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1980
Development of an Instrument to Measure the Concentration of Noncondensable Gases in Geothermal Discharges

FINAL REPORT

C. K. Blair and R. F. Harrison
Terra Tek, Inc.

January 1980
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Available from
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DEVELOPMENT OF AN INSTRUMENT TO MEASURE THE CONCENTRATION OF NONCONDENSABLE GASES IN GEOTHERMAL DISCHARGES

FINAL REPORT

Project Duration: October 1, 1978 - September 30, 1979

C. K. Blair
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Prepared for:
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720
Subcontract No. 3976822

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This work was supported by the Assistant Secretary for Resource Applications, Office of Industrial and Utility Applications and Operation, Division of Geothermal Energy, U.S. Department of Energy under Contract No. W-7405-ENG-48.

TR 80-5
January 1980

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ACKNOWLEDGMENTS

This study was supported by the Assistant Secretary for Resource Applications, Office of Industrial and Utility Applications and Operation, Division of Geothermal Energy of the U.S. Department of Energy and through the Lawrence Berkeley Laboratory under the Geothermal Reservoir Engineering Management Program, Order #3996822. The authors express their gratitude to the program's technical monitors, Alex Graf, Jack Howard, Pascal Rapier, and Werner Schwarz, and to the contract administrator, Rich Arriaga, of the Lawrence Berkeley Laboratory (LBL) for their advice, consideration, and review of this study. The engineering design drawings in Appendix 2 are reproduced by permission of Terra Tek; and the pressure transmitter specifications in Appendix 3, by permission of the Viatran Corporation.

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ABSTRACT

Reported herein is a summary of a project to design, construct, and test a device which will continuously measure the vapor phase concentration of noncondensable gases in saturated steam/water geothermal discharges. Descriptions of the design, operating procedures, measurement accuracy, and limitations of the device are included. Also presented are results of laboratory testing and of field demonstration of the instrument. Recommendations for further refinement and development of the apparatus are discussed.

PROJECT SUMMARY

This project was a one year program to develop an instrument having the capability of continuously measuring the concentration of noncondensable gases in the vapor phase of saturated steam/water geothermal discharges. During the course of the project, the engineering design of the instrument was completed, two devices were fabricated, laboratory testing of one device was conducted, and field testing of both units was performed at geothermal sites in the United States and in New Zealand.

Monitoring the level of noncondensable gases in discharges from hydrothermal systems is important in several aspects of geothermal development. In power plant applications, optimization of turbine exhaust pressure is highly sensitive to the quantity of noncondensible gas that must be removed in order to maintain condenser vacuum. Thus, a knowledge of noncondensible gas concentrations is required in initial plant design. Because the concentration of noncondensable gases in discharges from hydrothermal reservoirs changes with time, continuous monitoring is required to ensure efficient operation of the condenser system of a power plant. A knowledge of the history of noncondensible gas concentrations present in the discharge from a hydrothermal system throughout the production lifetime is also important in many aspects of reservoir engineering (e.g., development of reservoir models, determination of reservoir properties, formulation of production strategies, etc.).

Chemical and separation/volumetric displacement techniques are currently used to measure the concentration of noncondensable gases in geothermal discharges. Neither of these techniques are suitable for making instantaneous measurements or for continuously monitoring levels of noncondensables. The chemical technique requires laboratory analysis of a sample, and thus normally precludes on-site analysis. The separation/volumetric displacement technique requires a rather large equipment setup and also requires a source of cooling water.

The operation of the instrument is based upon partial pressure/perfect gas mixture principles. In a mixture of substances which can be idealized as perfect gases, the ratio of the partial pressure of a component to the total pressure of the mixture is equal to the mole fraction of the component in the mixture. Thus, by determining the noncondensable gas and steam partial pressures in a geothermal discharge, and by assuming the discharge to be a mixture of perfect gases, the molar ratio (and thus the volumetric ratio) of noncondensable gases to steam in the vapor phase of the flow can be determined.

The device used to determine the required pressures consists of a small capsule inserted into a section of pipe. The capsule, partially filled with water having boiling point characteristics representative of that being sampled, is vacuum-sealed. Pressure taps are connected to the capsule and to the wall of the pipe. As a saturated geothermal discharge is circulated through the pipe, the water in the capsule is heated to the temperature of the mixture and thus it exerts a pressure equal to the saturation pressure of water at the mixture temperature. The static pressure port in the wall of the pipe is exposed to the total pressure of the steam/noncondensable gas mixture. By measuring these two pressures, the molar ratio of noncondensable gas to steam can be determined.

In conjunction with additional measurements, the device can be used to determine the total noncondensable gas concentration (both that dissolved in the liquid phase and that in the vapor phase) in a two-phase geothermal discharge. In addition to device vapor phase noncondensable gas determination, chemical measurements to ascertain liquid phase noncondensable gas content and calorimetry measurements to determine flow steam quality (or enthalpy) are required.

The results of the laboratory and field testing have demonstrated the operability and versatility of the instrument developed during the program. Prior to commercialization of the device, it will be necessary to implement further design refinements required to improve performance and measurement accuracy. Necessary modifications and recommended additional development
testing are discussed within the report.

1.0 INTRODUCTION

1.1 Project Description

This project was a four quarter, multi-task program to develop an instrument which can continuously monitor the concentration of noncondensible gases in the vapor phase of geothermal discharges. A device having this capability would be valuable in many aspects of geothermal resource utilization (e.g., reservoir modeling and management, power plant design and operation, etc.).

The first task of the project, accomplished during the first quarter, consisted of completing the engineering design of the measurement device. During the second project quarter, procurement of materials for and fabrication of two instrument assemblies were completed. Laboratory testing (and device modification dictated by test results) of one unit was conducted during the second, third, and fourth quarter of the project. Field testing and demonstration of both units were completed at geothermal sites in the United States and in New Zealand during the final project quarter.

1.2 Instrument Application

Natural hydrothermal systems commonly contain quantities of noncondensible gases which are dissolved within the liquid water phase normally existing in high temperature, high pressure geothermal reservoirs. These noncondensible gas mixtures usually consist of carbon dioxide (typically 95 percent by weight), hydrogen sulfide (typically 3 to 4 percent by weight), and traces of other gases including nitrogen and hydrogen.

For discharges from high pressure, high temperature reservoirs, the flowing pressure drop through the bore is usually sufficient to yield a steam or steam/liquid mixture at the wellhead. The solubility of the gases within the liquid phase of the geothermal discharge at wellhead conditions is quite low and thus considerable gas is released from solution and then entrained within the steam phase.

Accurate measurement of noncondensible gas concentrations in geothermal flows is important due to the following:

1. Optimization of turbine exhaust pressure in power plant applications is sensitive to the quantity of noncondensible gas that must be removed in order to maintain the condenser vacuum.
2. Gas concentrations in a geothermal discharge typically vary with time. Continuous monitoring of the steam supply to a power station is required to ensure efficient operation of the condenser system.
3. Continuous measurement of gas concentrations in a geothermal discharge would aid in analysis of field potentials, development of reservoir models, and management of production wells.

Another important capability of the device is that of measuring the enthalpy (or quality) of a two phase sample flow. This is accomplished by obtaining noncondensible gas concentration measurements at at least two different sample pressures (by throttling the sample flow). The enthalpy of the flow is then calculated from the noncondensible gas concentrations and from steam quality versus throttling considerations. The accuracy of enthalpy measurements using this technique is a function of the sample pressure and quality and of the noncondensible gas concentration in the flow. A discussion of sample flow conditions which enable reasonably accurate determination of enthalpy using this technique is included in the Discussion of Device Capabilities section of the report. Calculation details for the technique are included as Appendix 1.

1.3 Theory of Operation

For a mixture of gases which can be idealized to be a mixture of independent substances, the total pressure of the mixture is equal to the sum of the partial pressures of each gas component. If the gas components can be idealized as perfect gases, the ratio of the partial pressure of a component to the total pressure of a mixture is equal to the mole fraction of the component in the mixture. For a mixture of gases which deviate from ideal behavior, component mole fractions can also be determined from partial pressure considerations. This is accomplished by use of ideal gas equations of state corrected for non ideal behavior via the introduction of suitable compressibility factors. Thus, by determining the noncondensible gas and steam partial pressures in a geothermal discharge, the molar ratio (and thus the volumetric ratio) of noncondensible gases to steam in the flow can be determined.

The device used to determine the required pressures consists of a small capsule inserted into a section of pipe. The capsule, partially filled with water having boiling point characteristics representative of that being sampled, is vacuum sealed. Pressure taps are connected to the capsule and to the wall of the pipe. As a geothermal discharge is circulated through the pipe, the water in the capsule is heated to the temperature of the mixture and thus it exerts a pressure equal to the saturation pressure of water at the mixture temperature. The static pressure port in the wall of the pipe is exposed to the total pressure of the steam/noncondensible gas mixture. By measuring these two pressures, the molar ratio of noncondensible gas to steam can be determined. The configuration of the device is schematically presented in Figure 1.

The partial pressure of a gas component is defined as the pressure of the component if it occupied the same volume as the mixture at the mixture temperature.
1.4 Design Specifications

The design specifications for the gas concentration measurement device, mutually formulated by Terra Tek, Inc., and Lawrence Berkeley Laboratory prior to project initiation, are included in Appendix B to Subcontract No. 3976822 between the Regents of the University of California and Terra Tek, Inc. These specifications are as follows:

Design Maximum Operating Conditions -
Temperature - 419°F (215°C)
Pressure - 290 psi (20 bars)

Sample Steam Qualities -
0 - 100 percent

Differential Pressure Measurement Ranges -
0 - 20 in. H₂O (0 - 50 cm H₂O)
0 - 200 in. H₂O (0 - 500 cm H₂O)

Resolution (Differential Pressure Measurement) -
0-20 in. H₂O range - 0.02 in. H₂O (0.5 mm)
0-200 in. H₂O range - 0.2 in. H₂O (0.5 cm)

Accuracy Requirements (Differential Pressure Measurement) -
± 0.5 percent of full scale reading

Accuracy Requirements (Gas Concentration Measurement) -
± 6 percent (for a 0.1 weight percent gas concentration at a total pressure of 145 psi)

---

2.0 DESIGN AND CONSTRUCTION

2.1 Drawing List

Outlined in Table 1 is a listing of the detail, assembly, and installation drawings for the device. Copies of these drawings are included in Appendix 2.

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2.2 Device Description

2.2.1 Vessel and Capsule

The general configuration of the vessel and of the capsule is outlined in the gas probe assembly drawing (4000001). As can be seen in this drawing, 316 stainless steel is used in all boundary parts and internal fittings.

The test section of the vessel consists of 2 inch diameter schedule 40 pipe. The inlet line to the vessel is reduced to 1 inch diameter schedule 40 pipe to match the size of typical wellbore sampling ports. The transition from 2 inch to 1 inch pipe is made with a concentric reducer to ensure that uniform test sample flows exist in the test section during operation. A globe valve rated for 300 psi service is located in the inlet line to enable throttling of the sample flow and isolation of the test vessel. A 1 inch threaded union is placed at the end of the inlet line to enable coupling of the device to wellbore sampling lines.

Access to the internal portion of the vessel is facilitated by a connection situated at the end of the test section consisting of a flat-faced flange, steam gasket, and an end block secured by six 1/4 inch diameter cap screws. The vessel exit line, welded to the end block, is 1/2 inch schedule 40 pipe. A 300 psi gate valve is located in the exit line to enable flow control and vessel isolation.

The capsule, detailed in Drawing 400003, consists of a section of 0.375 inch diameter x 0.035 inch wall tubing with ellipsoidal heads welded to each end. Two 0.125 inch diameter x 0.035 inch wall tubes are connected to the capsule for the purpose of initial capsule filling and for capsule pressure measurement. These tubes are welded to the end block portion of the vessel where penetration holes have been made. A shut off valve is screwed into the end block into the fill line penetration. The pressure measurement instrumentation is plumbed to the lower penetration with compression fittings and .125 inch diameter tubing.

A heat shield constructed from 1.250 inch diameter x .049 wall tubing is situated between the capsule and the vessel to minimize radiation heat loss from the capsule during operation. The heat shield is supported within the vessel by securely holding the vessel flange. The test capsule is supported within the shield by six locating fins welded to the exterior of the capsule.

The static pressure tap portion of the device is located in a straight section of 1 inch schedule 40 pipe, 22 inches long, positioned upstream of the measurement device. A 3/16 inch diameter hole, used for static pressure measurement, is located 6 inches from the downstream end of the pipe. A straightening vane, fabricated from 3/16-inch diameter tubing, is located near the entrance to the pipe to reduce turbulent eddy currents in the flow in the vicinity of the pressure tap hole.

