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December 1981
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SYSTEM TO PREVENT CLOGGING OF GAS SAMPLING TUBES

Contract H0308042
Charlton Technology Inc.

BUREAU OF MINES ★ UNITED STATES DEPARTMENT OF THE INTERIOR
Minerals Health and Safety Technology

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Title: System to Prevent Clogging of Gas Sampling Tubes

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Value/Impact of Results: Decrease in gas sampling problems at mine recovery projects. New knowledge about design, fabrication and use of permeation tube driers for general sampling of moist gas streams.

Users/Audience: MSHA Mine Emergency Operations Center, government and private researchers

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The Bureau of Mines utilizes special testing methods for the analysis of underground mine atmospheres for use during or after mine disasters and fires. These methods depend upon drawing sample gas to the surface through multiple tube bundles with the subsequent analysis of grab samples or the automatic analysis by often remotely located instruments on a continuous, 24-hour basis. During cold weather, low ambient temperature causes condensation and freezing of condensable vapors in the sample which can result in delayed response times or complete blockage of the sample line. This report covers research and resulting development conducted by the Bureau of Mines to produce a reliable method to selectively remove condensable vapors and particulate in the sample gas stream under worst-case field conditions. The effort resulted in two prototype systems which have greater field utility than originally anticipated. The innovative project resulted in two patent applications submitted through the Bureau of Mines.

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FOREWORD

This report was prepared by Charlton Technology, Inc. under USBM Contract number H0308042. The contract was initiated under the Mineral Health and Safety Technology Post Disaster Program. It was administered under the technical direction of Bruceton Administrative Office with L. E. Dalverny acting as Technical Project Officer. Alan G. Bolton, Jr. was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period February, 1980 to August, 1981. This report was submitted by the authors on December 18, 1981.

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SYSTEM TO PREVENT CLOGGING OF GAS SAMPLING TUBES

by

Kyle W. Charlton and Lloyd D. Bowman

ABSTRACT

The Bureau of Mines utilizes special testing methods for the analysis of underground mine atmospheres for use during, or after, mine disasters and fires. These methods depend upon drawing sample gas to the surface through multiple tube bundles with the subsequent analysis of grab samples or the automatic analysis by often remotely located instruments on a continuous, 24-hour basis. During cold weather, low ambient temperatures cause condensation and freezing of condensable vapors in the sample which can result in delayed response times or complete blockage of the sample line. This report covers research and resulting development conducted by the Bureau of Mines to produce a reliable method to selectively remove condensable vapors and particulate in the sample gas stream under worst-case field conditions. The effort resulted in two prototype systems which have greater field utility than originally anticipated. The innovative project resulted in two patent applications submitted through the Bureau of Mines.

INTRODUCTION

The Bureau of Mines has utilized special testing methods for analysis of underground mine atmospheres for use during, or after, mine disasters and fires. These methods depend upon drawing sample gas to the surface through multiple tube bundles with the subsequent analysis of grab samples or the automatic analysis by instruments on a continuous, 24-hour basis.

During cold weather, low ambient temperatures cause the condensation and freezing of condensable vapors in the sample. This can result in delayed response times or, with complete blockage, can prevent recovery of any sample gas from the mine atmosphere.

A cursory evaluation indicated that the sample must be kept above its dewpoint, or that drying methods must be employed to lower the dewpoint of the sample below that of the lowest expected ambient temperature. An overriding consideration was that any system developed to prevent the clogging of tube bundles must be rugged, reliable and fully adaptable for use in the field under the most adverse conditions.

The purpose of this contract was to develop a method to remove condensable vapors and heavier particulate in the sample gas stream or to otherwise prevent the plugging of the sample lines to permit uninterrupted gas sampling during post-disaster mine recovery efforts.

The contract was divided into two phases for an initial total duration of approximately ten months.

Phase 1 was to identify and evaluate possible methods to prevent clogging of the gas sample tubing. Phase 2 was to design, construct and demonstrate the most feasible systems to achieve the method of preventing clogging of mine gas sample tubing by frozen condensable vapors.

Phase 1

Task Description

The Phase 1 task description and considerations were as follows:

The contractor shall identify possible hardware designs for preventing the freezing and clogging of mine gas sampling systems and prepare engineering evaluations to determine the most technically and economically feasible method. Physical and chemical methods should be examined including the use of heating tapes, condensation traps, chemical desiccants and other conventional or new approaches. Simplicity and reliability are among the design factors that must be considered.

The proposed method shall have a minimal effect on the composition of the gas sample as taken from the mine atmosphere. Also, it shall not increase the time lag of the sampling system by an amount that would compromise the performance of the sampling and analytical equipment in use. The theoretical end effects on gas samples for various assumed initial conditions shall be reported.

The following information may be used to define initial conditions of a theoretical gas sample:

Sealed coal mine: Mine temperatures in the range of 10° to 25°C. Main gases are CO, CO_2, CH_4, O_2, N_2, H_2O, H_2, C_2H_6, C_2H_4. Ranges of concentrations in percent are:

	Range, percent
Carbon monixide (CO)	0.001 to 3
Carbon dioxide (CO_2)	0.03 to 10
Methane (CH_4)	0.5 to 75
Oxygen (O_2)	0.1 to 21
Nitrogen (N_2)	20 to 79
Water vapor (H_2O)	3
Hydrogen (H_2)	0 to 4
Ethylene (C_2H_4)	0 to 1
Ethane (C_2H_6)	0 to 1

Ventilated coal mine, known active fire: Except in immediate vicinity of fire, temperatures will range as above. The predominate gases will be CO, CO_2, O_2, N_2 and H_2O, with concentrations at the higher values of the ranges given above. There are usually significant quantities of particulates and condensable organic vapors, even in the ventilation flow upstream of the fire.

Consideration shall be given to power supplies, if required, for the proposed system. In the past, power to the field equipment has been provided from commercial utility lines, directly or indirectly, through the mine's power system, and/or from portable generators. The generators vary from large types on a truck chassis to the smaller kinds incorporated into recreational vehicles. Power quality can vary greatly, from usual utility quality to brown-out to intermittent outages which can be associated with mine operations. Rechargeable battery supplies may be an option. In general, the goal should be for a method using minimal electrical power.

Consideration should be given to overall size requirements for the possible systems. If there are to be separate components, then their separate specifications shall be reported. Packaging is important to consideration of transportation, handling and protection of the system from its environment. The system must be cost effective.

Any electrical equipment of the system that would be inserted into a mine borehole must meet MSHA's Schedule 2G permissibility requirements.

A Phase 1 report shall be submitted after completion of the above work. Each method shall be definitively described in writing and with all necessary drawings, photographs, etc. Included shall be lists of advantages and disadvantages of each method. In addition, the contractor will present his findings at an oral briefing.

Selection of Most Feasible Method

A number of methods have been used, in general, for prevention of freezing high dewpoint gas samples. These include electrically and steam-traced lines, hot air traced lines, sample dilution systems, heatless dryers, condensate trap systems and permeation drying systems. Most candidate methods were rapidly eliminated in this study on the basis of the impracticality for remote field applications or constraints of mine operations. Comments on the various candidate drying methods are summarized below.

Heat-Traced Sample Lines

Steam-traced and electrically-traced sample lines are frequently used in industrial monitoring applications. Charlton Technology, Inc. often employs electrically-traced sample lines in special stack monitoring applications where it is necessary to maintain sample of SO_2 and NO_x in the stack emissions at temperatures above the dewpoint in order to avoid condensation in the lines and the consequent loss of sample in the condensate. Such sample lines are thermally insulated and can maintain sample temperatures up to 350°F. For cold weather applications such heat-traced lines can maintain sample temperatures at 80°F with ambient temperatures as low as -140°F.

Steam-Traced Lines

In those locations where process steam is readily available (for example chemical plants, refineries) steam-tracing is a convenient, economical way to protect process lines from condensation or freezing. The desired temperature of the line can be controlled by the flow rate and the pressure of the steam. Most tracing runs of this kind are relatively short, and the handling of the condensate does not present a problem.

The steam requirements for any steam-tracing applications depend upon the heat transfer to the process lines and the loss of heat through the insulating jacket. In long runs, the temperature of the line will tail off as the steam condenses and only hot water remains within the system. For this reason, steam traps must be included as an integral part of the steam-traced system. The number and placement of these traps, of course, will depend upon the characteristics of the tube bundle, the ambient temperature extreme expected, the desired minimum operating temperature and the pressure of the available steam.

One manufacturer, Samuel Moore and Company*, provides empirical graphs for relating steam pressure, ambient temperature and bundle length for various operating temperatures. These curves show that a 2-tube bundle with tracer, operating with 150 psig steam and an ambient temperature of -40°F exhibits a temperature drop to 220°F about 140 feet from the steam inlet. This means that a trap must be supplied every 140 feet.

For the very long sample lines required for monitoring mine gas vapors (up to a mile from the borehole) it appears that the trapping requirements for the steam condensate would be impractical. For a maximum trapped length of 140 feet, a total of 38 traps would be required for one mile of sample line. This would introduce a significant service and maintenance problem in cold weather.

Electrically-Traced Lines

Electrically-traced tube bundles could be used to maintain the sample above the dewpoint temperature, but offer limitations that render their use impractical in remote mine sampling applications.

*Reference to specific brands, equipment, or trade names in this report is made to facilitate understanding and does not imply endorsement by the Bureau of Mines.

The major problem is that the system would be limited by the length of tube bundle that can be heated by an individual circuit. For a voltage of 120 Vac 60 Hz Dekatrace 2260 cable would have a maximum circuit length of 86 feet. This could be increased by going to 240 Vac power but even at the maximum voltage (600 Vac) we would still be limited to about 425 feet for each circuit. For a one-mile tube bundle this would require 12 separate heating circuits with interconnections and junction boxes every 425 feet. This would require about 7500 watts of power and would necessitate substitution of heavier wire in the tube bundle to replace the 22 AWG communications wire normally supplied. For this reason and for reasons of safety, the method is essentially impractical for remote mine sampling applications.

Hot-Air Traced Lines

An important advantage of hot air tracing over steam tracing is the elimination of the condensate problem and the requirement for trapping. An important advantage of air tracing over electrical tracing is that of safety. Hot air tracing, like steam tracing, can be employed in hazardous areas without danger of ignition.

A disadvantage of hot air tracing is the poor thermal conductivity of air when compared with steam or resistance heating elements. For this reason we do not recommend this approach for heating extremely long runs of tube bundle. However, it is an attractive method for short runs and would be both practical and useful as part of the dual-condensate trap and permeation drying systems.

Sample Dilution Systems

Charlton Technology, Inc. manufactures the DRYSTAK Model SD-12 Sample Dilution System for use in stack gas monitoring applications. The Model SD-12 is a precision dilution system capable of providing sample dilution ratios from 1:1 to 10,000:1.

An important advantage of a dilution system is for monitoring stack gases with high water content (up to 20% H_2O or higher). For example, if a stack gas containing 10% H_2O is diluted by a factor of 10, this reduces the dewpoint of the sample from 46°C to 7°C and eliminates any condensation problems in the sample line.

The concentration of water vapor in sealed coal mines can be as high as 4%. A sample of this atmosphere would have a dewpoint of about 29.2°C. To reduce the dewpoint of the sample to -26°C (lowest expected ambient) would require a sample dilution of about 70:1.

Although Charlton Technology, Inc. can provide a reliable dilution system with a dilution factor of 70:1, the dilution approach was ruled out for two reasons. The contract specifically states that the proposed sampling method shall have a minimal effect upon the composition of the sample. The dilution approach does not meet this requirement.

The dilution ratio would require all analyzers to operate with a seventy-fold increase in sensitivity. This is practical for hydrocarbons with an FID detector, but there would be a problem in the detection of the lower concentrations of CO, CO_2 and H_2. But more important is the fact that even wide variations in the concentration of O_2 and N_2 would be completely masked by the fixed concentrations of O_2 and N_2 in the dilution air.

Chemical Desiccant System

Desiccant systems, especially those based upon physical separation methods, offer promise for the removal of water vapor and organic condensates from mine gas vapors. The most exciting approach is to apply the separation principles of gas chromatography with the practical engineering techniques utilized in the design of the regenerative, heatless dryer.

The heatless dryer is an industrial workhorse used for removal of moisture from air. The dryer has two identical cylindrical chambers packed solidly with desiccant. Compressed air first passes into one desiccant chamber. As it moves upward through the desiccant, moisture is removed. Most of this ultra-dry air is discharged at the outlet for use. However, the remainder (a small fraction) is meanwhile expanding . the second chamber. It passes downward through this chamber, purging or reactivating the desiccant. A fixed time later, two solenoids operate and the direction of the airflow through the two chambers is reversed. The chamber which has been drying air is reactivated while the other chamber produces dry air. The result is a continuous stream of ultra-dry air delivered at the outlet. The moisture-ladened purge air is merely discharged into the atmosphere.

Typical gas chromatography adsorption columns (molecular sieve, activated carbon) will pass most of the components of the mine gas atmosphere (H_2, O_2, N_2, CH_4, C_2H_6, CO) but will strongly adsorb CO_2, H_2O and the heavier hydrocarbons. Special column supports are available, however (for example, Porapak N), which will provide a separation between CO_2 and H_2O. Thus, a gas chromatograph could conceivably be used to pass all of the mine gas vapors of interest, then backflush the water and heavy hydrocarbons to vent. The heatless dryer can, therefore, be considered as a form of large-scale gas chromatograph which passes all components of air except water, CO_2 and heavy organics. It uses "air" as its carrier gas.

We believe it would be feasible to develop a heatless dryer which would remove only water and heavy organics from the mine gas vapor.

However, since additional basic research work would be necessary, the heatless dryer approach was not one of the leading candidates for the field drying system.

A heatless dryer was constructed for the program to supply dry air for operation of the system ultimately selected. The heatless dryer is used to provide dry air only and does not have the constraints a unit would have to dry a mine atmosphere sample.

Dual Condensate Trap

Charlton Technology, Inc. personnel routinely employ commercial refrigeration dryers (Hankison) as well as special thermoelectric coolers for removal of condensate from sample streams. The Charlton Technology Model SC-20 is a refrigerated dryer designed for drying relatively small sample flows (10 liters per minute) to dewpoints as low as -10°C.

Typically, the Hankison-type dryer is operated just above freezing (34° to 35°F). Then the sample is reheated before introduction to the analyzer. Although refrigerated dryers operating at colder temperatures (to 10°F) are available, it would not be practical to employ refrigerated dryers for achieving dewpoints as low as the expected minimum ambient (-15°F).

We would consider instead a trap system which would utilize the ambient temperature itself to achieve condensation (or frosting). The system would utilize a special dual-condensate trap assembly. The two traps would alternately be exposed to the ambient temperature to trap out condensables then heated with hot, dry gas to purge the condensate.

The condensate trap system is a workable drying method. However, a conventional refrigeration system could not dry to the minimum temperature of -15°F. A specially designed dual system utilizing ambient temperature is feasible, but would only dry to about the ambient temperature at the dryer site. This would require lowering the dewpoint to some lower safe level of perhaps another 15°F or freezing could occur downstream in the transport line. The system is possible, but lacks the simplicity of permeation drying.

Permeation Drying System

The permeation dryer dries by removing water by diffusion through a membrane as shown in Figure 1. In gas sampling applications, it is desirable to remove the water in the vapor state before condensation occurs.

The water is removed by the use of Nafion™ (by E. I. du Pont de Nemours & Co., Inc.) membrane tube bundles. Nafion is a special perfluorosulfonic acid polymer which has excellent permeability of water

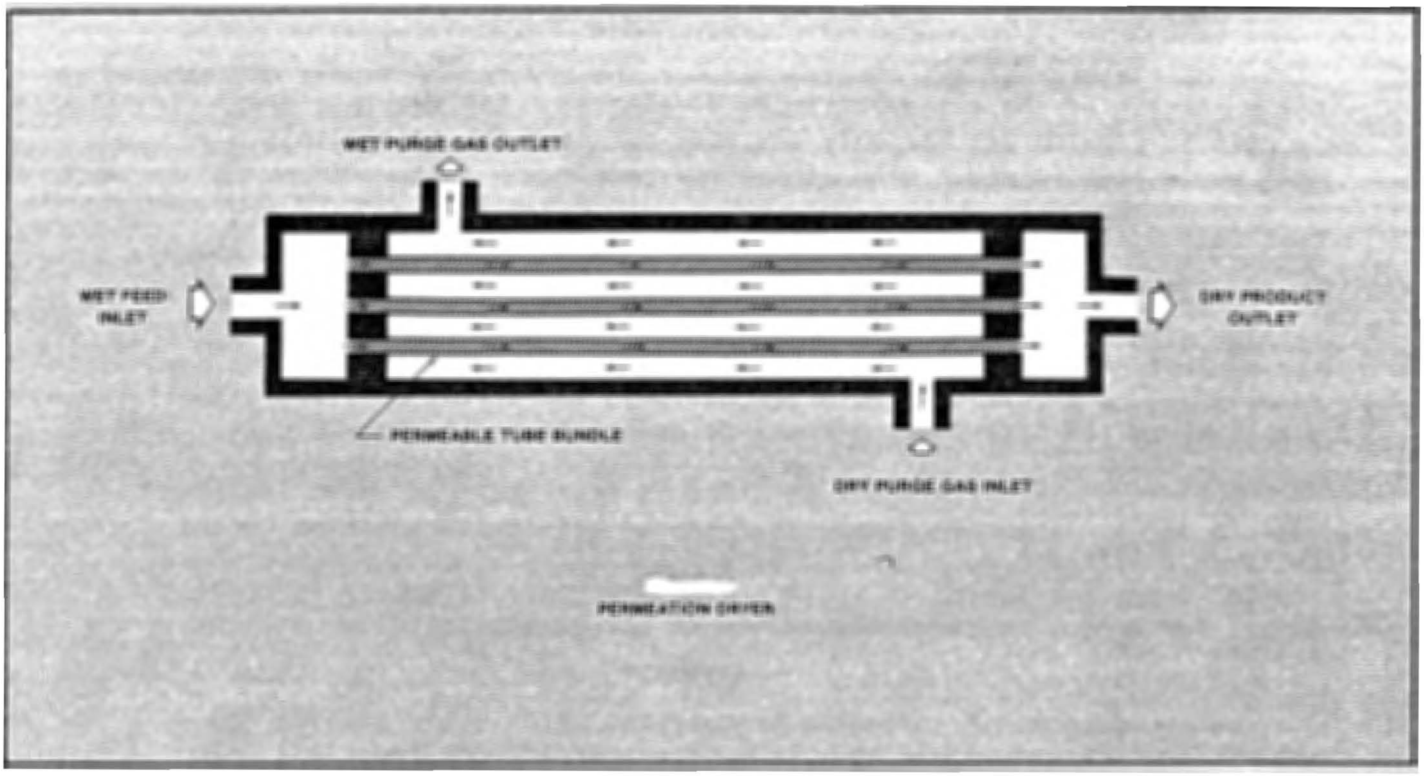


FIGURE 1
PERMEATION DRYER

with little or no permeability to sample. PermaPure™ dryers, manufactured by PermaPure Products, Inc. utilize Nafion tubing as the drying element.

The wet sample enters the inside of each tube in the bundle. Dry purge gas passes over the outside of the Nafion tubes and develops a partial water pressure drop from inside to outside. Water vapor permeates out of the wet sample stream into the purge air. The sample can be dried to less than -50°C dewpoint depending upon flowrates and temperatures. The drying efficiency, or ability to remove water, improves as temperature lowers.

The dry purge air used in the permeation dryer is generated by a dry air module. The module consists of an oilless compressor pressurizing ambient air to a heatless dryer. The purge air is dried by the heatless dryer to a dewpoint of -100°F.

Selected Approach

Since Charlton Technology, Inc. has had experience with all common drying systems, consideration of the major known advantages and disadvantages of the potential systems either eliminated them without further investigation or left them as a candidate method. Of the candidate methods, permeation drying seemed to offer the greatest advantages with also a very high probability of success. The permeation drying technique is inherently rugged and allows a great deal of flexibility in field applications. It was the clear first choice of a drying system with dual-condensate and heatless dryers as back-up methods.

Test Program

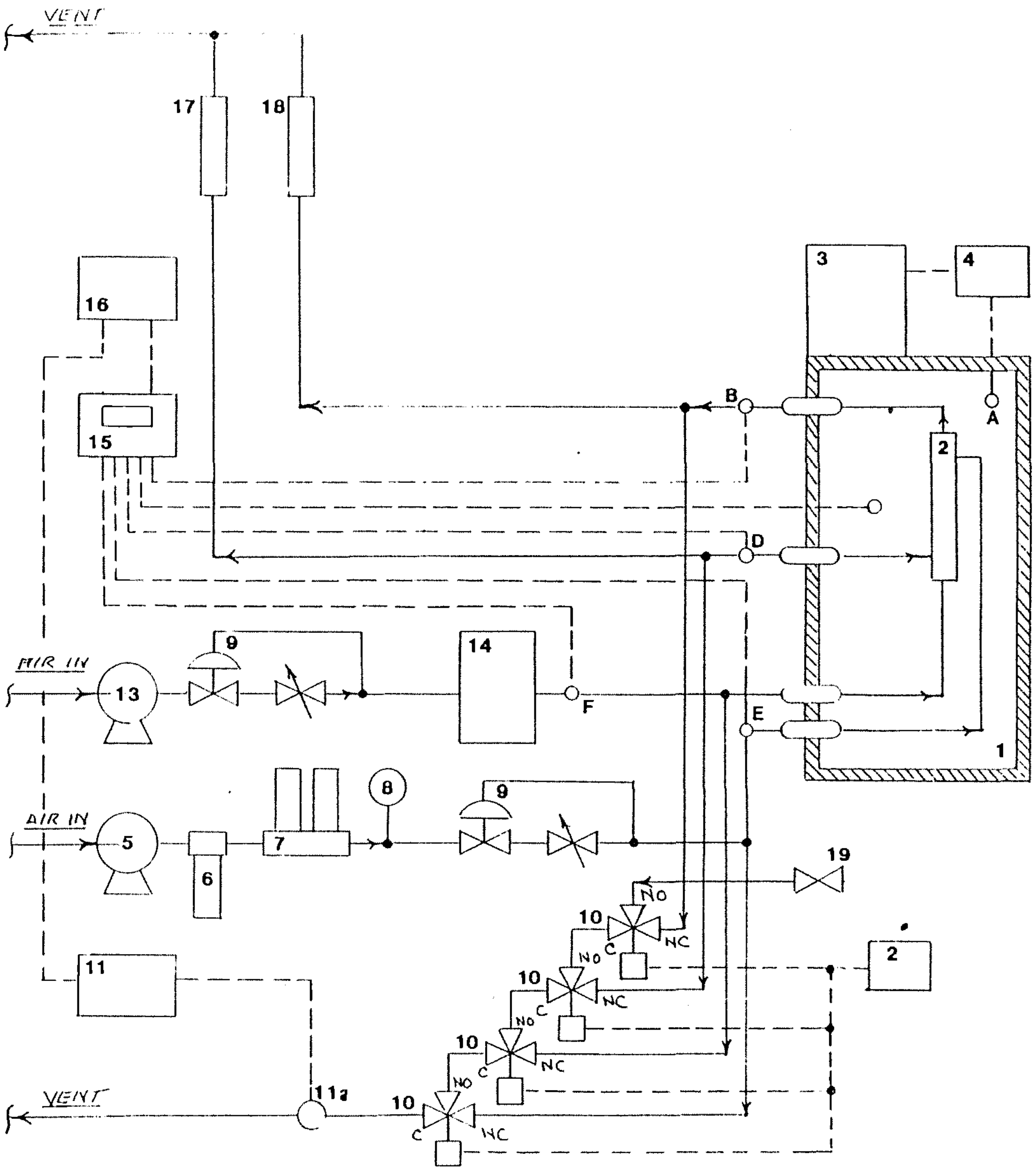
A test program was initiated to characterize the performance of permeation dryers and to size them for the specific contractual requirements. Also, calculations of tube and pump sizes for system support were done.

Support Test Equipment

Regardless of the method chosen, certain support test equipment was necessary, some of which had to be custom built or modified. The basic test system block diagram is shown in Figure 2. It includes the following sub-systems which form the calibration gas supply system:

A. Variable humidifier, Figure 3,
B. High capacity dry air supply, Figures 4 and 5, and
C. Multi-gas blending/calibration system, Figures 5, 6 and 7.

Photographs of the test area and related equipment are shown in Figures 8 and 9, and show most of the test equipment used. These photo-



ITEM	REQD	DESCRIPTION
19	1	SHUTOFF VALVE
F	1	J THERMOCOUPLE, SAMPLE INLET
E	1	J THERMOCOUPLE, PURGE INLET
D	1	J THERMOCOUPLE, PURGE OUTLET
C	1	J THERMOCOUPLE, CHAMBER TEMP.
B	1	J THERMOCOUPLE, SAMPLE OUTLET
A	1	TEMPERATURE SENSOR, REFRIG. UNIT
18	1	FLOWMETER, SAMPLE GAS, PORTER 150A
17	1	FLOWMETER, PURGE GAS, PORTER 150A
16	1	RECORDER, DUAL PEN
15	1	TEMPERATURE INDICATOR, THERMOCOUPLE INPUT
14	1	HUMIDIFIER, DWG No. 1202561-03
13	1	SAMPLE PUMP, THOMAS 2107
12	1	CONTROLLER, DWG No. 1202531-02
11	1	DEWPOINT HYGROMETER, EG&G MODEL 880
10	4	SOLENOID VALVE, SKINNER V5
9	2	FLOW CONTROLLER, CONOFLOW 41XT
8	1	PRESSURE GAUGE, 0-30 PSIG
7	1	HEATLESS DRYER, PUREGAS MODEL HF300
6	1	WATER TRAP, NORGREN
5	1	COMPRESSOR, THOMAS WOBL PUMP 807CE
4	1	THERMOSTAT
3	1	REFRIGERATION UNIT
2	1	PERMEATION DRYER (TEST COMPONENT)
1	1	ENVIRONMENTAL CHAMBER

DRAWN BY	KC	3/80
CHECKED		
APPROVED		
RELEASED		
REF. DWGS.		

CHARLTON ASSOCIATES, INC.
SAN DIEGO, CALIFORNIA

Code | Dwg. No. 1202531-01 | Rev.

