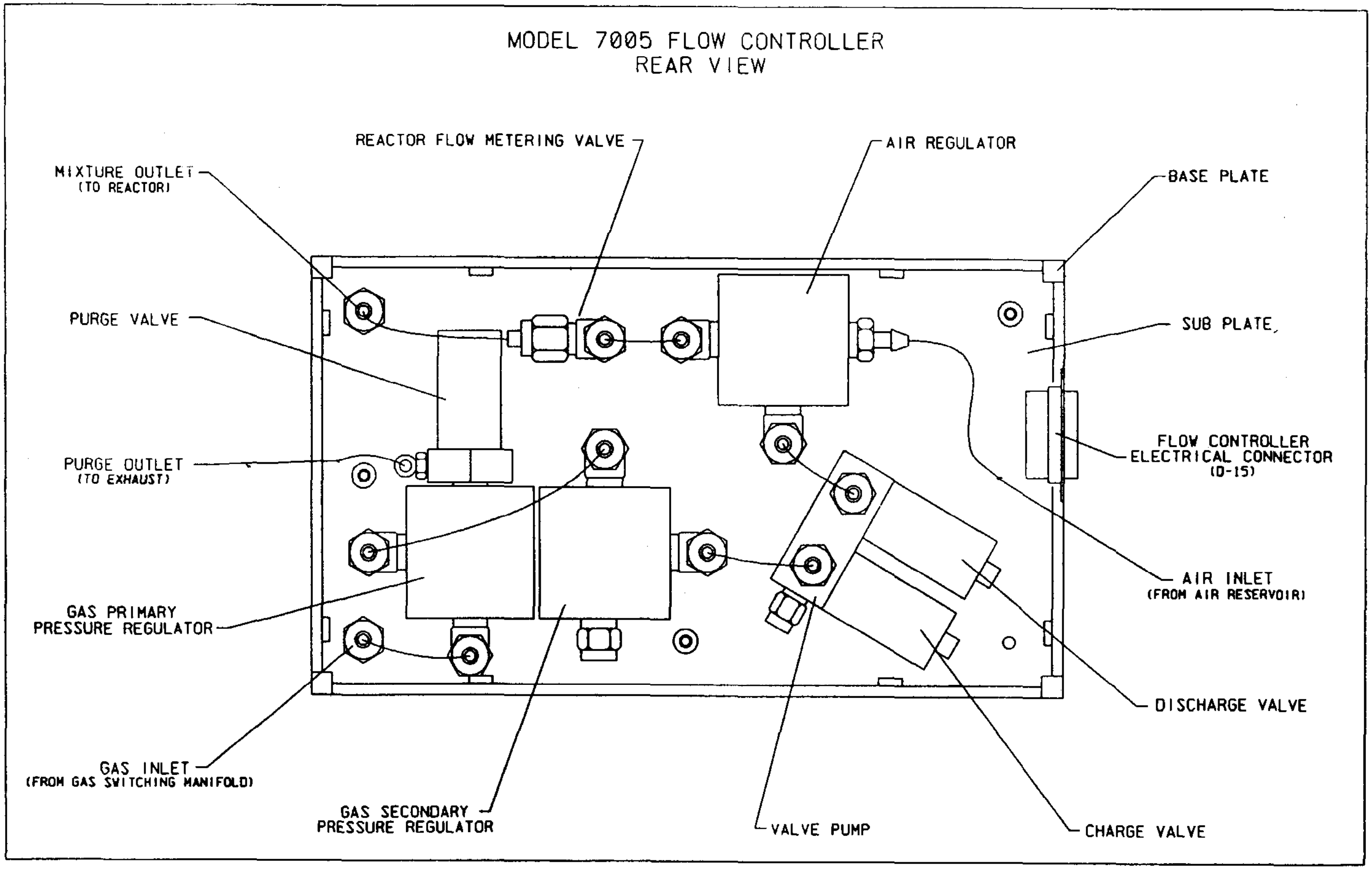

Fig. 4. Flow controller assembly diagram showing the location of all major gas and air flow control components and their attachment to the base plate (heat sink).