To isolate the sample flow from the pressure measurement instruments, a diaphragm assembly is connected to the static pressure tap. The diaphragm within the assembly was fabricated in a thin-walled, cylindrical shape using silicone rubber. The pressure measurement transmitters are plumbed to the isolation diaphragm assembly using compression fittings and 0.125 inch diameter tubing. The configuration of the diaphragm allows precise transmission of static pressure to the pressure transmitters without having fluid temperature effects in the closed transmitter/tubing/diaphragm assembly fluid circuit.

2.2.2 Instrumentation

To determine the gas concentration in a sample flow passing through the unit, two pressures must be measured. These pressures are:

1) The differential pressure between the capsule and the sample flow (static).

2) The absolute pressure existing within the test capsule.

Three pressure transmitters were selected to measure the required pressures - two differential measurement units and one absolute measurement unit. Two differential units were required due to the wide range of gas concentrations (and resulting wide range of differential pressures) which the device is designed to measure. Following is information relating to the selected transmitters:

Differential Transmitter (Low Range)

Manufacturer: Viatran Corp.
Model No: 704-115
Range: 0-50 inches water (differential)
Input: 105-115 volts AC or 10-14 volts DC
Output: 0-5 volts DC
Accuracy: ±0.25 percent of full scale reading

Differential Transmitter (High Range)

Manufacturer: Viatran Corp.
Model No.: 704-115
Range: 0-25 psi (differential)
Input: 105-115 volts AC or 10-14 volts DC
Output: 0-5 volts DC
Accuracy: ±0.25 percent of full scale reading

Absolute Transmitter

Manufacturer: Viatran Corp.
Model No.: 701-115
Range: 0-300 psia
Input: 105-115 volts AC or 10-14 volts DC
Output: 0-5 volts DC
Accuracy: ±0.25 percent of full scale reading

Manufacturer's specification sheets for the above units are included in Appendix 3.
Differential pressure transmitters with ranges larger than those outlined in the design specifications were selected to expand the measurement range of the device. As presented in the Discussion of Device Capabilities section of this report, instrument measurement accuracy remains within specification even with the expanded differential pressure measurement ranges.

A 100 ohm platinum resistance thermometer probe has been provided to measure the temperature of the sample flow. Measurement of the flow temperature is required to:
1) verify that the sample flow contains saturated steam and
2) verify the capsule absolute pressure measurement.

The temperature probe is inserted into the vessel upstream of the test capsule. The probe has a standard calibration accuracy of ±2°F at 400°F.

2.2.3 Installation

Drawings 400002 (Transmitter Hydraulic Connection Diagram), 400003 (Support Frame), and 400007 (Support, Instrumentation, and Instrumentation Installation) depict the installation scheme for the instrument. The installation details are as follows:
1) A triangular support frame is attached to two support gussets which are welded to the gas probe assembly.
2) Collars are welded to the sides of the support frame for use with support legs. Setscrews in the collars allow adjustment of the height of the unit.
3) The pressure transmitters are mounted on the front of the triangular frame. The transducers are connected to the appropriate pressure taps with 1/8 inch diameter stainless steel tubing.
4) To mitigate the effect of heat loss upon the accuracy of gas concentration measurement, the test vessel is insulated with 5 inches of refractory fiber. The insulation is applied in one inch layers banded as required with tie wires. The exterior of the insulated unit is covered with removable aluminum jacketing material.

2.3 Fabrication Procedure

Commercial hardware has been utilized in the gas probe design wherever possible. The only parts of the assembly requiring major machining or fabrication are the end block, flange, isolation diaphragm and housing, and the capsule end plugs.

Welded, threaded, or flanged connections are utilized in the assembly of the device. Shielded arc welding using E-316 filler metal is specified for all welded connections. Fabrication of the device proceeds as follows:
1) Individual parts detailed in drawings 400009 through 400019 are produced. The vessel flange and end block are machined integrally to ensure alignment at assembly.
2) Subassemblies detailed in drawings 400003 through 400008 are completed.
3) The gas probe unit is assembled per drawing 400001.
4) Transmitter and support frame installation is completed per drawings 400002 and 400022.
5) Insulation and jacketing is installed on the unit per drawing 400022.

3.0 TESTING PROGRAM

3.1 Laboratory Testing

3.1.1 Test Program

The primary objectives of the laboratory test program were as follows:
1) To demonstrate the operability of the measurement device (or identify and perform modifications required to make the device operable).
2) To experimentally determine the measurement accuracy of the instrument.

To meet the objectives, the testing program was divided into the following tasks:
1) Determine the performance characteristics of the diaphragm used to isolate the vessel from the pressure transmitters.
2) Verify the performance of the capsule portion of the instrument.
3) Determine the effect of steam flow rate upon the measurement accuracy of the device.
4) Verify pressure transmitter performance specifications.
5) Establish comprehensive procedures for device startup and operation.

3.1.2 Test Apparatus

Outlined in Figure 2 is a schematic of the apparatus constructed at the University of Utah for the purpose of conducting startup and calibration testing of the measurement instrument. Photographs of the installation are included as Figures 3 and 4. Following is a description of the apparatus.

Saturated steam with a quality of approximately 100% and at a temperature of approximately 275°F was supplied to the unit through one inch schedule 40 piping. Valves used for regulation and isolation of the steam flow were located at
After passing through the measurement instrument, the steam flow was condensed in a water-cooled heat exchanger. The condensate was discharged into a tank situated on a weighing scale for the purpose of measuring the steam flow rate.

Carbon dioxide was injected into the steam supply line at a point approximately ten feet upstream from the unit. The CO₂ was supplied from a regulated, high pressure container. Gauges were located in the CO₂ line to measure temperature and pressure. The CO₂ flow rate was measured by a shielded rotameter. CO₂ was regulated by a needle valve located in the supply line downstream of the rotameter.

Output from the pressure transmitters on the device was measured using a 5-1/2 digit multimeter and using a two-channel strip chart recorder. Temperature probe resistance was also measured using a 5-1/2 digit multimeter.

3.1.3 Test Procedures

The following procedures were developed to accomplish previously outlined tasks 1, 2, and 3:

3.1.3.1 Diaphragm Performance

1) Fill the static pressure tap diaphragm housing, connecting tubing, and differential pressure transmitter housings with water.

2) With the capsule and the vessel vented to ambient, zero and calibrate the differential pressure transmitters.
FIGURE 3. Laboratory Test Apparatus

FIGURE 4. Laboratory Test Apparatus
3) Temporarily install a water manometer and a pressure gauge to read vessel pressure.

4) With the capsule side open to ambient, pressurize the vessel over a range using the CO₂ delivery system. Record transmitter outputs and corresponding pressure gauge and/or manometer readings at each specific vessel pressure.

3.1.3.2 Capsule Performance

1) Fill the capsule, connecting tubing, and the differential and absolute pressure transmitter housings with water.

2) With the capsule and vessel vented to ambient, zero and calibrate the differential and absolute pressure transmitters.

3) Isolate the capsule. Initiate steam flow to the vessel.

4) After thermal equilibrium has been obtained, vent the capsule for approximately two to three seconds.

5) Record pressure transmitter output and vessel flow temperature over a range of vessel static pressures (achieved by throttling the flow at the inlet to the device.)

3.1.3.3 Device Accuracy and Flow Effects

1) Complete setup of the capsule and static pressure fluid circuits.

2) Obtain steady state data (flows, temperatures, and pressures) for vessel flows containing a range of CO₂ concentrations with the steam supply fully open.

3) Repeat step 2 at two intermediate steam flows (approximately 20% and 50% of the maximum flow). Throttle the flow on the outlet side of the vessel.

3.1.4 Results

3.1.4.1 Diaphragm Testing

Initially, a commercially available diaphragm was used in the static pressure tap fluid circuit. The diaphragm was fabricated from silicone rubber in the form of a thin-walled disc.

During initial testing, a problem with this diaphragm configuration was identified. Upon filling and purging the pressure transmitters and associated connecting tubing with water up to the isolation diaphragms, the output from the differential pressure transmitters was found to vary considerably with time (with the capsule and the vessel vented to ambient). Previous testing of the empty transmitters indicated very little zero drift with time. Presented in Figures 5 and 6 are curves depicting the output voltage versus time of both differential transmitters following fill.

The identified problem was diagnosed as a dependence of transmitter output upon the temperature of the fill liquid. This dependence was due to the inability of the closed transmitter/connecting tubing/isolation diaphragm system to change in volume (without deflection of the transmitter diaphragms) as the volume of the purge liquid varied with change in temperature. This resulted because the isolation diaphragm was unable to increase system volume with change in fluid temperature.

To correct the identified problem, the current isolation diaphragm concept was formulated. A cylindrically-shaped diaphragm which collapses upon application of a positive pressure gradient (from the outside to the inside of the diaphragm) was selected. Testing indicated that the diaphragm was able to compensate the volume of the transmitter/tubing fluid circuit as required with change of the fluid temperature. Output versus time (with the redesigned isolation diaphragm installed) of the differential pressure transmitters following fill is presented in Figures 5 and 6.

FIGURE 5. 0-50 in H₂O Differential Pressure Transmitter Output versus Time.
Response characteristics of the redesigned isolation diaphragm/pressure transmitter system were determined by venting the capsule side of the transmitters while pressurizing the vessel. A pressure gauge with 1/4 psi divisions and a vertical water manometer with 1/10 inch divisions were also connected to the vessel during the test. Indicated in Figures 7 and 8 are the transmitter outputs versus the manometer/pressure gauge outputs over a range of vessel pressures.

As can be seen from these figures, the measurement accuracy of the 0-50 in. H₂O transmitter/isolation diaphragm is well within the accuracy of the water manometer over the pressure range of 0-20 in. H₂O. The measurement accuracy of the 0-25 psi transmitter/isolation diaphragm is within 8% even over the 0-20 in. H₂O pressure range. Over a 2-25 psi pressure range, the 0-25 psi transmitter was found to be accurate within 3.3% when calibrated to the low range.

### 3.1.4.2 Capsule Testing

Capsule testing was conducted per the previously outlined procedure. Presented in Figure 9 is a curve depicting capsule absolute pressure (as indicated by the 0-300 psia pressure transmitter) versus the steam saturation pressure (corresponding to the temperature of the flow measured by the resistance thermometer over a range of flow temperatures).
As shown in the figure, capsule pressure ceases to correspond to saturation pressures which are below atmospheric pressure. This is probably due to either incomplete purging of the capsule circuit or to vacuum leakage in the capsule circuit when pressures are below atmospheric. Because the measurement device will not be required to operate at conditions which will create sub-atmospheric pressures in the capsule, this is not considered to be a problem. The capsule was found to perform properly at temperatures above 212°F after being cooled to room temperature (creating a vacuum within the capsule), however.

For testing with saturation pressures ranging from 20-45 psia, the capsule pressure as measured with the 0-300 psia pressure transmitter agreed with the steam saturation pressure inferred from the resistance temperature probe within 8.6%.

3.1.4.3 Device Accuracy and Flow Effects

Initially, the static pressure tap consisted of a piece of 1/4 inch diameter tubing penetrating into the inner surface of the heat shield assembly. This pressure tap was adjacent to the center of the capsule assembly.

While preparing for functional testing with steam/CO₂ injection, the device was operated with steam flow only. During this period, the output from the differential pressure transmitters (which indicates the pressure difference between the capsule and the vessel flow) was found to change with time. Closer investigation indicated that steam supply pressure to the test apparatus (and thus test vessel velocity) was also changing with time due to inherent characteristics of the steam system.

The problem was thus diagnosed as a dependence of static pressure measurement upon test vessel steam velocity. This dependence of static pressure measurement upon velocity was due to flow interferences in the vicinity of the static pressure tap caused by the capsule and heat shield assemblies. Per Streeter (Reference 1, pg. 439) errors in static pressure measurement normally vary with velocity as follows:

Error = const. x (velocity)²

Or by utilizing the Darcy-Weisbach equation, errors in static pressure measurement normally vary with driving head (or pressure) as follows:

Error = const. x (ΔP)

Included as Figure 10 is a plot of static pressure measurement error versus driving head (supply pressure minus ambient pressure) obtained during testing of the initial device configuration. As can be seen in the figure, the static pressure measurement error was essentially linear with driving head; the slope of the curve is approximately 7.1 in. H₂O/psi.

To correct the identified problem, the current static pressure tap configuration was designed. After modifying the device, steam flow testing was conducted. During this testing, dependence of differential pressure transmitter output upon driving head was again observed, although the dependence was much less than that of the previous design.

Included as Figure 11 is a plot of static pressure measurement error versus driving head data obtained following installation of the redesigned pressure tap. Again, the pressure measurement error was essentially linear with driving head; the slope of the curve is approximately 0.8 inch H₂O/psi.