FIGURE 2
SYSTEM DIAGRAM - PERMEATION DRYER TEST ASSEMBLY

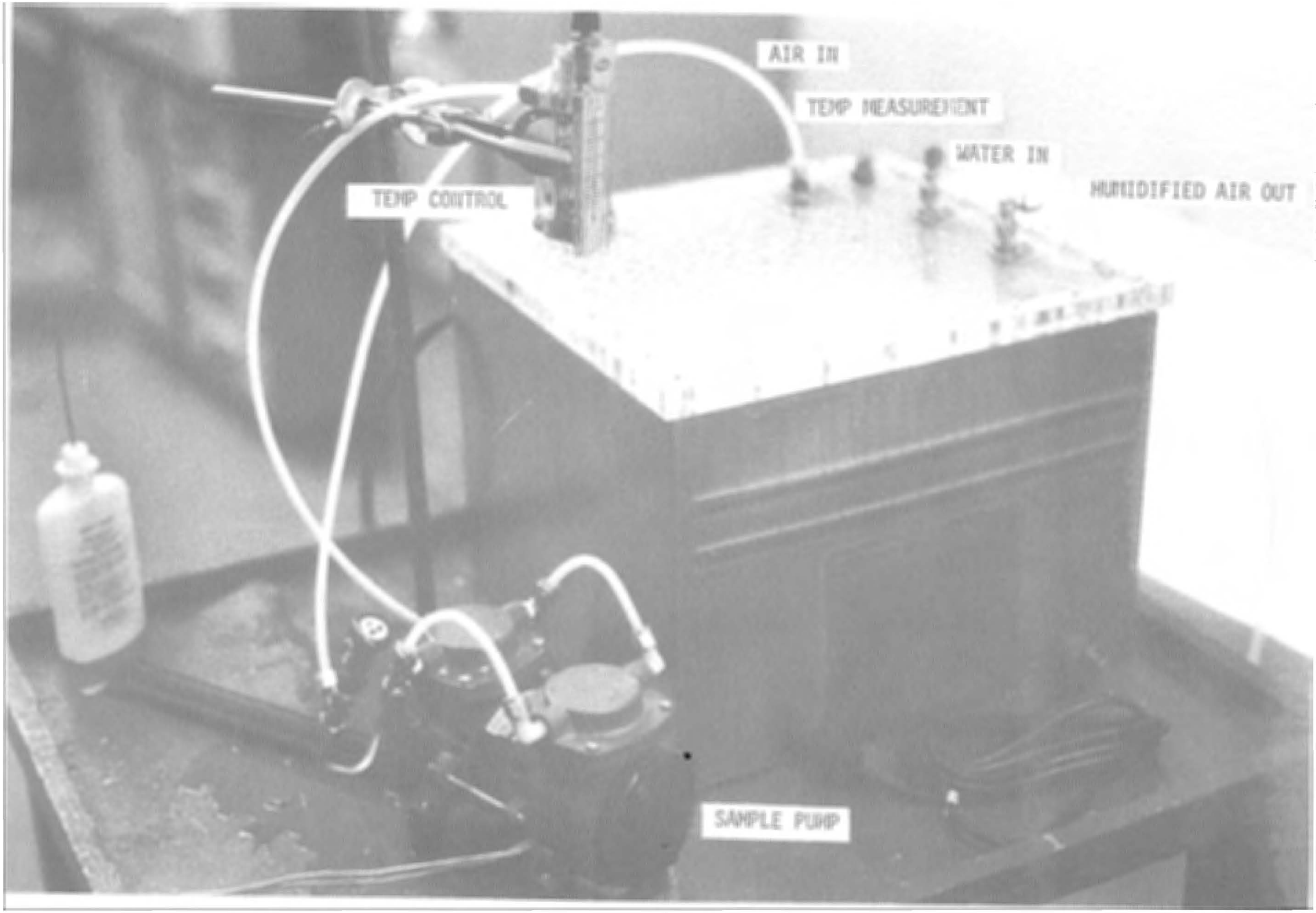


FIGURE 3.
VARIABLE HUMIDIFIER

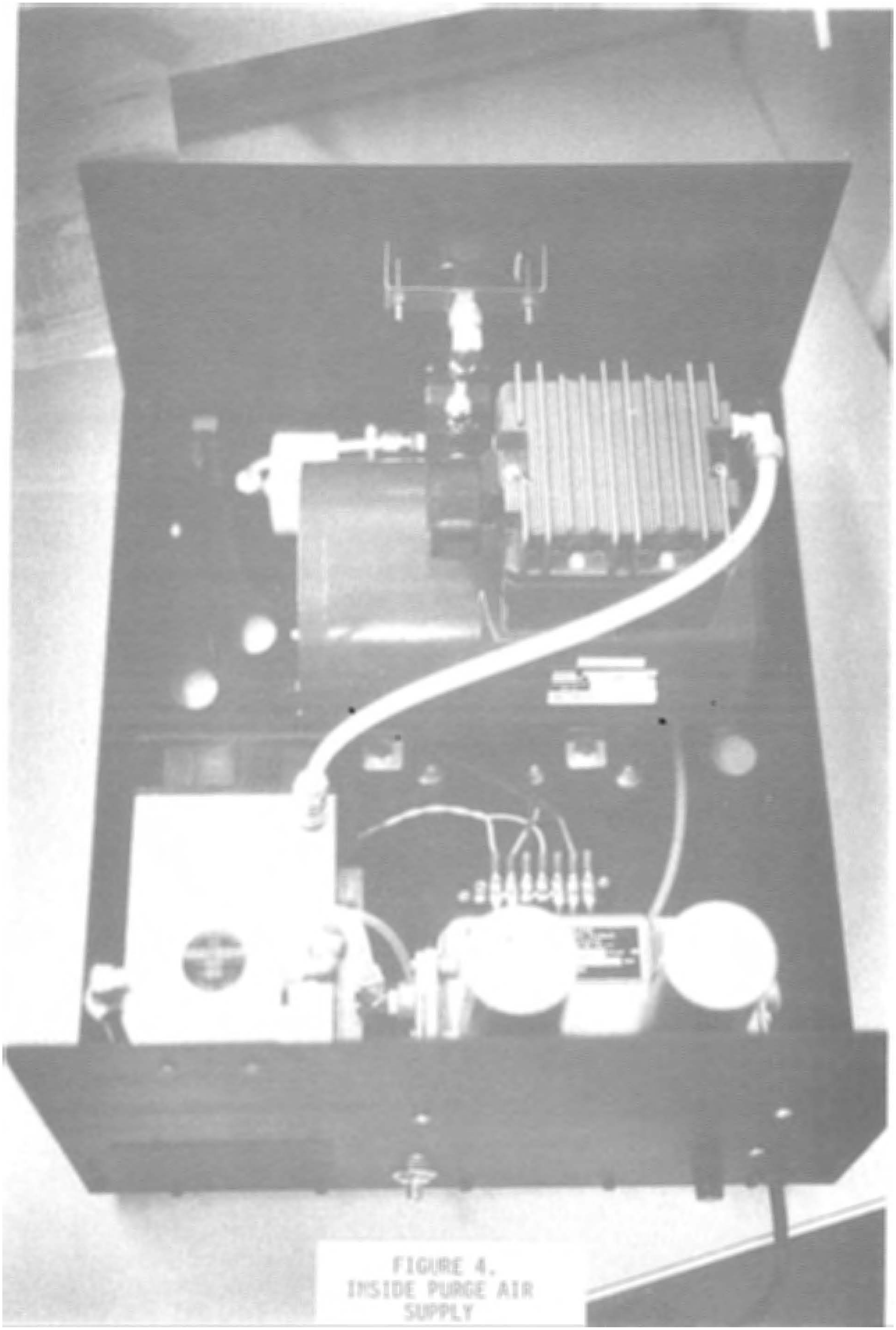


FIGURE 4.
INSIDE PURGE AIR SUPPLY

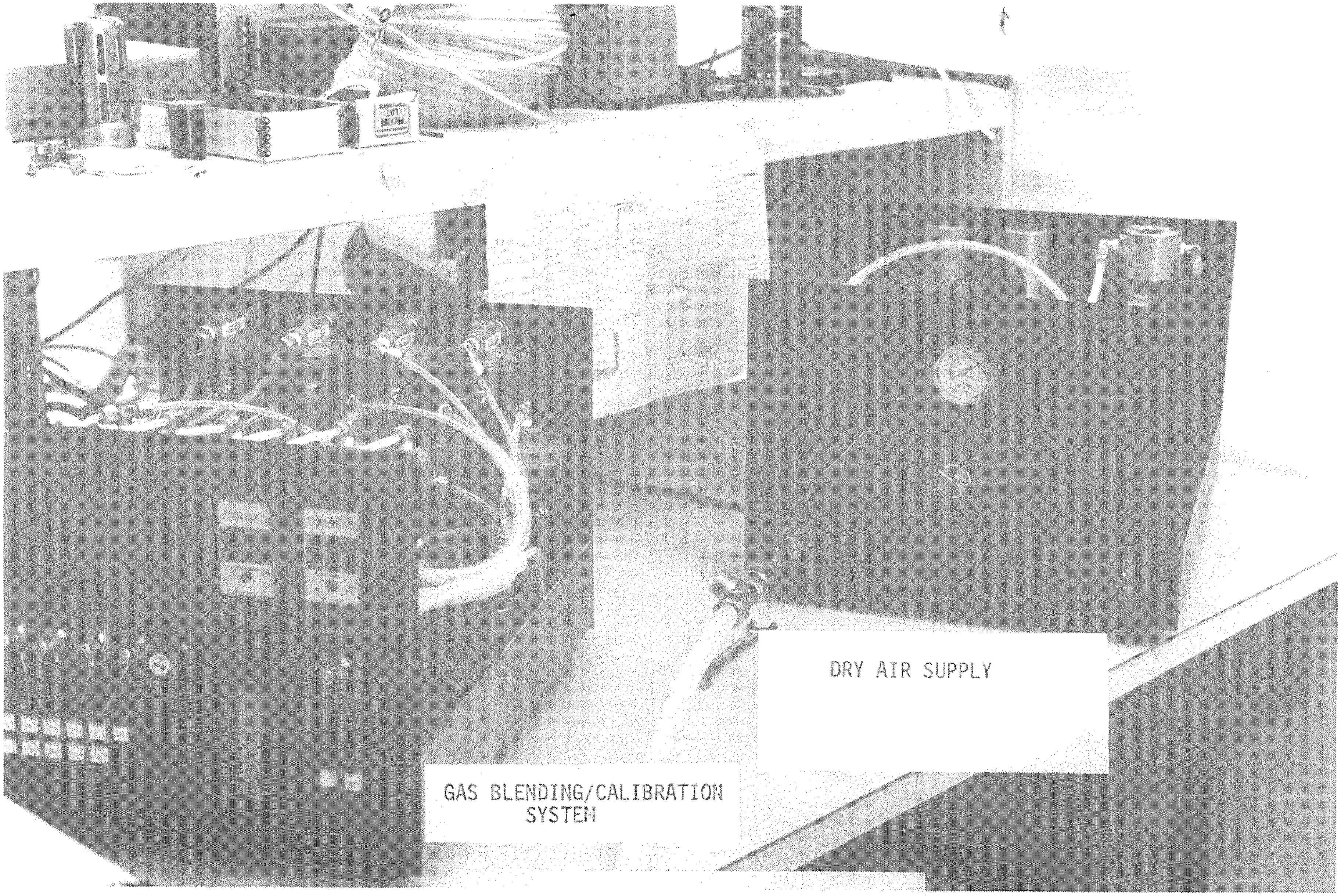


FIGURE 5.
DRY AIR SUPPLY & GAS BLENDING/CALIBRATION SYSTEM

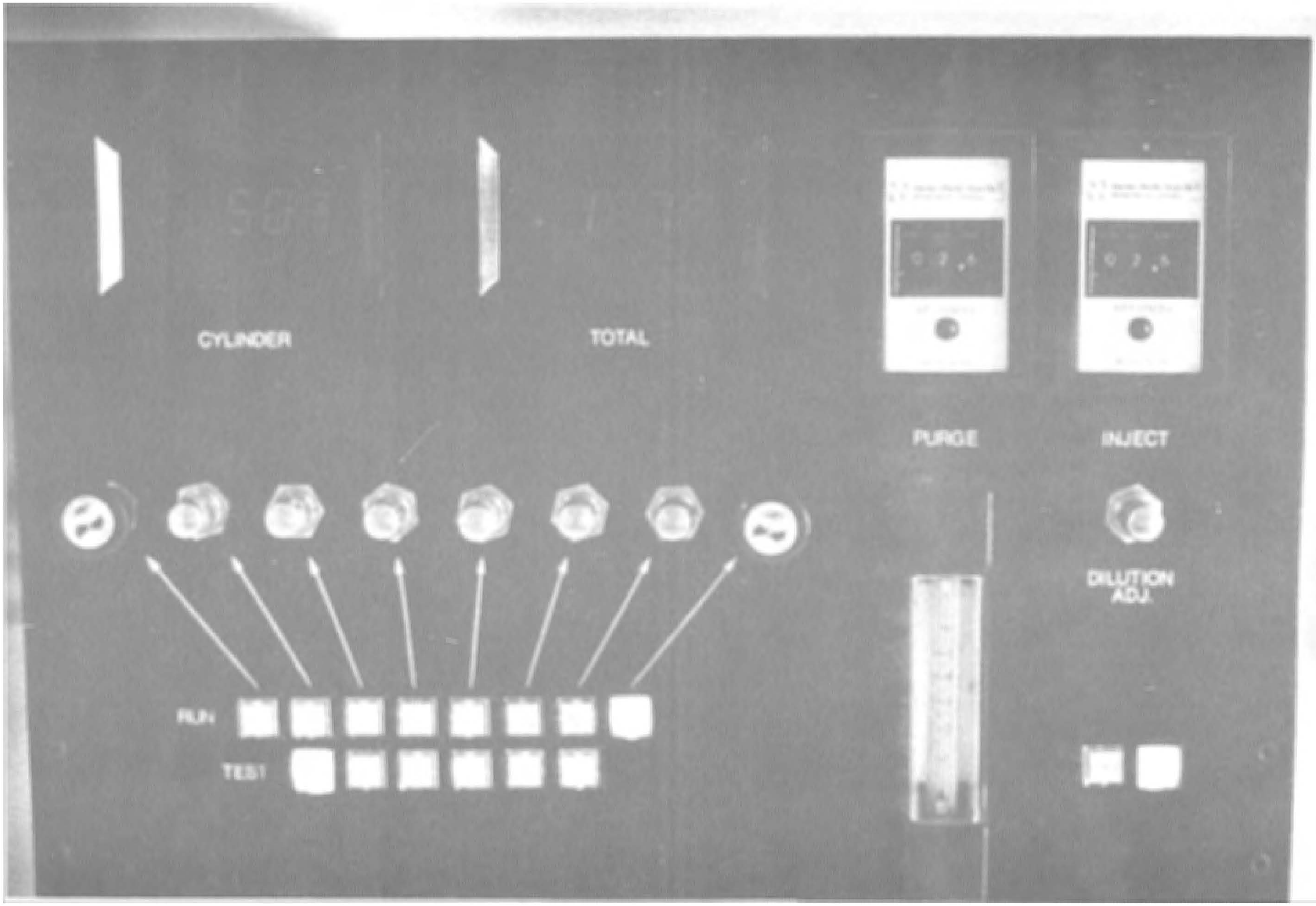


FIGURE 6.
FRONT VIEW
CALIBRATION CONTROLLER

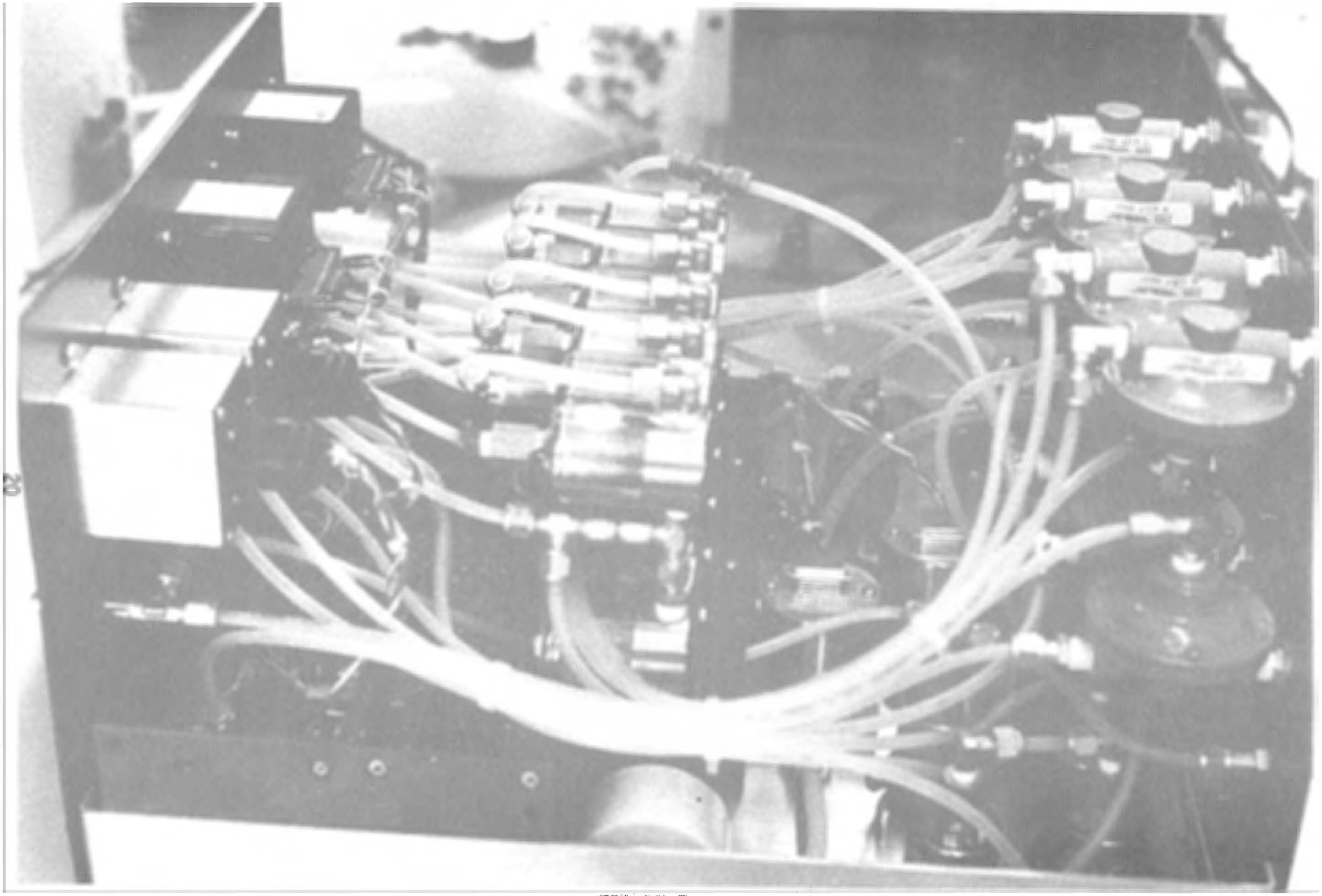


FIGURE 7.
MINE ATMOSPHERE SIMULATOR - INSIDE VIEW

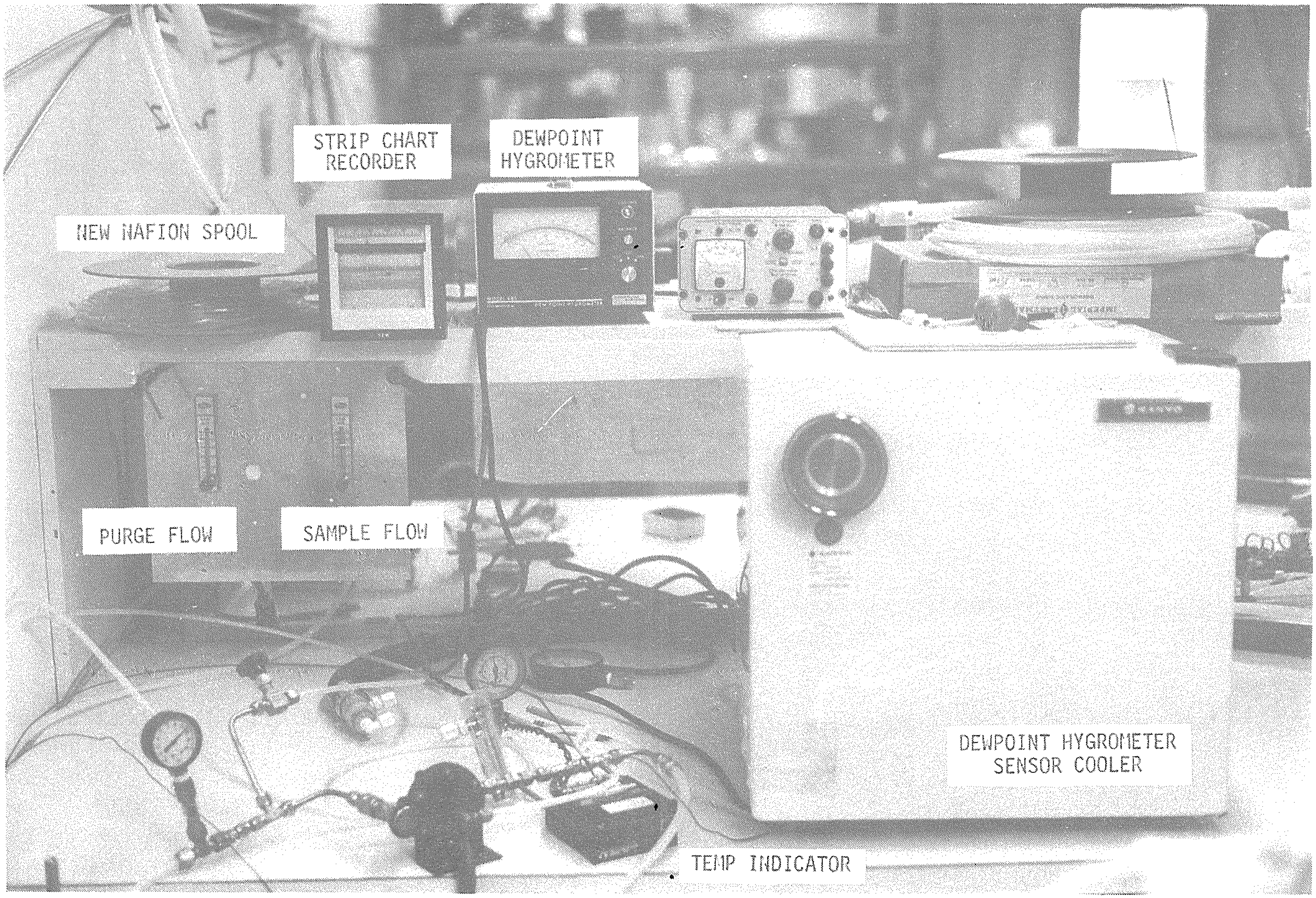


FIGURE 8.
BU MINES TEST AREA
DRYER TEST EQUIPMENT

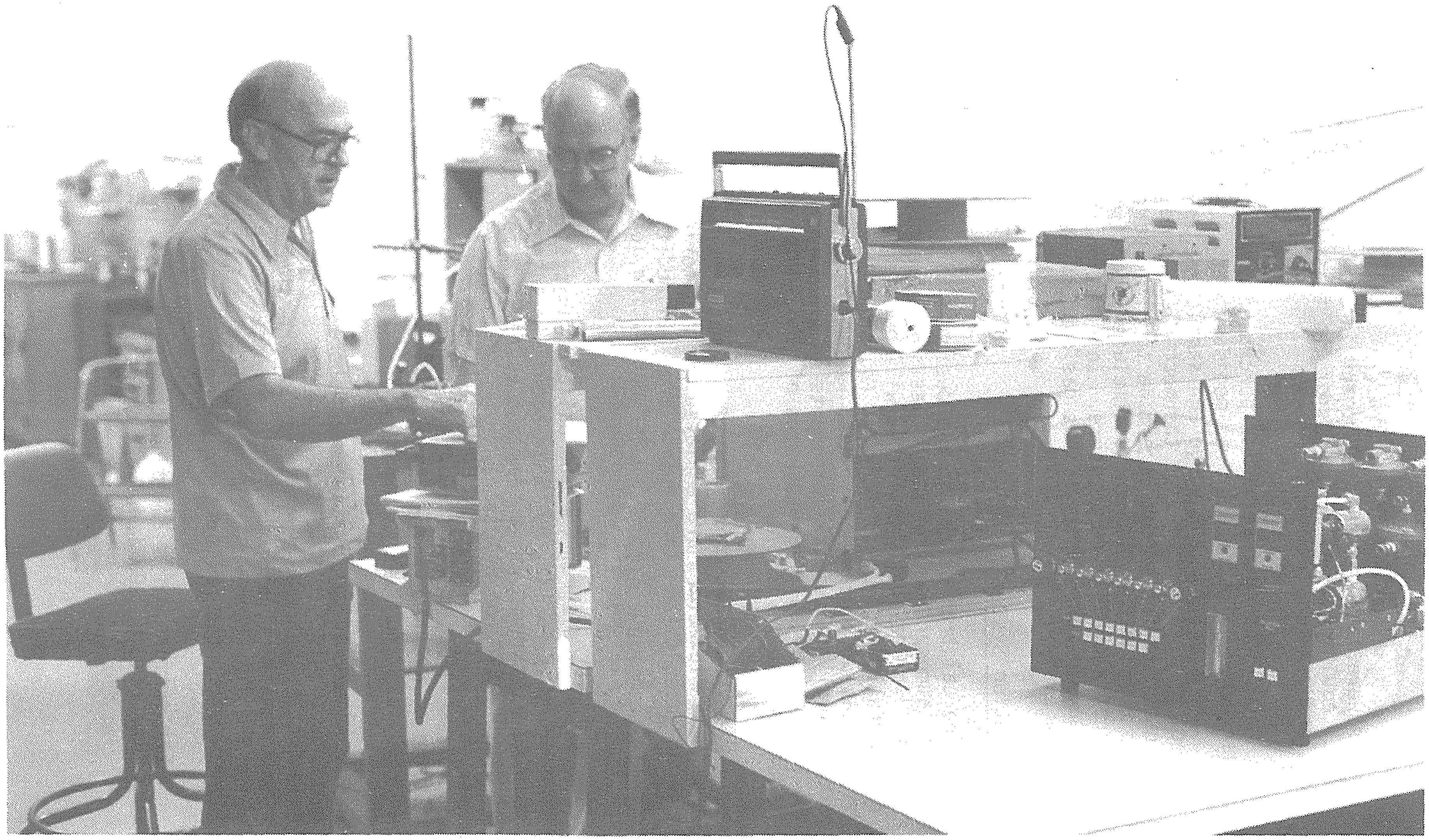


FIGURE 9.

BU MINES TEST AREA

graphs were taken in May, 1980, and in some cases show partially completed equipment. All elements of the test system were subsequently completed.

A top-loading freezer was purchased and used to simulate low ambient temperatures. The freezer was modified with a plate which holds bulkhead connectors for the purge and sample gas inlets and outlets. The connectors were fitted with thermocouples to measure the gas temperatures. Subsequent modifications were made to allow partial deployment of longer dryers outside the chamber to simulate a portion of the dryer in the stable borehole air temperature. In addition, a gas chromatograph was purchased to verify the various gas concentrations generated by the calibration system.

Calibration System

The calibration system was designed to provide simulated mixtures of mine atmospheres for use in testing and evaluation of the prototype system. The calibration system will permit the simultaneous blending of the following gases: H_2, O_2, N_2, CH_4, C_2H_4, C_2H_6, CO and CO_2. The system can provide concentration ranges from 10 parts per million to 100% for all individual components except oxygen (500 parts per million to 21% for oxygen). Photographs of the calibration system are shown in Figures 6 and 7.

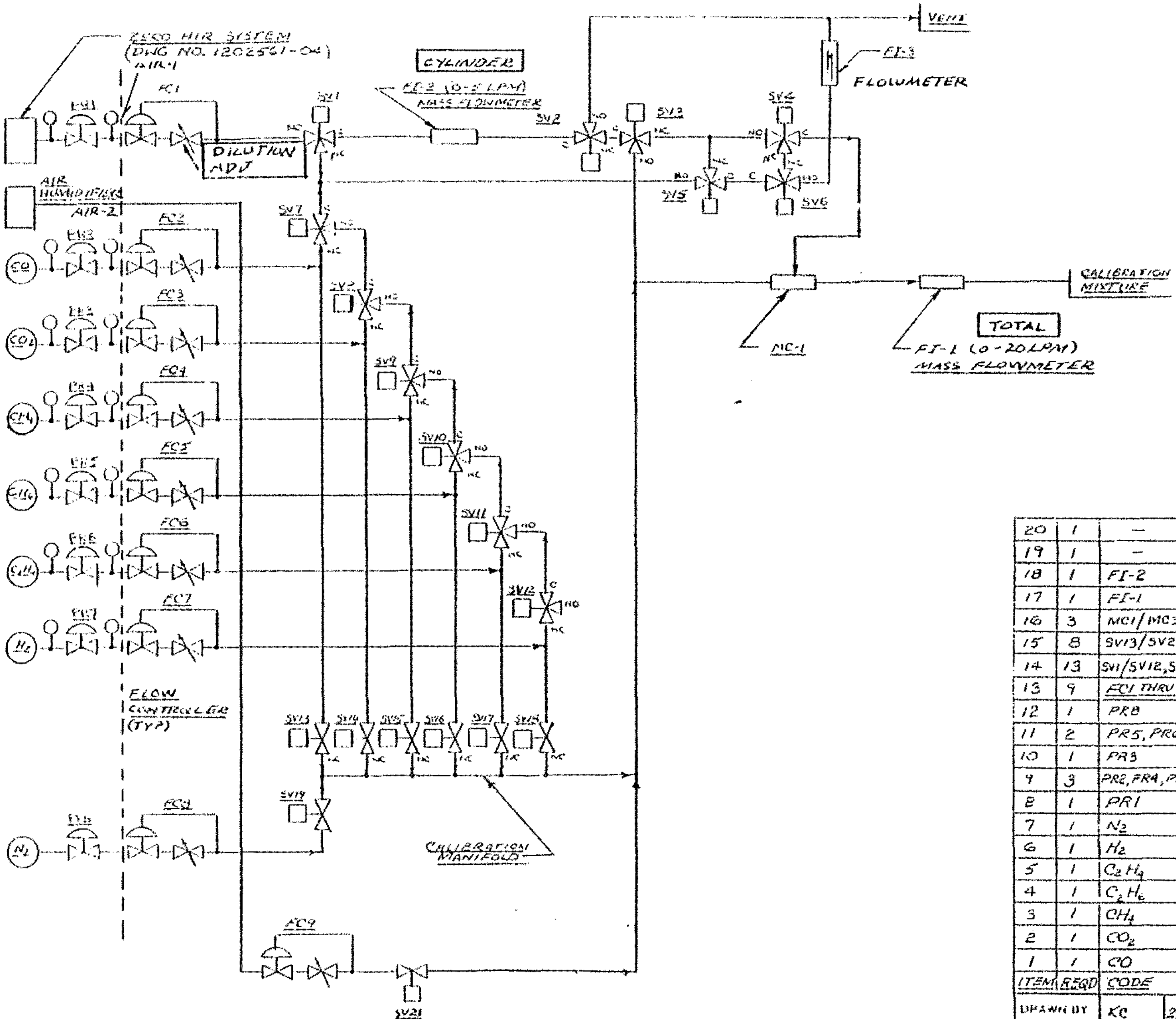
The system design differs from that described in the proposal in that mass flowmeters are employed for monitoring flow rates of the component gases rather than rotameters. In addition, a special sample injection system is provided for generating low concentrations (to 10 parts per million) of a component.