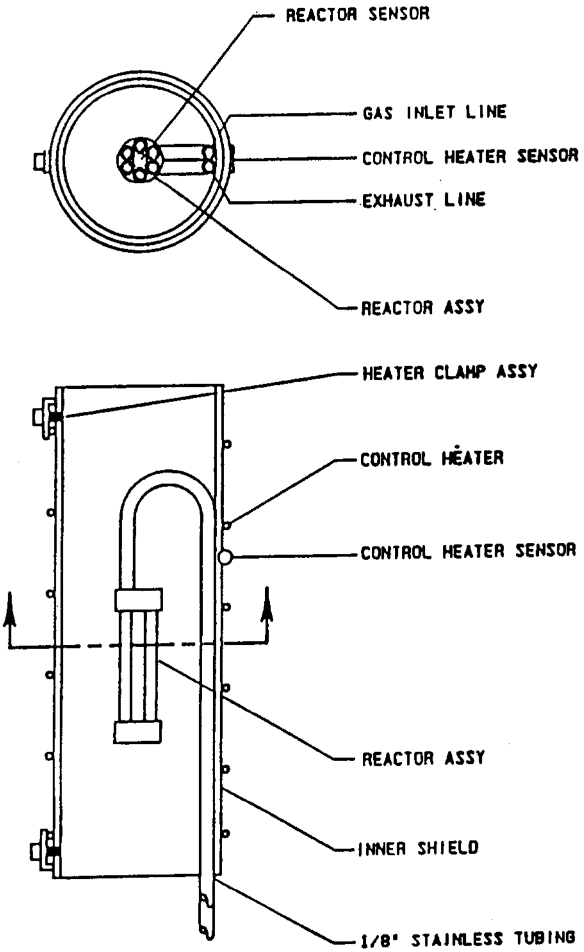

Fig. 5. Catalytic reactor assembly diagram showing the hexagonal organization of the six Pt/Pd-packed tubes about the Pt RTD reactor temperature sensor.

ambient temperature fluctuations and improves the stability of gas and air metering and mixing. The layout of the flow control components within the flow controller subassembly is shown in Fig. 4. The gas metering is accomplished with a valve-switched cavity (sample loop of constant volume) that fills at one pressure and empties at a lower pressure. Both the filling and emptying pressures (i.e. the pressure differential across the valve pump) are controlled by the pressure regulators (gas secondary pressure regulator and air regulator) as shown in Fig. 4.

The catalytic reactor shown in Fig. 5 has a volume of approximately 1.2 cm^3 with a catalyst bed volume of approximately 0.8 cm^3 and a void volume of about 0.4 cm^3. The catalyst is proprietary and consists of a mixed platinum palladium oxide supported on gamma alumina. The catalyst particles have an average diameter of approximately 0.05 cm. The combustion

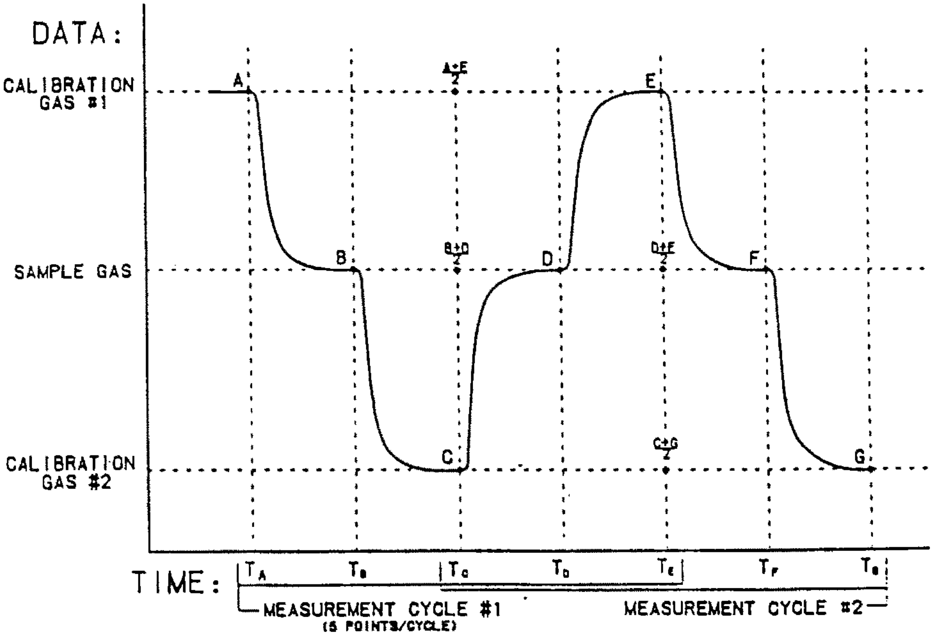

Fig. 6. Continuous calibration burn sequence showing two consecutive five-point measurement cycles. Each measurement cycle includes three calibration points (2 high and 1 low or 1 high and 2 low) and two sample gas points. The heating value calculation is done at the midpoint of the measurement cycle.

of air-diluted natural gas samples (ca. 4%) is more than 99.9% complete in this bed at total gas/air flows of 200 sccm or less (8 sccm of gas).