After conducting steam flow testing of the device (with the redesigned static pressure tap installed), functional testing with steam/CO₂ flows was performed. The device was operated with a steam supply pressure of approximately 50 psia (corresponding to a saturation temperature of 281°F). The CO₂ concentration in the flow mixture was varied from between 1 and 10 percent by weight during testing. The device was operated with no throttling of the flow; the average steam flow rate through the device was approximately 0.15 lb/sec.

Included as Figure 12 is a plot of CO₂ concentration per the measurement device versus the CO₂ concentration determined by measurement of steam and CO₂ flows. This curve was generated

FIGURE 10. Static Pressure Measurement Error versus Driving Head (Original Pressure Tap Configuration)
FIGURE 11. Static Pressure Measurement Error versus Driving Head (Redesigned Pressure Tap Configuration)

from data obtained during testing at the aforementioned conditions. As seen in the figure, measurement errors as large as 45 percent were incurred during the testing.

In view of recognized velocity dependence problems and due to the discrepancy in device measurement exemplified in Figure 12, it was decided to conduct a series of steam/CO₂ flow tests with low steam flow rates. Testing was performed with a steam supply pressure of approximately 60 psia and a steam flow rate of approximately 0.01 lb/sec. Included as Figure 13 is a summary of the data obtained during the testing.

Testing conducted at low sample flow rates yielded reasonable agreement between the device gas concentration measurement and the gas concentration indicated by flow measurement. Agreement between the two measurements was within 10 percent for gas concentrations ranging from between two and eight weight percent.

3.2 Field Testing

3.2.1 Field Testing - U.S.

3.2.1.1 Test Program

The primary objectives of the field testing program were as follows:

1) To demonstrate the operability of the device in a variety of geothermal environments.

2) To verify device measurement accuracy in a variety of geothermal environments using an alternate measurement technique.

A series of field tests at Roosevelt (Phillips Petroleum Company) and the Geysers (Union Oil Co.) were conducted to meet the outlined objectives.
3.2.1.2 Test Apparatus

Outlined in Figure 14 is a schematic depicting the configuration of the apparatus set up at each test site. Photographs of the installations at Roosevelt and the Geysers are included as Figures 15 and 16, respectively.

A separation/condensation/volumetric displacement noncondensable gas concentration measurement technique was selected for verifying the measurement accuracy of the device. The hardware required for the alternate scheme was connected in parallel to the measurement device.

The measurement device was plumbed to the proximity of the main wellhead discharge line with 1 inch piping components. Final attachment to the sampling port on the main line was made with flexible hose to eliminate the transmission of vibration to the instrumentation. A dial pressure gauge was located in the sample line to enable determination of steam conditions (in conjunction with device instrumentation). The sample flow was discharged to ambient surroundings after passing through the instrument.

The hardware for the alternate scheme consisted of a Webre-type separator, a condenser coil immersed in a water-filled drum, a condensate collection graduated cylinder, and a graduated gas collection drum. The two-phase sample flow from the wellhead was first circulated through the separator, where it was divided into two single phase flows -- one consisting of water and one consisting of a mixture of steam and noncondensable gases. The steam/noncondensable gas flow from the separator...
FIGURE 15. Roosevelt Test Apparatus

FIGURE 16. Geysers Test Apparatus
was then circulated through the immersed tubing coil where the steam was condensed. The water flowing from the coil was collected in a graduated cylinder; the noncondensable gases in the flow displaced a measured volume of water in the graduated drum. By measuring the condensate volume and noncondensable gas volume collected over a period of time, the ratio of noncondensable gas to steam in the sample flow was determined.

3.2.1.3 Roosevelt Testing

3.2.1.3.1 Test Procedure and Results

Testing using the instrument and using the alternate scheme was conducted in the Roosevelt Geothermal Field on a well owned by Phillips Petroleum Company. Data was collected using a sample flow from the main wellhead discharge line (containing two-phase flow) and on the steam line located downstream of the separator.

Testing conducted on both sampling ports consisted of obtaining gas concentration measurements using the instrument and using the alternate scheme over a range of sample pressures. At each test condition, instantaneous output from the instrument was recorded for a period of time sufficient to ensure that a representative average noncondensable gas concentration measurement was obtained. With the alternate scheme, each measurement was obtained over a 10 to 15 minute sampling period. Measurements using the two techniques were not made simultaneously. Also, one long term test (approximately 12 hours) was conducted on the steam sampling port using the device.

Due to the range of the absolute pressure transmitter installed on the instrument, testing could not be conducted at full line pressure. Sample flows were throttled at the entrance to the test apparatus to keep pressures within the range of the transmitter. Noncondensable gas concentrations at line conditions were extrapolated from the test data, however.

Included as Figure 17 is a comparison of noncondensable gas concentration measurements made on the two phase line using the device and using the alternate scheme. Figure 18 presents a comparison of measurements made on the steam line. Although measurements using both techniques were not made simultaneously, comparison is warranted due to the consistency of wellhead flow conditions throughout testing. In both of these figures, actual sample pressures have not been specified. Also, molar noncondensable gas to steam concentrations have been multiplied by an unspecified constant. The results have been presented in this manner per the request of Phillips Petroleum Company due to the proprietary nature of the information. During the 12-hour instrument test on the steam line, data consistent with those of the short term tests were obtained throughout the testing period.

Conditions in the two-phase line were such that the enthalpy (or quality) of the sample flow could be calculated from the noncondensable gas concentration data obtained at different sampling pressures. Again, the actual data cannot be presented due to proprietary considerations. However, deviation between the steam quality values calculated from data obtained using the two techniques was less than 5%.
3.2.1.3.2 Discussion of Results

As shown in Figure 17, gas concentrations measured during testing on the main wellhead discharge line using the device were somewhat higher than those measured using the alternate scheme. In extrapolating the results to line conditions, there is a 25% variation in noncondensable gas concentrations determined using the device and using the alternate scheme. There are two possible causes for the disparity between the two measurements:

1) Due to the quality of the sample flow, in using the small Webre separator installed in the apparatus, it was difficult to obtain a dry steam sample. Thus, there was probably some liquid carryover in the steam discharging from the separator, causing a low noncondensable gas to steam ratio to be measured using the alternate scheme.

2) Considerable fluctuation in the differential pressure output from the device was observed during testing. This fluctuation was caused by variation in the static pressure measurement caused by flow conditions. Noncondensable gas concentrations were calculated using the average of the minimum and maximum differential pressure observed during the testing period. Integration of the differential pressure output during the testing period would yield more precise noncondensable gas concentration measurements.

Per Figure 18, there was a considerable difference between the noncondensable gas concentration measurement obtained using the device and using the alternate scheme while testing on the steam line located downstream of the separator. In comparing the data with the results from testing on the two-phase line, it appears that the device measurement is in error. It is hypothesized that the discrepancy is caused from sampling of a superheated flow (due to the boiling point loss at separation and due to throttling of the sample flow between the main line and the device). When the device is used to measure superheated flows, low noncondensable gas concentration measurements result due to generation of erroneously high steam partial pressures in the capsule portion of the device. Superheating on the order of 1°F would account for the discrepancy observed during testing. Unfortunately, the precision of instrumentation installed in the test apparatus was not sufficient to determine if superheating of the sample flow occurred.

3.2.1.4 Geysers Testing

3.2.1.4.1 Test Procedure and Results

Testing using the instrument and using the alternate scheme was conducted in the Geysers Geothermal Field on a well owned by Union Oil Company. Nominal conditions of the discharge from the well were as follows:

- Pressure - 133 psig
- Quality - 95.8 - 98.5 percent (Union Oil Measurement)

Per Union Oil personnel at the site, quality of the well discharge was last measured during September, 1978.

Sample flows were tapped from a port located on the main wellhead discharge line upstream of the separator. All testing was conducted with sample flows at essentially the same pressure as the main wellhead line (negligible throttling of the sample flow existed due to the flow rates present and due to the configuration of the test apparatus). Unfortunately, it was not possible to operate both the instrument and the alternate measurement apparatus simultaneously due to throttling considerations.

On the first afternoon of testing, a series of measurements were made using the alternate scheme. Sampling periods for these measurements ranged from between 5 to 30 minutes. Two additional measurements using the alternate scheme were made during the following two days of testing. A summary of the measurements made using this technique are included in Table 2.

<table>
<thead>
<tr>
<th>RUN NO.</th>
<th>SAMPLING PERIOD (Minutes)</th>
<th>SAMPLE PRESSURE (psig)</th>
<th>MOLAR RATIO* (NONCONDENSABLES TO STEAM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/2/79</td>
<td>17</td>
<td>133.0</td>
<td>3.42 x 10^-4</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>132.6</td>
<td>2.02 x 10^-4</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>132.0</td>
<td>2.50 x 10^-4</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>132.1</td>
<td>2.75 x 10^-4</td>
</tr>
<tr>
<td>10/3/79</td>
<td>6</td>
<td>130.0</td>
<td>2.91 x 10^-4</td>
</tr>
<tr>
<td>10/4/79</td>
<td>12</td>
<td>131.0</td>
<td>2.55 x 10^-4</td>
</tr>
</tbody>
</table>

*Calculated assuming atmospheric pressure of 14.7 psia.

On the second day of testing, noncondensable gas concentration measurements were made using the instrument. Data from the device (capsule pressure and differential pressure via the low range transmitter) were continuously recorded for a period of approximately six hours. Included as Figure 19 is the actual output from the device over the testing period. Table 3 presents calculated values of noncondensable gas concentrations at selected times during the test (as denoted by run numbers in Figure 19). Due to a calibration problem with the 0-50 in. H2O differential pressure transmitter (caused by exposing the transmitter to a high vacuum during overnight shutdown), output from the 0-25 psi differential transmitter was recorded during the third day of testing. Data over a two hour testing period is included as Figure 20. Calculated values of noncondensable gas concentrations during this period are presented in Table 4.
FIGURE 19. Device Output at Geysers - 0-50 in. H₂O Pressure Transmitter

FIGURE 20. Device Output at Geysers - 0-25 psi Pressure Transmitter

3.2.1.4.2 Discussion of Results

As can be seen in Figure 19 and Table 3, considerable variation in noncondensable gas concentration was observed during the second day of testing. It should be noted that well conditions also varied considerably during testing (as exemplified by the measured steam saturation pressures).

Noncondensable gas concentration measurements obtained using the instrument (using the low range transmitter) approximate those acquired from the alternate measurement scheme. Due to the variable nature of the gas concentration in the sample flow, and due to the inability to make simultaneous measurements using the device and the alternate scheme, detailed comparison of results is not warranted.

Although the measurement precision was not high using the 0-25 psi transmitter (measured differentials were less than 1 psi), the results are useful in depicting relative changes in noncondensable gas concentrations. As shown in Figure 20, fluctuations in measured noncondensable gas concentrations during the third day of testing...
were much lower than those observed during the previous day's testing. Also, it should be noted that line conditions were much more stable during the third day of testing.

3.2.2 Field Testing - New Zealand

The major start on the project in New Zealand began in September 1979 with the arrival of the capsule unit and the pressure transducers.

The transducers were converted to 12 v DC operation; the two differentials maintaining their scales of 0-50" and 0-25 psi. However, the 300 psi total pressure transducer changed calibration slightly to 2.22 volts at 150 psi instead of 2.5 volts.

A sophisticated test unit is required to recalibrate this unit to avoid contamination within the diaphragm cell. So, until such a unit can be adapted, it was decided to carry out testing with a master gauge on the steam/water line.

On receipt of the new type isolating diaphragm the unit was set up.

One major change from the American unit was the static pressure tap on the high pressure side of the transducers.

Pressure tapping geometry as tested and published by Livesey Jackson & Southern - "Static hole error problem" - Aircraft Eng. Vol. 34, 1962, was incorporated.

This tapping has been found to be most satisfactory and is used exclusively by D.S.I.R. Wairakei and University of Auckland researchers in dynamic steam/water mixture pressure readings.

Instrumentation was completed by a digital voltmeter in parallel with an Eastline Angus 4" paper recorder model MS411B. A four way switch was built into the circuit to read the three transducers and battery voltage.

The first test run was at Broadlands Bore 27. Pressure 10.7 Bar, Gauge 155 psig, Enthalpy 709 BTU/lb, Dryness fraction 0.47.

One continuous reading was taken over a 20 minute period, the 25 psi differential transducer settling down to a plus or minus 25 mV reading relatively fast.

A senior chemical sampling technical officer took three flasks of separated steam using the Webre separator. The results were:

Flash 1 Flash 2 Flash 3 Gas Unit
Mole % 4.25063 5.66563 5.8011 5.82

The chemists acknowledge that our reading of 5.82 mole percent is the most correct considering residual gases (a very minor percentage) which were not determined by them.