The flow diagram for the calibration system is shown in Figure 10. Pure gas (C.P. Grade, 99.0% or above) is introduced from Size 1A cylinders to a solenoid valve sampling system. A zero air system provides clean, dry air for dilution.

Mass flowmeters (FI-1, FI-2) with digital readout permit accurate setting of all flow rates. Differential pressure flow regulators (FC1 and FC9) are employed to maintain each flow rate at a constant value.

A simulated calibration atmosphere is prepared by introducing zero air and/or nitrogen into a calibration manifold and monitoring the flow rate (up to 20 liters per minute) on the digital output of FI-1. Individual component gases are first directed to the low range mass flowmeter where the flow rate is accurately adjusted to the desired level, then introduced to the calibration manifold.

For example, if a 2% concentration of CO_2 in air is to be generated at a flow rate of 20 liters per minute:



20	1	—	ZERO AIR SYSTEM, DWG NO. 1202561-04
19	1	—	HUMIDIFIER, DWG NO. 1202561-03
18	1	FI-2	MASS FLOWMETER, MATHESON
17	1	FI-1	MASS FLOWMETER, MATHESON
16	3	MC1/MC3	MIXING CHAMBER, DWG NO. 1202561-02
15	8	SV13/SV20	SOLENOID VALVE, SKINNER V52DA2055
14	13	SV1/SV12, SV21	SOLENOID VALVE, SKINNER V54DA1075
13	9	FC1 THRU FC9	FLOW CONTROLLER, CONOFLOW H41XT
12	1	PR8	PRESSURE REG AIRCO. 15-75 (580)
11	2	PR5, PR6	PRESSURE REG., AIRCO 18-30 (350)
10	1	PR3	PRESSURE REG., AIRCO 18-75 (320)
9	3	PR2, PR4, PR7	PRESSURE REG., AIRCO 18-75 (350)
8	1	PR1	PRESSURE REG., CONOFLOW H40XT
7	1	N_2	AIRCO ALUM CYL., 140 SCF, 99.995% N_2
6	1	H_2	AIRCO ALUM CYL., 140 SCF, 99.995% H_2
5	1	C_2H_4	AIRCO ALUM CYL., 140 SCF, 99.5% C_2H_4
4	1	C_2H_6	AIRCO ALUM. CYL., 140 SCF, 99.0% C_2H_6
3	1	CH_4	AIRCO ALUM. CYL., 140 SCF, 99.0% CH_4
2	1	CO_2	AIRCO ALUM. CYL., 140 SCF, 99.6% CO_2
1	1	CO	AIRCO ALUM CYL., 140 CF, 99.3% CO
ITEM	REQD	CODE	DESCRIPTION

DRAWN BY	KC	2/80	CHARLTON ASSOCIATES INC. SAN DIEGO, CALIFORNIA
CHECKED			SYSTEM FLOW DIAGRAM
APPROVED			CALIBRATION SYSTEM
RELEASED			
REF DWGS			DWG No. 1202561-01 Rev

FIGURE 10.
SYSTEM FLOW DIAGRAM
CALIBRATION SYSTEM

CO_2 = 400 cubic centimeters per minute, and
Air = 19.6 liters per minute.

Air from the zero air system is introduced to the calibration manifold through SV21 and adjusted to 19.6 liters per minute by means of a flow controller FC9. Carbon dioxide is then introduced to the low range mass flowmeter by actuating SV8, SV1 and SV5. The flow rate is then adjusted to 400 cubic centimeters per minute by means of a flow controller, FC3. The CO_2 is then directed to the calibration manifold by deactivating solenoid valves SV8, SV1 and SV5, then actuating SV14. The gas from the calibration manifold then passes through two mixing chambers (MC-1, MC-3) before introduction to the instrumentation or equipment under test.

If an extremely low concentration of a component gas is to be prepared, a special injection dilution system is employed. This is similar in principle to the injection of a precise volume of sample gas into a gas chromatograph column. By carefully controlling both the volume of the injection, the rate of injection and the flow rate of diluent gas very precise dilution can be achieved for concentrations down to one part per million or lower.

As an example, assume that a concentration of 15 parts per million of CO in air is to be generated and that the total flow rate of the mixture is to be 20 liters per minute. A flow rate of exactly 19.0 liters per minute is introduced to the high range mass flowmeter (FI-1) by adjusting FC9. A flow rate of 1.0 liters per minute is then directed through the low range flowmeter (FI-2) by adjusting FC1. A flow of CO gas is introduced to the system by actuating SV7. The CO passes through valves SV5 and SV6, then through rotameter FI-3. The short piece of tubing between the common (C) ports of SV5 and SV6 represents the "sample loop" of the injection system. The flow of sample through FI-3 is then reduced to "just purge" the loop. The contents of the loop is injected into the 1.0 liters per minute stream by actuation of solenoid valves SV2, SV3, SV4 and SV5. When SV3, SV4 and SV5 are deactivated, the loop is purged with fresh sample.

The rate of injection is controlled by means of a solid state timer with digital thumbwheel switch. The loop size is fabricated to a volume of 100 microliters (0.100 cubic centimeters). The concentration of diluted gas is determined by:

$$C_2 = \frac{(C_1)(R)(L)}{Q} \tag{1}$$

where C_1 = the initial concentration of gas in the cylinder,
C_2 = the final diluted concentration in parts per million,
R = the injection rate in injections per minute,

L = the loop size in cubic centimeters,
and Q = the total flow rate of diluent in cubic centimeters per minute.

Thus, for a loop size of 100 microliters (0.100 cubic centimeters) and a desired concentration of 15 parts per million CO in air:

$$15 = \frac{(0.99)(R)(0.1)(10^6)}{(20{,}000)}$$

$$R = 3.03 \text{ injections per minute.}$$

Thus, the cycle time for injection would be 60/3.03 = 19.8 seconds.

The water content of the calibration blend is adjusted to a desired value between 0.5% and 3.0% by passing the dilution air through a humidifier before mixing with the gases from the calibration manifold. The water content is adjusted by contacting the dilution air with water at a controlled temperature. The operator can bypass the humidifier by actuation of solenoid valves SV20 and SV21.

All operating controls for the calibration system are located on the front panel of the calibrator. Panel lights indicate which components are being introduced to the blending system. Individual calibration potentiometers are provided on each channel to account for differences in mass flowmeter response for different gases. This permits readout of all mass flows directly in engineering units.

Gas Chromatograph System

A Carle gas chromatograph was operated and seven test gases were injected. Both thermal conductivity (TCD) and flame ionization detection (FID) channels operated.

A copy of the chromatogram is shown in Figure 11. One of the gases of interest, hydrogen, is not shown but can be detected by the chromatograph. However, it is important to note that hydrogen produces a negative peak, therefore, cannot be analyzed with the other gases unless the baseline is offset.

Permeation Dryer Tests

The Nafion permeation drying material comes in tubular and membrane form, but for gas systems, tubular Nafion is more convenient. However, there are only three sizes available, namely: 0.025, 0.040 and 0.114 inner diameter. The larger inner diameter is preferred for this application because of the reduced susceptibility to plugging, greater durability and simplicity of construction.

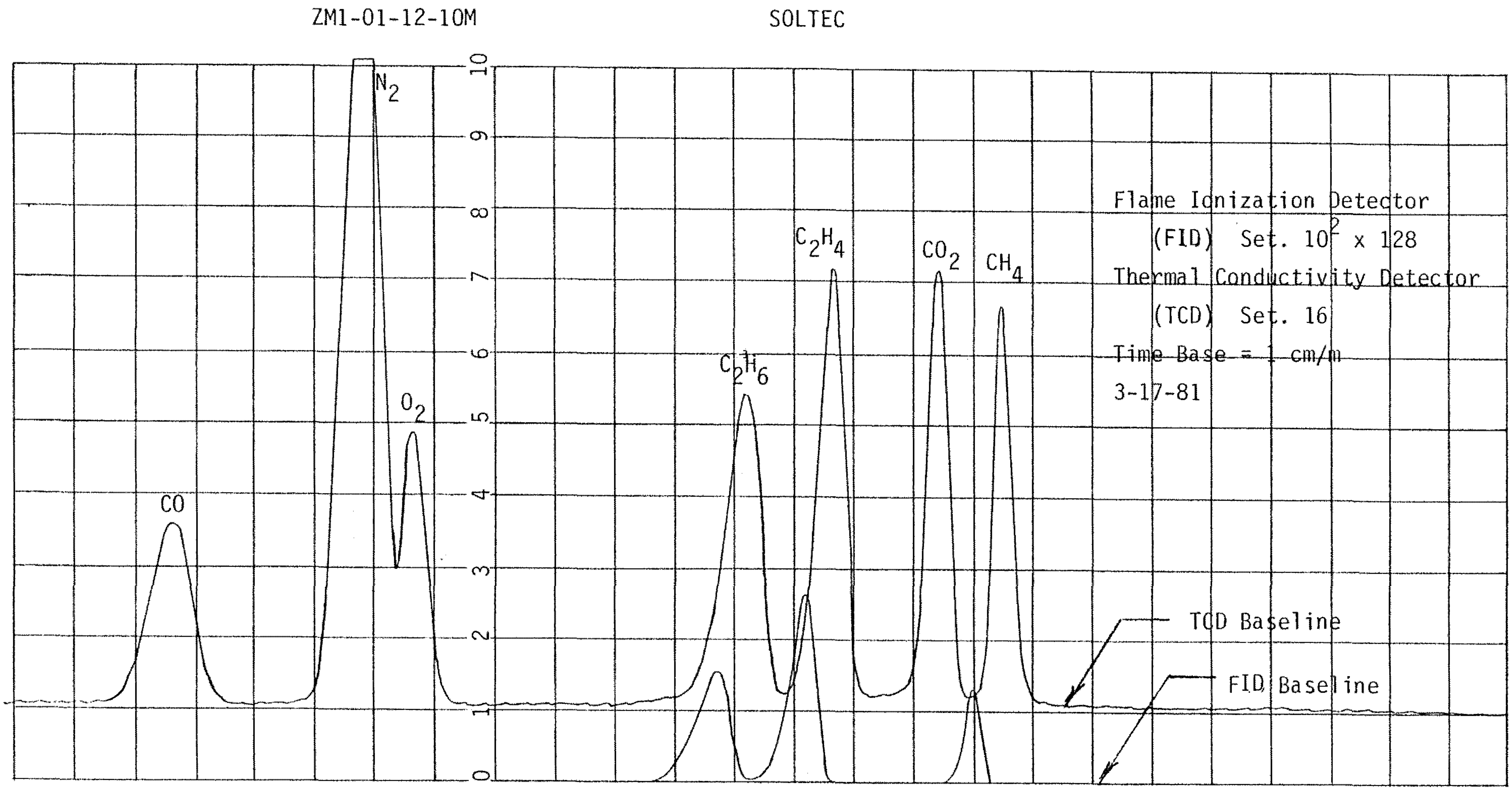


FIGURE 11.
SAMPLE CHROMATOGRAM
CARLE GAS CHROMATOGRAPH

Poiseuilles equation for non-compressible gases indicates that there would be a loss in pressure of less than 2 psi across a 2-meter length of Nafion 810 tubing at a flow rate of 20 liters per minute. The flow equation used by Hertzberg and Litton[1] for compressible gases would provide a higher, more realistic value. However, there are a number of variables and unknowns in the use of Nafion tubing which makes any flow calculation much more complex than for flows through conventional tubing.

1/ Hertzberg, M. and Litton, C., Multipoint Detection of Products of Combustion with Tube Bundles, Bureau of Mines RI 8171, 1976.

An unexplained characteristic of the large bore Nafion tubing is the tendency to flatten or develop an elliptical cross section. Vacuum (25 inches of mercury) does not appear to distort the small-bore tubing, but does tend to increase the flattening of the large-bore Nafion. Although the vacuum does not completely cut off the flow, the flow rate is significantly decreased. Tests on the large-bore Nafion showed a flow difference of a factor of about better than three between pressure and vacuum on the tubing.

Nafion tubes exhibit mechanical properties which are a function of polymer characteristics, the amount of water absorbed, and the temperature. In the standard PermaPure single-tube dryers the individual tubes are mounted rigidly at the ends, therefore tend to distort in a somewhat serpentine manner as the elongation varies between the two fixed points with the operating conditions. Dry polymer has a density of 1.98 grams per cubic centimeter. As it absorbs water, however, the volume increases at approximately twice the rate of the weight increase. Geometric distortion, under ordinary operating conditions may explain, at least in part, the tendency of the cross section to develop into an elliptical shape.

Additional variables which affect the flow rate are the restrictions of the seals at the tube ends, the wall friction, and the extent of the non-isothermal and non-adiabatic conditions of operation. The development of accurate, predictive equations for the Nafion dryer required data from empirical tests for determination of worst cases of temperature, gas density, flow, time and sample dewpoint.

Special Dryer

A dryer was constructed to test the proposed design approach in which a portion of the tube would be at upper borehole temperature and a portion at the outside ambient temperature. The purpose of this approach was to precondition the sample before it was exposed to possible outside subfreezing temperatures while taking advantage of the increase in water removal efficiency at the lower ambient temperatures.

Initially, it was planned to fabricate a four-tube dryer ten meters long. The plan was modified to use only a single tube until the Nafion performance had been better characterized. Also, the use of parallel tubes required a common header or manifold, and Nafion, a Teflon-like material, posed a special bonding problem. The fabrication of a single tube dryer can be done easily with conventional tubing fittings.

The Nafion bonding problem was studied and resolved. The solution was to pre-treat the Nafion with an etchant available from Fluorcarbon Company. Treatment with the etchant allows Nafion to be readily bonded to epoxy systems.

The dryer was constructed of a single 1/8-inch outer diameter Nafion tubular membrane inside a 3/8-inch outer diameter thermoplastic tube, 50 feet long. Special tee fittings at each end allowed the sealing of the tubes and acted as ports for the sample and purge gases. Figure 12 shows the dryer in the cold chamber connected to the bulkhead fittings and thermocouples.

The Nafion as supplied by duPont varies in cross section from rounded to somewhat flattened. Flows were compared in a 50-meter length of the Nafion under both vacuum and pressure conditions. The flows were 1.4 liters per minute under a vacuum of 20.5 inches of mercury and 5 liters per minute with a pressure of 15 psig.

A noticeable increase in tubing collapse accompanied the vacuum test. Since the sample is under vacuum in the proposed system, the most reliable flow configuration was to flow the purge gas through the membrane tube under pressure and pull the sample through the outer tube surrounding the dryer tubing. This maintained a slight positive pressure on the inside of the membrane which stabilized flow restriction caused by deformation of the tubing cross section. Tests showed high efficiency for this configuration and all subsequent tests were conducted with the inverse flow.

Preliminary Testing and Evaluation

Preliminary tests were made to characterize performance of several of the same model dryer (PermaPure Products Model PD-625-12PS). The units were tested for pressure drop, conditioning time and dewpoint in the product gas as a function of flowrate and dryer temperature. In addition, five of the units were connected in series to allow observation of the drying profile as a function of dryer length. A 6-foot, 200-tube dryer was procured from PermaPure but did not perform as hoped. Initially the purge fittings leaked and it was found that they were cross-threaded. After the leaks were fixed, however, the dryer still would not dry below about -10°C. Subsequent tests also produced unsatisfactory performance, and work with the dryer was discontinued.

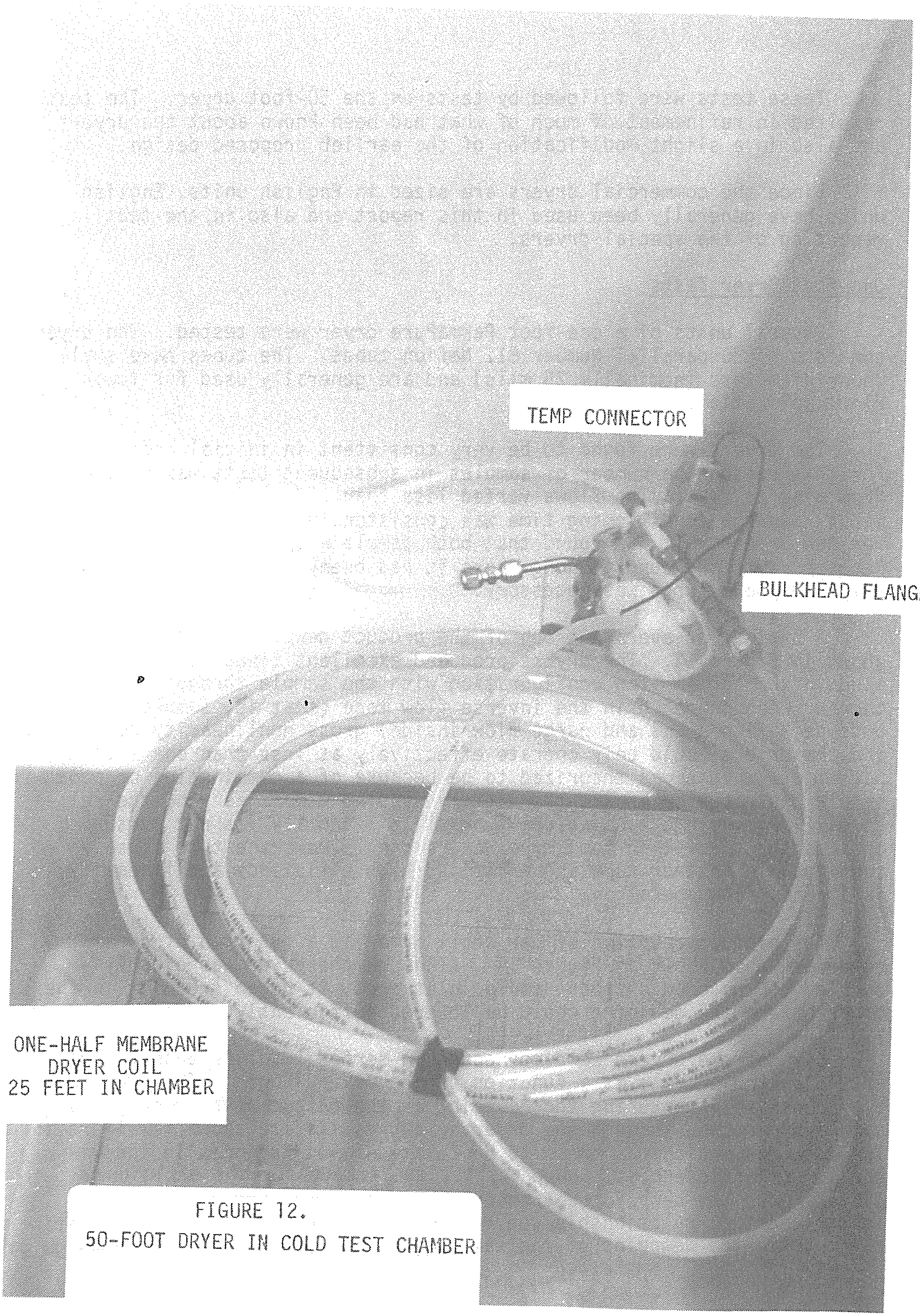


FIGURE 12.
50-FOOT DRYER IN COLD TEST CHAMBER

These tests were followed by tests on the 50-foot dryer. The tests resulted in refinement of much of what had been known about the dryers, and also in a slight modification of the earlier proposed design.

Since the commercial dryers are sized in English units, English units have generally been used in this report and also in the test reporting of the special dryers.

One-Foot Dryer Tests

Several units of a one-foot PermaPure dryer were tested. The dryer consists of 50 parallel Number 811 Nafion tubes. The tubes have small inner diameters (nominally 25 mils) and are generally used for lower flow applications.

The dryers were found to be very consistent in initial testing. For this reason the number of samples in subsequent tests was reduced from nine to five. The flows varied less than ±5% at 10 liters per minute and the conditioning time was consistently less than 2 hours for new dryers. It was found that both sample and purge flows were necessary for the conditioning where it had been believed earlier that only a dry air purge was necessary.

A typical or average graph of the product dewpoint versus flow is shown in Figure 13. The dryers produced excellent linearity when operated in the normal flow configuration with the sample through the Nafion tubes. When operated in the inverse flow mode (that is, sample flow outside Nafion tubes and purge flow inside) gross nonlinearity resulted and the dryers could only operate effectively at less than one liter per minute. This was theorized to be because of a combination of poor sample distribution around the tightly bundled membranes and the relatively large volume housing the tubes. This anomaly was not pursued because the special 50-foot dryer has a single membrane tube closely contained in another tube and exhibited high efficiency and linearity in inverse flow operation.

The product dewpoint of the small dryer as a function of dryer temperature is shown in Figure 14. Although the dryer was closely coupled to the cold chamber sample inlet port, it began freezing in the dryer before the dewpoint could be lowered sufficiently.

Five of the dryers were connected in series to allow observation of the drying profile as a function of the dryer length. This was done by successively measuring the dewpoint at the output of each dryer as the sample progressed through the dryer. The results are shown in Figure 15. The data dispersion was shown to be related to differences in individual dryer efficiencies. When correction is made for the efficiency differences, the dewpoint decrease was linear with respect to dryer length and that relationship would be expected to remain in our operating range until the dewpoint of the sample gas approaches that of the purge gas.

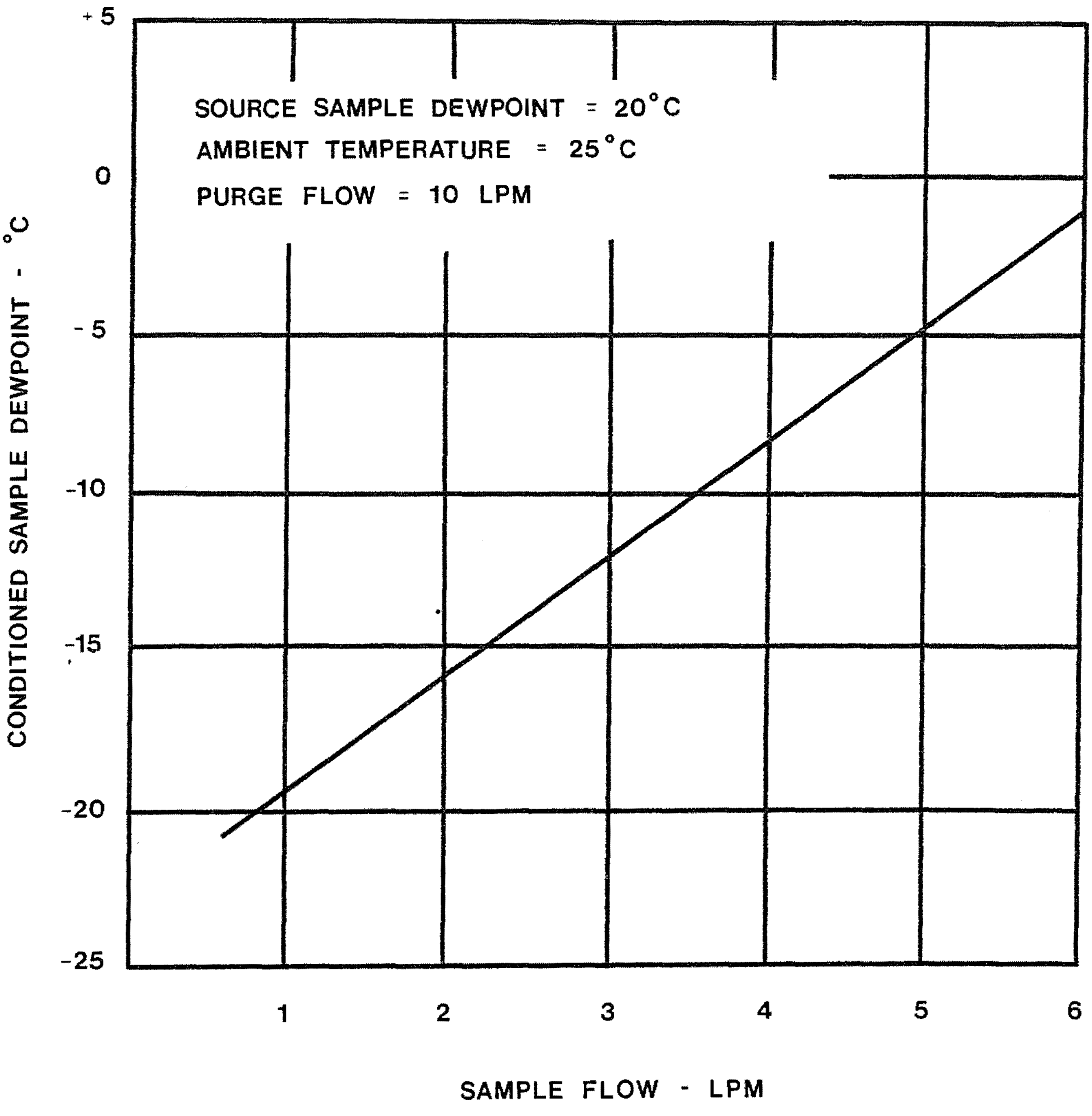


FIGURE 13.

TYPICAL DRYER PERFORMANCE

STANDARD DRYER

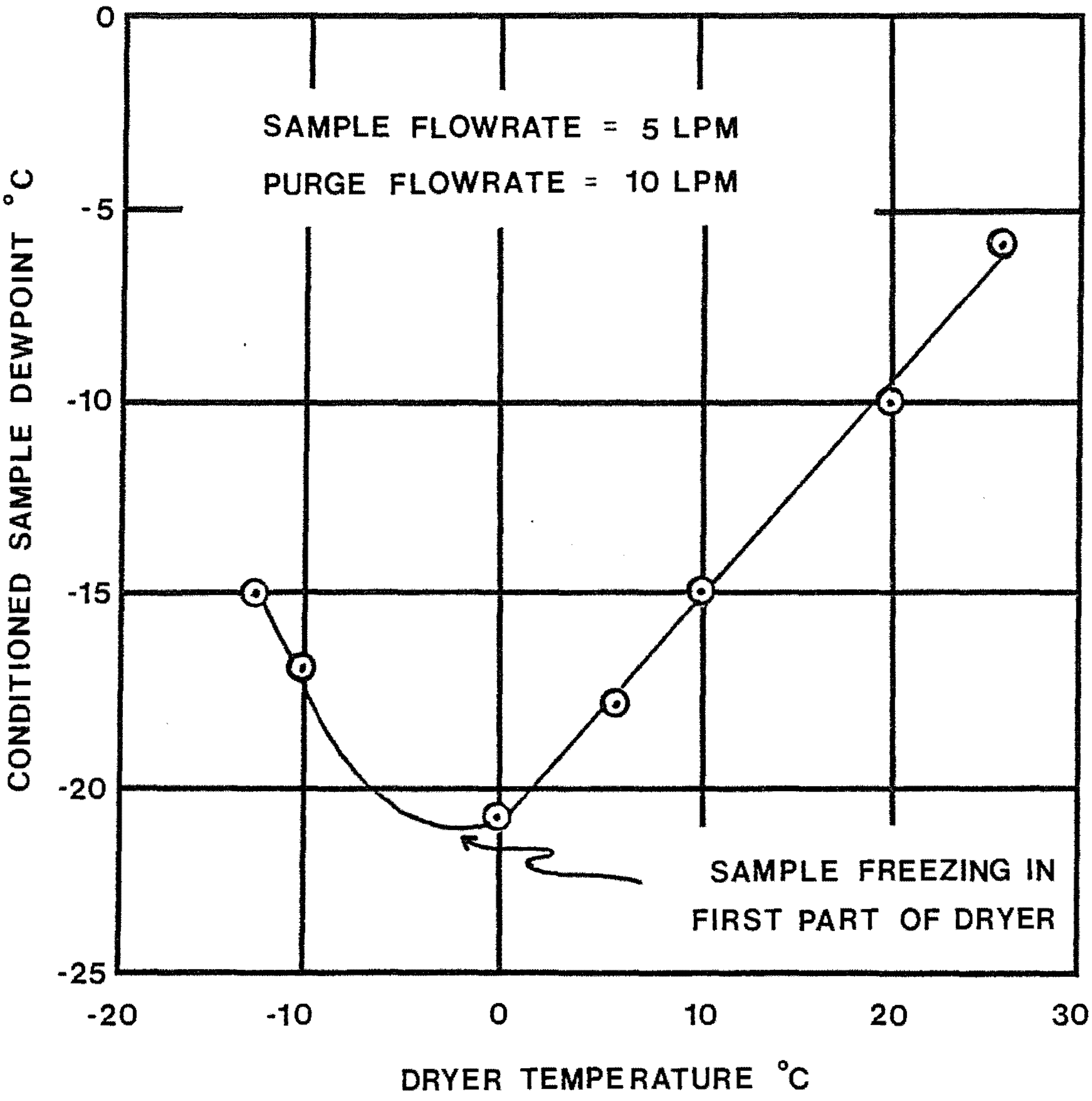


FIGURE 14.