It should be noted here that the design of the Hart Scientific Gas Energy Meter as illustrated in Figs. 1 and 2 and described in this paper is covered by a patent application which has been filed with the U.S. Patent and Trademark Office.

Calibration and calculation algorithm

The gas calorimeter is continuously calibrated for both zero offset and gain. This is accomplished by burning two different calibration gases alternately with the unknown sample gas. The rate of gas consumption, nominally 6 sccm, is low enough that a cylinder of calibration gas will last for approximately 18 months. Figure 6 illustrates a typical measurement cycle in which the burn sequence is: calibration gas #1 (A), sample gas (B), calibration gas #2 (C), sample gas (D), calibration gas #1 (E), sample gas (F), calibration gas #2 (G), etc. A calculation is based on a measurement cycle including 5 data points (seven points are shown in Fig. 6). The sample net heating value is calculated by linear interpolation or extrapolation from the corresponding values for the calibration gases at the midpoint of the measurement cycle so that instrument calibration changes and drift effects are minimized. The burn interval for any one gas is typically set for between 2.5 and 15 min. This allows a sample value to be reported every 5–30 min. The continuous calibration provides for extremely good accuracy and precision and is really only practical because the gas consumption is so low.

As most gas purchase contracts are written on the basis of gross heating value, the gas calorimeter was designed to determine both the net and gross heating values. The net heating value is simply the heat of combustion of a hydrocarbon mixture

$$C_nH_{(2n+2)}(g) + O_2(g) = nCO_2(g) + (2n+2)/2H_2O(g) + \text{net heat} \quad (1)$$

where all reactants and products are in the gas phase. The gross heating value is larger than the net heating value as it includes the heat available from the condensation of product water to the liquid phase as shown in eqn. (2)

$$C_nH_{(2n+2)}(g) + O_2(g) = nCO_2(g) + (2n+2)/2H_2O(1) + \text{gross heat} \quad (2)$$

The net heating value (NHV) is calculated directly from the pump rate necessary to maintain the set temperature of the calorimeter reactor. The gross heating value (GHV) is calculated from the net heating value and the measurement of the water content of the calorimeter exhaust by use of eqn. (3)

$$\text{gross heat} = \text{net heat} - (2n+2)/2 \times \Delta H_{\text{vap},H_2O} \quad (3)$$

Other gas properties of interest are obtained from the net and gross heating values by use of empirical correlation equations. The following equations given for mole fractions of inerts (e.g. N_2 and CO_2) X_i, specific gravity SG, and base condition compressibility Z were developed using regression techniques and standard gas mixture data.

$$X_i = 1.0000 - \Big((\text{NHV})/\big(8.19769\text{E}05(\text{GHV}/\text{NHV})^2$$
$$-1.844003\text{E}06(\text{GHV}/\text{NHV}) + 1.037741\text{E}06\big)\Big) \quad (4)$$

$$\text{SG} = 6.696\text{E}-04\text{NHV} - 5.233\text{E}-02X_i \quad (5)$$

$$Z = 0.243258\ (GHV/NHV) + 0.728056 \quad (6)$$

The 10 standard gas mixtures used in the correlation had values for NHV ranging from 739.88 to 1133.99 BTU/SCF, X_i ranging from 0.0000 to 0.1903, SG ranging from 0.5903 to 0.7054, and Z ranging from 0.9964 to 0.9984.

RESULTS AND DISCUSSION

The gas calorimeter has undergone extensive testing. Laboratory tests have involved measurement of standard gas mixtures, obtained from both IGT (Institute of Gas Technology) and Scott Specialty Gas, as well as the measurement of field gas samples obtained from proportional samplers located at various field sites in Utah and Wyoming (supplied by Questar Development Corp.). The field gas samples were often run blind with Questar or Mountain Fuel personnel supplying the Net and Gross Heating Values as determined by high resolution GC analysis only after we had determined the heating values with our calorimeter. True field tests of the calorimeter were carried out at three different locations: a large pipeline metering station located in Payson Canyon near Payson, Utah; the Mountain Fuel Supply gas laboratory located in Salt Lake City, Utah; and at Hart Scientific's manufacturing facility in Provo, Utah. In the field tests, the heating values measured with our calorimeter were compared to the BTU values reported by an Applied Automation on-line gas chromatograph (Payson Canyon), a Cutler–Hammer calorimeter and a Hewlett–Packard 5880 gas chromatograph (Salt Lake City), and a HP 5880 A gas chromatograph (Provo). The field installations have ranged from an indoor location at the Salt Lake City gas laboratory to an uninsulated metal shed at the Payson site and finally to a completely unprotected installation on an outside back wall of Hart's building in Provo. In addition to the laboratory and field tests, the calorimeter has been run in an environmental test chamber at temperatures from −25 °F to +125 °F.