As the unit was not rechargeable in the field, it was taken back to the Lab and modified for easier refilling. This consisted of the addition of a valve and a bleed point, both of which can be plugged after filling.

The remaining tests were run at Broadlands 22. 10 Bars, 145 psig, Dryness 99%; gas variable as required.

The test was reasonably successful; the partial pressure of the gas reading 0.64 volts (3.2 psi) was obtained within 3 minutes. However, after a further 5 minutes all the differentials drifted to read negative readings over a short period.

Several reruns were made achieving similar results.

The unit was set up over a 48 hour period in the laboratory. The capsule unit filled with distilled water pressurized by air and plugged as per procedure, the static tapping side also filled with water and pressurized by air and sealed the differential maintained a reading of 12.5 psi over the whole period and the total tapping pressure maintained 80 psi.

At no time was drift noticed.

A second test was set up again at 80 psi total pressure with 25 inches of water differential no deviation or drift was recorded over a 48 hour period.

The only explanation for the drift to date is the environment where the test was set up.

The unit was attached to a pilot condenser unit with cooling towers etc., using 2 tons steam per hour. Conditions were wet and humid, and with 3 pumps vibration is high.

The present status of the unit is that I am awaiting the finishing of a full test shed with two water (hot at 11 Bar) two steam (11 Bar) and one gas line (25 Bar 125°C) all 1" diameter schedule 40 steam pipe. The test rig is principally for the design of a pressure tapping for steam/water flow testing orifice plates etc. but will be available to gas testing.

Both the Ministry of Works and D.S.I.R. N.Z. consider the unit to show great promise and are confident that the present problems will be easily overcome.

4.0 OPERATING PROCEDURES

The following device operating procedures were developed during the course of the laboratory and field testing program.

4.1 Initial Startup

Prior to installing insulation and jacketing on the completed gas probe assembly, it is necessary to fill and purge the capsule and static pressure tap fluid circuits with water. The

1Written by: G. D. McDowell, Department of Scientific and Industrial Research, State Highway 1, Wairakei, New Zealand.
procedure for filling is as follows:

4.1.1 Static Pressure Tap Circuit

1) Obtain a tank with a capacity of approximately 2 gallons having a discharge line located at the bottom.
2) Elevate the tank to above the device (approximately 3 feet).
3) Attach the discharge line from the tank to the isolation valve positioned in the lower vent port on the high pressure housing of the 0-25 psid pressure transmitter.
4) Isolate the vessel portion of the device. Plumb a branch line from the tank discharge line to the vessel (attached to a convenient port). (NOTE: This procedure is necessary to maintain the same pressure on both sides of the static pressure tap isolation diaphragm during fill operations.)
5) Fill the tank with clean water.
6) Remove the upper vent plug from the high pressure port housing of the 0-25 psid pressure transmitter. Open the isolation valve in the lower vent port of the same pressure transmitter.
7) Allow the water to flow from the 0-25 psid pressure transmitter housing for approximately 5 minutes. Reinstall the vent plug into the housing.
8) Remove the upper vent plug from the high pressure side of the 0-50 in. H₂O pressure transmitter. Allow water to flow from the transmitter housing for approximately ten to fifteen minutes.
9) Replace the vent plug on 0-25 psid transmitter.
10) Remove the vent plug from the top of the static pressure tap isolation diaphragm housing. Allow water to flow from the housing for approximately 5 minutes.
11) Reinstall the vent plug on the 0-50 in. H₂O transmitter.
12) Remove the vent plug from the top of the static pressure tap isolation diaphragm housing. Allow water to flow from the housing for approximately 5 minutes.
13) Replace the diaphragm housing vent plug.
14) Lower the fill tank such that the water level in the tank coincides with the centerline elevation of the isolation diaphragm housing.
15) Close the isolation valve on the 0-25 psid transmitter housing. Remove the fill line and then securely cap the valve.
16) Proceed to capsule setup.

4.1.2 Capsule

1) Obtain approximately 2 gallons of water having boiling point properties characteristic of those of the geothermal flow to be sampled.
2) Place the water in a pressurizable tank having a discharge line which draws from the bottom of the tank. Pressurize the tank to approximately 30 psi.
3) Attach the pressure tank discharge line to the capsule fill valve located at the top of the device.
4) Remove the upper housing vent plug from the high pressure side of the 0-25 psid pressure transmitter.
5) Open the valves isolating the pressure tank from the capsule. Allow water to flow from the transmitter housing for approximately ten to fifteen minutes.
6) Replace the vent plug on 0-25 psid transmitter.
7) Remove the upper housing vent plug from the high pressure side of the 0-50 in. H₂O pressure transmitter. Allow the water to flow from the transmitter housing for approximately five minutes.
8) Replace the vent plug on the 0-50 in. H₂O pressure transmitter.
9) Loosen the lower portion of the pressure capsule housing on the 0-300 psia absolute pressure transmitter until water flow is present. Allow the water to flow for approximately five minutes.
10) Retighten the pressure capsule housing on the 0-300 psia transmitter.
11) Elevate the pressure tank to above the device.
12) Open the pressure tank to atmosphere. Lower the tank until the water level within it coincides with the centerline of the test vessel.
13) With the static pressure port open to atmosphere, zero and calibrate the differential pressure transmitters. Adjust the absolute pressure transmitter such that it reads atmospheric pressure. Also adjust the span on the absolute pressure transmitter.
14) Shut the capsule isolation valve. Detach the fill line from the device and then cap the valve.
15) Insulate the unit with 5 layers of one inch thick refractory fiber. Allow for access to the capsule isolation valve.
16) Initiate sample flow to the device. Allow the unit to reach thermal equilibrium (determined by monitoring capsule pressure).
17) Vent the capsule through the capsule isolation valve for approximately one second. Following venting, monitor
capsule pressure until an equilibrium condition is attained.

18) Repeat step 17 until the capsule reaches the same equilibrium pressure after two venting cycles.

19) Securely cap the capsule isolation valve. Add insulation in the vicinity of the isolation valve. Add the aluminum jacketing material to the exterior of the insulation.

4.2 Normal Operation

The procedure for normal operation of the measurement device is as follows:

4.2.1 Startup

1) Plumb the device to the line to be sampled. Make final attachment to the sampling port with a section of flexible hose to eliminate the transmission of line vibrations to the device.

2) Level the instrument.

3) Attach a suitable discharge line to the device.

4) Connect a 12 volt DC source to the input terminal box for the pressure transmitters.

5) Connect the output terminals from the pressure transmitters to a multi-pen strip chart recorder. Attach the leads from the resistance temperature probe to a digital multimeter.

6) Fully open the 1/4 inch needle valve located on the discharge end of the device.

7) Gradually initiate sample flow through the device.

8) Allow the unit to reach thermal equilibrium. Commence recording data required for determining the gas concentration of the sample flow (pressure transmitter outputs plus secondary information such as sample temperature and pressure, etc.).

9) Calculate sample noncondensable gas concentration per the procedure outlined in Appendix 4.

4.2.2 Shutdown

1) Isolate the sample flow to the vessel.

2) Uncouple electrical and instrumentation leads.

3) Detach the plumbing leading to the device.

4) Drain the unit, cool it to ambient temperature, and then fully close the inlet and outlet line valves.

5.0 DISCUSSION OF DEVICE CAPABILITIES

5.1 Mechanical Design

5.1.1 Materials

An austenitic stainless steel (Type 316) was the material selected for use in the instrument pressure boundary and internal fittings. This material was selected due to its corrosion resistance properties and due to its machine-ability and weldability.

The isolation diaphragm used in the static pressure tap line was fabricated from silicone rubber. This material was selected due to its ability to withstand high temperatures and moderately corrosive environments while maintaining flexibility.

5.1.2 Design Margins

The gas probe device will be exposed to three operating conditions -- startup, normal operation, and shutdown. Presented in Tables 5, 6 and 7 are listings of the instrument components affected during operation in each of the three modes. Also included in the Tables are listings of allowable pressures for the device components. Supplementary calculations are included in Appendix 5.

<table>
<thead>
<tr>
<th>TABLE 5</th>
<th>GAS PROBE DESIGN Pressures — Components Affected by Startup</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITEM</td>
<td>DESIGN PRESSURE*</td>
</tr>
<tr>
<td>Capsule (Dwg. No. 400003)</td>
<td>Full Vacuum (See Appendix 5)</td>
</tr>
<tr>
<td>1/8&quot; O.D. x 0.035 wall tubing</td>
<td>Full Vacuum (See Appendix 5)</td>
</tr>
<tr>
<td>Isolation Valve (Dwg. No. 400008-1)</td>
<td>Full Vacuum (Ref. Whitney Valve Co., Catalog)</td>
</tr>
<tr>
<td>Capsule Diaphragm Housing (Dwg. No. 400004)</td>
<td>Full Vacuum (See Appendix 5)</td>
</tr>
<tr>
<td>1/8&quot; Swagelok Connector (Dwg. No. 400004-1)</td>
<td>Full Vacuum (Ref. Swagelok Co., Catalog)</td>
</tr>
<tr>
<td>1/8&quot; Swagelok Male Connector (Dwg. No. 400002)</td>
<td>Full Vacuum (Ref. Swagelok Co., Catalog)</td>
</tr>
<tr>
<td>Transmitters (Dwg. No. 400002-1,2,3)</td>
<td>Full Vacuum (Ref. Vendor Specs., Appendix 3)</td>
</tr>
</tbody>
</table>

*At Startup Conditions:
Startup Conditions: [1] Capsule at full vacuum
[2] Vessel at 290 psi
[3] Ambient at 14.7 psi

Prior to and at the initiation of startup, the capsule, capsule pressure tap and fill lines, and all pressure transmitters will be exposed to nearly a full vacuum. Vessel pressure will instantaneously increase to as high as 290 psi at startup (with the capsule at full vacuum).

During normal operation, the capsule and associated pressure measurement hardware will be at a pressure only slightly lower than the vessel pressure. All pressure boundary portions of the instrument vessel will be exposed to the design pressure of 290 psi.
In order to obtain accurate gas concentration measurements, it is essential that the test capsule be maintained at the same temperature as the geothermal flow. Very small temperature differences between the test capsule and the sample fluid cause large errors in gas concentration measurements for low gas concentration flow.

Contained in Appendix 6 are calculations which quantify the effect of vessel heat losses upon gas concentration measurement accuracy. These calculations indicate that by adding a radiation shield around the capsule and by insulating the vessel with at least five inches of refractory fiber, gas concentration measurement errors due to capsule/sample flow temperature differentials will be reduced to negligible values.

5.2.1.2 Instrumentation Effects

The pressure transmitters selected for measuring the differential pressures between the test capsule and the sample flow and for measuring the absolute capsule pressure have an accuracy of 0.25 percent of the calibrated span. Presented in Appendix 7 are curves depicting the maximum possible gas concentration measurement error due to pressure transmitter accuracy.

As can be seen in Appendix 7, it is necessary to use two differential pressure transmitters to obtain the required gas concentration measurement accuracy. By using two differential pressure transmitters (ranges 0-50 in Hg0 and 0-25 psi), the error in measurement of gas concentration is less than 2 percent throughout the operating pressure range for gas concentrations of 1 percent (by weight) or greater. The error in gas concentration measurement for a flow containing 0.1 percent (by weight) noncondensable gas is less than 8 percent for steam saturation pressures of 36 psi or greater.

5.2.1.3 Boiling Point Effects

Boiling point elevation of brines due to dissolved solids has a pronounced effect upon the accuracy of the measurement device. If pure, distilled water is used in the capsule portion of the unit, this effect upon measurement accuracy is quantified in Appendix 8. Due to the high sensitivity of measurement accuracy to brine composition, it is necessary to use a brine having the same characteristics as that being sampled in the device capsule.

5.2.2 Experimentally Determined Accuracy

During laboratory testing, device noncondensable gas concentration measurements were found to agree within 10 percent of measurements made via flow metering for noncondensable gas concentrations ranging from 2 to 8 percent by weight. This testing was conducted with steam saturation pressures of approximately 50 psig. As shown in Appendix 7, measurement accuracy is highly dependent upon steam saturation pressures with lower accuracy corresponding to lower pressures. Thus, the measurement error of the device would be expected to be less than 10 percent for
steam saturation pressures greater than 50 psig. Direct comparison of device measurement with that of an alternate scheme was possible only during testing conducted at the Roosevelt Area for previously discussed reasons. During testing on a two phase line in the Roosevelt Area, extrapolation of data indicated that device measurement differed approximately 25 percent from that of the alternate technique.