SMALL DRYER EFFICIENCY VERSUS TEMPERATURE

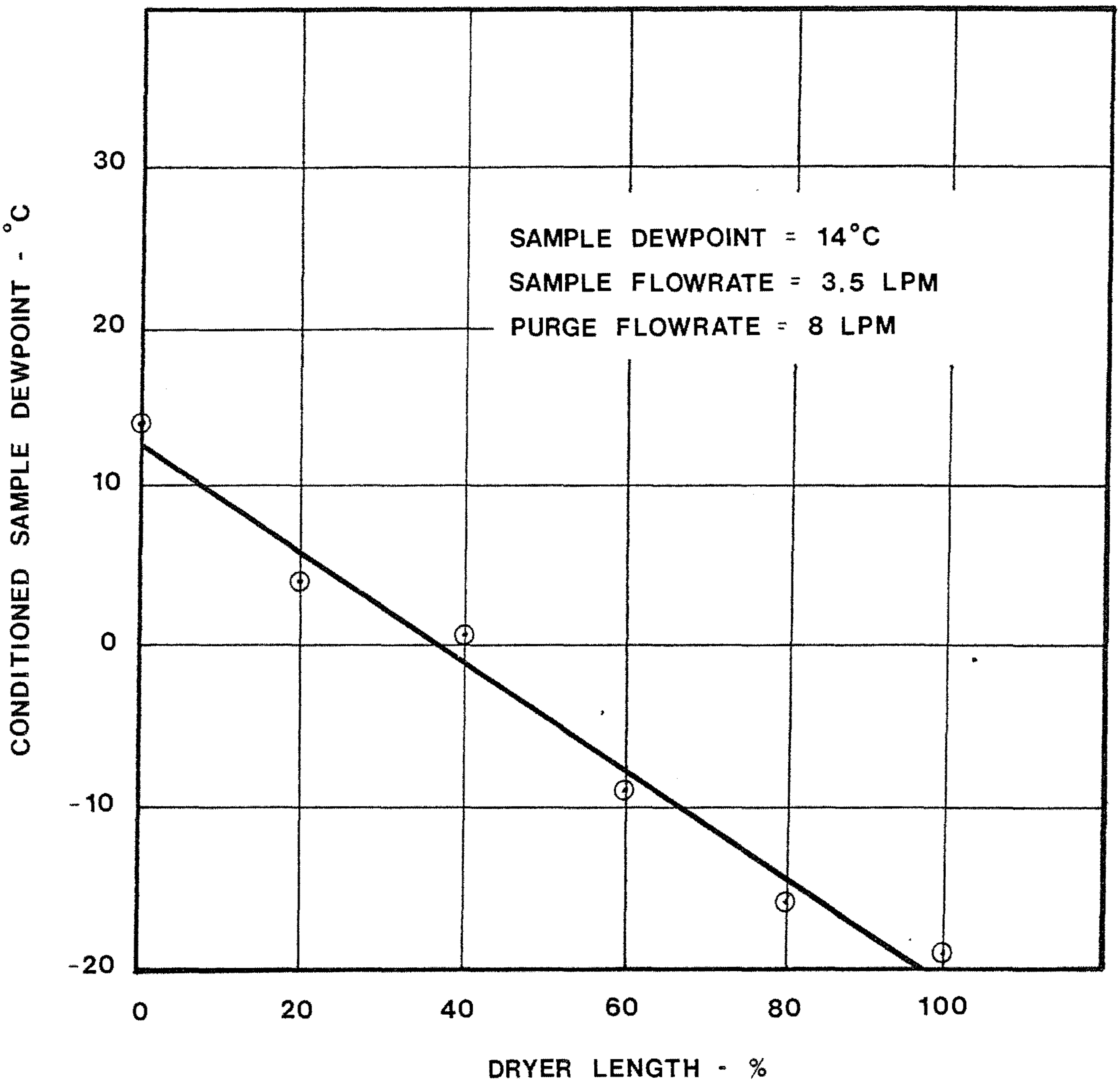


FIGURE 15.

DRYER EFFICIENCY VERSUS DRYER LENGTH

Fifty-Foot Dryer Tests

The 50-foot dryer tests were conducted with 25 feet of the dryer held at a nominal 23°C to 25°C, while the remaining 25 feet was in the temperature chamber where the temperature was varied from 23°C to -20°C. This was to simulate a dryer with half its length through the top of a lightly sealed borehole and the other half exposed to lower outside air temperatures (see Figure 16). Initially it was assumed that the optimum placement of the dryer would be partially in the borehole. This would allow the dryer to dry the sample low enough to preclude drop-out.

In the above described configuration, the sample gas enters the dryer through the end of the dryer held at a stable temperature and exits at the cold end of the dryer. The purge gas flow is counter-current to that of the sample gas; that is, it enters the cold end of the dryer and exits the warmer end.

The combined results of the dryer dewpoint versus length and temperature are shown in the family of curves in Figure 17. In addition, the temperature profile of the dryer for the various colder temperature levels is super-imposed on the dewpoint curves. The temperature curve is derived from end points and from data on previous experiments. Therefore, the profile is an approximation, but is believed to be accurate for purposes of these tests. It was adequate to predict whether or not line blockage would occur at the particular test temperatures. The slight positive swing in dryer temperature near the end of the dryer is caused by entry of the warmer purge air. The horizontal axis displays the dryer length. The vertical axis is temperature in degrees centigrade for both the dewpoint and temperature profiles.

For simplicity, "dewpoint" is used throughout this discussion, although below 0°C the hygrometer actually measures frost point. Although the difference will amount to nominally a few degrees centigrade, the frost point is actually what is shown in the figure.

The dewpoint has a constant slope over the constant temperature portion of the dryer, then increases to reflect greater drying efficiency as it enters the cooled half of the dryer. Data was taken at cold chamber temperatures of 23°C, 10°C, 0°C, -10°C and -20°C. Sample flow was constant at 8 liters per minute and the purge at the recommended level of 1.5 times the sample flow of 12 liters per minute.

Through temperatures of 23°C to -10°C the dewpoint remains below the dryer temperature and no water dropout and subsequent freezing occurs. The shaded area, however, indicates a portion of the dryer where the sample dewpoint is higher than the dryer temperature and freezing would be expected. In the tests, the dryer did perform with no problem until -20°C where it gradually began losing sample flow as freezing occurred.

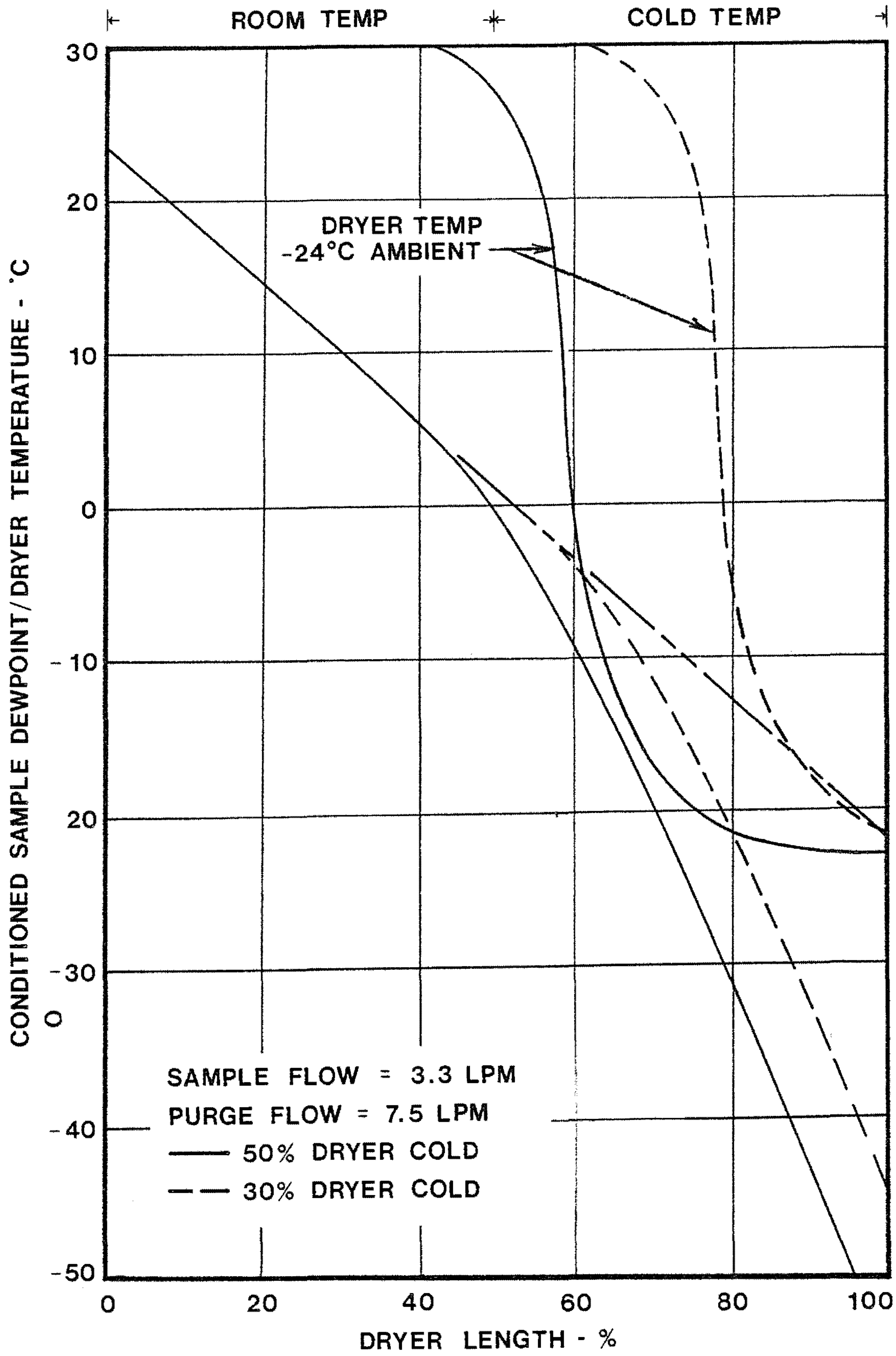


FIGURE 16.

50-FOOT DRYER TEMPERATURE PERFORMANCE - A

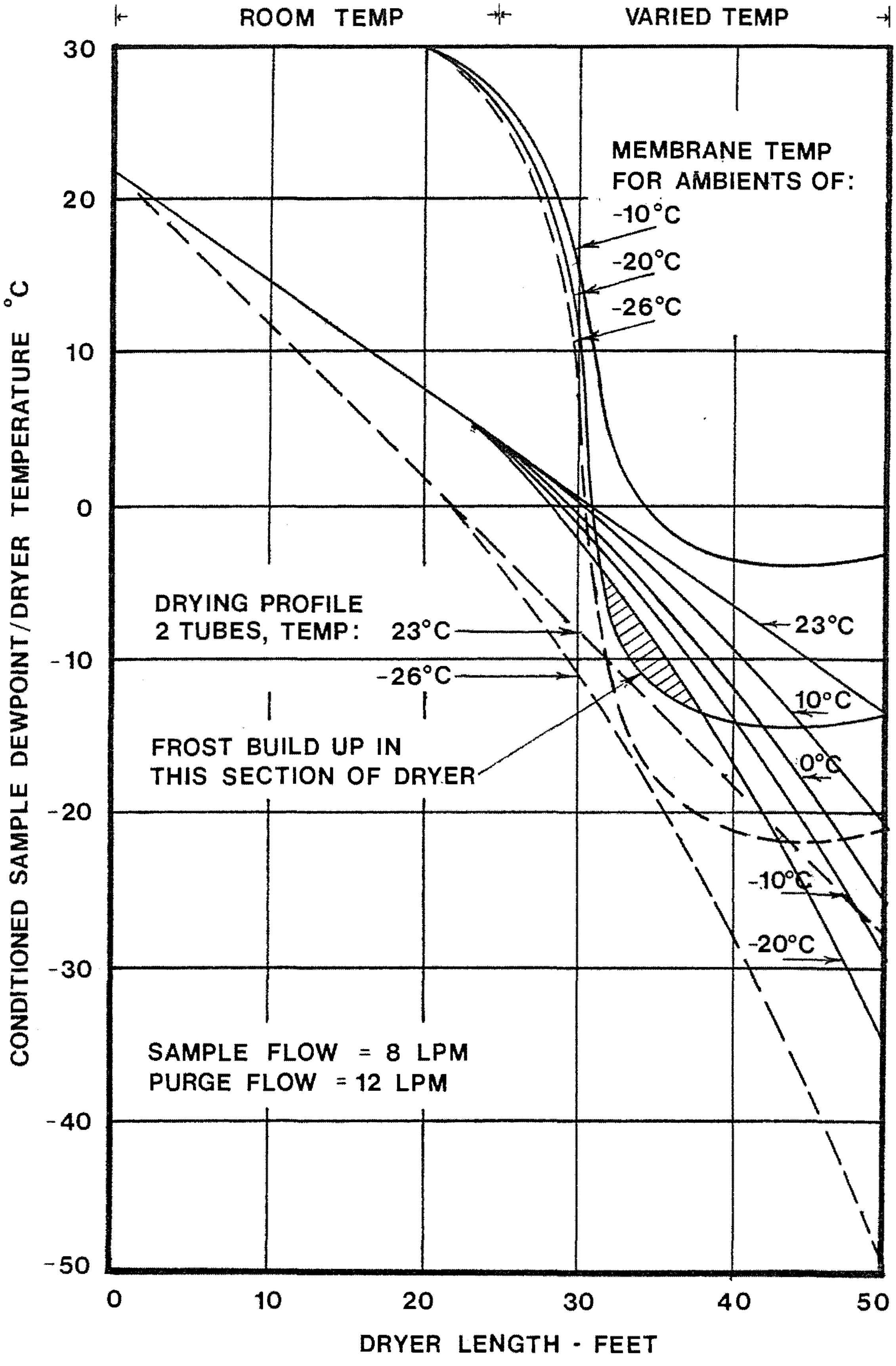


FIGURE 17.

50-FOOT DRYER TEMPERATURE PERFORMANCE - B

There were various options open in resolving the freezing problems with the test dryer, while still maintaining the advantages of the proposed system design. The simplest solution was to increase the basic efficiency of the dryer. Doubling the dryer area would produce the drying curve shown by the dotted line. The expected temperature profile of the dryer with half the dryer exposed to -26°C is also shown by dotted lines. As the closeness of the dotted lines indicates, freezing in the line could be marginal. Therefore, an additional safety margin was needed.

The single-tube, 50-foot dryer at 8 liters per minute has an efficiency roughly equivalent to a single-tube, 30-foot dryer at 5 liters per minute. A flowrate of 20 liters per minute would require four 1/8-inch drying membranes. Doubling that to produce the efficiency shown by the dotted line in Figure 16 and adding about a 25% margin would mean that the dryer for each sample point would contain ten parallel tubes of 1/8-inch Nafion, 30 feet long. Therefore, this was our new design criteria for the prototype system.

After the initial testing of the 50-foot dryer, operating parameters were altered to make the dryer a scale version of the planned engineering model design. The test parameters were essentially at the worst case for the system, differing only in the test minimum temperature of -24°C instead of the design minimum of -26°C. However, at -24°C ambient, the frost point of the product gas out of the dryer was at least -55°C, the point where the hygrometer meter pegs negative.

Figure 16 shows the approximate drying curve and dryer temperature as a function of dryer length in percent. The curves are approximate because only end point data was taken and the shapes of the curves were determined from previous test data.

It may appear from the curves that the dryer could be shortened to about 80% of its length and still safely have a dewpoint lower than the minimum ambient temperature of -26°C. However, the dryer is designed with a margin for drying variations in the production dryers and also to allow for lower temperatures in the horizontal transport lines after the sample has left the dryer.

Displacement of the curves on the horizontal axis to represent more or less dryer exposed to the lower temperatures shows that the optimum performance occurs with between 60% to 70% of the dryer in the borehole and the remainder in the ambient air. With such placement, the dryer retains considerable margin in the frost point of the conditioned sample and also has a healthy margin between the dryer temperature along the dryer length and sample frost point as the sample progresses through the dryer.

Engineering Model Dryer

The engineering model dryer was approximately 10 meters long. It contained nine 1/8-inch outer diameter Nafion tubes. The ends of the tubes were pre-treated with a fluorocarbon etchant "Tetra-Etch" from W.T. Gore and Associates, and then solidly encapsulated in a 3/4-inch stainless steel header with Epoxylite 4141-35. The tubes were contained in a 3/4-inch Teflon tube (see Figure 18). Note that conventional Swagelok tube fittings were used in the engineering model, but custon designed fittings would be necessary in the prototype to allow a four-dryer system to be lowered into a 3-inch diameter borehole, a clear disadvantage of having the dryer in the borehole.

Engineering Model Dryer Test Results

The 9-tube engineering model dryer was fabricated and tested with 50% of the dryer in the cold chamber. The Nafion tubing total length was about 30 feet, 8 inches, and the sample flow was 20 liters per minute.

The test results are shown in Figure 19. The test was run only down to a dryer temperature of -15°C because at that point the dewpoint hygrometer measuring the conditioned sample had no more range left at about -55°C. The dryer, as configured, met the specifications with ease.

Dryer Size Versus Sample Flowrate

The permeation dryer size can be scaled to reflect a variety of sample flowrates. The advantages of using the minimum flowrate are:

1. Longer transmission distance for given transport tube size,
2. Down-size pump requirements,
3. Longer particulate filter life,
4. Reduced system size and cost,
5. Lower purge flowrates, and
6. Reduced thermal requirements.

The level to which sample flows can be reduced will depend on the requirements of the analysis system including the number of analyzers and individual analyzer requirements for the gases to be measured. the sample transmission time required, and minimum number of sample points per borehole.

The following table shows the total sample flows versus dryer length for a 9-tube, 3/4-inch outer diameter dryer and for a 25-tube, 1-inch outer diameter dryer:

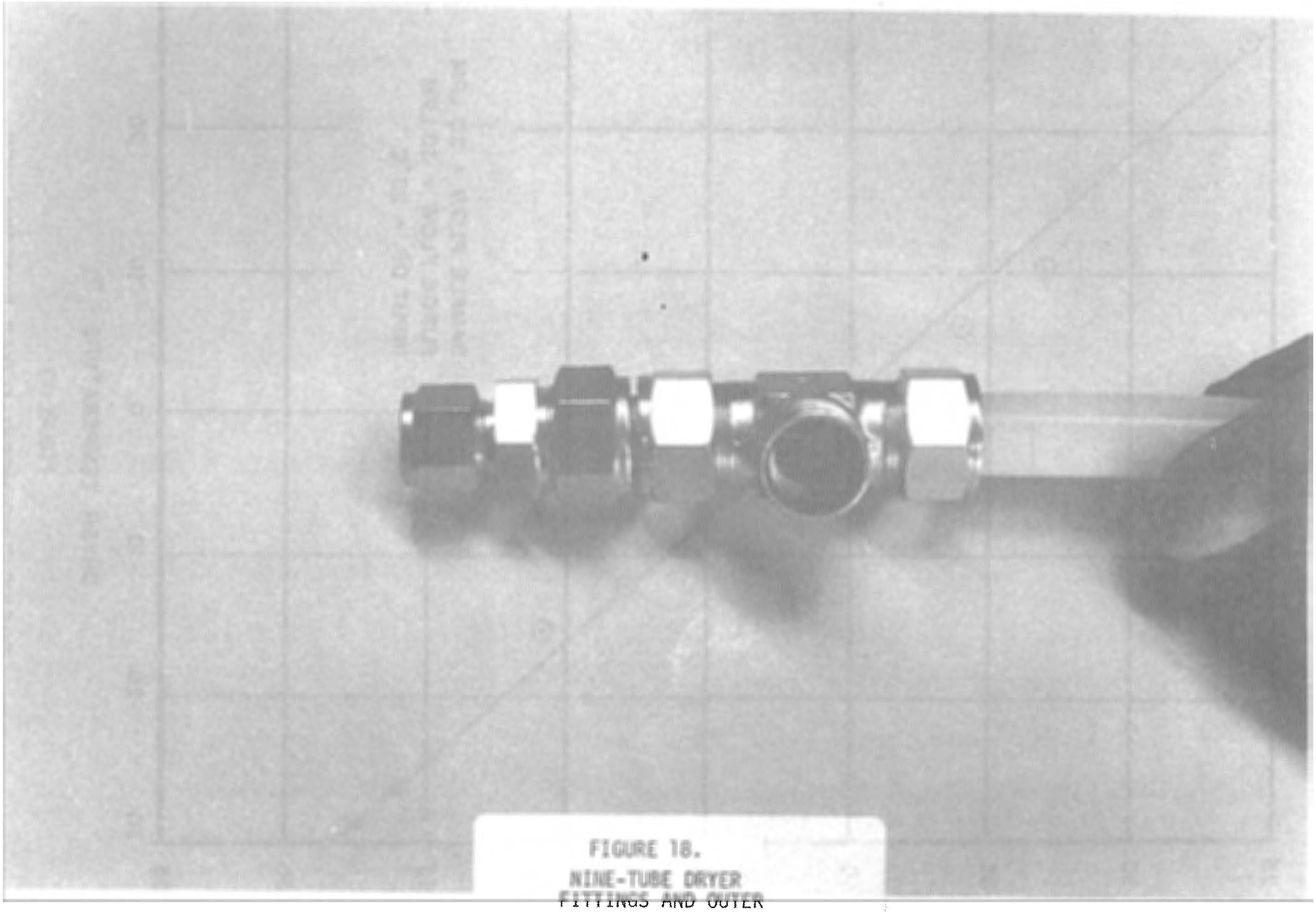


FIGURE 18.

NINE-TUBE DRYER FITTINGS AND OUTER TEFLON SHELL

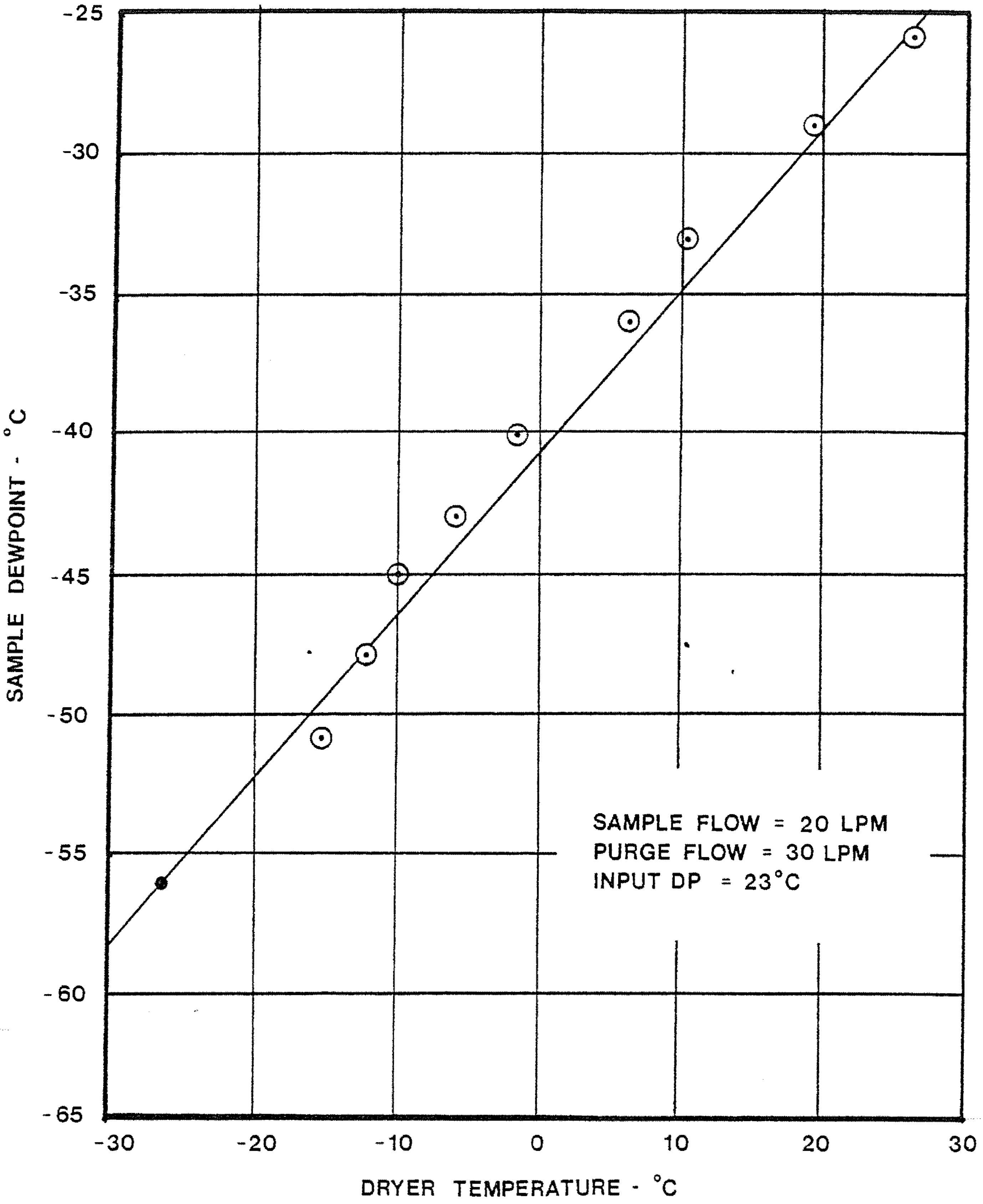


FIGURE 19.

ENGINEERING MODEL DRYER PERFORMANCE

Table 1. - Dryer sizing

Sample flow LPM	9-tube dryer length, M	25-tube dryer length, M	Purge gas flow, LPM
20	10	3.6	30
10	5	1.8	15
5	2.5	0.9	7.5
2	1	0.4	3
1	0.5	--	1.5

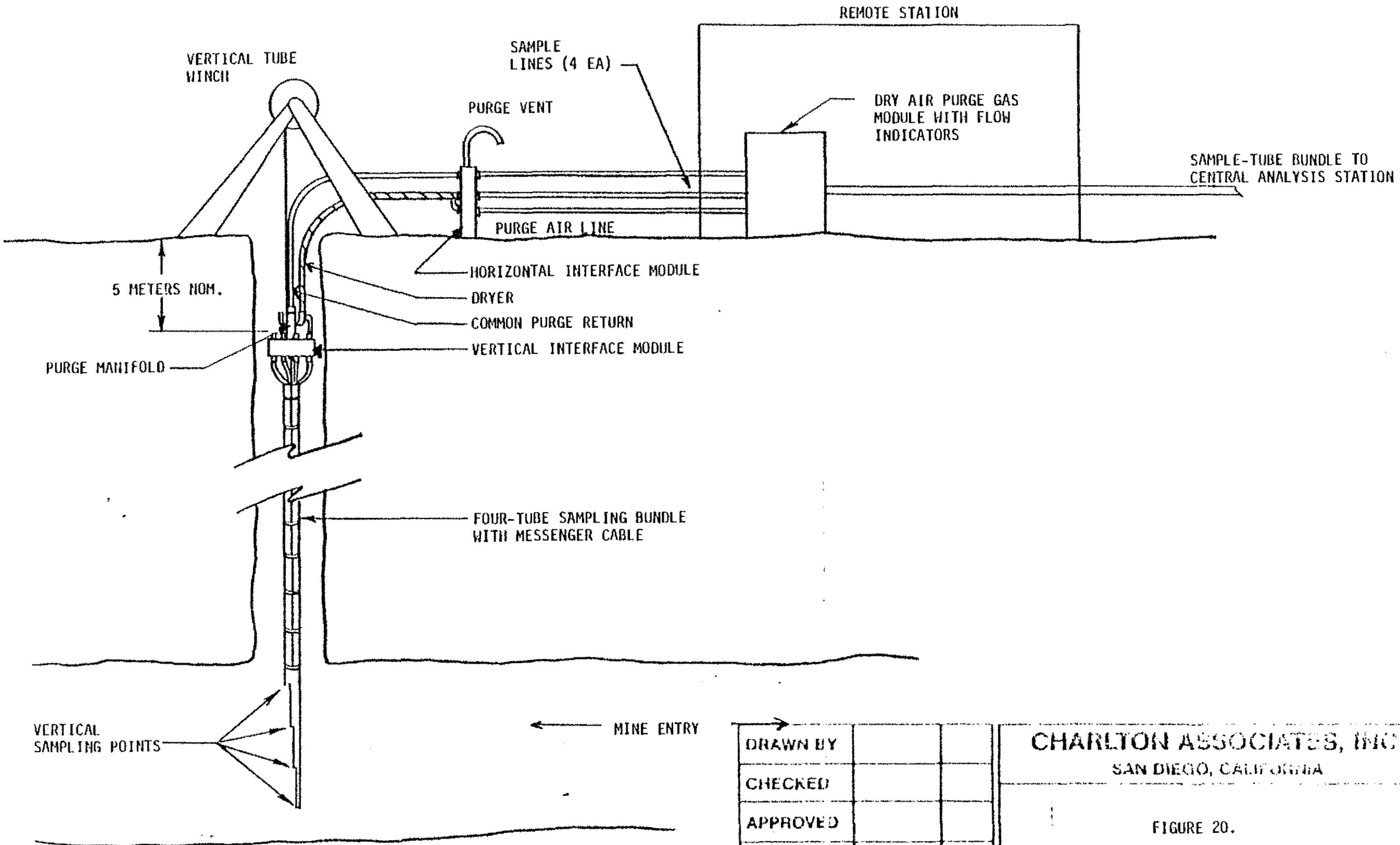
The maximum length for the 1/4-inch inner diameter sample transport tube, assuming a single sample pump, is about 1,000 feet for a sample flowrate of 20 liters per minute. The maximum flowrate is proportional to tubing length for a fixed inside diameter. In this case, we were using the maximum inner diameter tube used in the past Bureau of Mines tubing bundles (1/4-inch inner diameter). Bundles with 3/8-inch inner diameter are available and are included in the data in the following table:

Table 2. - Sample transport tube sizing

Sample flowrate	Transport distance in feet	
	1/4-inch I.D.	3/8-inch I.D.
20	1,000	1,800
10	2,000	3,600
5	4,000	7,200
2	10,000	18,000
1	20,000	--

At 20 liters per minute, the sample could only be brought to the surface of the borehole and would need additional provision for transport through the horizontal lines. The above transport distances can be increased by putting pumps in series along the transport line. The pumps could be air operated from a high pressure line. The use of high pressure air is planned for heating the sample tubes out of the borehole and a higher air flowrate could be provided to operate both the heater and added sample pump or pumps. The air line would be larger than the sample lines because it would carry all the air for the heater and pump. In addition, it would carry all the purge air for the sample dryers and would typically run up to 1.5 times the total sample flowrate. The fact that the air can be pressurized at the air source helps reduce the size of the air line.