The laboratory performance of the gas calorimeter in measuring both the net and gross heating values for a number of standard (certified) gases is given in Table 1. The capability of the gas calorimeter in determining the mole fraction inerts, specific gravity and base compressibility is shown in Table 2. The field performance of the gas calorimeter is illustrated in a number of figures which are discussed in turn below.

TABLE 1

Certified standard gases as measured by the Hart gas calorimeter

Gas source	Net HV	Meas.	Diff.	Gross HV	Meas.	Diff.
Scott	918.65	918.52	−0.13	1019.0	1018.7	−0.3
IGT	921.45	922.06	+0.61	1021.1	1021.6	+0.5
IGT	944.59	944.26	−0.33	1046.2	1046.8	+0.6
Scott	947.75	948.38	+0.63	1050.9	1051.6	+0.7
Scott	950.56	950.52	−0.04	1053.6	1053.8	+0.2
Scott	976.16	976.20	+0.04	1081.4	1081.1	−0.3
Scott	998.94	998.64	−0.30	1105.9	1105.4	−0.5
IGT	1002.4	1003.2	+0.80	1108.9	1109.5	+0.6

TABLE 2

Gas properties calculated from gross and net heating values

x_{inerts} [a]	Error [b]	SG [c]	Error [d]	Z [e]	Error [f]
0.1903	−0.0002	0.63377	−0.00060	0.99839	−0.00008
0.0600	−0.0010	0.60620	0.00140	0.99790	0.00000
0.0380	−0.0007	0.59827	0.00165	0.99785	0.00004
0.0350	−0.0011	0.61811	−0.00444	0.99765	0.00003
0.0230	−0.0019	0.60211	0.00107	0.99771	0.00005
0.0260	−0.0013	0.61167	−0.00411	0.99766	0.00006
0.0170	−0.0004	0.61929	−0.00138	0.99753	0.00001
0.0160	−0.0005	0.62928	0.00285	0.99741	−0.00006
0.0240	−0.0007	0.66078	−0.00383	0.99716	−0.00008
0.0000	−0.0010	0.70537	0.00064	0.99643	−0.00002
	Std. dev. ±0.0011		Std. dev. ±0.00275		Std. dev. ±0.00005

[a] Mole fraction inerts, i.e. $x_{N_2} + x_{CO_2} + x_{O_2}$. The values in the column are those certified by the standard gas mixture supplier.

[b] The difference in x_{inerts} as certified and x_i as calculated by eqn. (4).

[c] The specific gravity of the gas mixture as calculated from the total composition.

[d] The difference in SG as calculated from composition and eqn. (5).

[e] The compressibility at 60 °F and 14.137 psi as calculated from the total composition.

[f] The difference in Z as calculated from composition and eqn. (6).

The field installation of the gas calorimeter is shown in Fig. 7. The installation was similar whether the calorimeter was located at the remote metering site (Payson Canyon), the Salt Lake City gas laboratory or on the back outside wall of the Hart manufacturing facility in Provo. The performance of the calorimeter was within specifications at all sites, although the recommended field installation should at least provide protection from direct exposure to sunlight, rain, and blowing dust. Typically the calorimeter and the audit instrument (GC or other calorimeter) were in best agreement whenever the audit instrument had been recently calibrated.

During the field tests at the Payson Canyon site, the gas calorimeter was in reasonable agreement (±1 BTU/SCF) with the Applied Automation on-line GC whenever the GC had been recently calibrated. However, the GC showed both a larger temperature coefficient (day/night variation) and a tendency to drift by as much as 5 BTU/SCF between the weekly or biweekly calibration periods. Also the on-line GC was quite noisy in comparison to the Hart gas calorimeter. Figure 8 shows data typical of the comparison between the Hart gas calorimeter and a gas chromatograph. In this instance the data presented are for a 20 day testing period during August and September of 1988, in which an HP 5880 A GC was used to continuously monitor the city gas in south Provo and then compared with the Hart calorimeter running as it would in a typical field installation. The bold line represents the NHV reported by the gas calorimeter while the fine line represents the heating value data calculated from the natural gas