As previously discussed, it is anticipated that device measurement accuracy could be improved by implementing the instrument modifications outlined in the Commercialization Plan section of this report.

5.3 Measurement Accuracy -- Enthalpy

The accuracy of the device in measuring the enthalpy (or quality) of a flow is a function of (1) the quality of the flow, (2) the ratio of noncondensable gases to steam in the flow, (3) the ratio of sample pressure to line pressure at which data is obtained, and (4) the accuracy of the device in measuring noncondensable gas concentrations. Included as Appendix 1 is a discussion of device enthalpy measurement capability.

As presented in Appendix 1, the device can measure the quality of a flow with reasonable accuracy when:

1) Noncondensable gas concentrations are relatively high (1 mole percent or greater).
2) Line steam qualities are relatively low (50 percent or less).
3) Small sample pressure/line pressure data ratios are possible (0.5 or less).

Testing conducted during development of the device was not sufficient to experimentally verify the enthalpy measurement capabilities of the instrument.

5.4 Device Limitations

5.4.1 Flow Velocity

With the current device configuration, there is an error in static pressure measurement which is proportional to the square of the sample flow velocity passing through the device. Associated with the error in static pressure measurement is an error in measurement of noncondensable gas concentrations. The error in measurement can be minimized by operating the device at a low, essentially constant velocity. This can be achieved by throttling the sample flow on the outlet side of the test vessel. Included in Appendix 9 are calculations outlining noncondensable gas concentration measurement errors versus sample velocity. As shown in these calculations, the device will yield acceptable gas concentration measurement accuracy if it is operated with sample velocities below 30 ft/sec in the static pressure tap pipe.

A device modification which would reduce the effect of velocity upon static pressure measurement is discussed in the Commercialization Plan section of this report.

5.4.2 Two Phase Flow

Entrained liquid or mist in a two phase sample flow has the potential of producing errant static pressure measurements. This effect was illustrated during testing of the device at the Roosevelt Geothermal Area. Large fluctuations in measured sample flow static pressure were observed during testing on the two phase line. However, the average of the measured noncondensable gas concentrations approximated results obtained via an alternate measurement technique.

It is envisioned that dampening or integration of the output from the device will enable precise measurement of noncondensable gas concentrations in two phase flow. This device modification is outlined in the Commercialization Plan section of the report.

5.4.3 Phase Disproportionation

The capability of the instrument is that of measuring the molar ratio of noncondensable gases to the steam portion of a saturated steam/water geothermal discharge. No determination of the concentration of noncondensables is made. Thus, chemical measurements on the brine as well as gas phase noncondensables measurements are required to determine the total amount of noncondensables in the discharge.

In sample flows which contain a substantial percentage of steam, the bulk of the noncondensable gases are present in the vapor phase of the sample flow. For small percentages of flashing, significant amounts of noncondensables are present in both the liquid and gas phase. Thus, chemical measurements on the brine as well as gas phase noncondensables measurements are required to determine the total amount of noncondensables in the discharge.

In sample flows which contain a substantial percentage of steam, the bulk of the noncondensable gases are present in the vapor phase of the sample flow. Per Ellis and Mahon (Reference 2, pg. 279), in a typical geothermal discharge having CO2 as the predominant noncondensable gas, 90 percent or more of the CO2 in the total discharge is contained within the vapor phase for flows having steam qualities of 10 percent or greater. Thus, in such flows, gas phase noncondensables measurements yield a good approximation of the amount of noncondensable gases in the total discharge.

5.4.4 Scale and Solids Deposition

During the operation of the device in a two phase flow, it is possible that scale could be deposited in the vicinity of the static pressure tap. This deposition could affect the accuracy of static pressure measurement.

The amount of field testing that has been conducted to date was insufficient to assess the effect of scaling upon device performance. If future testing indicates that a problem does exist, it will be necessary to periodically clean the static pressure tap assembly.
5.4.5 Sample Superheating

Due to the principle of operation of the device, the measurement instrument functions properly only when used to sample saturated steam/water flows. When the device is used to measure superheated flows, low noncondensible gas concentration measurements result due to the generation of erroneously high steam partial pressures in the capsule portion of the device. This problem was demonstrated during Roosevelt field testing conducted on a steam line located downstream of a separator.

Because the device can only sample saturated flows, care will have to be exercised in its application. When used to sample a very dry saturated flow, the configuration of the attachment of the device to the main line will have to be such that negligible throttling of the sample flow occurs. Sample flows obtained from steam discharge lines from separators could be superheated by the boiling point loss at separation as well as by throttling of the steam.

It could be possible to measure noncondensable gas concentrations in superheated flows by coupling the measurement device to a desuperheater.

6.0 COMMERCIALIZATION PLAN

6.1 Device Modification

During the course of the testing program, it became evident that incorporation of some instrumentation modifications would improve measurement accuracy and permit easier operation of the device. These recommended modifications are as follows:

1) Extension of the main body of the instrument to enable repositioning of the static pressure tap to directly upstream of the capsule assembly.

2) Dampening of the output from the differential pressure transmitters (by either mechanical or electrical means).

3) Addition of isolation valves to the differential pressure transmitters.

Repositioning of the static pressure tap to directly upstream of the capsule assembly would decrease the velocity dependence problems present in the current design. Presently, the static pressure tap is located in a section of 1 inch pipe located upstream of the vessel portion of the device (which is fabricated from 2 inch pipe). The improved performance would be realized from decreased sample velocities in 2 inch versus 1 inch pipe and from decrease in the pressure difference in the sample flow between the point of static pressure measurement and the location of the capsule assembly.

During testing, sample flow static pressures were found to fluctuate considerably. These fluctuations were propagated through the transmitters and thus result in considerable noise in the recorded signal. A more interpretable signal and hence more accurate reading of noncondensible gas concentration would be obtained by dampening either the static pressure tap line or the output from the differential pressure transmitters (via an integrating circuit).

During the storage of the instrument at ambient temperature, a high vacuum exists in the capsule/pressure transmitter portion of the device. At times, this vacuum causes a drift in the calibration of the low range differential pressure transmitter, necessitating capsule venting and transmitter recalibration. The addition of isolation valves to the transmitter connection lines would correct this problem.

6.2 Further Testing

Following implementation of the outlined device modifications, additional laboratory testing of the instrument is recommended. This testing will assess the effect of the modifications upon device measurement accuracy, determine device response characteristics when exposed to sample pressure and gas concentration transients, and will assess the long term reliability of the device.

6.3 Commercialization

Following completion of device modification and testing, a brochure describing instrument design and capabilities will be prepared. This brochure will be distributed to companies and organizations involved in geothermal energy utilization. The response to this distribution will be used to assess the market potential of the device.

Upon verifying the market for the device, preparations for manufacturing will be made. The design of the device will be re-reviewed to ensure that applicable codes and standards are satisfied and that no safety concerns exist. Detailed fabrication and assembly procedures as well as associated quality assurance and quality control programs will be developed.

To ensure successful introduction of the device to the geothermal industry, it will probably be necessary to provide consulting services to the initial purchasers. On site assistance during initial startup and operation of the device would aid in training personnel to use the device and would facilitate expedient solution of any problems encountered. This close cooperation with initial purchasers would also enable compilation of a record of device operating experiences in a variety of geothermal environments.

7.0 ACKNOWLEDGEMENTS

Appreciation is expressed to Lawrence Berkeley Laboratory for providing support for the project under the Geothermal Reservoir Engineering Management Program. The technical review provided by J. H. Howard, P. Rapier, and R. Fulton of LBL throughout the project was very beneficial.

The efforts of G. D. McDowell of the New
Zealand Department of Scientific and Industrial Research were of primary importance during initial design of the device and during the field testing program. The DSIR’s support of Mr. McDowell during the New Zealand field testing is appreciated.

Laboratory facilities provided by the Mechanical Engineering Department of the University of Utah were instrumental in the development of the device. The cooperation and assistance of Phillips Petroleum Company and of Union Oil Company in providing facilities for and in reviewing data from the field testing program are greatly appreciated.

8.0 REFERENCES


APPENDIX 1

DISCUSSION OF DEVICE ENTHALPY MEASUREMENT CAPABILITY

Configuration:

\[ \text{Wellhead Discharge Line} \]

\[ P_1, T_1, X_1, h_1, n_1 \]

\[ \text{Sampling Conditions} \]

\[ P_2, T_2, X_2, h_2, n_2 \]

\[ P = \text{Pressure} \]
\[ T = \text{Temperature} \]
\[ X = \text{Quality} \]
\[ h = \text{Enthalpy} \]
\[ n = \text{Mole Fraction Noncondensible Gas to Steam} \]

Governing Equations:

1. \[ X_1 = \frac{h_1 - h_f}{h_f g_1} \]

2. \[ X_2 = \frac{h_2 - h_f}{h_f g_2} \]

Assuming a constant enthalpy process:

\[ h_1 = h_2 \] or

3. \[ h_f g_1 X_1 + h_f = h_f g_2 X_2 + h_f \]

4. \[ n_1 = \left( \frac{\text{No. Moles Gas}}{\text{No. Moles Steam}} \right) \]

5. \[ n_2 = \left( \frac{\text{No. Moles Gas}}{\text{No. Moles Steam}} \right) \]

6. \[ X_1 = \left( \frac{\text{No. Moles Steam}}{\text{Total Moles H}_2\text{O}} \right) \]

7. \[ X_2 = \left( \frac{\text{No. Moles Steam}}{\text{Total Moles H}_2\text{O}} \right) \]

Assuming no interaction of noncondensables with liquid phase:

8. \[ X_1 = \left( \frac{\text{No. Moles Steam}}{\text{No. Moles Steam}} \right) = n_2 \]

\[ X_2 = \left( \frac{\text{No. Moles Steam}}{\text{No. Moles Steam}} \right) \]

or

\[ X_1 = X_2 \frac{n_2}{n_1} \]

Substituting 8) into 3) and solving for \( X_1 \):

9. \[ X_1 = \frac{h_f - h_f}{h_f g_1 = (h_f g_2) \frac{n_2}{n_2}} \]
NOTE: The above analysis neglects noncondensible gas/liquid phase interactions. For increased accuracy, these interactions should be considered via use of Henry's Law for gas solubility and Raoult's Law for vapor/liquid solution equilibrium.

Instrument Accuracy

To assess the accuracy of the device in measuring steam quality, the maximum error in \( X_1 \) was calculated using 9) over a range of sample pressures, line qualities, and noncondensable gas concentrations. In 9), the enthalpies were assumed to be absolute values; \( n_1 \) and \( n_2 \) were assigned uncertainties based upon device capabilities. The results are shown in the following figures.

As shown in the figures, the device can be used to measure line quality where:
1) Noncondensible gas concentrations are relatively high.
2) Line steam qualities are relatively low.
3) Small sample pressure/line pressure ratios are possible.