The approach using the borehole temperature to keep the front end of the dryers warm is shown in Figure 20.



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CHECKED		
APPROVED		
RELEASED		
REF. DWGS.		

CHARLTON ASSOCIATES, INC.
SAN DIEGO, CALIFORNIA

FIGURE 20.
SAMPLING CONFIGURATION UNDERGROUND MINE ATMOSPHERES

Code | Dwg. No. | Rev.

Proposed Revised System

The conceptual design of the in-borehole system was changed after the July 14, 1980 meeting in Burceton to reflect the changes requested. The two major changes were:

1. To keep the dryers and associated components out of the borehole, allowing the borehole to remain sealed with only the sample tube in the borehole, and

2. To assume no electrical power availability at the borehole.

Dryers Outside Borehole

All elements of the drying system are contained in an insulated heavy polyethylene carrying base which is built with stainless steel hinges and clasps. The case contains the filter, dryers, heater and flow monitors in a form fitting clamshell made of high insulation material. Gas connections are made to bulkhead fittings through the side of the case which means that the insulation and interior connections will not have to be disturbed except for servicing or routine maintenance.

For field installation, the standard vertical tubing bundle is installed in the borehole and tied off as is currently being done. Connectors are then installed on the individual tubes in the handle and insulation around the exposed bundle from the borehole to the dryer case. The input and output connections are then made to the drying system ports and the system is operational when high pressure air is available from the central station.

No Electrical Power at the Borehole

The major problem in drying the sample outside the borehole was in keeping the sample temperature above its dewpoint ahead of and in the dryer. However, the requirement for heat at the borehole and restriction from having a source of electrical power at the borehole posed a unique problem. For this reason, vortex heat was proposed to provide a hot air blanket between the sample handling components and a thick outer insulation jacket.

Since the permeation dryers require a dry air source, the dry air would be piped under pressure from the central station. The air would be near the ambient temperature after transport through the long, exposed tube bundles, but could be used to drive a heat generator and then used for the purge gas. However, the heat generator would require more air and a higher pressure than would be necessary for the purge system alone.

Assuming the availability of high pressure air, a number of heating methods are possible. These include friction heating, electrical power generation and vortex heating. Vortex heaters have no moving parts and therefore have a reliability advantage. For this reason, they were considered first.

Vortex tubes use high velocity air spiraling down the inside of a tube to maintain a stream of reflected air spiraling through the center of the tube in the opposite direction. The linked streams form a forced vortex which results in a transfer of heat from the inner core of air to the outer core. The vortex tube thus produces hot air through one outlet and cold air through the opposite end of the tube. The orifice choice controls the total quantity of air and relative amounts of hot and cold air.

The purge air requirement for a four-dryer system operating a 20-liters per minute dryer would be 100 to 120 liters per minute. A type 106-4 vortex tube from Vortec Corporation will require 190 liters per minute at 80 psig to produce heated air at 300 Btu/hour. The air would be used to warm the sample conditioning system, then would serve as the purge gas for the dryers. At least some of the cold air could be mixed with the purge inlet air if needed and would serve to increase the dryer efficiency because of its lower temperature.

A 3/4-inch line would be necessary to transmit the air one mile to the site and would require a 100 psi dry air system. It should be remembered that the flow of 190 liters per minute is for one borehole only. A 19-borehole system as described by Fink and Adler[2/] would require 3,600 liters per minute for purge and heating air.

2/ Fink, Z. J. and Adler, D.T., Continuous Monitoring System for Mine Gas Concentrations Using Tube Bundles, Bu Mines RI 8060, 1975.

Larger gas engine commercial compressors can deliver over 3,600 liters per minute at 100 psi and heatless dryers are available which can handle similar flowrates. However, it is a large system and not one amenable to rack mounting. The system could be designed so that the air supply only provided purge gas for higher ambient temperature operation and switched in a parallel leg when thermal control became necessary. Reduction of sample flowrate, number of boreholes and number of samples per borehole results in a 1:1 savings in purge air. The air needed for thermal control using the Vortex heated output would decrease proportionately as the number of boreholes decreased, but not for the dryer size or number of sample points per borehole.

Meeting to Discuss New Design Criteria

A meeting was held at the Bruceton facility on August 21, 1980. The purpose of the meeting was to discuss the system, to offer alternatives in providing heating and to review the implications of the worst-case specifications on the system design. In addition, a patent application regarding the dryer and schedule and cost impacts of the new design were discussed. Attendees at the technical portion of the meeting were:

L. D. Bowman	Charlton Technology
K. W. Charlton	Charlton Technology
E. Chilton	Bureau of Mines
L. E. Dalverny	Bureau of Mines
T. J. Fisher	Bureau of Mines
R. J. Jackson	MSHA
E. J. Miller	MSHA
J. E. Vrosek	MSHA

The following was decided at the meeting and used as a basis for a modified prototype design.

Heater Power

1. Batteries are undesirable because of long-term reliability questions.
2. Gas is undesirable because of explosive hazard of flames.
3. The communications lines in the tube bundle could be considered as a means of transmitting power from the central to the borehole site.
4. Systems with moving parts are less desirable for reliability reasons.
5. Use of auxiliary generators for start-up power is not always feasible. The system must be "self-contained".
6. Catalytic heating is acceptable.

Filtering

1. Electrostatic precipitators are not desirable because of the high voltage and explosive hazard.
2. Baffles and cyclone separators are acceptable. Small cyclone separators are used by one MSHA group and seem to be effective. It may be the only filter necessary. Coalescing filters are possible if the maintenance interval is long enough.

Alarms

1. Alarms may be better if they can warn of both high and low conditions.
2. Battery operation is not desirable.

Specifications

The target specifications for the prototype were to be modified as follows:

1. Flows: Decrease sample flow from each sample point from 20 liters per minute to 10 liters per minute.
2. Sample points: Decrease the maximum number of sample points per borehole from four to three.

3. The maximum tubing bundle length from the borehole to the sheave is four feet. It is also four feet from sheave block to dryer.

4. Tube bundle size: Whether the sample tube bundle could consist of four tubes or seven tubes is yet to be determined. A 7-tube bundle would allow the use of four of the tubes for purge/heating air. A 4-tube bundle would necessitate running an auxiliary tube for air because the extra tube would not be large enough for the purge flow.

Consultant

The services of a consulting thermodynamicist were determined to be necessary because of the complex thermal variables in the newly proposed system.

Communication Wires in Tube Bundles

The use of the wire pair in the tube bundle to transmit power was considered. The standard wires are 22-gauge twisted leads which have a resistance of about 16.86 ohms per thousand feet, or 89 ohms per mile. This would allow a maximum power transfer to the borehole of less than 17 watts for 110 volts source power, which is not enough to help appreciably with the heating requirements. For safety reasons and wire insulation limitations, it would not be desirable to use a voltage much higher than 110 RMS volts.

The design direction was modified to exclude the use of power at the borehole. This necessitated emphasis on the thermal characteristics of the system before the design could proceed further. Therefore, a meeting was held at Bruceton facility to discuss the system and to define essential specifications which influence the thermal design. As a result of the meeting, a proposal to cover a two-month extension of Phase 2 of the program was submitted.

Phase 2

Under the guidelines established at the end of Phase 1, Phase 2, the development of two prototype sample conditioning systems, was started.

Preliminary Thermal Design

The primary impact of the modified design goals was the requirement for a somewhat sophisticated thermal control system. The conceptual design of the heated sample conditioning system is shown in Figure 21. For purposes of estimating the heat required to prevent the water in the sample from freezing at -26°C, the following was assumed:

1. Insulation covers the sample bundle in two areas: (1) between the borehole top and sheave block top, and (2) between the sheave block top and input to the dryer container with an air gap between the insulation and tubing bundle; and

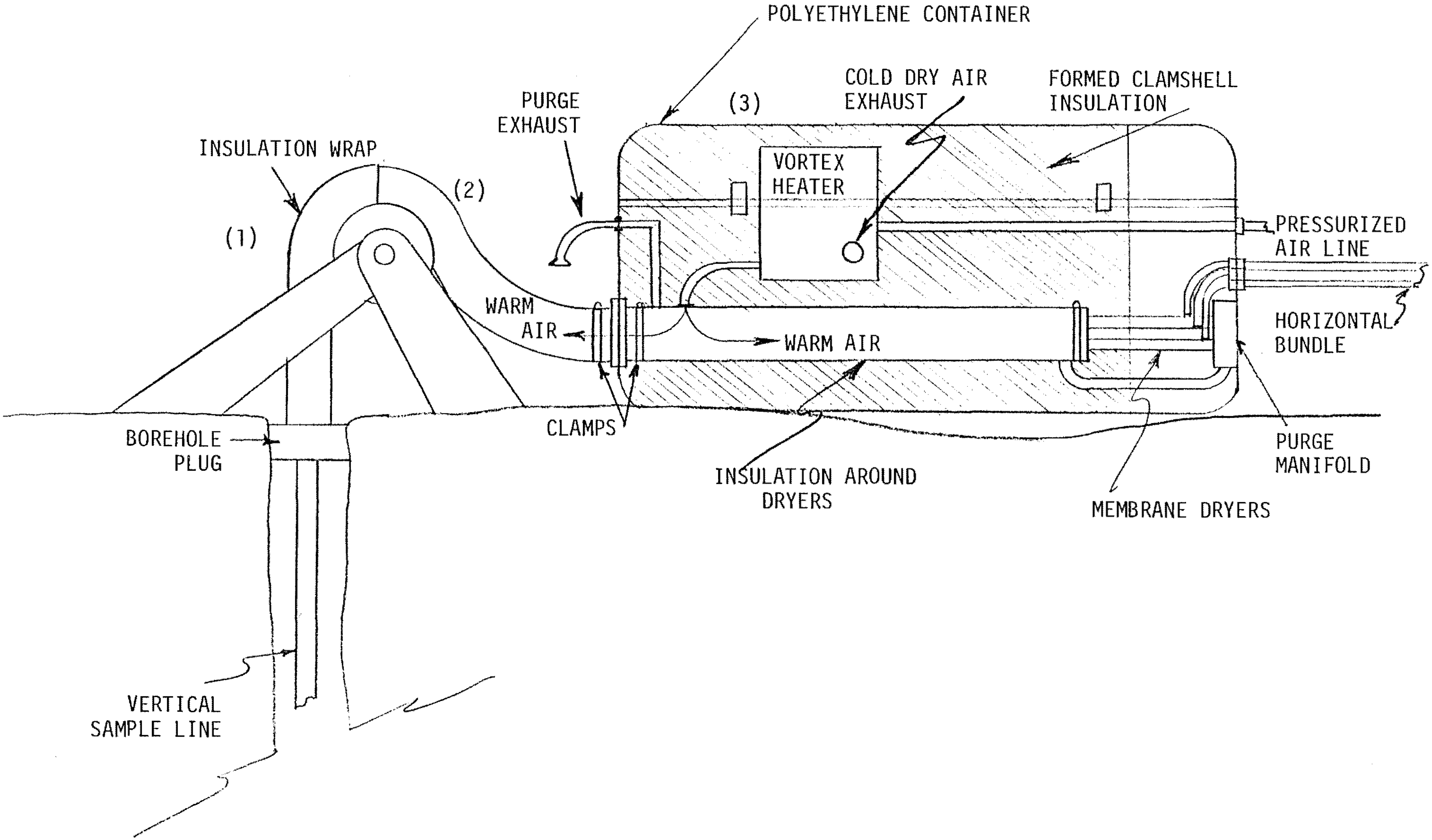


FIGURE 21.

PHASE 2 HEATED DRYER SYSTEM

2. Warm air is provided to heat the section (2) between the sheave block and dryer container and the inside of the insulated dryer container.

Heat loss would therefore be from four areas:

1. Insulated section (1),
2. Insulated section with warm air (2),
3. Sample air warm up (by 9°F) for margin, and
4. Dryer container (3).

For the insulated sections (1 & 2) the heat loss is calculated from:

$$q = \frac{2\pi L K \Delta T}{\ln\frac{R_o}{R_i}} \qquad (2)$$

where R_o = outer insulation radius, 2 inches,
R_i = inner insulation radius, 1 inch,
L = length, 8 feet,
ΔT = temperature difference across insulation, 99°F,
and K = thermal conductivity of insulation, .03 Btu/hr-Ft^2-°F/Ft.

Therefore:

$$q = 108 \text{ Btu/hr} = 32 \text{ W}$$

For the insulated section with warm air at a temperature of 18°F higher than the passive section, the heat loss is about 19 W.

The heat loss for sample air warm up is dependent on sample flow which is assumed to be the maximum of 20 liters per minute. From:

$$q = WC_p \Delta T \qquad (3)$$

where W = mass flow rate,
C_p = specific heat capacity of air,
ΔT = 5°C (9°F).

The heat loss is only about 2 W.

The heat loss from the dryer container with dimensions of two feet by two feet by one foot is found from:

$$q = \frac{KA_s \Delta T}{x} \qquad (4)$$

where K = insulation thermal conductivity, .03Btu/hr-Ft^2-°F/Ft,
A_s = container outside area, 16 Ft^2,
ΔT = Container temperature difference, dryer section to outside, 99°F,
and x = insulation thickness, 4 inches = 0.33 Ft.

Therefore:

$$q = 42\ W.$$

The total power required for the system at the lowest ambient temperature is, therefore, 113 watts. The power supplied by the proposed vortex system is about 80 watts. Therefore, either a larger vortex or supplemental heating was required.

The system is feasible, but the power requirement described above for the worst-cases equilibrium condition also does not take into account the start-up and transient power required. For these reasons, the addition of a high output heat source for transient operation was investigated. The most promising candidate was flameless catalytic heating, although redesign would be necessary for this application because the only known commercial units are designed for applications where power is not critical and, as a result, have higher start-up power requirements than could be supported by our constraints.

Prototype Drying System

The conceptual prototype block diagram using the new design criteria and dual heating system is shown in Figure 22. The sample lines are enclosed in an insulation jacket from the borehole seal to the dryer container and are enclosed in a similar jacket inside the container. In addition, the container is fully insulated inside and all components possible are kept outside the container to reduce the heat load.

The sample temperature is kept above the worst-case dewpoint by constant temperature flowing warm air inside the insulation. Once the sample is cleaned of particulate and dried, it is allowed to seek the ambient temperature as it is transported through the horizontal tube bundle to the central station for analysis. The horizontal bundle consists of four tubes, three for sample and one for gas valve actuation by high pressure. A separate, larger diameter line is provided for the purge and heating air.

Heat is supplied by a vortex heater with back-up by a flameless catalytic heater to provide high level, short-term heat for start-up for fast cooling ambient transients and for the margin needed at the lowest ambient temperatures.

All flows are monitored by differential pressure switches which alarm at the central station is there is a flow blockage.

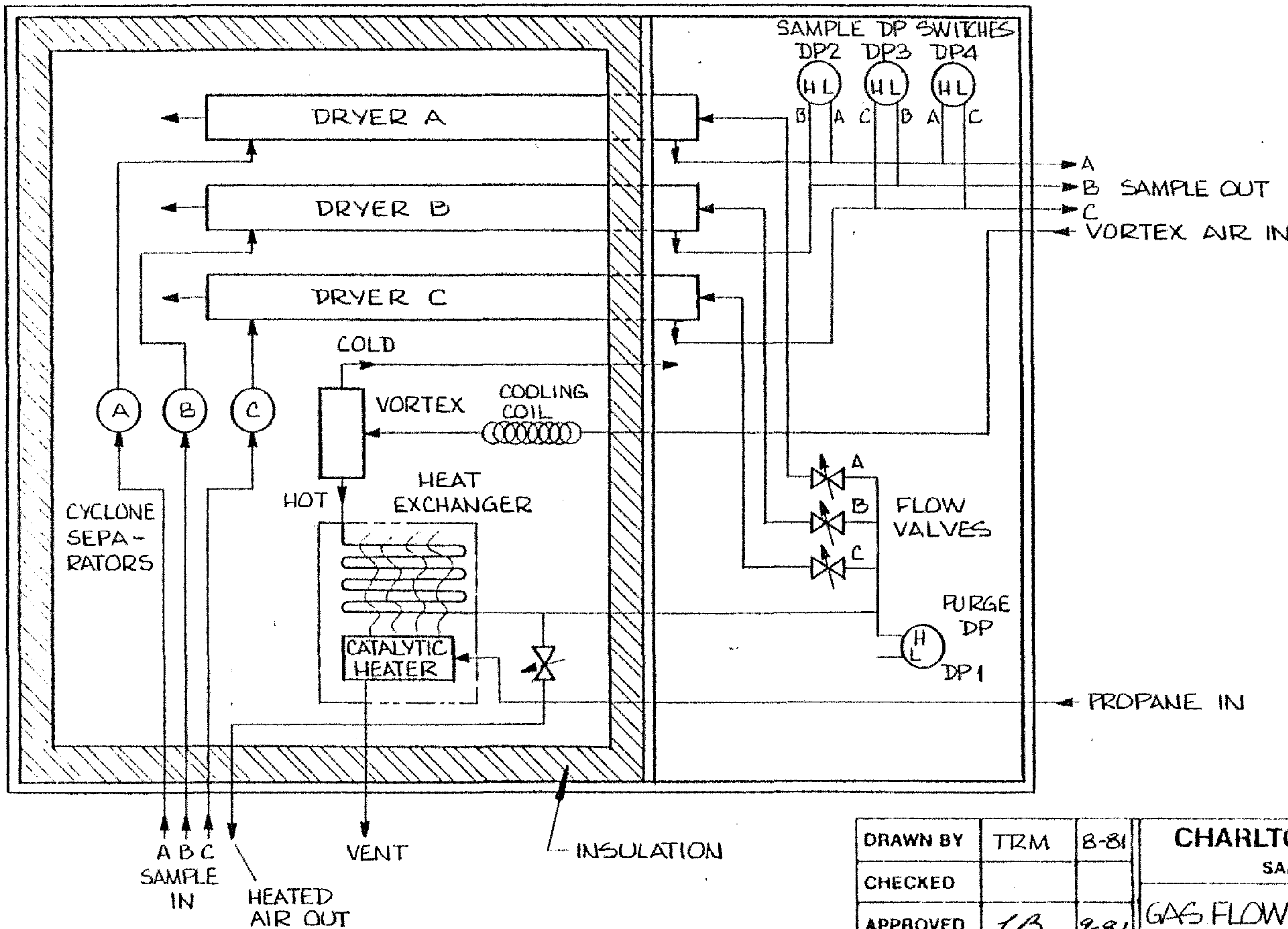


FIGURE 22.
DRYER SYSTEM FLOW
DIAGRAM

DRAWN BY	TRM	8-81
CHECKED		
APPROVED	TB	9-81
RELEASED		
REF. DWGS.		

CHARLTON ASSOCIATES, INC.
SAN DIEGO, CALIFORNIA

GAS FLOW SYSTEM DIAGRAM
DRYER SYSTEM PLUMBING
BU MINES

Code	Dwg. No.	Rev.
102	1000001	

Vortex Heater

The vortex heater operates from a 1 cubic foot per minute dry air source at 80 psig and provides about 90 watts continuously into a low pressure air stream. A portion of the heating air is used as purge air for the dryers after being used for heating. To supply the 80 psig to the vortex would require proportionately more at the pump site, depending on transmission distance and line cross-section.

Flameless Catalytic Heater

The catalytic heater is used to speed up the initial warm-up of the system and for transient heat requirements during rapid decreases in ambient temperature.

The catalytic heater produces heat without a flame. The heat is produced by the reaction of propane and oxygen on a platinum surface which acts as a non-consumable catalyst. The reaction is initiated by warming the platinum with a hot wire grid, then introducing the fuels to the catalyst. The reaction is self-sustaining once started and is terminated by switching off the fuel.

The heater uses propane which is universally available as a commercial heating/cooking fuel. Also, the fittings are conventional and at least as available as the fuel.

Calculated warm-up times for outside temperatures of 0°F and -15°F are shown in Figures 23 and 24. The warm-up times are shown for various quantities of heat, but in the worst case the system can be ready for operation in half an hour. If the warm-up is started early in the borehole installation operation, the dryers should be ready essentially when the installation is complete. The readiness state can be detected by observing the temperature alarm light, which will go out when the system is ready for operation.

During the 30 minute warm-up, the purge air is flowing but the sample air is not. Once the warm-up temperature is achieved, the catalytic heater's fuel supply is switched off and the sample pump turned on. The vortex unit continues to produce 300 Btu per hour to maintain the system above the worst case dewpoint temperature.

New design tasks for the heating system included:

1. Modified catalytic heater ignition wire and power supply;
2. Catalytic heater valve control electronics;
3. Addition of a heat exchanger;
4. Temperature sensor/switch; and
5. Venting the catalyzed effluent.

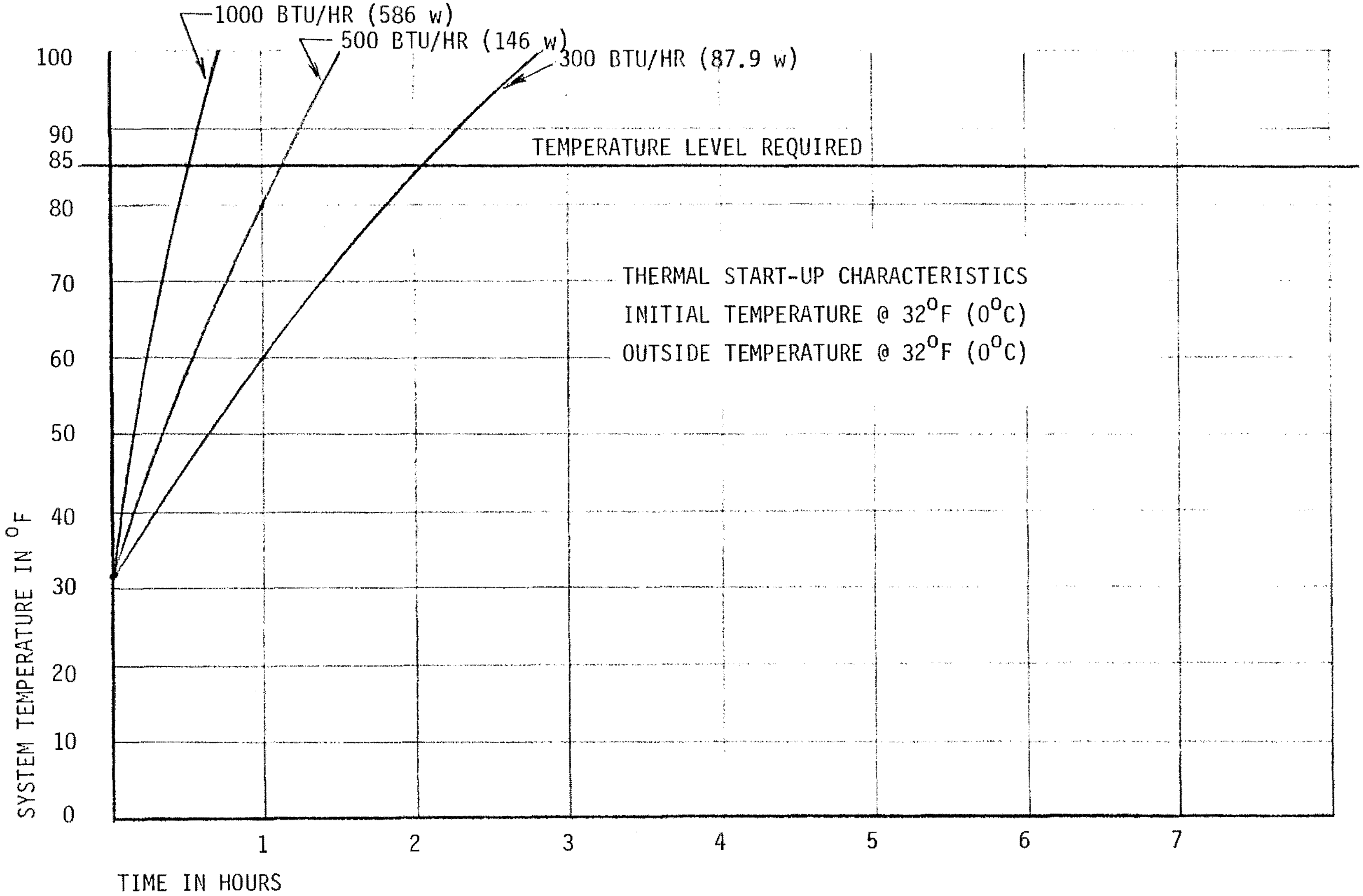


FIGURE 23.
THERMAL START-UP CHARACTERISTICS, 0°C

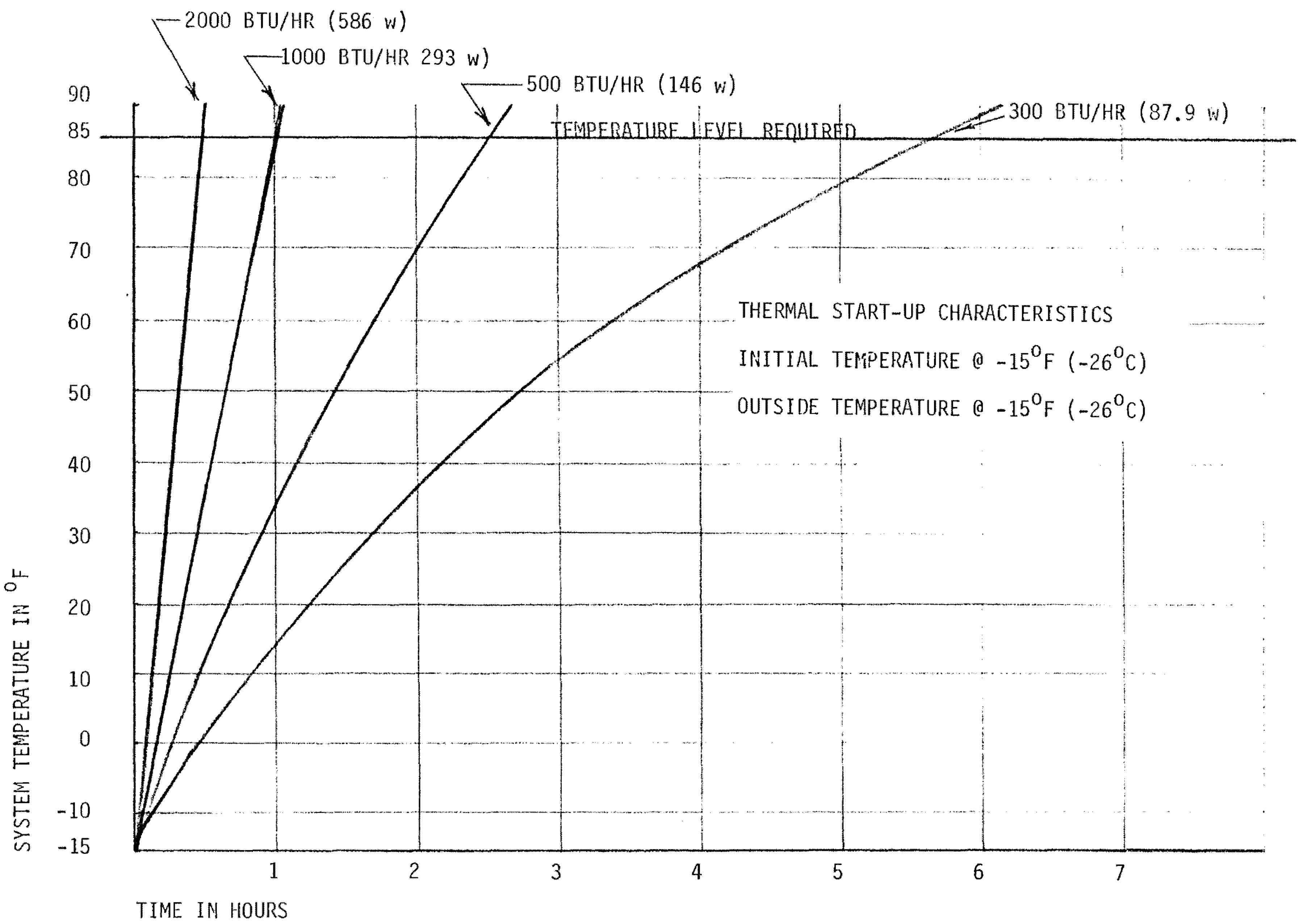


FIGURE 24.
THERMAL START-UP CHARACTERISTICS, -15°C

Particulate Removal

Particulate matter is removed by means of cyclone separators ahead of each dryer. Large collection cups are provided for the collected particulate to allow long-term operation without the need for frequent maintenance. The separators will remove particulate down to about one micron.