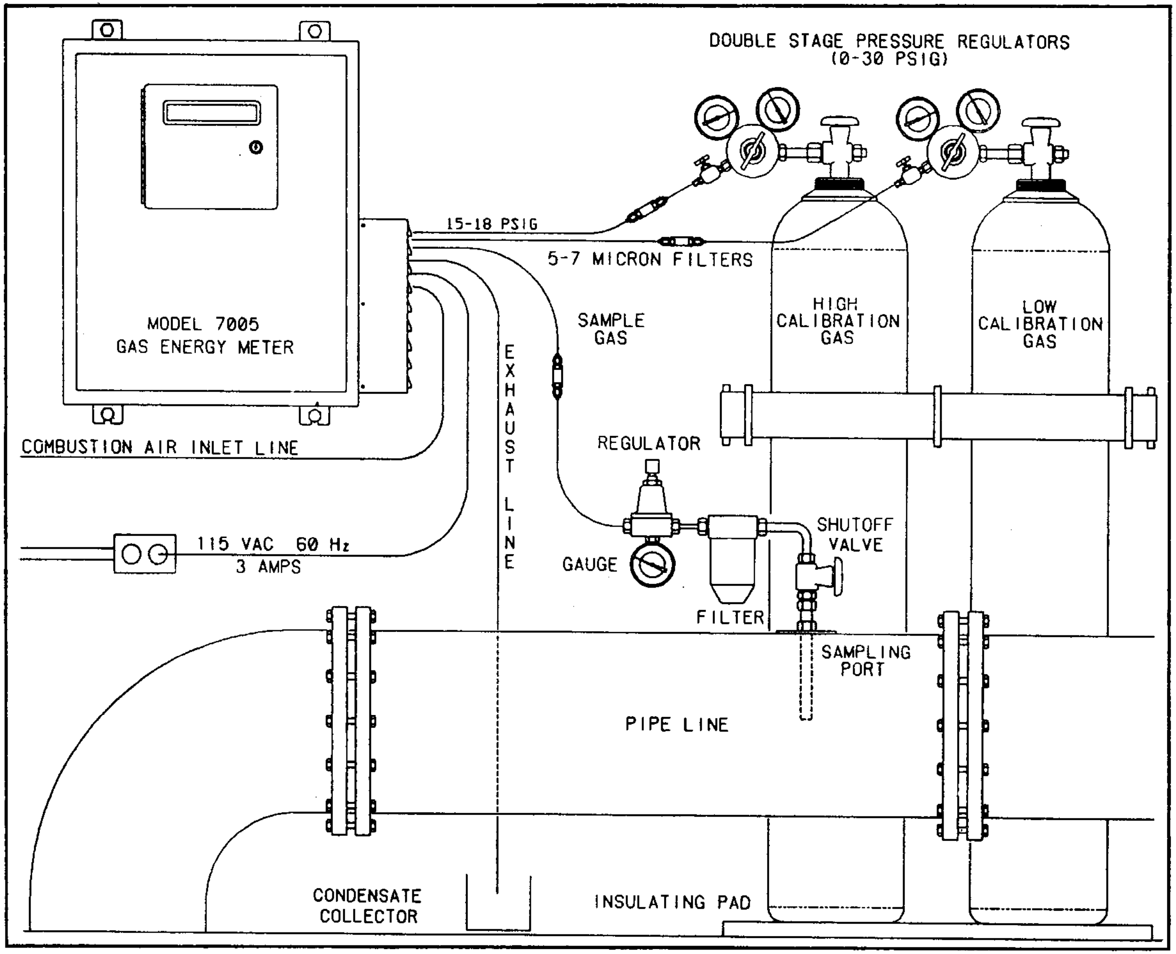

Fig. 7. Field installation of the Hart gas calorimeter. The recommended site requirements include an unheated, uninsulated shelter to protect the calorimeter from the elements and heat traced sample lines to prevent sample condensation.