FIGURE A1-1. Maximum Steam Quality Measurement Error Vs. Nondimensionalized Sample Pressure — Molar Ratio Noncondensables to Steam = 0.1

FIGURE A1-2. Maximum Steam Quality Measurement Error Vs. Nondimensionalized Sample Pressure — Molar Ratio Noncondensables to Steam = 0.1
NOTES:

1. Use 1/4" stainless steel tube and Swagelok stainless steel fittings as equipped.
NOTES:
1. BREAK ALL EDGES .005/.010 RAD. UNLESS OTHERWISE SPECIFIED

**2. SHIELDED ARC WELDS**

E-316 FILLER
NOTES:
1. BREAK ALL EDGES .005/.010 RAD. UNLESS OTHERWISE SPECIFIED

3. N. S. NATIONAL SEMICONDUCTOR
2. SHIELDED ARC WELD E-308 FIlLED

REVIZIONS

<table>
<thead>
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<th>APPROVED</th>
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<tr>
<td>4-C</td>
<td>1</td>
<td>DELETE DIAPHRAGM, SEAL, WELD VENT</td>
<td>8/18</td>
<td>C.J.B.</td>
</tr>
</tbody>
</table>

DIAPHRAGM                    NS-LX 4000 SS 5/16  
DIAPHRAGM BODY                4000 SS  
VENT GASKET                   4000 SS  
DIAPHRAGM SEAL                N.S. LX 4000 SS  
DIAPHRAGM PLUG 4000 SS  
CAP CONNECTOR 5/16 TAPER 5050 - 5/16 5/6
NOTES: 1. BREAK ALL EDGES .005/.010 RAD. UNLESS OTHERWISE SPECIFIED
2. SHIELDED ARC WELDS

E-316 FILLER

NOTES: 1. BREAK ALL EDGES .005/.010 RAD. UNLESS OTHERWISE SPECIFIED
2 SHIELDED ARC WELDS
E 3/16 FILLE

NOTES: 1. BREAK ALL EDGES .005/.010 RAD. UNLESS OTHERWISE SPECIFIED
E. SHIELDED ARC WELDS

E-316 FILLER

NOTES: 1. BREAK ALL EDGES .005/.010 RAD. UNLESS OTHERWISE SPECIFIED
NOTES: 1. BREAK ALL EDGES .005/010 RAD. UNLESS OTHERWISE SPECIFIED
NOTES: 1. BREAK ALL EDGES .005/.010 RAD. UNLESS OTHERWISE SPECIFIED
NOTES:
1. BREAK ALL EDGES .005/.010 RAD. UNLESS OTHERWISE SPECIFIED
2. FABRICATE END BLOCK INTEGRALLY WITH FLANGE TO ENSURE HOLE ALIGNMENT. PLACE ALIGNMENT MARK ON PARTS AS SHOWN.
NOTES:
1. BREAK ALL EDGES .005/.005 RAD. UNLESS OTHERWISE SPECIFIED.
2. SEE NOTE 2 DRAWING 400016

SECTION A-A

AUXILIARY VIEW B-B
NOTES: 1. BREAK ALL EDGES .005/.010 RAD. UNLESS OTHERWISE SPECIFIED
NOTES: 1. BREAK ALL EDGES .005/.010 RAD. UNLESS OTHERWISE SPECIFIED
NOTES:

1. BREAK ALL EDGES .005/010 RAD. UNLESS OTHERWISE SPECIFIED
2. SHIELDED ARC WELDS E-316 FILLER
SECTION A-A

5. SURFACE ROUGHNESS OF INTERIOR PIPE MUST BE LESS THAN 300 MICRO INCH.

4. THE EDGE OF THE HOLE ON THE INSIDE OF THE PIPE MUST HAVE NO BURRS. EDGE MAY BE VERY SLIGHTLY ROUNDED.

3. RADIUS 1 END OF PART 1 TO 1.52 PIPE TO ASSEMBLY.

2. SHIELDED ARC WELDS E-316 FILLER.

- A-A:

NOTES:
1. BREAK ALL EDGES 0.05/0.10 RADIUS UNLESS OTHERWISE SPECIFIED.

6 PLACES

SEE NOTE 3
SEE NOTE 4

1" NPT

1" NPT

2.0

4.0

6.0

22.0

1/8" REAMER
1 DIAPHRAGM HOUSING

2 HOUSING COVER

3 DIAPHRAGM

4 GASKET

---

Details - Static Pressure Tap Diaphragm

<table>
<thead>
<tr>
<th>Material Code</th>
<th>Material</th>
<th>Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gasket</td>
<td>Garlock 506/7735</td>
<td>Asbestos</td>
</tr>
<tr>
<td>2</td>
<td>Diaphragm</td>
<td>ASTM F145</td>
<td>Silicone Diaphragm</td>
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<tr>
<td>3</td>
<td>Housing Cover</td>
<td>-</td>
<td>316 Stainless Steel</td>
</tr>
<tr>
<td>4</td>
<td>Diaphragm Housing</td>
<td>-</td>
<td>316 Stainless Steel</td>
</tr>
</tbody>
</table>

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Assembly |

Part No: 400024
APPENDIX 3

PRESSURE TRANSMITTER SPECIFICATIONS

PRODUCT BULLETIN NO. 64

Output: 0-5V DC Fully Isolated
Pressure Ranges: 0-5" W.C. Fully Isolated through 0-25 PSID
Maximum Pressure Overload: 2000 PSID—Bidirectional
Supply Input Voltages: 12 & 24V DC or 115 & 230V AC
Type: 4-wire

This transmitter is designed for differential pressure applications typical for process control installations, including flow measurements with orifice plate and flow tube devices. The Model 704 can withstand bidirectional line pressure overloads up to 2000 PSI. Standard ranges are 0-5" W.C. through 0-25 PSI Differential. These units can also be operated to a 10 PSI vacuum on either or both pressure ports.

The pressure cavity will accept any fluids compatible with 316 stainless steel and Hastelloy C. Pressure flanges are zinc plated carbon steel or optionally 316 stainless. Pressure ports are 3/8" NPT on 23/4" centers; flange adapters are available for conversion to 3/8" NPT and center-to-center dimensions of 2" or 2½". Two 3/8" NPT purging ports are provided in each pressure flange.

The Model 704 includes Viatran's exclusive field calibration system providing a standardized calibration signal at 100%, operated by a PC toggle switch. Zero and span adjustment is ±25% FSPR. Interchangeable electronic chassis are another feature standard to the 700 Series transmitters. 700 Series enclosures are weatherproof and have been designed to meet the requirements for Class I, Group C & D, Division 1 & 2 hazardous locations. The 24V DC input instruments have been designed for intrinsic safety.
Dimensions

Specifications

Full Scale Pressure Range (PSI)
0-15, 25, 40, 60, 75, 100, 150, 200, 250 PSI

Differential Base Pressure
2000 PSI

Pressure Reference Pressure
Not applicable. See Pressure Capsule Material

Supply Voltage
Model 704-12: 12V DC
Model 704-24: 24V DC

Regulation
Less than ±0.5% over full supply voltage range

Output Signal
0-5V DC

Load Impedance
1 Kiloohm minimum

Accuracy
Better than ±0.25% FSIR of calibrated span including effects due to linearity and hysteresis.

Repeatability
Better than ±0.1% FSIR

Combined Zero & Span Temperature Effects on Accuracy
Not Applicable

Compensated Temperature Limitation
-20 to +110°F based on actual operating temperature.

Temperature Limits
-30 to +125°F

Range Adjustment
25% FSIR screwdriver adjustable at PCB board-mounted potentiometer. PTM33 provides external adjust.

Range Calibration Signal
100% calibration signal provided by maintain-contact toggle switch.

Range Calibration Signal Accuracy
Better than ±1.0% FSIR. Exact pressure to output correlation data provided on calibration data card.

Test Output
0-5V DC

Ripple
Model 704-12: Less than ±0.06% FSIR
Model 704-24: Less than ±0.06% FSIR
Model 704-115: Less than ±0.15% FSIR

Circuit Protection
Potentiometer does not affect calibration. Units operating from A/C supply are fuse protected. Units operating from D/C supply are fuse protected. Units require a fuse rating of 24 volts - above 20 volts to 50 amperes at 0.02 milliseconds. 12 volts - above 10 volts to 50 amperes at 0.02 milliseconds.

Insulation Resistance
Better than 10 Megohms at 500 VDC

Proof Pressure
±300 PSI single ended with less than ±0.5% FSIR drift in calibration. PTM54 provides ±300 PSI optional.

BURST Pressure
750 PSI

Long-Term Stability
Better than ±0.25% FSIR over six months.

Resolution
Infinite

Frequency Response
Flat to 7 Hz

Shock & Vibration
Less than 2.5 g's per G, except normal to diaphragm. Negligible error in remaining two planes.

Housing & External Cover Material
Copper-free cast aluminum with weather and chemical resistant epoxy coating. PTM29 provides Nuff protection for severe corrosion environment.

Pressure Capsule Material
316 and Hastelloy C stainless steel and Viton o-ring.

Pressure Flanges are Grove panel steel or 316 stainless steel plugs as required.

Process Pressure, Port (P)
1/8" NPT female, supplied with 3/4" Multiflange plate or 316 stainless steel plugs as required.

Reference Pressure, Port (LO)
See Process Pressure Ports

Purging Port
1/8" NPT female, supplied with Cadmium plated steel or 316 stainless steel plugs as required.

Electrical Connection
Integral mounting flange provides bushing and mounts to Viatran "Z" pipe mounting bracket Part #PTA1

Enclosure Classification
Weatherproof enclosures designed for Class 1, Group C & D, Div. 1 & 2 hazardous locations.

Weight
Less than 12 lbs. (4.72 Kilograms)

* Best Fit Straight Line

** Measured fluid temperature in excess of the compensated temperature limit may be acceptable depending on ambient temperature conditions.

Viatran
CORPORATION
300 INDUSTRIAL DR • GRAND ISLAND, N Y 14072
TEL 716-773-1700 • TWX 710 260-1353

52
PRODUCT BULLETIN NO. 42

Model 701

Output: 0-5V DC fully isolated
Pressure Ranges: 0-5 thru 0-15,000 PSI
Supply Input Voltages: 12 & 24V DC or 115 & 230V AC
Type: 4 wire only

This transmitter is designed for medium and high pressure ranges from 0-5 thru 0-15,000 PSI. Like other units in the 700 Series, it delivers a 0-5V DC output proportional to applied pressure. It is available with a variety of input voltage options, but all provide the 5V output signal in a four wire system. The Model 701 can be used for both gage and vacuum pressures and a special range is available for 3-15 PSI applications.

The pressure cavity is suitable for corrosive applications and will accept any fluids compatible with 17-4, 17-7 or 303 stainless steels. An all inconel pressure cavity is available as an optional modification. Also available as an optional modification is a ¼” NPT purging port. For out of service cleaning the pressure cavity can be completely exposed by removing the pressure cap.

The Model 701 includes the integral 100% FSPR calibration system, full scale zero control, span control sufficient to provide a ±0.25% ranging adjustment and other features standard to the 700 Series transmitters. 700 Series enclosures are weather tight and have been designed to meet the requirements for Class 1 Group C & D applications. 24V DC input types have been designed for intrinsic safety.
Dimensions

Specifications

Full Scale Pressure Range (FSPR)
0.5, 10, 15, 25, 50, 100, 200, 300, 500, 1000, 2000, 3000, 5000, 10,000 and 15,000 PSI. Also, 0.5, 10 and 15 PSI vacuum and 3-15 PSI gage pressure reference cavity is common with conduit connections.

Differential Base Pressure
Not Applicable.

Reference Pressure
Model 701-12: 12 VDC ±2.5 VDC 4 wire
Model 701-24: 24 VDC ±2.5 VDC 4 wire
Model 701-115: 105-125 VDC 4 wire
Model 701-230: 220-240 VDC 50 Hz 4 wire

Regulation
Less than ±0.1% change in output over supply voltage range

Output Signal
0-5 V DC fully isolated

Load Impedance
Not Applicable.

Accuracy Best Fit
Better than ±0.35% of calibrated span including errors due to linearity and hysteresis.

Repeatability
Better than ±0.1% FSPR
Less than ±1.5% FSPR per 100°F
Less than ±0.75% FSPR per 100°F

Combined Temperature Effects
Less than ±0.75% FSPR per 100°F

Combined Pressure Effects For Electronic Chassis When Supplied Separately
Less than ±0.75% FSPR per 100°F

Compensated Temperature Limits
0 to 180°F (See modifications) Based on actual operating ambient temperature of electronics chassis.

Diaphragm Temperature Limits
-30 to +250°F (See modifications)

Operating Temperature Limits
-65 to +250°F

Range Adjustment
±25% FSPR screwdriver adjustable from panel front.

Range Calibration Signal
100% FSPR calibration signal operated from panel front push button. Five point calibrate system optional. (See modifications)

Range Calibration Signal Accuracy
Less than ±1%. Exact pressure to output correlation data provided on calibration data card shipped with unit.

Test Output
0-5V DC ±25% FSPR screwdriver adjustable from panel front.

Zero Adjustment
Less than ±5% over full adjustment ranges

Interaction Between Zero & Span Ripple
Model 701-12: Less than ±0.06% FSPR
Model 701-24: Less than ±0.08% FSPR
Model 701-115: Less than ±0.15% FSPR
Model 701-230: Less than ±0.15% FSPR

Proof Pressure
Less than ±0.75% FSPR per 100°F

Burst Pressure
Less than 20.75% FSPR per 100°F

Long-Term Stability
0°F to 180°F (See modifications) Based on actual operating ambient temperature of electronics chassis.