Flow Alarms

Alarms were proposed to monitor the three sample flows, the fuel flow chamber temperature and the purge flow. The alarms are actuated by adjusting differential pressure switches monitoring low level pressure differences when correct flow levels are present. Since the only communications means available between the borehole site and the central station is a pair of 22-gauge wires, it was necessary to design a system which could handle both the alarms and the heater power on the pair of communication lines.

Prototype Catalytic Heater

A Model 3P12 catalytic heater was purchased from Thermal Systems. The 3P12 was chosen because it was the smallest available, had about the right heat output and had the basic safety circuitry for automatic electric ignition with automatic shutdown for failure to ignite or for lack of propane. Other heaters investigated were foreign made with no ready access to the manufacturers' engineering staff and questionable future availability. Others used piezo-electric or open flame manual ignition or had other characteristics not suited to the design constraints.

The specifications of the standard Thermal Systems Model 3P12 are as follows:

Heat Output:	2700 Btu
Fuel Consumption:	1/8-pound per hour
Ignition Power:	3 amps at 12 volts
Running Power:	0.3 amps at 12 volts
Size:	14-inches x 12-inches x 4-3/4-inches

The heater comes with a thermostat which provides the input to the ignition and gas control system. When the temperature drops below the set level, power is applied to a heater wire in contact with the catalytic surface. The surface is heated and the gas valve and vent blower are actuated. When the catalytic reaction has started, power to the heating wire is shut off. At that point, the total electrical power drops to 300 milliamps at 12 volts (3.6 watts) for the duration of the heating. When the preset temperature is reached, the propane supply solenoid closes and the system drops back into standby where it consumes no power. When the catalytic heater is not operating, the power lines in the horizontal tube bundle are used to transmit status information to the central station.

Since the maximum power possible into the dryer module down the one mile communication line is about 17 watts at 110 volts RMS, the existing heater did not have adequate starting power. The Thermal Systems engineering personnel felt that the power could be lowered significantly by heating only a small area of the catalyst and letting the reaction spread the heat to the balance of the catalytic bed. This results in some "wasted" or uncombusted gases during start-up, which was not critical to this application.

In addition, a small improvement was made in the running power of 3.6 watts by using some of the vortex heater air to vent the heater product gas to the atmosphere instead of using the blower. This would reduce the running power to about 3.2 watts and remove a mechanical part with its inherent unreliability from the system.

Since there were no major modifications to the heater, Thermal Systems agreed to assign the modified unit a model number which would allow it to be procured in the future as a standard item. The model is 3P12-M-1.

The heater consumes 1/8-pound of propane per hour to produce 2,700 Btu. At that rate, a five-gallon propane tank would heat continuously for 170 hours. It was shown that 2,000 Btu would raise the module and input sample line to 85°F from the worst case -15°F in about 30 minutes. At that rate, the five-gallon tank would handle the initial warm-up and have nearly 170 hours of heating capacity to handle the intermittent cold transients that the vortex heater could not keep up with. In practice, this should be sufficient to allow unattended operation for several months under the worst anticipated weather cycle.

Dryer

A prototype dryer was constructed and tested. The dryer consisted of 18 Nafion 1/8-inch tubes in a one-inch tube. The dryer was 2.4 meters long with an active drying surface 2.2 meters long. The initial conditioning time was somewhat longer than the last dryer and the drying ability only about -15°C where the design specification was -26°C. This was believed to be due to batch-to-batch differences in the Nafion production at the time.

When the dryer was subjected to low temperatures, the efficiency increased as it had done with the experimental dryers and has gradually increased as the testing has progressed. However, the margin allowed in the design seems to be sufficient because all of the dryers fabricated after the initial development testing have met the drying specifications.

Particulate Removal

A small nylon cyclone separator was purchased from Mine Safety Appliances (MSA). The price of $18 was attractive, but the unit required several modifications for this application, which would make it less price competitive. Also, the cyclone was designed for personnel sampling in the 1.5 to 2-liters per minute range. Increasing the rate to 10 liters per minute was possible, but would have resulted in extensive redesign, so use of the MSA cyclone was not pursued.

System Design

After initial development, the conceptual prototype system was changed in two important ways. The first was that the dryers were to be only partly heated to take advantage of the considerable increase in drying efficiency at the lower ambient temperatures. Approximately the last one-third of the dryer was to be exposed to the ambient temperature, which would cause the dewpoint of the product (dried sample) to improve (lower) as the ambient temperature lowered. This would result in a smaller, less costly dryer, while assuring that the sample dewpoint was always lower than the ambient temperature with about a -15°C margin. The second change in the conceptual design was that all system elements, including the gas tank and flow sensors, would be inside the container with the dryers and other system elements. The container would be compartmented into two sections. One section insulated and thermally controlled, and the other subject to ambient temperatures. The temperature controlled compartment would contain the filters, control circuitry and heaters. Also, the first two-thirds of the dryers would be in the heated section with the two sections separated by a bulkhead. The dryers run through the bulkhead and unheated compartment to connectors which tie them to the outside horizontal tube bundle. The unheated compartment also contains the propane tank and pressure switches.

The propane tank is designed to be easily removed for filling and could be transported separately in the field for ease of handling. The tank is to be equipped with a float gauge that indicates the quantity of propane in the tank.

Air Supply

A larger dry air supply than the units built early in the program was needed to operate the prototype with the vortex heater. The new air supply was sized to provide between 6 and 7 cubic feet per minute at 100 psig.

Catalytic Heater

The standard catalytic heater purchased from Thermal Systems was tested and found to be satisfactory. It was then returned to the manufacturer for modification and test with a new catalyst warmer and remotely powered warm-up system.

Cyclone Separator

A Model 18 cyclone separator previously manufactured by Union Industrial Equipment Corp. (UNICO) was received from Bendix. The Model 18 has optimum performance at 9 liters per minute, however, the Bendix cyclone suffered the same configuration problems as the MSA unit. The cyclone was designed by UNICO for analysis of respirable particulate, therefore has no way to attach a sample inlet line. Also, it has a very small collection cup.

Figure 25 shows the Bendix cyclone in a special housing which was fabricated for it. The Model 18 has two curved inlet plates which cause a vortex as the air swirls around the inner circumference of the tube. The larger particulate drops down into the cup as the cleaned sample is withdrawn upward through the center of the vortex.

The housing was fabricated from clear acrylic to aid in observing the particulate drop-out during testing. It is a rugged housing and relatively inexpensive to machine, so may be satisfactory for field units. The advantage of viewing the inside of the particulate collection cup would likely be lost in an environment with clinging or sticking particulate, however.

The general disadvantage of the Bendix unit is that, while it is adequate for the coarse filtering allowable in mine atmosphere sampling, the filter is not adequate for many scientific applications, most of which are for respirable particulate. The cyclone is a product with a very limited market in a large company and is not priced competitively. The concern is future availability of a critical element in a system.

The Bendix cyclone was given a crude test with three ranges of particulate matter; namely, fine volcanic ash, fine sand and room dust. The cyclone collected the particulate with no detectable drop-out in the sample effluent. The cyclone does remove particulate, but quantifying its performance would require equipment and manpower not within the scope of the current effort.

At the suggestion of Mr. L. E. Dalverny of the Bureau of Mines, a paper on cyclone size sample was obtained. The paper[3/] described the development of a cyclone for ambient air selective monitoring. The unit was developed by the California Department of Health and its performance characterized from 8 to 27 liters per minute. Dr. John, principal investigator at the Department of Health, was most helpful and cooperative in a phone conversation, and sent a set of detailed prints to allow us to fabricate the cyclone. Although the cyclone packaging was modified considerably, the critical dimensions affecting performance were not modified. Performance of the cyclones was not characterized in detail, but verification of particular removal was done by tests similar to those done on the Bendix unit. A drawing of the cyclone is shown in Figure 26.

3/ John, Walter and Reischi, George, A Cyclone for Size-Selective Sampling of Ambient Air, Journal of the Air Pollution Control Association, Volume 30, No. 8, August, 1980.

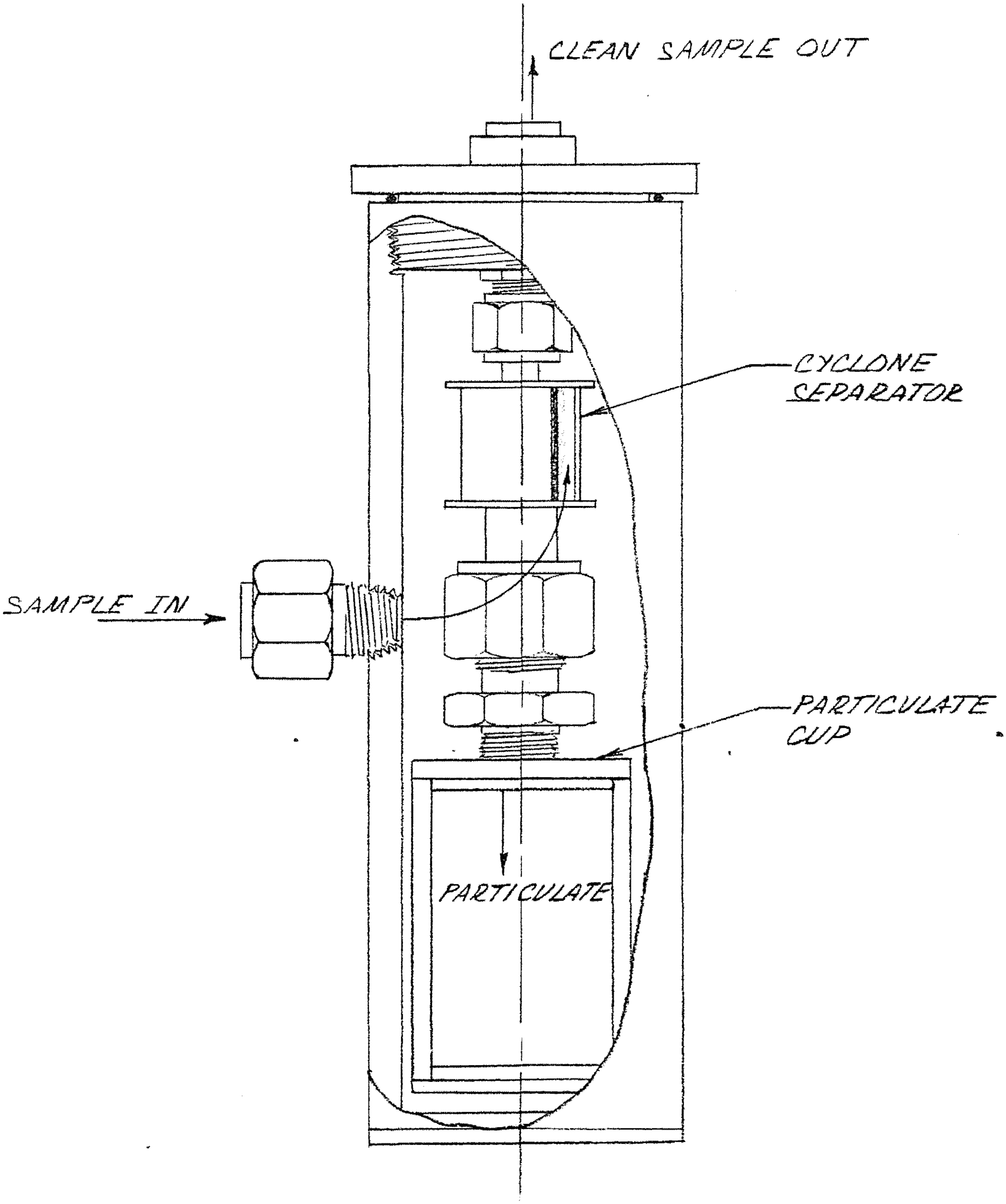


FIGURE 25.
CYCLONE SEPARATOR ASSEMBLY

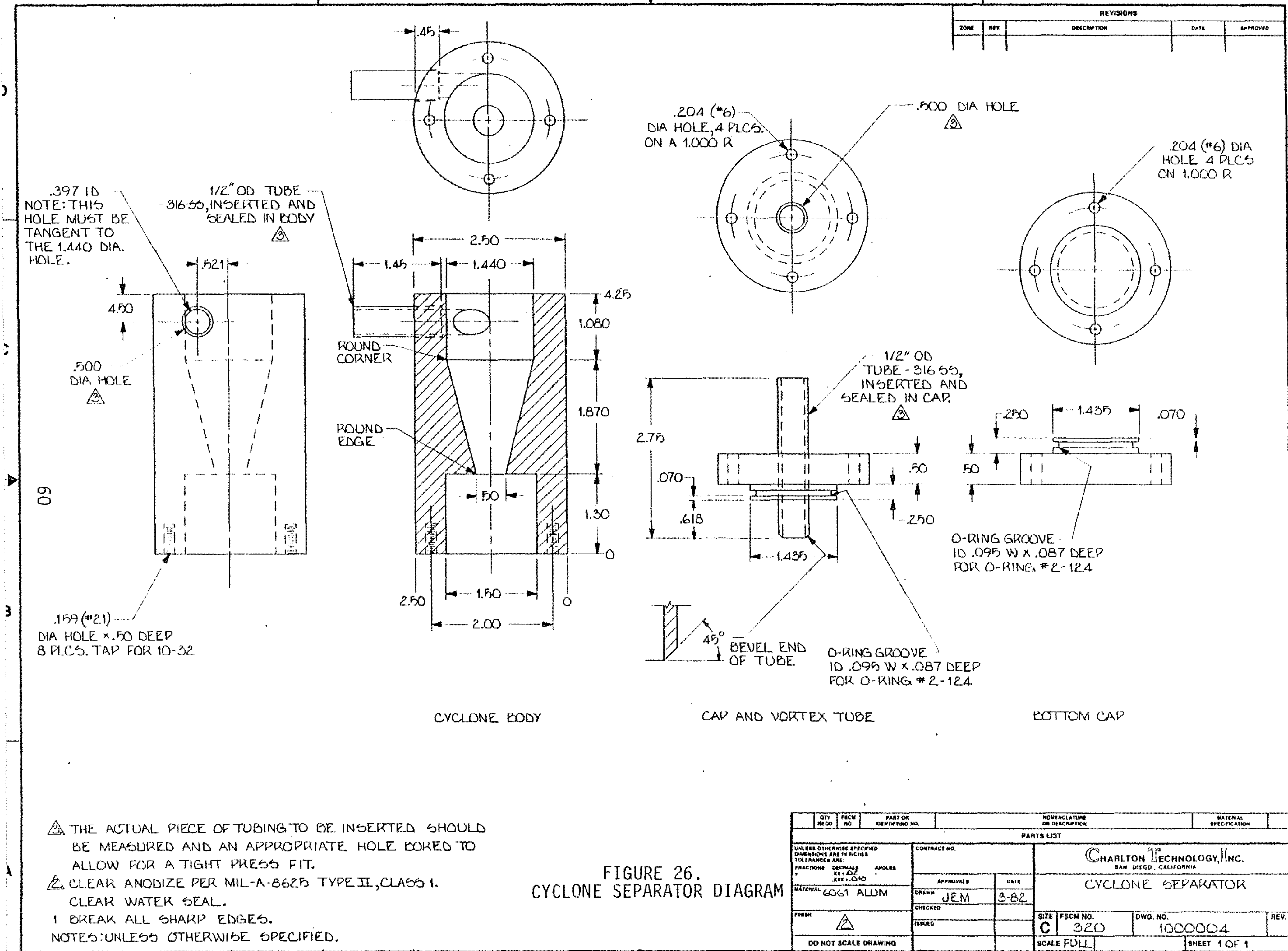


FIGURE 26.
CYCLONE SEPARATOR DIAGRAM

Dryer Fabrication

The dryer fabrication proceeded smoothly after refinement and modification of certain procedures. Problems in the fabrication of the first dryers were:

1. Poor release of encapsulation mold after curing;
2. Leaks through headers; and
3. Dryer shrinkage causing excessive stress on the Nafion tubes and reduction of exposed header length due to contraction of the Nafion.

The encapsulation mold problem was caused by a high surface contact with the encapsulation compound and uneven application of mold release to a complex mold.

The mold consisted of a shallow metal cup with .100 inch pegs fitted through the cup. The pegs held the individual Nafion tubes in the correct pattern and in a uniform pattern across the header face during curing. Small but numerous areas of attachment between the encapsulation compound and the pegs or mold body made it difficult to remove the mold without damaging it. Actually, the molds typically lasted for only two or three headers.

The problem was resolved by designing a mold with a very shallow cup and snug, but removable, pins. After curing, the pins are individually removed and then the cup simply twisted off the header end.

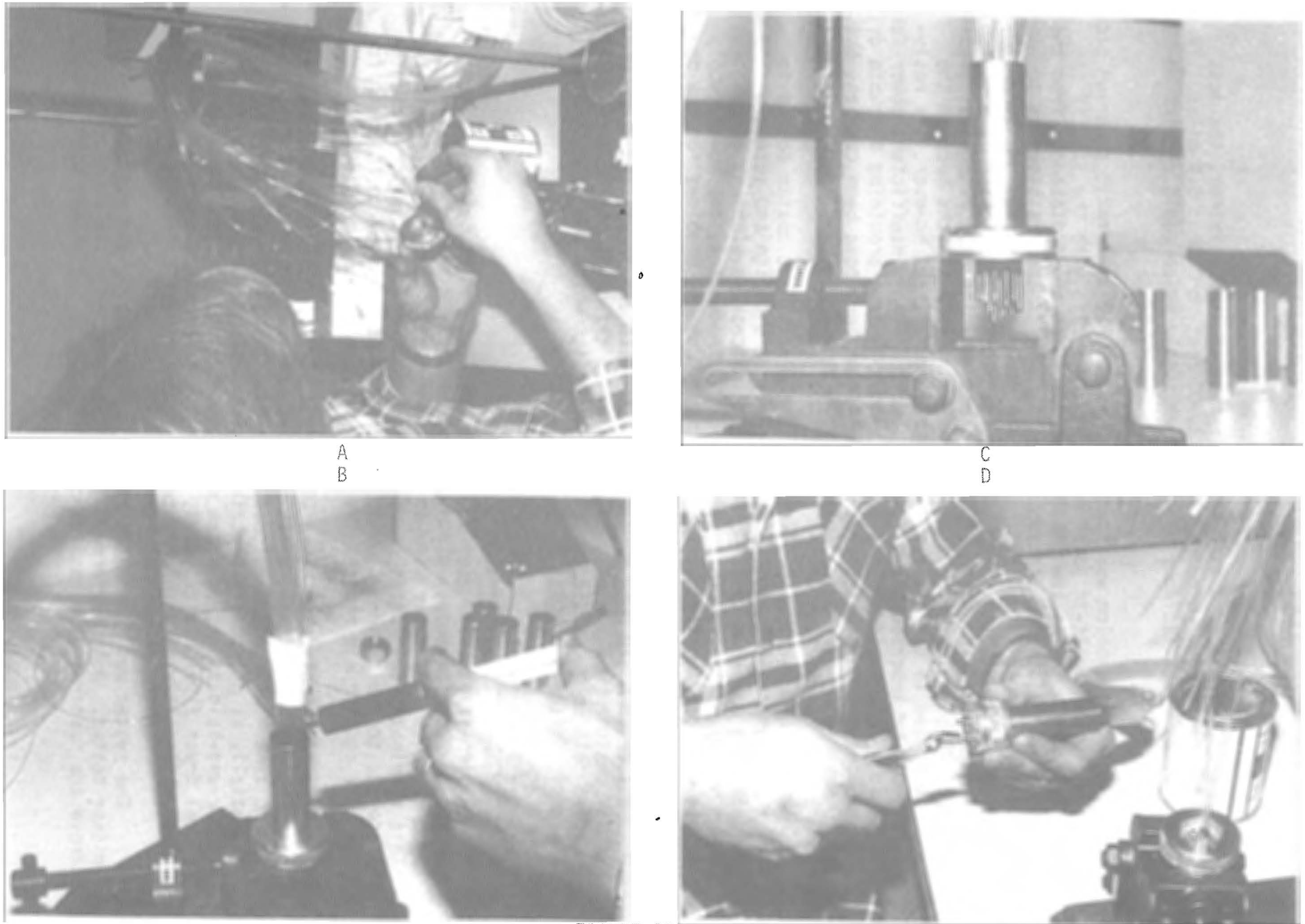
Photographs of the process are shown in Figure 27. Photograph A shows placement of the individual Nafion tubes on the pegs as they are individually inserted in the tubes. Photograph B shows injection of the encapsulation compound into the header and Photograph C shows the header during curing. Photograph D shows removal of the pins after curing.

The problem of leaks through the header was determined to be caused by channeling between two adjacent Nafion tubes where the encapsulation compound could not properly flow. This was resolved by finding a lower viscosity compound.

The Nafion shrinkage problem was resolved by drying the Nafion bundle for several hours prior to final assembly. In a dry state, the Nafion shrinks to its minimum size and, once fixed in the dryer, is able to expand as it picks up moisture without stressing the dryer or Nafion tubes.

Catalytic Heater Power Supply

In testing the power supplies for the catalytic heater system, two performance problems were discovered. The first was that the supplies



A
B
C
D

FIGURE 27.
DRYER FABRICATION

would not drive the load over the full mile of line. Rather, the most line that could be handled was about 3,700 feet, or about 0.7 miles. This is caused by low efficiency of the power supply which would require redesign to improve.

The second problem was that the supplies had an erratic power-up problem. Th supplies switch built-in power resistors in series with the line if the line resistance is too low (that would occur for short distances from the borehole to the central station). The purpose of the resistors is to reduce the power dissipation in the main power transistors. However, the detection and switching circuitry had an internal signal race problem and if the power is switched on, the resistors were inserted regardless of line length. This would not be a problem on short line lengths because the resistors need to be in anyway. On the longer lines, however, the resistors would be inserted and dissipate power, leaving insufficient power for the load. This would prevent the power supply from providing adequate drive and the heater would not operate. The fix may not have been complex, but would have required considerable redesign time.

When the power supply designer for the catalytic heater seemed to be having continual technical problems with his design and seemed unable to deliver a workable unit, we undertook in-house development of our own power supply. Although this seemed possibly redundant, the power supply delays were causing serious scheduling and monetary problems for the program. At that point we had enough experience with the system, and in particular the catalytic heater, to where we were confident that we could build a supply which would meet specifications. Although the outside power supply designer was the original designer of the catalytic heater electronics, we felt we had a simpler conceptual design which would not suffer the basic design conflicts in the first design.

Improved Power Supply

A simplified block diagram of the new Electronics System is shown in Figure 28. The supply differs from the earlier design in that AC is used to drive the heater wire and DC power supply for the electronics. This eliminates the losses occurring in the other supply which converts AC to DC, transmits the DC down line, then reconverts it to AC again for the wire igniter and reduces the DC to operate the heater electronics.

The new supply also has a DC operated transmitter at the boresite that applies a DC signal, which contains information on the status, to the AC line. A receiver decodes the status signal and displays it essentially as previously described, except that an automatic switch and sample-and-hold system provides continuous automatic status on the individual dryer flows, purge flows, dryer box temperature and fuel tank level while allowing uninterrupted operation of the catalytic heater.

The system was fabricated and the heater supply and status transmitter tested. Both performed without any problem. The power supply drove the heater over a resistance equivalent to 1.2 miles, with margin.

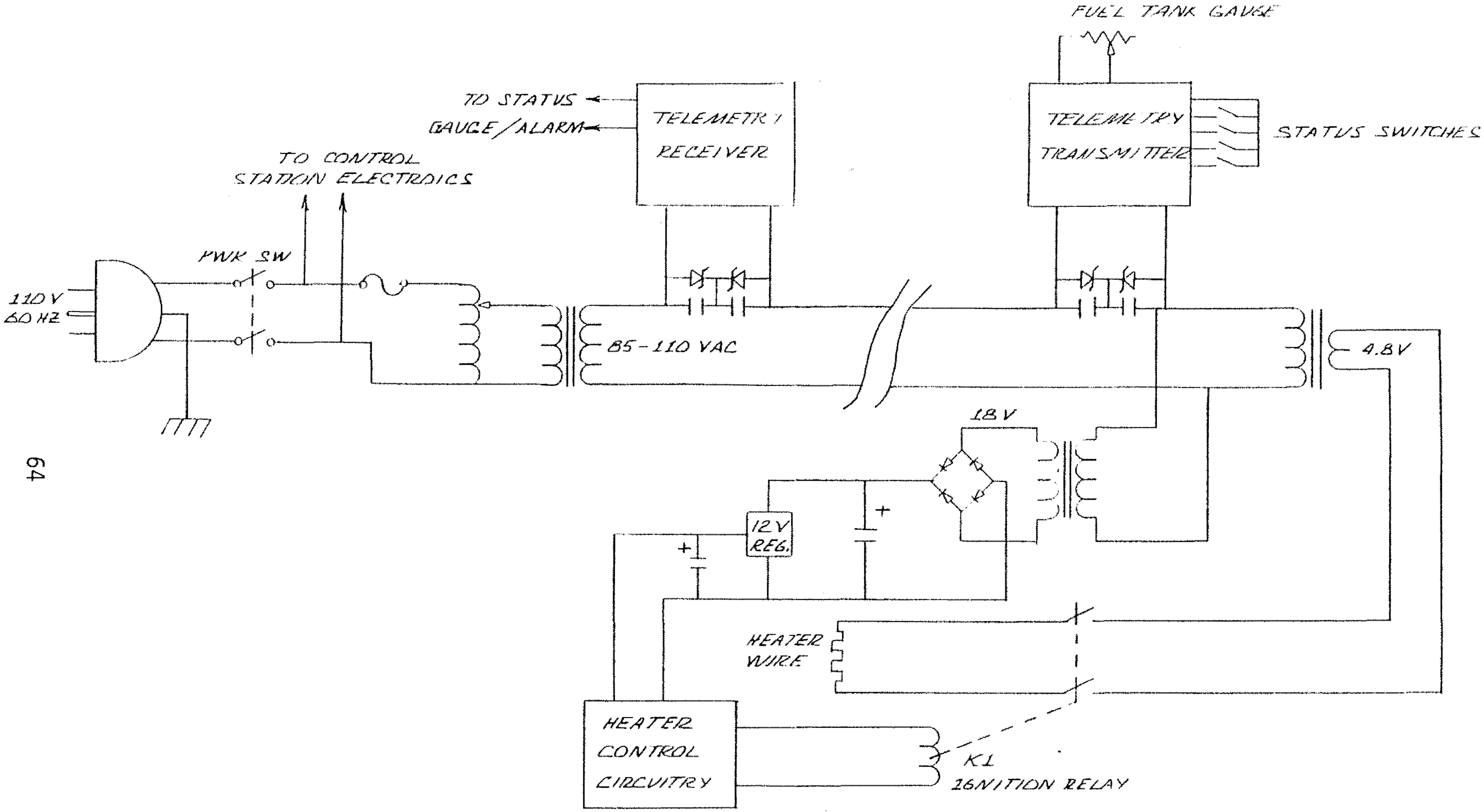


FIGURE 28.

SIMPLIFIED BLOCK DIAGRAM
CATALYTIC HEATER/ALARM SYSTEM

Transmitter

A schematic of the transmitter is shown in Figure 29. The transmitter consists of two identical constant voltage regulators of opposite polarity.

AC is coupled directly through C1 and C2. The DC on the line is directed to the appropriate regulator, either U1 for fuel measurement or U2 for status determination by the blocking diodes D3 and D4. The regulators have an output of 1.25 volts which is applied across resistors which are a measure of the status. This constant voltage across a resistance provides a constant, predictable current regardless of other resistances, thereby making the system independent of the line resistance. The applicable line currents for each of the switches is shown on the schematic. Table 3 shows the resulting line current for all possible combinations of the binary weighted resistor values. These currents are decoded in the receiver to indicate which combination of resistors have been actuated.

Receiver

A schematic of the receiver is shown in Figure 30.

U14 is an oscillator which drives a scaler, U5, to provide the system timebase. One function of the timebase is to drive relay K1 at about a 20-second interval, thereby reversing the line polarity to the transmitter to alternately provide inputs to the receiver on the fuel level and alarm status.