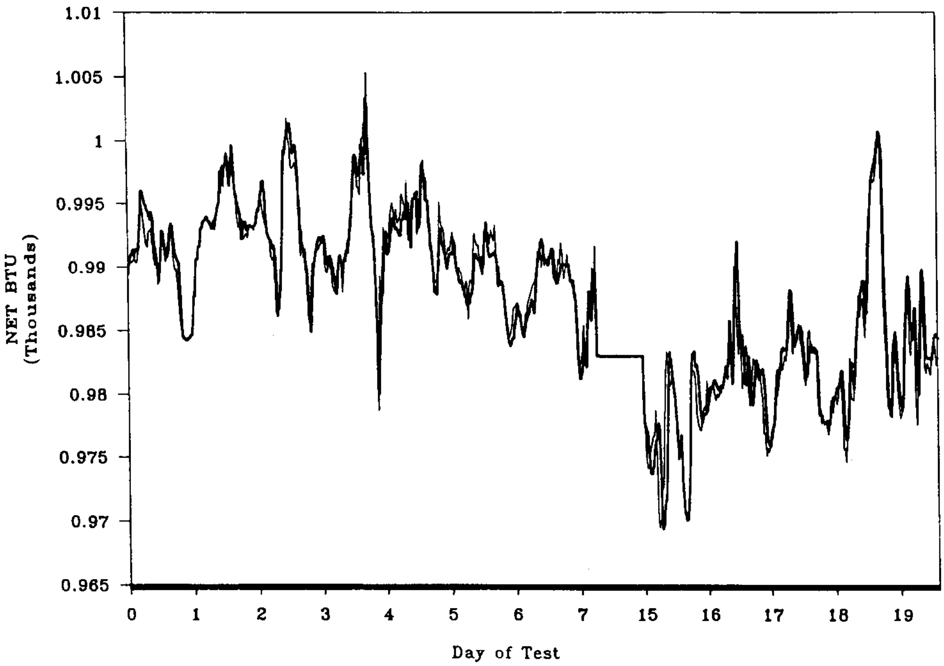

Fig. 8. Provo field test data comparing measurement of the net heating value of the city gas with the Hart gas calorimeter (bold line) and a HP 5880A gas chromatograph equipped with the Natural Gas Analyzer accessory package (fine line).

composition. The agreement between the two instruments is excellent with most of the values virtually superimposed. The ordinate scale is 5 BTU/division and the agreement between the Hart calorimeter and the HP GC is better than ±1 BTU/SCF throughout the testing period.

Figures 9 and 10 show typical performance comparison data for the Hart gas calorimeter against the Cutler–Hammer calorimeter in Salt Lake City. The data given in these two figures are for 2 days out of an 8 day testing period. In Fig. 9, gross heating value data for the Salt Lake City gas are given at 30 min intervals for a 24 h period as determined by the Hart energy meter and the Cutler–Hammer calorimeter operated by Mountain Fuel Supply in their gas laboratory. At least two features of this data set are of interest. Firstly, the GHV of the Salt Lake City gas was quite variable during the test period with values ranging from approximately 1060 to 1100 BTU ft^{-3}, a spread of almost 40 BTU. Secondly, the GHV data reported by the Hart calorimeter and by the Cutler–Hammer calorimeter were in poor agreement for a period of approximately 16 h between calibration adjustments made to the Cutler–Hammer calorimeter. The discrepancy between the two instruments was attributed to the Cutler–Hammer calorimeter drifting out of calibration and needing to have its burner cleaned in order to bring it back into agreement with the Hart calorimeter and with a co-located

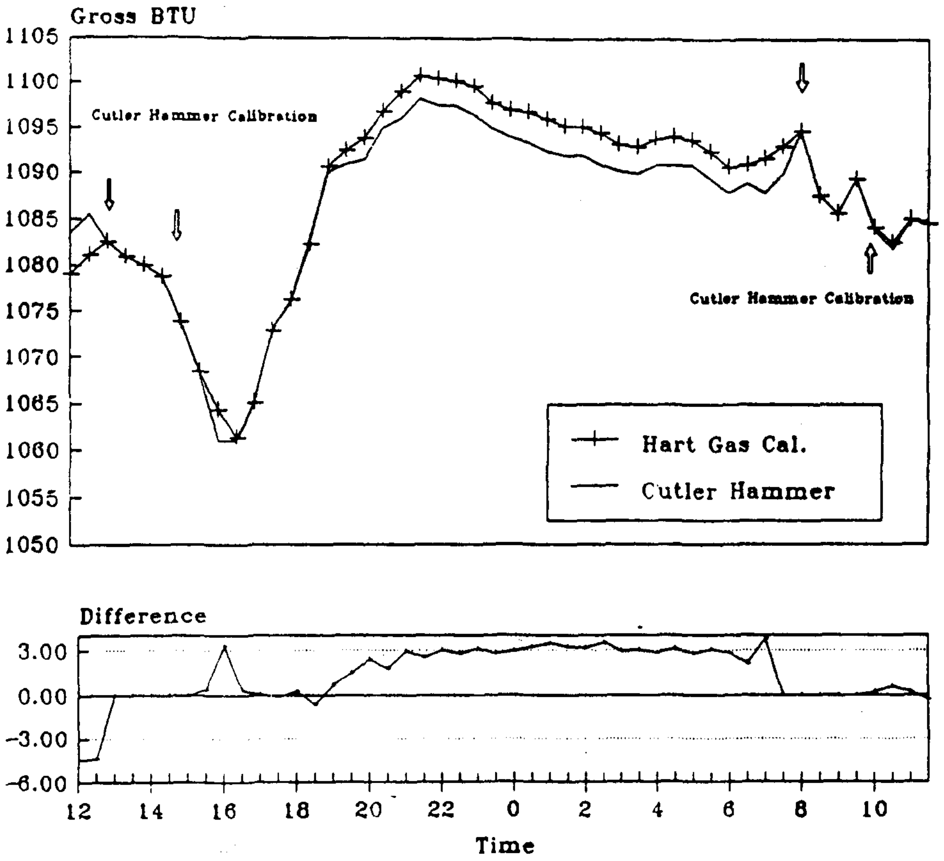

Fig. 9. Salt Lake City field test data comparing the measurement of the gross heating value of the city gas with the Hart calorimeter (+) and a Cutler–Hammer calorimeter (−). The agreement was poor during the time period shown as the C–H calorimeter was out of calibration.