Resolution
Better than 0.25% of FSPR over full adjustment ranges

Position Sensitivity
Better than 20% of FSPR

Frequency Response
Less than 0.25% of FSPR per 100°F

Vibration Error
Less than ±0.25% per 0.1 g

Housing & External Cover Material
Copper free cast aluminum with weather and chemical resistant epoxy coating. 303, 17-4 PH, 17-7 PH stainless steels and Buna-N o-ring. Includes materials wetted by process fluids. (See modifications)

Process Pressure Port

Reference Pressure Port

Purging Port

Electrical Conduit Connection

Mounting

Enclosure Classification

Nameplate & Pressure Capsule Material

Pressure Capsule Material

Total Circuit Capacitance

Total Circuit Inductance

Total Circuit Time Constant

Weight

Circuit Protection

Viatran CORPORATION
300 INDUSTRIAL DR. GRAND ISLAND N.Y. 14072
TEL. 716-773-1700. TWX. 710-260-1353
APPENDIX 4
NONCONDENSABLE GAS CONCENTRATION
CALCULATION PROCEDURE

Idealizing the noncondensable gas/steam mixture as a mixture of perfect gases:

\[
P_t V = N_t RT
\]

Where:
- \( P_t \) = Total pressure of mixture
- \( V \) = Volume of mixture
- \( N_t \) = No. of moles in mixture
- \( R_t \) = Gas constant
- \( T \) = Mixture temperature

Utilizing Dalton's rule for partial pressures:

\[
P_s = \frac{N_s RT}{V_s}
\]

\[
P_g = \frac{N_g RT}{V_g}
\]

Where subscripts denote:
- \( s \) = Steam properties
- \( g \) = Noncondensable gas properties

\[
\frac{P_g}{P_s} = \frac{N_g RT}{N_s RT} = \frac{N_g}{N_s} \text{ (Molar Ratio)}
\]

Utilizing Amagat's rule for partial volumes:

\[
V_g = \frac{N_g RT}{P}
\]

\[
V_s = \frac{N_s RT}{P}
\]

\[
\frac{V_g}{V_s} = \frac{N_g RT}{N_s RT} = \frac{N_g}{N_s} \text{ (Volume Ratio)}
\]

\[
\frac{P_g}{P_s} = \frac{N_g}{N_s} \cdot \frac{V_s}{V_g}
\]

Ratio of partial pressures equals molar and partial volume ratio

To account for non-ideal behavior of gases, the compressibility factor can be introduced to the perfect gas equation of state as follows:

\[
P_e V = ZN_t RT
\]

Where:
- \( Z \) = Compressibility factor
- Other variables as previously defined

Utilizing Dalton's Rule for partial pressures:

\[
P_s = \frac{Z_s N_s RT}{V_t}
\]

\[
P_g = \frac{Z_g N_g RT}{V_t}
\]

(subscripts as previously defined)

or:

\[
\frac{P_g}{P_s} = \frac{Z_g N_g RT}{Z_s N_s RT} = \frac{Z_g N_g}{Z_s N_s}
\]

or:

\[
\frac{N_g}{N_s} = \left(\frac{P_s}{P_g}\right) \left(\frac{Z_s}{Z_g}\right)
\]

On a molar volume basis:

\[
\hat{V}_s = \frac{V_s}{N_s}
\]

\[
\hat{V}_g = \frac{V_g}{N_g}
\]

Where:
- \( \hat{V}_s \) = Molar volume of steam
- \( \hat{V}_g \) = Molar volume of gas

or:

\[
\hat{V}_s = \frac{V_s}{N_s} = \frac{N_g}{N_s}
\]

\[
\hat{V}_g = \frac{V_g}{N_g} = \frac{N_g}{N_s}
\]

Thus:

\[
\frac{N_g}{N_s} = \left(\frac{P_s}{P_g}\right) \left(\frac{Z_s}{Z_g}\right) \hat{V}_s
\]

Utilizing Amagat's rule for partial volumes:

\[
V_g = \frac{Z_s N_s RT}{P_t}
\]

\[
V_s = \frac{Z_s N_s RT}{P_t}
\]

\[
\frac{V_g}{V_s} = \frac{Z_s N_s RT}{Z_s N_s RT/PT} = \left(\frac{Z_s}{Z_g}\right) \left(\frac{N_g}{N_s}\right)
\]

If the molar weights of the constituents are known, then:

\[
\frac{N_g}{N_s} \hat{V}_g = \frac{V_g}{V_s}
\]

Where:
- \( \hat{V} \) = Molar weight of component
- \( W \) = Mass of component
- Subscripts as previously defined

Using the device:

- \( P_g \) = Output from 0-50 in. H₂O or 0-25 psid differential pressure transmitter
- \( P_s \) = Output from 0-300 psia absolute pressure transmitter

Calibration Constants:

- 0-50 in. H₂O unit = 9.99 in. H₂O/VDC
- (Low and high range calibration)
APPENDIX 5
MECHANICAL DESIGN CALCULATIONS

Gas Probe Stress Calculations

Capsule Collapsing Pressure

\[ P = \frac{86,670}{D} - 1386 \quad (\text{Machinery's Handbook, pg. 448}) \]

Where:
- \( P \) = External collapsing pressure (psi)
- \( t \) = Wall thickness (in)
- \( D \) = Outside Diameter (in)

For 3/8" OD x .035 wall tube

\[ P = \frac{86,670 \times 0.035}{0.375} - 1386 = 6703 \text{ psi} \]

⇒ Capsule will not collapse at startup

1/8" OD Tube Collapsing Pressure

\[ P = \frac{86,670 \times 0.035}{0.125} - 1386 = 22,682 \text{ psi} \]

⇒ Tube will not collapse at startup

Diaphragm at Vacuum

\[ \sigma = \frac{14.7 \text{ psi} \times \pi (0.25\text{in})}{4} = 3 \text{ lb.} \]

\[ \tau = \frac{3 \text{ lb.}}{0.458 \text{ in}^2/\text{in} \times 0.5 \text{ in}} = \text{low} \]

\[ \tau = 17 \text{ psi} @ P = 300 \text{ psi} \]

Weld on Swagelok Connector:

Allowable Threaded Pipe Pressure

\[ \tau = \frac{2 (\text{tm} - A)SE}{1 - (y)\frac{D}{P} (\text{tm} - A)} \]

Where:
- \( \text{tm} \) = Minimum pipe wall thickness, in.
- \( P \) = Maximum internal pressure, psi
- \( SE \) = Maximum allowable stress, psi
- \( D \) = OD of pipe, in.
- \( y \) = Temperature coefficient
- \( A \) = Allowance for threading

Solving for \( P \):

\[ P = \frac{PD}{2(\text{SE} + \text{Py})} + A \quad (\text{Marks Handbook, 8th Ed., pg. 8-149}) \]

Table:

<table>
<thead>
<tr>
<th>Pipe Size</th>
<th>A</th>
<th>Pallow</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2&quot; sch. 40</td>
<td>.05714</td>
<td>2117 psi</td>
</tr>
<tr>
<td>1&quot; sch. 40</td>
<td>.06957</td>
<td>1635 psi</td>
</tr>
<tr>
<td>2&quot; sch. 40</td>
<td>.06957</td>
<td>1194 psi</td>
</tr>
</tbody>
</table>

Flange and End Block

\[ 6-1/4-20 \text{ UNC Cap Screws. Bolt Center} = 3.10" \]

Force exerted on connection =

\[ 300 \text{ psi} \times \frac{\pi (2.38 \text{ in})^2}{4} = 1334 \text{ lbs.} \]

Stress in Cap Screws -

\[ \sigma = \frac{1334 \text{ lbs.}}{6(0.0269 \text{ in})^2} = 8,270 \text{ psi} \quad \text{assuming no preload} \]

Assuming y.p. = 30,000 psi

\[ F.S. = \frac{30,000}{8,270} = 3.63 \]

Shear in Flange -

\[ \tau = \frac{1334 \text{ lbs.} \times (0.5 \text{ in}) (2.38 \text{ in})}{14} = 357 \text{ psi} \Rightarrow \text{F.S. High} \]
Shear in Flange Weld -
\[ \tau = \frac{1334 \text{ lbs.}}{\pi(1/8')(2.38')} = 1000 \text{ psi} \rightarrow \text{F.S. High} \]

Bending in Flange -
\[ M = 1334 \text{ lbs.} \times .36'' = 480 \text{ in-lbs} \]
\[ \sigma = \frac{MC}{I} = \frac{(480 \text{ in-lbs})(.25 \text{ in})}{.5(2.38')^3} = 6.88 \text{ psi} \rightarrow \text{F.S. High} \]

Static Pressure Tap Diaphragm Assembly

Cover:

\[ \sigma_{\text{max}} = 3a^2 \text{ (Spotts, Design of Machine Elements, Eq. 12-68)} \]
\[ q = 300 \text{ psi} \]
\[ a = \frac{1.13}{2} \text{ in.} \]
\[ h = 0.5'' \]
\[ \sigma = \frac{3(300 \text{ lb/in}^2)(1.13'')^2}{4(0.5 \text{ in})^2} = 287 \text{ psi (F.S. High)} \]

Body:

\[ \sigma_{\text{max}} = \frac{3a^2}{8} \text{ (Spotts, Design of Machine Elements, Eq. 12-4, 12-5)} \]
\[ b = \frac{2.63}{2} = 1.32 \]
\[ a = \frac{1.13}{2} = 0.57 \]
\[ \sigma_{\text{max}} = \frac{(0.57)^2(300)}{1.32^2 - .57^2} (1 + \frac{1.32^2}{0.57^2}) = 437 \text{ psi (F.S. High)} \]

Cap Screws
\[ F = 300 \text{ psi} \times \frac{(1.13)^2}{4} = 300.86 \text{ lbs.} \]
\[ \sigma = \frac{300.86 \text{ lb.}}{(6)(.0265 \text{ in}^2)} = 1864 \text{ psi F.S. High} \]
Problem 2 - Calculate the temperature of the test capsule.

Convective heat transfer coefficient on the outside of test capsule:

\[
\bar{h}_c A_t (T_{\text{steam}} - T_{\text{capsule}}) = \epsilon \sigma (T_{\text{capsule}} - T_{\text{Shell}})
\]

where:
- \( A_t = \frac{\pi}{12} (0.375 \text{ ft})^2 + 2\pi \left( \frac{0.375}{12} \text{ ft} \right)^2 \)
- \( \epsilon = 0.8 \) (Stainless @ 500°F)
- \( T_{\text{Shell}} = 399.79^\circ \text{F} \) (using 5" of insulation)

Solve by Trial and Error for \( T_{\text{capsule}} \)
Shield is a Perfect Absorber of Radiation
From The Shield.

3) Effect of Gases Upon Radiation is Neglected.

Note: All of these assumptions yield a conservatively low value of the capsule temperature.

Heat Balance On Shield:

\[ h_c A_s (T_{steam} - T_{shield}) + \epsilon \sigma (T_{capsule} - T_{shell}) = 0 \]

Heat Balance On Capsule:

\[ h_c A_c (T_{steam} - T_{capsule}) = \epsilon \sigma (T_{capsule} - T_{shell}) \]

Parameters:

\[ h_c = 198 \text{ BTU/hr ft}^2 \] (Previous Calc)

\[ A_s = \pi (5.75') (1.25') = 0.157 \text{ ft}^2 \]

\[ \epsilon = 0.8 \] (unpolished, T=500°F)

\[ T_{shell} = 399.79 \]

\[ A_v = 0.030 \text{ ft}^2 \]

Solution Technique:

1) Assume Capsule Temp.

2) Calculate Shield Temp. From Capsule Heat Balance.

3) Check Shield Heat Balance

4) Iterate As Required

From Capsule Heat Balance:

\[ T_{shell} = T_{capsule} - h_c A_v (T_{steam} - T_{capsule}) \]

\[ = T_{capsule} - 4.332 \times 10^9 \text{ (Tcapsule - Tshell)} \]

Heat Balance On Shield:

\[ 62.172 (T_{steam} - T_{shield}) + 1.3712 \times 10^{-9} (T_{capsule} - T_{shield}) = 1.3712 \times 10^{-9} (T_{shell} - T_{shell}) \]

<table>
<thead>
<tr>
<th>Tcapsule</th>
<th>Tshell</th>
<th>Left Side Shield</th>
<th>Right Side Shield</th>
</tr>
</thead>
<tbody>
<tr>
<td>399.95</td>
<td>399.86</td>
<td>8.700</td>
<td>0.261</td>
</tr>
<tr>
<td>399.99</td>
<td>399.97</td>
<td>1.740</td>
<td>0.638</td>
</tr>
</tbody>
</table>
Conclusion: Capsule temperature is 399.99'. Further calculation is meaningless due to accuracy considerations. The shield is effective in keeping the capsule at essentially the same temperature as the steam flow.