A current proportional to the fuel level is fed through a sample-and-hold circuit to a one-milliamp panel meter on the "fuel" part of the cycle.

Likewise, the status current is directed through an analog to digital converter which sets flip-flops U7-A through U11-A. U7-B through U11-B are identical flip-flops and require identical information on two consecutive cycles to actuate Q1 through Q5 to indicate an alarm condition which is indicated by panel-mounted LED's CR17 through CR13.

K1 can be deactivated by placing S2 in the status position, in which case only the status information is received and indicated. This is to decrease wear on the relay where fuel level may not be needed or needed infrequently in somewhat warmer weather.

The system voltages of +18, -14 and +5 are all derived from the +18 volt power supply. +18 volts is fed directly to the circuits and is used to generate +5 by voltage regulator U17 and -14 by voltage inversion circuitry utilizing the oscillator U3.

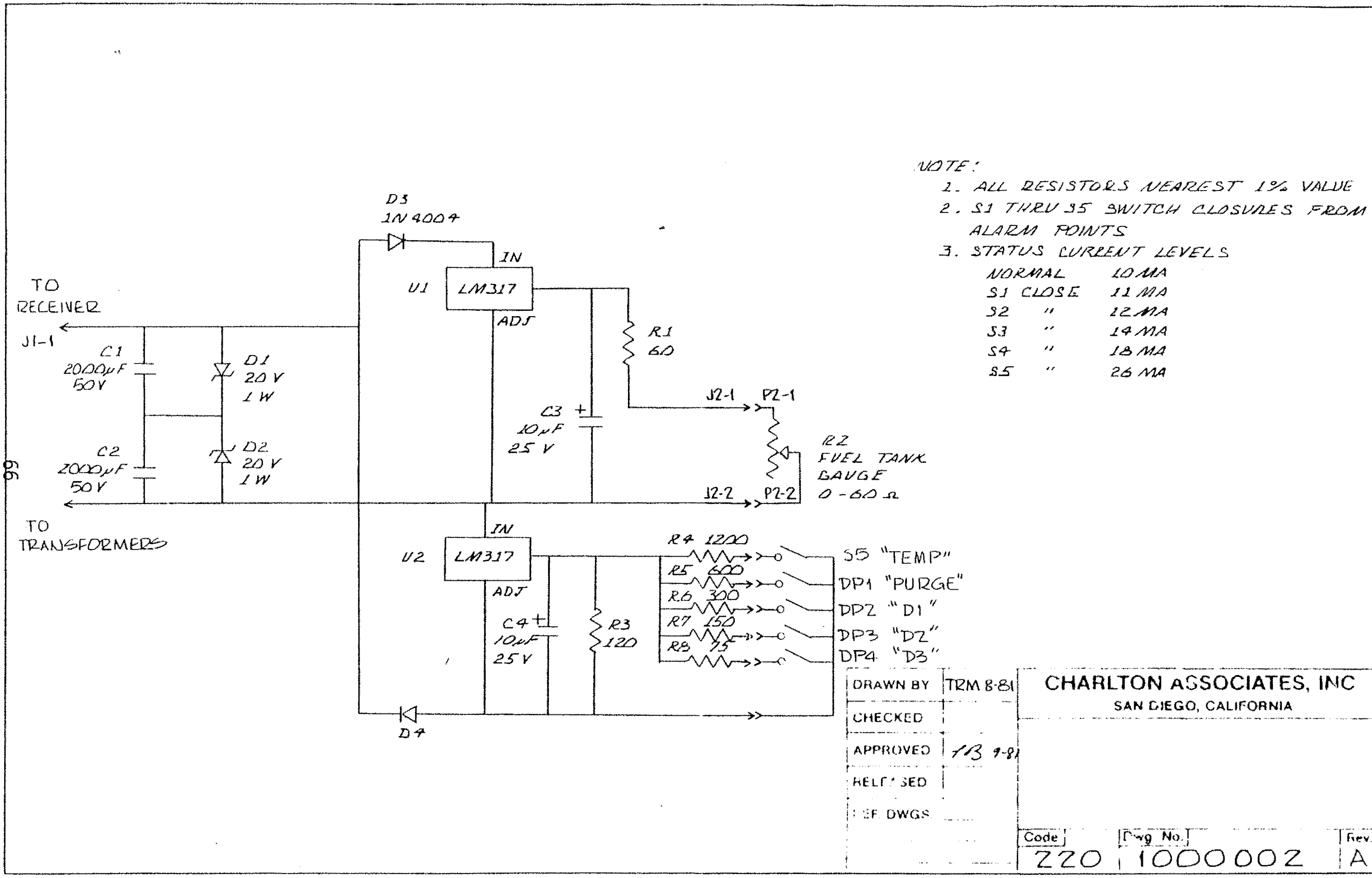


FIGURE 29.
SCHEMATIC - TELEMETRY TRANSMITTER

Table 3 - Transmitter output current

SWITCH	$D_3D_2D_1$ P T	I_{LOOP} mA
T	0 0 0 0 1	11
P	0 0 0 1 0	12
D_1	0 0 1 0 0	14
D_2	0 1 0 0 0	18
D_3	1 0 0 0 0	26
TP	0 0 0 1 1	13
TD_1	0 0 1 0 1	15
TD_2	0 1 0 0 1	19
TD_3	1 0 0 0 1	27
PD_1	0 0 1 1 0	16
PD_2	0 1 0 1 0	19
PD_3	1 0 0 1 0	28
D_1D_2	0 1 1 0 0	22
D_1D_3	1 0 1 0 0	30
D_2D_3	1 1 0 0 0	34

SWITCH	$D_3D_2D_1$ P T	I_{LOOP} mA
TPD_1	0 0 1 1 1	17
TPD_2	0 1 0 1 1	21
TPD_3	1 0 0 1 1	29
TPD_1D_2	0 1 1 1 1	25
TPD_1D_3	1 0 1 1 1	33
$TPD_1D_2D_3$	1 1 1 1 1	41
OPEN	0 0 0 0 0	10
TD_1D_2	0 1 1 0 1	23
TD_1D_3	1 0 1 0 1	31
PD_1D_2	0 1 1 1 0	24
PD_1D_3	1 0 1 1 0	32
TD_2D_3	1 1 0 0 1	35
PD_2D_3	1 1 0 1 0	36
TPD_2D_3	1 1 0 1 1	37
$D_1D_2D_3$	1 1 1 0 0	38
$PD_1D_2D_3$	1 1 1 1 0	40
PD_1D_2T	1 1 1 0 1	39

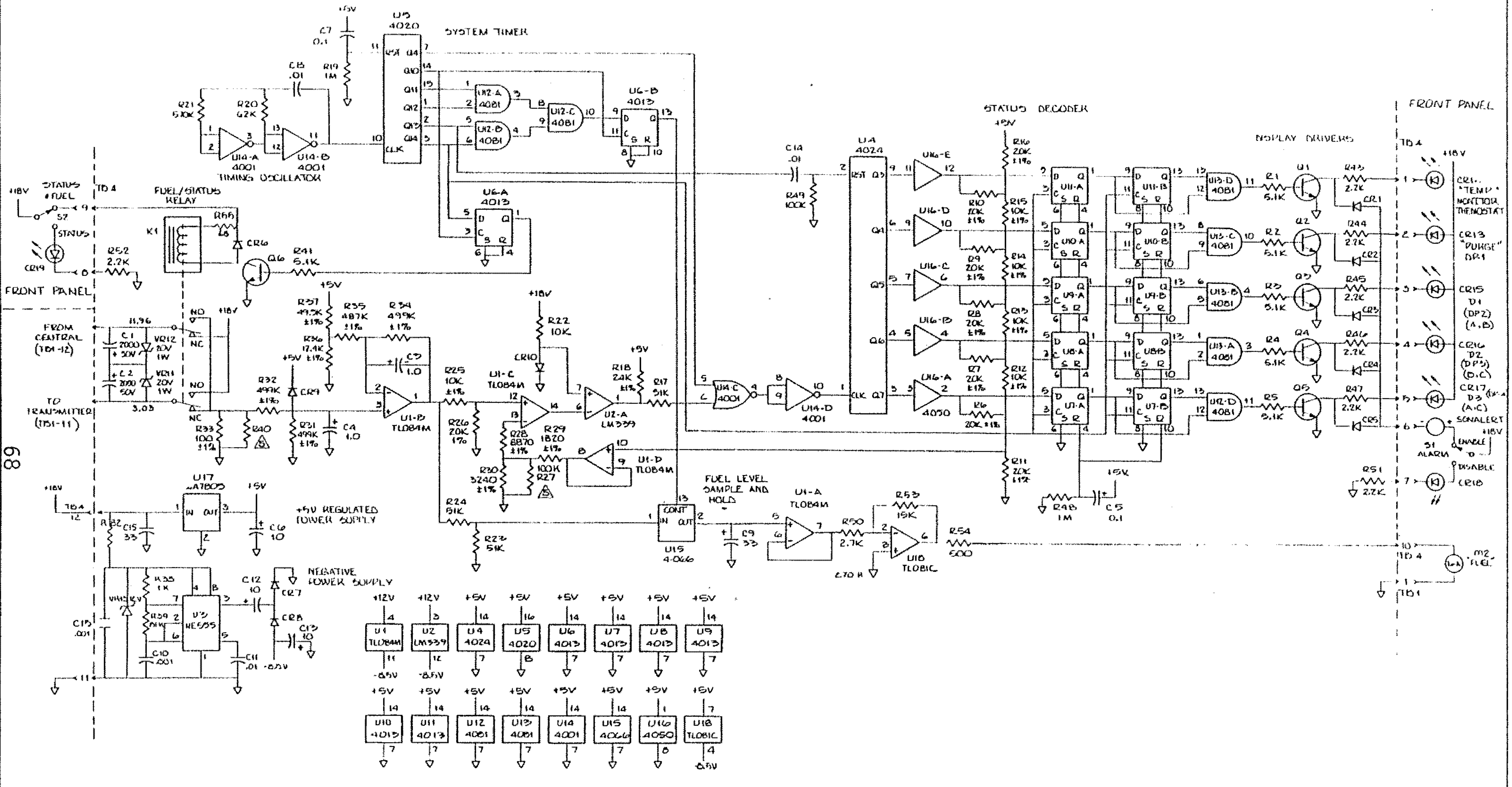
T = Temperature

P = Purge

D_1= Dryer 1

D_2= Dryer 2

D_3= Dryer 3



6. ALL LED'S ARE TYPE NV908.
5. (△) VALUE TEST SELECTED
4. ALL NPN TRANSISTORS ARE 2N2222.
3. ALL DIODES ARE 1N0908.
2. ALL CAPACITORS ARE IN MICRO FARADS.
1. ALL RESISTORS ARE IN OHMS ±5% , 1/4 W.
NOTES: UNLESS OTHERWISE SPECIFIED

FIGURE 30.
SCHEMATIC: TELEMETRY RECEIVER

DRAWN BY	TRM		CHARLTON ASSOCIATES, INC. SAN DIEGO CALIFORNIA
CHECKED			SCHEMATIC TELEMETRY RECEIVER
APPROVED			
RELEASED			
REF DWGS			220 · 1000001 · B

12-Volt Power Supply

The circuit in the field module which generates the +12 volts for the propane heater electronics is shown in Figure 31.

The Electrical System Diagram is shown in Figure 32.

Prototype 1 Evaluation

The thermal tests were divided into pre-test and temperature tests. Pre-testing was done at the Charlton Technology, Inc. facility. The temperature testing was done at Ryan Aeronautical Environmental Facilities in San Diego. Ryan has large thermal chambers with temperature programming and automatic temperature monitoring.

Dryer System Pre-Tests

Initial testing on the dryer box consisted of measuring the heat build-up and decay rates from the vortex heater with the dryer box in complete field operating configuration. For this test, the vortex was operating at 156 liters per minute instead of 180 liters per minute because of an apparent diminished capacity in the air supply. However, since warm air was not sent into the input tube bundle insulator, this was the right amount of heat for the box interior.

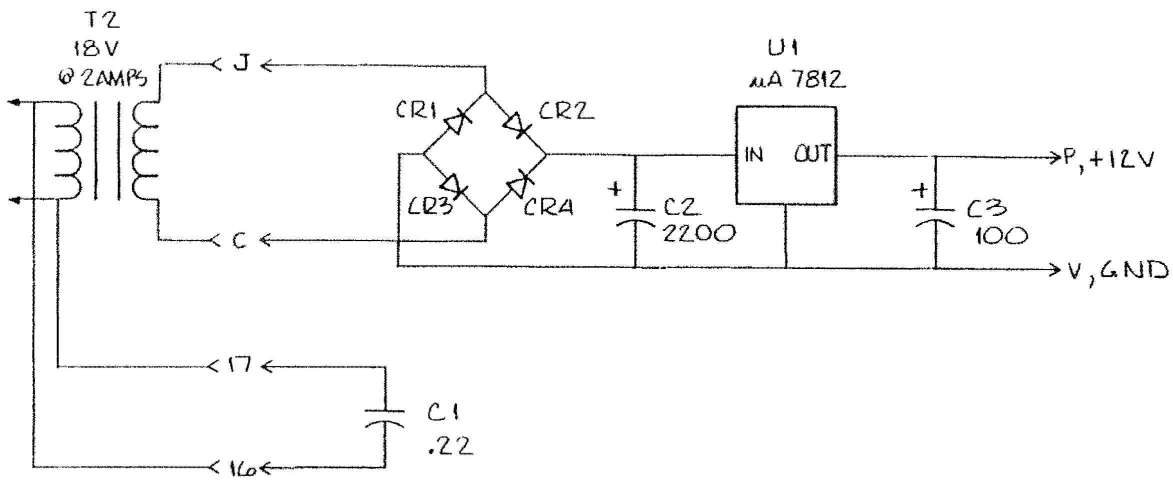
A plot of the thermal increase is shown in Figure 33 and the decay is shown in Figure 34. The slope of the internal air temperature shows about a 7°C rise per hour. The decay with the power input off is about the same or 3°C per hour. These results are consistent with preliminary thermal calculations. Warm-up from a low temperature using the vortex alone would take several days. This is why the vortex, which is intended to provide a low but continuous heat output, is backed up by short-term, high-heat output from a catalytic heater. Although the catalytic heater produces a lot of heat for a short time, the relatively large mass of the dryer system (large mass of cyclone separators, fittings, heat exchanger, inner box, etc.) should allow long cycling intervals by acting as heat storage medium.

At the test flow rate, the vortex was producing about 75 watts, which is approximately the power the main box should receive. The sample inlet tube was blocked so it was not necessary to generate the heat for it.

Air Distribution

The air distribution in the system was checked next to verify the following:

1. Adequate air feed to the base of the catalyst. The catalyst needs an oxygen flow from the base to the top of the catalytic bed to support the reaction. Air from the purge outlet is fed to the catalyst



2. ALL DIODES ARE 1N4005.
1. ALL CAPACITORS ARE IN MICRO FARADS.
NOTES UNLESS OTHERWISE SPECIFIED

DRAWN BY	TRM	8-81
CHECKED		
APPROVED	TB	9-81
RELEASED		
REF. DWGS		

CHARLTON ASSOCIATES, INC.
SAN DIEGO, CALIFORNIA

Code	Dwg. No.	Rev
220	1000003	

FIGURE 31.
SCHEMATIC - +12V POWER SUPPLY

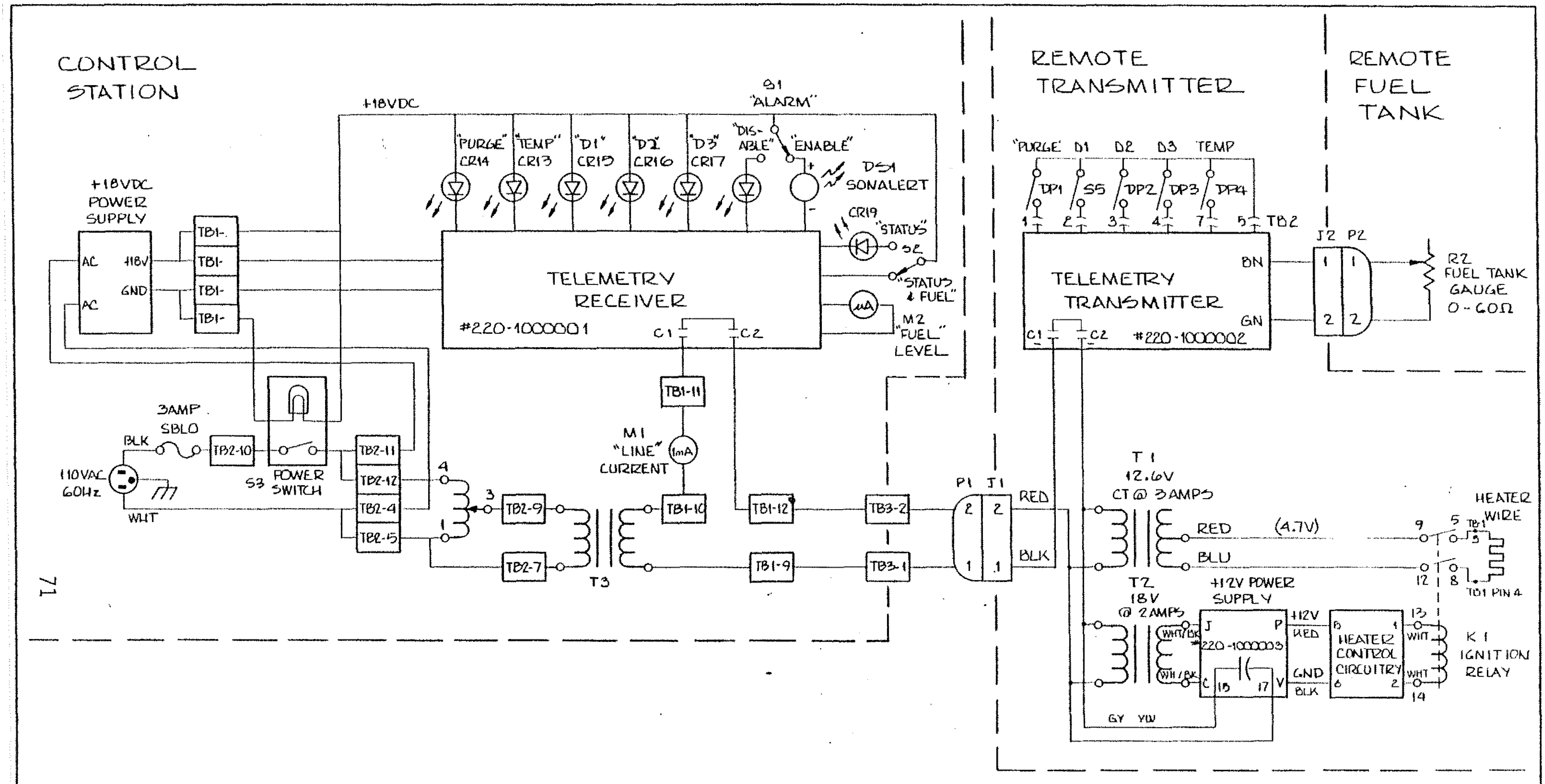


FIGURE 32.
ELECTRICAL SYSTEM DIAGRAM

DRAWN BY	TRM	8-81	CHARLTON ASSOCIATES, INC. SAN DIEGO, CALIFORNIA
CHECKED			ELECTRICAL SYSTEM DIAGRAM BU MINES - CATALYTIC HEATER / ALARM SYSTEM
APPROVED	1/3	9-81	
RELEASED			
REF. DWGS.			Code 101 · Dwg. No. 1000001 · Rev A

1. ALL LED'S ARE TYPE NV908.

NOTES: UNLESS OTHERWISE SPECIFIED

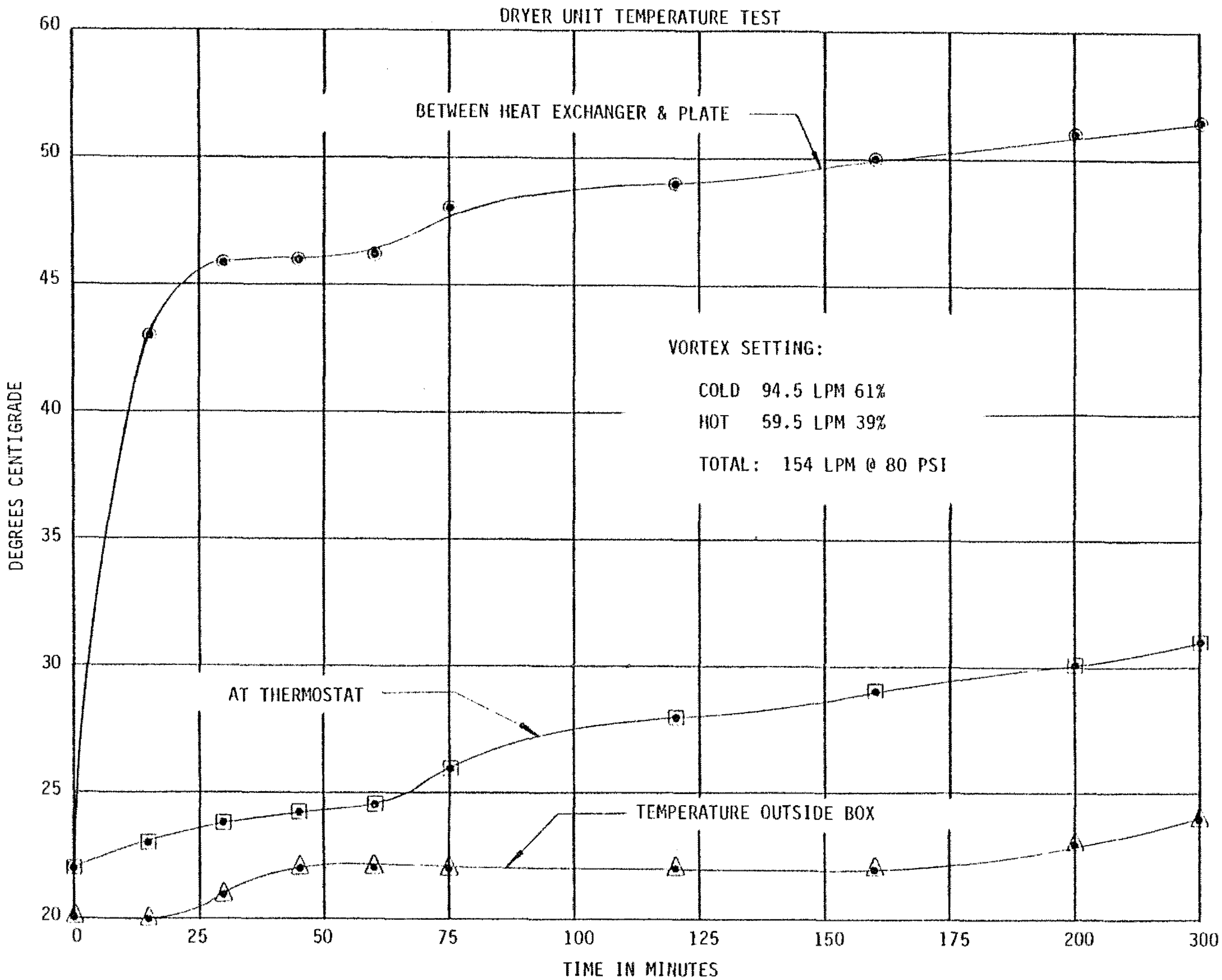


FIGURE 33.
DRYER BOX THERMAL INCREASE

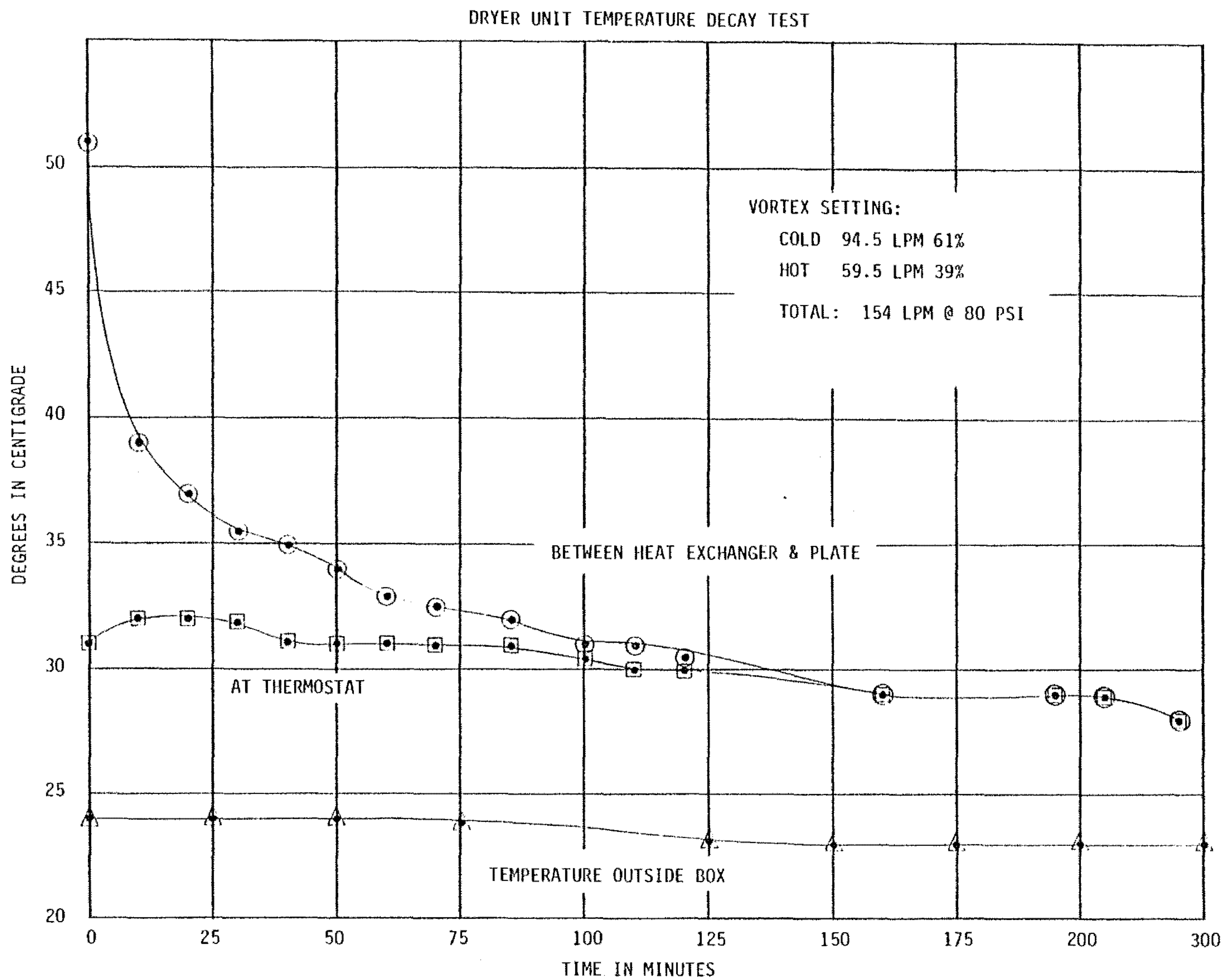


FIGURE 34.
DRYER BOX THERMAL DECAY

and the reacted products exhausted. The standard catalytic heaters have a blower to pull air over the catalyst and exhaust the products, but our system relies on the positive pressure in the box.

2. Air flow over power supply. The catalytic heater power supply components require cooling. The cold air from the vortex is used for this purpose.

3. Proper distribution of purge air in dryers and sample tube inlet bundle.

Dryer System Temperature Tests

The earlier supply was installed in Prototype 1 for basic thermal tests of the system. For the testing, the vortex heat source was disabled by running a lower flow through the system. This allowed air for the catalytic heater, but provided negligible power from the vortex.

A plot of the temperature versus time is shown in Figure 35. The temperatures plotted are the temperatures directly in front of the heater, the ambient temperature at the control thermostat, the air temperature down the sample inlet insulator (covering the borehole-to-dryer sample line) and the cyclone body temperature. The cyclone temperatures were chosen because the cyclones are one of the large mass elements that are expected to act as storage reservoirs for heat.

The system performed as expected. The catalytic heater received sufficient air to ignite reliably and remain on until the thermostat shut it off. Cycling was repetitive and reliable. One minor problem worth noting was overcome before testing was underway. The problem was caused by very slow response of the thermostat to heater power-up. The problem was resolved by removing the cover from the thermostat, thereby allowing more rapid exposure to the box air temperature rise.

The outside temperature was 20°C at test start and increased to 24°C at the end of the test 5.5 hours later. This was felt to have negligible effect on the internal thermal behavior for the relatively short-term test.

On start-up, the heater immediately turned on and stayed on for ten minutes. This was the length of time to bring the air at the thermostat on the other end of the box from the heater to the thermostat shut-off temperature of about 42°C. The turn-on heat transient produced a noticeable overshoot at the thermostat relative to the other times it turned on because of the higher temperature it attained.