HP–GC natural gas analyzer system. Data showing the comparison of the Hart calorimeter and the Cutler–Hammer calorimeter for a subsequent day are given in Fig. 9. Here the agreement between the two instruments is indeed excellent. A point to remember here is that the field installable calorimeter performed better than the audit instrument that was being used for billing city gas customers. In the upper half of both Figs. 9 and 10, both the Cutler–Hammer and the Hart calorimeter gross heating value data have been plotted at 30 min intervals. In the lower half of each figure, the difference between the two instruments is plotted for the same time periods. The notations on Fig. 9 indicate the points at which the Cutler–Hammer calorimeter was cleaned and recalibrated (twice). The data shown in Fig. 10 illustrate the typical agreement between the two instruments early in the 8-day test period and after the Cutler–Hammer calorimeter was recalibrated.

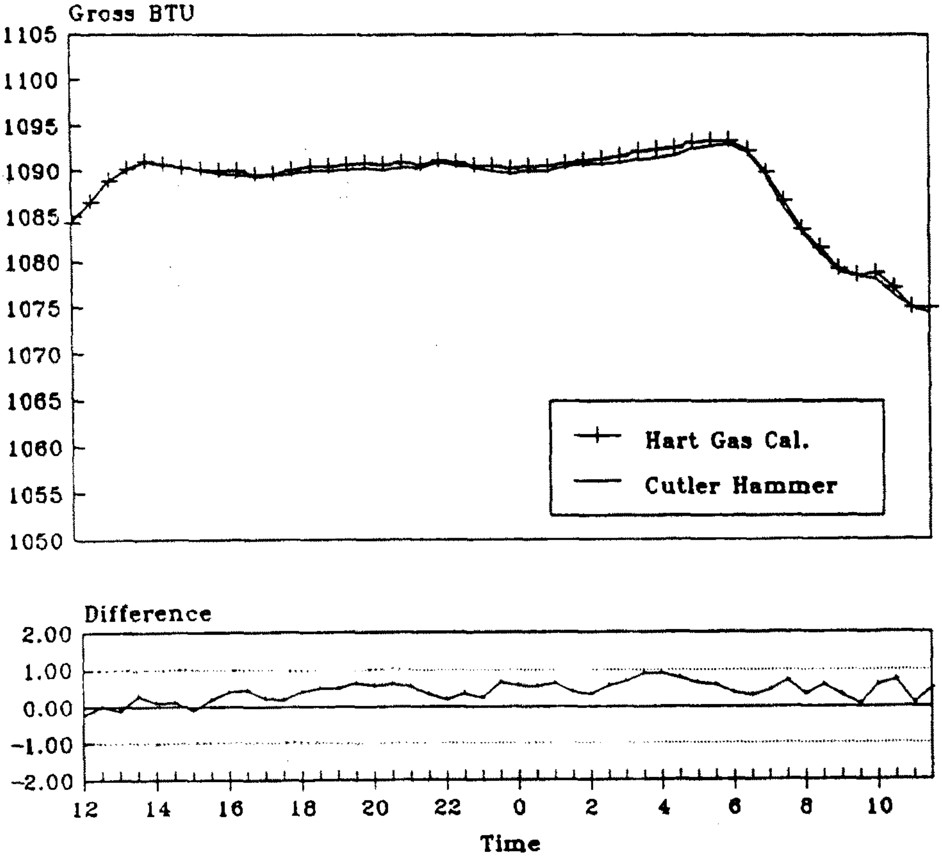

Fig. 10. Salt Lake City field test data comparing the measurement of the gross heating value of the city gas with the same two calorimeters as in Fig. 9. The agreement was excellent after calibration of the "audit" instrument.