APPENDIX 7
THEORETICAL NONCONDENSABLE GAS CONCENTRATION MEASUREMENT ERROR

Accuracy check - Transmitters

\[ P_G = N_G RT \]
\[ P_S = N_S RT \]

\[ N_G = P_G \left( \frac{\text{Mole gas}}{1 \text{lb mole steam}} \right) \]
\[ N_S = P_S \left( \frac{\text{Mole steam}}{1 \text{lb mole steam}} \right) \]

Assuming gas is primarily CO₂

1 lbm gas = 1 lbm steam

\[ \left( \frac{\text{Mole gas}}{\text{Mole steam}} \right) = \left( \frac{44.01 \text{ lbm gas}}{18.016 \text{ lbm steam}} \right) \]

Transmitter Accuracies:

Viatran 0-25 psi (Differential): 0.25% Full Scale
1/4 span - 0 - 6.25 psi ± 0.0156 psi
Full span - 0 - 25 psi ± 0.0625 psi

Viatran 0-50in H₂O (Differential): 0.25% Full Scale
1/4 span - 0-12.5in H₂O(0-0.451 psi) ± 1.128x10⁻³ psi
Full span - 0-50in H₂O(0-1.806 psi) ± 4.514x10⁻³ psi

Viatran 0-300 psi (Absolute): 0.25% Full Scale
1/4 span - 0-75 psi ± 0.1875 psi
Full span - 0-300 ± 0.75 psi

Using 1 0-25 psi Differential Unit and 1 0-300 psi absolute:

Using 2 Differential(Ranges 0-50in H₂O and 0-25psi) and one 0-300psi absolute transmitters:

<table>
<thead>
<tr>
<th>Steam Saturation Press. (Ps, PSIA)</th>
<th>Max. Error in Gas Percent Measurement (by Weight) @ .1%</th>
<th>@ 1%</th>
<th>@ 5%</th>
<th>@ 10%</th>
<th>@ 20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>290</td>
<td>13.4%</td>
<td>1.5%</td>
<td>0.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>145</td>
<td>26.9%</td>
<td>3.2%</td>
<td>1.0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72.5</td>
<td>52.96%</td>
<td>5.5%</td>
<td>0.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>106.93%</td>
<td>11.2%</td>
<td>1.1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>193.3%</td>
<td>20.2%</td>
<td>1.9%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Maximum Error in Gas Percent Measurement (by Weight)

<table>
<thead>
<tr>
<th>Steam Saturation Press. (Ps, PSIA)</th>
<th>@ .1%</th>
<th>@ 1%</th>
<th>@ 5%</th>
<th>@ 10%</th>
<th>@ 20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>290</td>
<td>1.2%</td>
<td>0.6%</td>
<td>0.5%</td>
<td>0.8%</td>
<td>0.5%</td>
</tr>
<tr>
<td>145</td>
<td>2.4%</td>
<td>1.3%</td>
<td>1.0%</td>
<td>0.8%</td>
<td>1.0%</td>
</tr>
<tr>
<td>72.5</td>
<td>4.1%</td>
<td>0.6%</td>
<td>0.6%</td>
<td>0.8%</td>
<td>0.5%</td>
</tr>
<tr>
<td>36</td>
<td>8.2%</td>
<td>1.3%</td>
<td>1.1%</td>
<td>0.8%</td>
<td>1.1%</td>
</tr>
<tr>
<td>20</td>
<td>14.9%</td>
<td>2.3%</td>
<td>1.2%</td>
<td>1.5%</td>
<td>1.2%</td>
</tr>
</tbody>
</table>

NOTE: Transmitters are assumed to be used at full scale or 1/4 scale only.

FIGURE A7-1. Measurement Accuracies Using One 0-25 psi Viatran Differential Transmitter

FIGURE A7-2. Measurement Accuracies Using Two Viatran Differential Transmitters (0.50 in. H₂O, 0.25 psi.)
APPENDIX 8

BOILING POINT ELEVATION EFFECTS

Effect of Dissolved Salts upon Gas Concentration Measurement Accuracy

Assuming gas is primarily CO₂ - Measured gas concentration (lbm gas) / (lbm steam) = (P_{total} - P_{sat}) / P_{sat_{H₂O}}

(44.0 lbm gas) / (1 lbm mole steam) = (18.016 lbm steam)

Error Calculation Procedure -
1. For a given gas concentration and flow temperature, calculate P_{total}.
2. For a given brine concentration, determine the saturation pressure at the flow temperature.
3. Calculate the measured gas concentration and the resulting measurement error.

Brine Properties -

J.L. Haas, Jr. has developed an empirical formula based on a reference substance technique which indicates the relationship between brine saturation temperature and pure H₂O saturation temperature (at the same pressure).


This relation is:

\ln T₀ = (a + b x)^{-1} \ln T_x

Where: T_x = Brine Temperature (°K)
       T₀ = Corresponding pure water temp. (°K)
a, b = Concentration dependent polynomials

a = 1.0 + (5.93582 x 10^{-6}) x + (-5.19386 x 10^{-5}) x^2
  + (1.23156 x 10^{-5}) x^3

b = 0.0 + (1.15420 x 10^{-6}) x + (1.41254 x 10^{-7}) x^2
  + (-1.92476 x 10^{-6}) x^3 + (-1.70717 x 10^{-9}) x^4
  + (1.05390 x 10^{-10}) x^5

Where: x is the molal concentration of NaCl in water (mole NaCl/KgH₂O)

At 400°F Brine Temp (T_x):

<table>
<thead>
<tr>
<th>NaCl Molality</th>
<th>NaCl Weight Concentration</th>
<th>a</th>
<th>b</th>
<th>T₀ (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.711x10^{-2}</td>
<td>0.1%</td>
<td>1.00</td>
<td>1.979x10^{-8}</td>
<td>399.95</td>
</tr>
<tr>
<td>0.0855</td>
<td>0.5%</td>
<td>1.00</td>
<td>9.970x10^{-8}</td>
<td>399.75</td>
</tr>
<tr>
<td>0.1711</td>
<td>1.0%</td>
<td>1.00</td>
<td>2.015x10^{-7}</td>
<td>399.49</td>
</tr>
<tr>
<td>0.855</td>
<td>5.0%</td>
<td>1.00</td>
<td>1.077x10^{-6}</td>
<td>397.20</td>
</tr>
<tr>
<td>1.711</td>
<td>10.0%</td>
<td>1.00</td>
<td>2.279x10^{-6}</td>
<td>394.25</td>
</tr>
<tr>
<td>3.421</td>
<td>20.0%</td>
<td>1.00</td>
<td>4.647x10^{-6}</td>
<td>388.34</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Brine Concentration (WT.%)</th>
<th>Gas Concentration (WT.%)</th>
<th>Flow Temperature (°F)</th>
<th>Psat_{H₂O} at Flow Temperature (PSI)</th>
<th>Psat_{Brine} at Flow Temperature (PSI)</th>
<th>T_{H₂O} at Psat_{Brine} (°F)</th>
<th>Indicated Concentration (WT.%)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>0.1</td>
<td>400°F</td>
<td>247.1</td>
<td>397.28</td>
<td>239.52</td>
<td>7.83</td>
<td>7.734</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.76</td>
<td>776.3</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18.05</td>
<td>80.5</td>
</tr>
<tr>
<td></td>
<td>20.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>28.36</td>
<td>41.8</td>
</tr>
<tr>
<td>10.0</td>
<td>0.1</td>
<td>400°F</td>
<td>247.1</td>
<td>394.25</td>
<td>321.28</td>
<td>16.82</td>
<td>16,720</td>
</tr>
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<td>190.76</td>
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TABLE A8-1. Gas Concentration Measurement Error Versus Weight Percent Dissolved Salt (High Salt Concentrations)
<table>
<thead>
<tr>
<th>Brine Concentration (WT.%)</th>
<th>Gas Concentration (WT.%)</th>
<th>Flow Temperature (OF)</th>
<th>PsatH2O at Flow Temperature (PSI)</th>
<th>PsatBrine at Flow Temperature (PSI)</th>
<th>TH2O at PsatBrine (OF)</th>
<th>Indicated Concentration (WT.%)</th>
<th>Error (%)</th>
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<tbody>
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<td>0.75</td>
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<td>400°F</td>
<td>247.1</td>
<td>246.40</td>
<td>399.75</td>
<td>0.79</td>
<td>690.0</td>
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<td>69.7</td>
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<td>10.72</td>
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<td>21.5</td>
<td>7.7</td>
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</table>

**FIGURE A8-1.** Gas Concentration Measurement Error versus Weight Percent Dissolved Salt (Low Concentrations)

**FIGURE A8-2.** Gas Concentration Measurement Error versus Weight Percent Dissolved Salt (High Concentrations)
APPENDIX 9

SAMPLE VELOCITY EFFECTS

Static Pressure/Velocity Dependence Problem

Error typically \( \alpha \) const. \( x V^2 \) (Ref. Streeter)

Present error as:

\[
\text{Diff. Pressure Measurement Error} = V_{\text{max}, \text{choked}} \times V^2
\]

Range of Velocities

\( P = 310 \text{ psi}, \ M = 1.677 \text{ lbm/sec} \)
(Ref: Design Report)

\[
V_{\text{pipe}} = \frac{M}{\rho A} = \frac{1.677 \text{ lbm/sec}}{.6688 \text{ lbm/ft}^2 (.00600 \text{ ft}^2)} = 417.9 \text{ ft/sec}
\]

\( P = 27 \text{ psi}, \ M = .1317 \text{ lbm/sec} \)

\[
V_{\text{pipe}} = \frac{M}{\rho A} = \frac{.1317}{.0659 (.006)} = 333.1 \text{ ft/sec}
\]

As tested:

\( M = .152 \text{ lbm/sec} \)
\( P = 48 \text{ psia} \Rightarrow \rho = .1130 \)
\( V = \frac{.152}{.1130 (.006)} = 224.2 \text{ ft/sec} \)

Only average velocity has been measured, instantaneous velocities must be inferred from pressure measurement.

\[
\Delta P = \rho \Delta h = \rho f \frac{V^2}{2g} = \rho (\text{const}) V^2
\]

\( V_{\text{ave}} = 224.2 \text{ ft/sec} \)

\( \Delta P_{\text{ave}} = 48.6 \text{ psi } 12.5 \text{ psi} = 36.1 \text{ psi} \)

\( \rho_{\text{ave}} = .1143 \text{ lbm/ft}^3 \)

\[
\Rightarrow \text{const.} = \left( \frac{\Delta P_{\text{ave}}}{\rho} \right) \left( \frac{1}{V_{\text{ave}}} \right) = \left( \frac{36.1}{.1143} \right) \left( \frac{1}{224.2} \right)^2 = 6.28 \times 10^{-3}
\]

TABLE A9-1. Measured Static Pressure Error versus Velocity

<table>
<thead>
<tr>
<th>Error (in. H2O)</th>
<th>( P ) (PSI)</th>
<th>( \rho ) (lbm/ft^3)</th>
<th>( V^2 ) (ft^2/sec^2)</th>
<th>( V ) (ft/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.17</td>
<td>49.02</td>
<td>.1152</td>
<td>50,453.17</td>
<td>224.62</td>
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<tr>
<td>-.97</td>
<td>48.41</td>
<td>.1134</td>
<td>50,220.77</td>
<td>224.10</td>
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<td>-4.70</td>
<td>48.23</td>
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</tr>
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<td>45.29</td>
<td>.1070</td>
<td>48,771.76</td>
<td>220.84</td>
</tr>
<tr>
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<td>.1197</td>
<td>51,215.61</td>
<td>226.31</td>
</tr>
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<td>227.05</td>
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<td>.1129</td>
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<td>223.17</td>
</tr>
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<td>48.63</td>
<td>.1143</td>
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<td>223.12</td>
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</table>

FIGURE A9-1. Static Pressure Measurement Error Versus Velocity Squared in pressure Tap Assembly.

From Figure A9-1, the slope = 10 in. H2O/4500 ft^2 SEC^2 which yields the following over the velocity range of the instrument (for transmitters zeroed at test condition).
If the differential pressure transmitters are zeroed at no velocity, the static pressure measurement error vs. velocity is:

<table>
<thead>
<tr>
<th>Velocity in 1&quot; Pipe (FT/SEC)</th>
<th>Static Pressure Meas. Error (in. H2O)</th>
<th>(PSI)</th>
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<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>10</td>
<td>.2</td>
<td>.0072</td>
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<td>.8</td>
<td>.029</td>
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<td>1.8</td>
<td>.065</td>
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<td>.354</td>
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<td>80</td>
<td>12.8</td>
<td>.462</td>
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</table>

Gas concentration measurement error:

\[
\eta = \frac{P_\text{G}}{P_\text{S}} \times 100\% \\
(\text{Weight percent assuming gas to be CO}_2)
\]

For \( V = 0 \), error = 0

<table>
<thead>
<tr>
<th>Velocity (FT/SEC)</th>
<th>Steam Sat. Pres. (PSIA)</th>
<th>% Error in Gas Concentration Measurement</th>
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<td>10</td>
<td>290</td>
<td>.6%</td>
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<td></td>
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<tr>
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<td>50</td>
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<tr>
<td>20</td>
<td>290</td>
<td>.6%</td>
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<td>.6%</td>
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<tr>
<td></td>
<td>50</td>
<td>3.52%</td>
</tr>
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