As stated earlier the gas calorimeter has undergone environmental testing in both an environmental chamber and in an unsheltered outside installation. The environmental chamber tests to date have consisted of limited operation (less than two months) at each of the temperature limits, −25 °F and +125 °F respectively. The specified accuracy and precision (±1 BTU and ±0.5 BTU) have been observed under these limiting isothermal ambient conditions with temperature fluctuations in the test chamber of less than ±2 °F. These same accuracy and precision specifications have also been met in chamber experiments in which the temperature has been scanned at rates of up to 25 °F h^{-1}. Figure 11 shows the NHV data obtained for the measurement of a standard gas mixture during ambient temperature fluctuations in the outside environment. The bold line represents the error in the NHV measurement, i.e. the difference between the reported and certified values, during a 20 day testing period. The error does follow a diurnal pattern, although the error is always less than the specified ±1 BTU/SCF

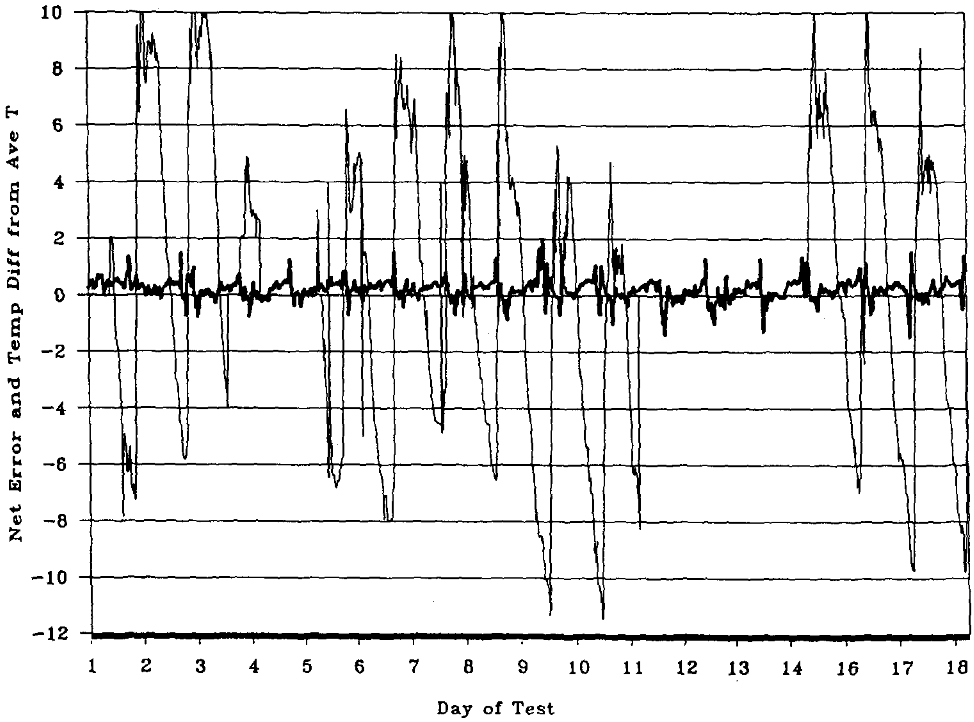

Fig. 11. Environmental test data showing error in net heating value (bold line) resulting from rapid daily temperature fluctuations (fine line).

even during rapid temperature changes when the sunlight first hits the calorimeter enclosure. The temperature fluctuations are plotted as differences from the mean temperature and show about a 20 ° C extreme variation during each day of the test period.

CONCLUSION

The Hart Scientific Gas Calorimeter described in this paper was designed to address a very real and significant problem for the gas industry. The need for a low cost field-deployable gas energy meter has developed from the shift of gas billing from a volume to an energy basis and from the Federal Energy Regulatory Commission's ruling that gas pipelines should be regulated as common carriers. This "need" was the subject of a GRI solicitation for proposals to develop new gas measurement instrumentation in 1984. More recently, this "gas industry need" resulted in our receiving U.S.-DOE support for the development of the field-deployable gas calorimeter described in this paper.

The performance data given in this paper prove that the concept of using a Catalytic Combustion Flow Calorimeter for the field measurement of natural gas energy content has been successfully demonstrated. The Hart Scientific gas energy meter described is: suitable for remote installation, as accurate as present laboratory calorimeters (or gas chromatographs), operates continuously for precise accounting at custody transfer points, and is low in cost. At present, there are no alternative low cost products capable of making real time and continuous BTU and specific gravity measurements with the same accuracy at remote field sites.

ACKNOWLEDGMENTS

We would like to thank Mike Hirst, and Alma Schurig of Hart Scientific as well as Glade Hall of Mountain Fuel Supply, and Lew Flaim of Questar Pipeline Inc. for their invaluable technical support of this work. We would also like to acknowledge the strong financial support provided for development of the Hart gas energy meter by Questar Development Corp. and the administrative assistance provided by Mike Benefield of Questar Development Corp. Support of this work by the U.S. Department of Energy through the awarding of Phase I and II SBIR grants (DE-AC03-87ER80456 and DE-AC03-87ER80456-A001) to Hart Scientific, Inc. is also gratefully acknowledged.