The turn-on intervals increase in time as the heat transfer device (for heating sample line air), cyclones and other masses gradually stabilize, thus stopping absorbing heat from the air at the control temperature. The interval was gradually stabilized at a rate which would keep pace with the heat loss. Actually, at these ambient temperatures, the vortex

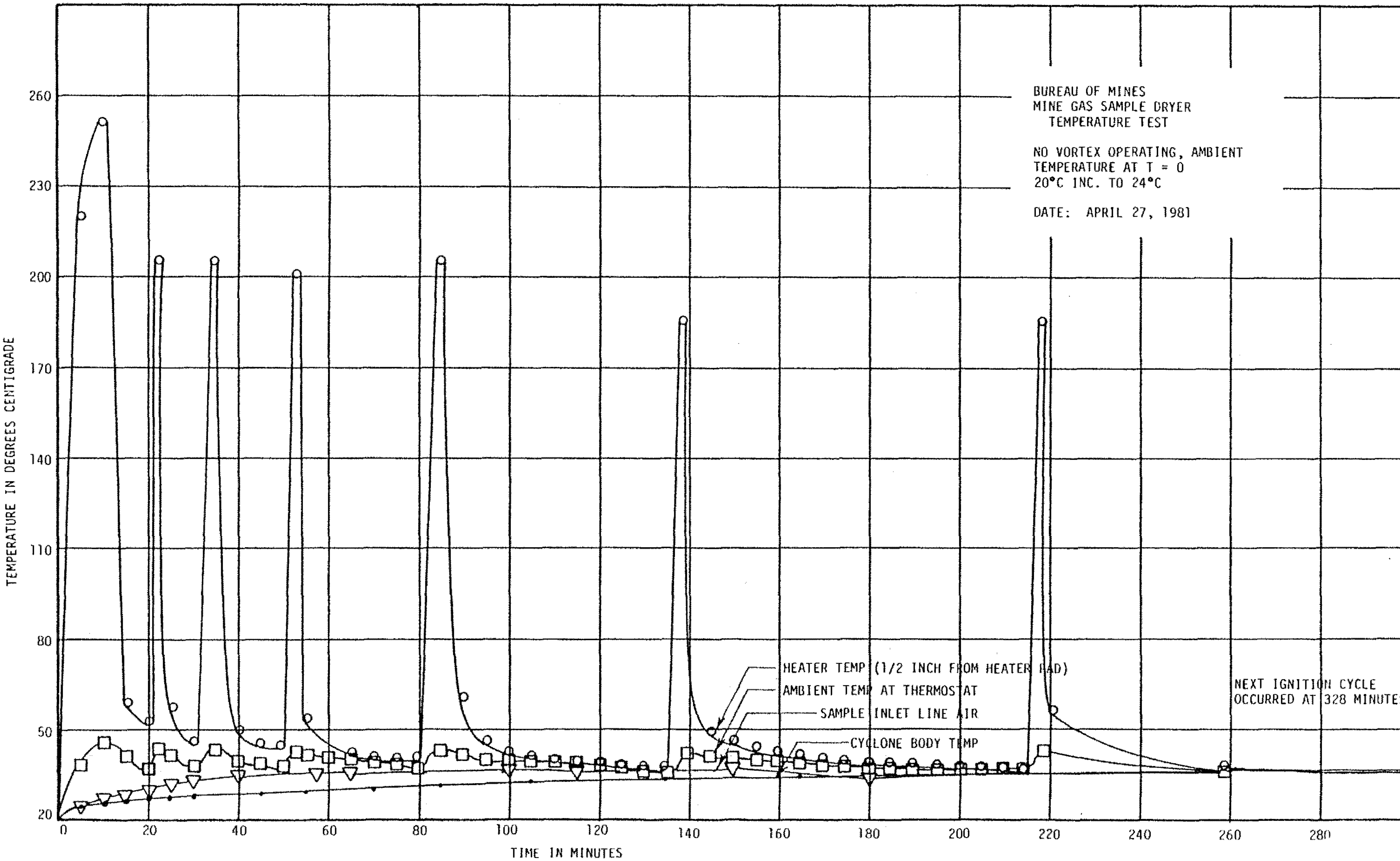


FIGURE 35.
MINE GAS-SAMPLE DRYER TEMPERATURE TEST

is expected to hold the system temperature stable without assistance from the catalytic heater. Another alternate to be considered in future systems is use of only one heat source in some applications, particularly for only one dryer or smaller dryer systems. Even for the largest system, the catalytic heater power, for example, would last weeks to many months without fuel refill, depending on the temperature extremes. Where a smaller dryer or single dryers are used, the elimination of the vortex would allow a considerably downsized air supply.

The final ignition of the test is not shown, but occurred at T = 328 minutes. Comparing the average of ratios of any interval to the preceeding interval or from a graph plotting the intervals versus time, a subsequent power-up would have been expected of the catalytic heater 180 minutes, or 3 hours, after the power-up at 328 minutes.

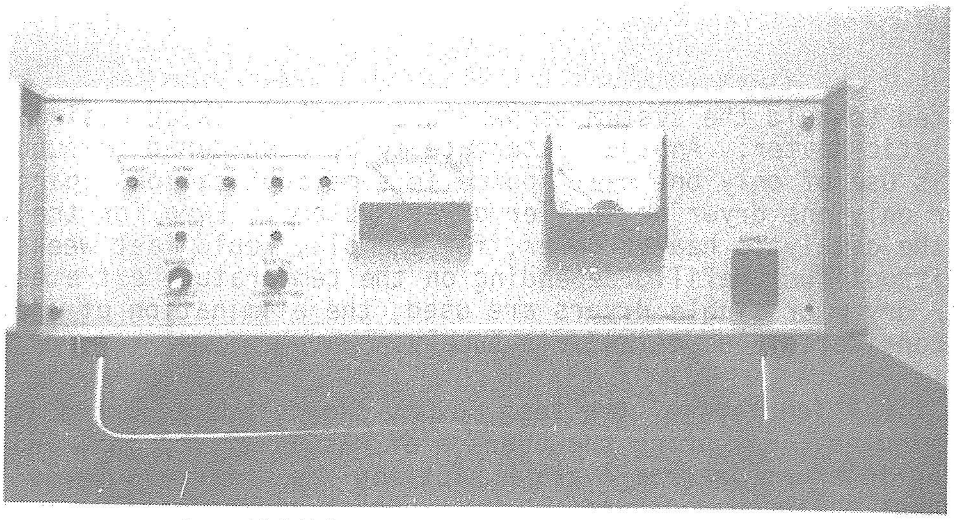
The catalytic heater remained on for a very short time, nominally 2.5 to 4 minutes after the initial turn-on power demand. The propane usage rate is 1/8-pound per hour. For any average on-time minutes, a five-gallon tank of propane would support about 3,400 ignition cycles at the conditions of temperature shown.

Photographs of Prototype 1 are shown in Figures 36 and 37.

Figure 37B is a photograph of the interior of the electronics at the central station. The large circuit board in the center is the receiver which receives and decodes the constant current signals from the transmitter and alarms for a flow malfunction in one of the dryers or the purge line, or for a low temperature in the heated portion of the field unit.

The receiver also monitors and displays the fuel level of the propane tank. A switch was added to the front panel to disable the receiver cycling relay which causes the receiver to constantly monitor status and not display fuel level. This was done to lengthen the life of the relay where fuel level was unimportant or required infrequently, such as once per day. A red light is visible on the front panel whenever the fuel measurement is disabled.

Figure 37A shows the inside of the heated chamber with the three dryers. The black cylinders in the center are the cyclone separators. The catalytic heater and heat exchanger are attached to a plywood bulkhead to the right of the dryers. The electronics components in the center are for both the heater and the status, Figure 36A. The vertical board is the 12-volt regulated power supply. The transformers at the top of the board are the heater wire stepdown and the 12-volt transformers. The other electronic circuit is the status transmitter for the alarms and fuel gauge. The differential pressure switches are visible at the top of the photograph.

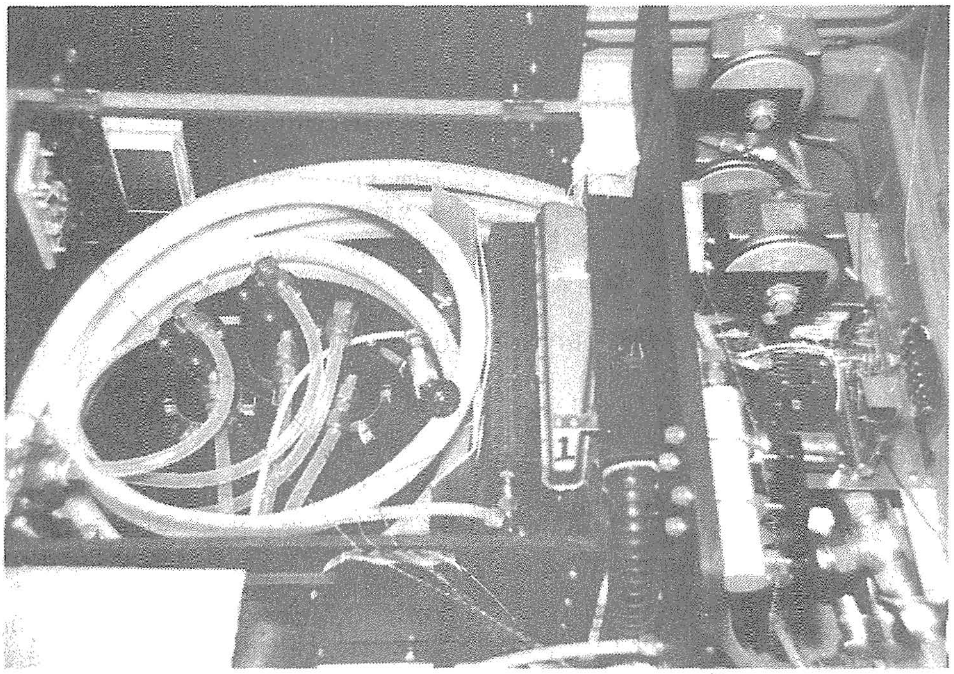


A. CENTRAL ELECTRONICS FRONT PANEL

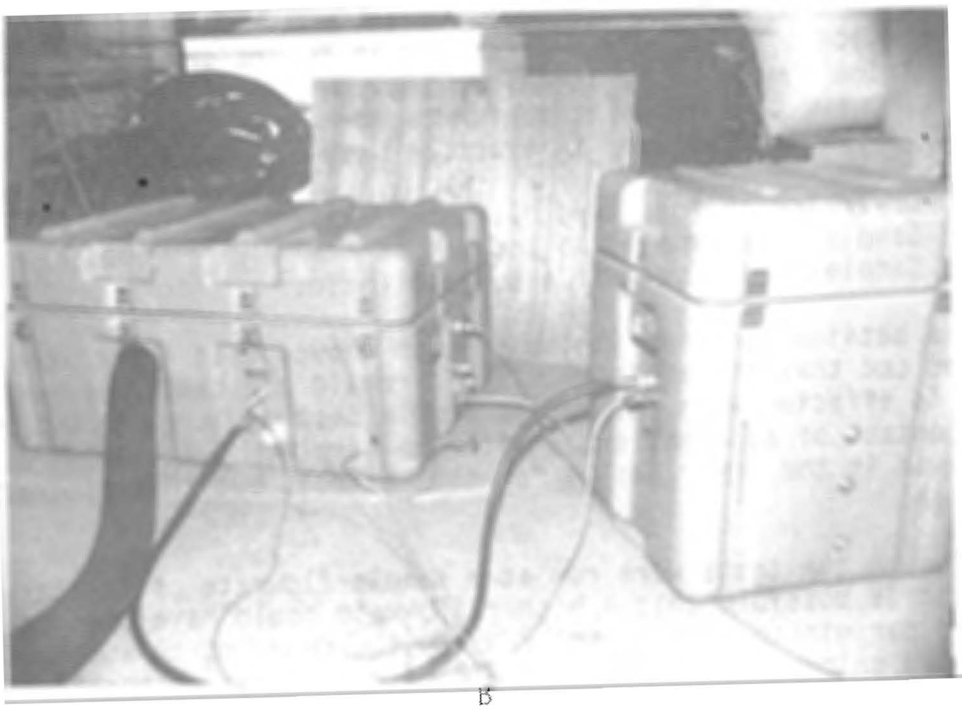
B. CENTRAL ELECTRONICS INTERIOR

C. SAMPLE CONDITIONER ELECTRONICS

FIGURE 36.
PROTOTYPE ELECTRONICS PHOTOGRAPHS



A



B

FIGURE 37.
PROTOTYPE SYSTEM PHOTOGRAPHS

Figure 37B shows the system in its field configuration, except for a number of small thermocouple wires coming out of the larger container.

The large case is the field system shown with the insulated sample bundle from the borehole entering the side. The smaller container houses the propane tank. The cable to the propane tank is connected to the fuel level potentiometer.

Figure 37C is an exterior view of the Central Station Electronics.

Preliminary Performance Testing

In checking out the uncovered completed system prior to temperature testing, it was discovered that the membrane dryers' efficiency had decreased. Since all three dryers decreased the same amount, roughly from 10 liters per minute to over 5 liters per minute for the target dewpoint, the cause seemed to be fundamental to the design. The dryers are stable at the lower efficiency so it should be correctable in future designs. Further testing would be necessary to determine the cause, but the most likely reason is that the multiple Nafion bundles had "settled" together with time and did not have the optimum sample gas-to-Nafion surface contact. This could be resolved in future dryers by inserting collars in the bundle or by simply making the dryer larger. The best solution, however, would be to perform a more detailed characterization of the dryer performance and interaction between the following:

1. Dryer length for fixed Nafion quantity;
2. Sample residence time; and
3. Sample volume-to-Nafion surface ratio.

Data obtained earlier in the program showed that the dryers could be scaled and that the efficiency would remain constant. However, the scaling is affected when the Nafion bundle becomes large enough to restrict contact of adjacent tubes with the sample. A factor of about 20% was allowed in the dryer design for this effect, but that apparently was not enough.

Although the tests were run at a sample flowrate of 5 liters per minute, it is possible that a higher flowrate could have been used. At 10 liters per minute, the dryers reduced the dewpoint to about -8.7°C, which would extrapolate to about -28°C at an ambient temperature of -26°C. That does not leave enough margin and freezing would likely occur near the output end of the dryer. Operating at 5 liters per minute produced a dewpoint (actually a frost point) of about -33°C which does leave enough margin. Further testing could verify that greater than 5 liters per minute flowrates could be handled by the existing dryers.

Temperature Testing

The system was installed in a large temperature chamber at the Ryan Aeronautical Environmental Test Facility in San Digeo. Ryan personnel took photographs of the system and test equipment in place and these are shown in Figure 38. Initially the dryer box was taken to 10°C, 0°C and then to -10°C. As the temperature was lowered, the sample output dewpoint decreased from about -10°C to -22°C during short-term testing of only 3 to 4 hours. This was not enough time for the system to stabilize, but was used for preliminary troubleshooting.

Several problems were uncovered and corrected.

Purge Air

The dryer purge air we were using was dry enough to remove water from the sample but apparently had a dewpoint near -35°C. As the ambient temperature lowered, the vortex heater hot air output lowered, as was expected, from in the 80's to the 50's, but then within minutes fell to below 10°C.

The sudden drop in vortex hot air output was caused by water freezing and blocking the cold end, thereby destroying the vortex action. The purge air heatless dryer size was increased to reduce the dewpoint to better than -70°C. During subsequent testing, the vortex output tracked ambient, and freezing in the cold output did not occur.

Sample Line

Although the vortex blocking problem was resolved, the heat provided to the incoming sample line was insufficient to keep the sample line warm for the full eight feet. This was improved by adding insulation to the line and by pre-heating the vortex air. However, the heat was still too low.

The sample line heating problem needed work, and was closely related to the mechanics involved in field installation of the insulation. It was planned originally to provide a one-inch thick, flexible, foam rubber tube which was slit on one side to allow the tie wire around the sheave block to be secured. The rubber tube was then taped and warm air flowed through the tube in operation to keep the sample line above the sample air dewpoint. However, it was necessary to add a multiple wrap of good insulation and add more heat to the line. For purposes of the test, the line was shortened to three feet and a one-inch wrap of Kaowool ceramic insulation was added. The Kaowool decreased the temperature drop-off rate from start of the cold test from 16 degrees per hour to 6 degrees per hour. The heating air into the sample bundle stabilized the sample into the test chamber (equivalent of borehole output) at 18°C for an ambient of -26°C, which is still too low. However, the vortex was operating as designed with the proper flow ratios and temperatures except

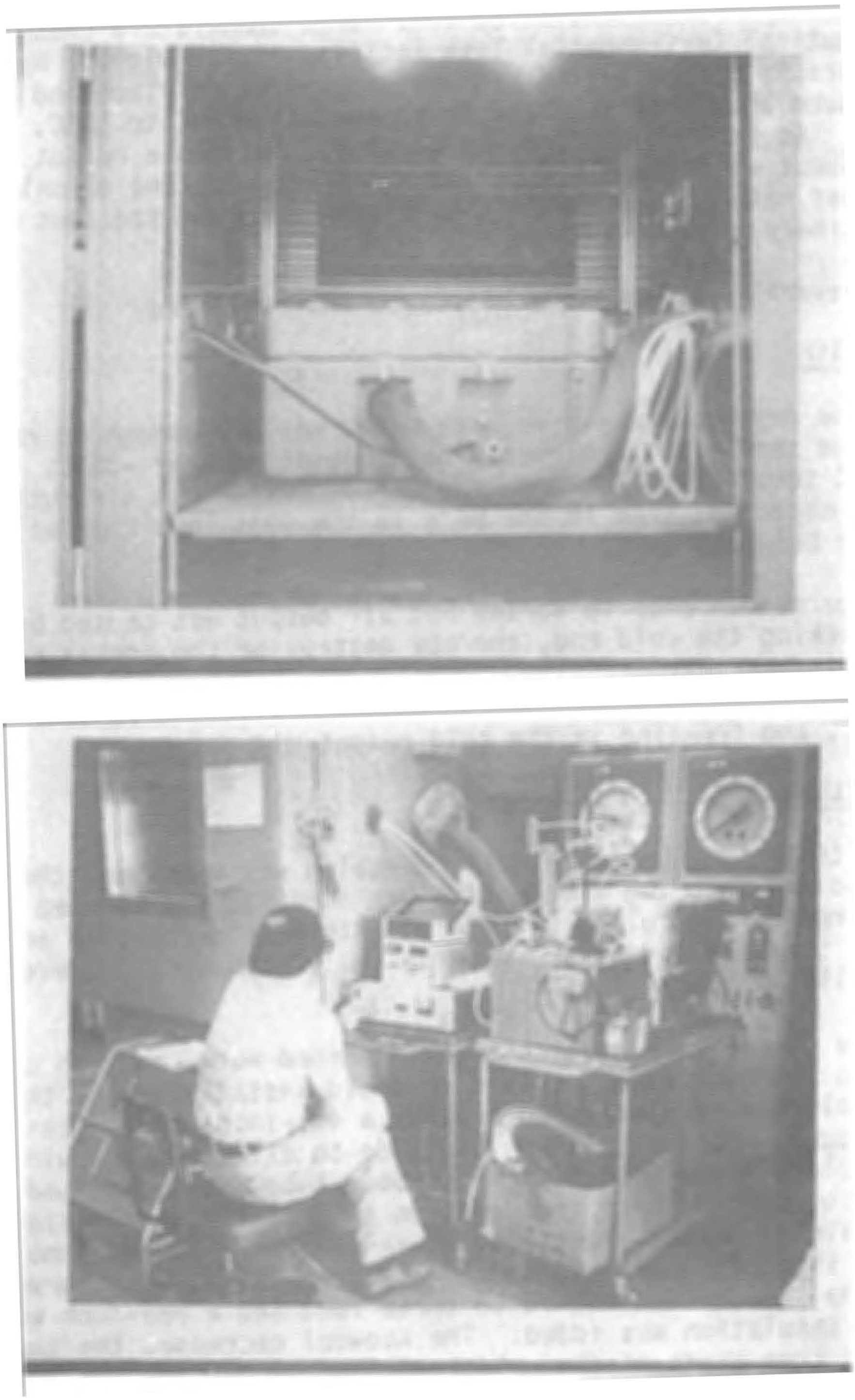


FIGURE 38.
ENVIRONMENTAL TEST SET-UP

that the total flow was low. The low flow problem has not been resolved, but the correct flow would have been expected to keep the sample line above the sample dewpoint, even for a longer tube. The basic problem is that more heat than necessary is given to the dryer chamber, leaving too little for the sample bundle. There are several ways of correcting that, which time did not permit at Ryan.

Catalytic Heater

The catalytic heater performed as expected, although about three days were spent experimenting with the optimum system temperature. Initially it was felt that the lowest possible temperature would be best because that would allow the greatest dryer efficiency and lowest propane usage. However, the need to pre-heat the vortex air and increase the heat into the sample line required an increase in the control temperature. The temperature tests were finally run with the catalytic heater turning on at 31°C and off at about 42°C. This provided the following stabilized system temperatures after seven hours at an ambient of -26°C after soaking one hour at -10°C. Where cycling of the readings occurs, the minimum and maximum temperatures are shown.

Monitoring Point	Temperature in °C
Catalytic Heater Thermostat	31 to 42
Vortex Cold Air Fitting	-24
Vortex Warm Air Fitting	52
Air in front of Catalytic Heater	54 to 167
Heat Exchanger Output Fitting	48 to 53
Electronics Compartment	-10
Air into Sample Bundle	26
Air out of Sample Bundle	18
Purge Air into Dryers	-7
Inside Plastic above Dryer Section	-19

The temperatures at the vortex heater are the temperatures of the brass fittings on the hot and cold ends, so the actual air temperatures would be expected to be somewhat higher on the hot end and lower on the cold end.

The catalytic heater cycled on every 10 minutes at -26°C ambient. Of this time, the catalyst heater wire is on for about 1 minute, 20 seconds, and the heater for about 2 minutes, 30 seconds. Since the gas turns on when the catalyst warmer does, the heater is using propane for nearly four minutes out of ten minutes, or a duty cycle of 40%. At that rate, the five-gallon fuel tank would be expended in about 2½ weeks. At -10°C ambient, the cycle time is about 20 minutes with a duty cycle of 20%, so the fuel would last about 10 weeks. Larger fuel tanks could be used without affecting system design except for the fuel tank container size.

A graph of the temperature test at -26°C ambient is shown in Figure 39.

The final temperature test was done by reducing the ambient temperature to -10°C for about one hour and then to -26°C for the remainder of the day.

Figure 39 shows that all critical internal temperatures had stabilized and that the dewpoint was stable at about -33°C at the -26°C ambient. This means that the system, from the sample input on, performed as designed. The catalytic heater was cycling every 9 to 10 minutes. All temperatures stabilized at the levels expected except for the sample line inlet temperature, which was too low.

Specification Modifications

The basic drying system performed as expected once a variety of thermal adjustments were made. The test at Ryan was the first opportunity to look at the combined system at low temperature and much of the time was spent modifying the thermal system. The catalytic heater performed very well and could do an adequate job even if it were considerably downsized.

The hot air sample warming system was found to be inadequate. Although one obvious solution is to increase the insulation and heatflow into it, some additional effort would be needed to investigate materials and to test the system. At this time, however, the contract funding had been expended.

Funding limitation necessitated a change in priorities and some deviations from the specifications in order to verify performance at -26°C. However, Charlton Technology, Inc. believes that sufficient data was obtained to prove the technology and that useable drying systems have resulted.

Deviation from the target specifications were as follows:

Sample Flow of 10 Liters per Minute

The system did not have sufficient margin to dry at 10 liters per minute below about -15° to -20°C ambient temperatures. Final tests were conducted at 5 liters per minute which the system can handle. We believe that 10 liters per minute could be achieved readily with slightly larger dryers or preferably with the same amount of Nafion in longer dryers.

Test Durations of 24 Hours

The lowest temperature required, -26°C, is the most demanding on the system. Time permitted only 7 hours continuous at -26°C, but the system temperatures and operation had stabilized within about 2 hours

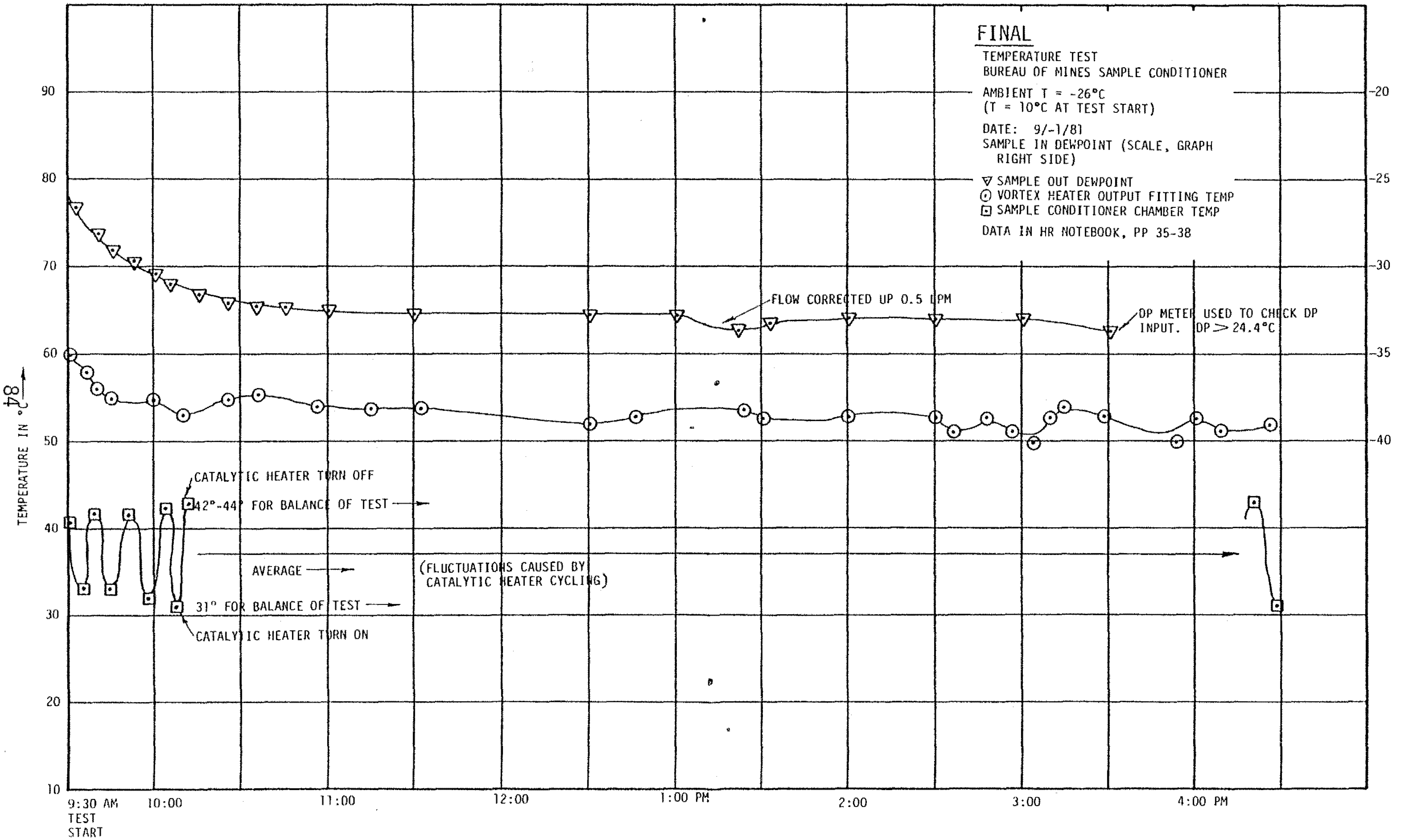


FIGURE 39.
FINAL TEMPERATURE TEST

after the chamber was at -26°C, and continued to produce a frostpoint significantly lower than the -26°C ambient temperature at a sample flow-rate of 5 liters per minute. It did not seem productive to spend much more time at the interim temperatures, although there were about 45 hours of testing at -10°C of the 9 days at Ryan during preliminary evaluation and troubleshooting.

The high end temperature of 38°C was not done at Ryan. The system was operated at Charlton Technology, Inc. at an internal temperature higher than 38°C with no apparent problem. Actually, the most temperature sensitive elements of the system, the electronics, are exposed to ambient or near ambient temperatures and can routinely operate well above 38°C. The only system components affected by the higher temperatures would be the dryers which would still have considerable margin with a dewpoint below 0°C. The catalytic heater and associated ignition electronics would be inactive above the control setpoint of 30°C.

Testing of Simulated Gas Mixtures

When this program was initiated, the sample water removal method had not been chosen, although there were a number of options. Of the options, some, such as refrigeration, are known to cause loss of sample and the loss varies from one gas to another. A gas blending system was constructed to simulate various compositions of mine atmospheres to evaluate gas losses, if any. However, as the program progressed, permeation drying by use of Nafion membranes was selected as the most promising method in part because of the known specificity of Nafion for water.

There is extensive history in the industry on sample loss through Nafion, including previous work done by Charlton Technology, Inc. Virtually all Charlton Technology Model SC-10 DRYSTAK units in the field are used in CO, CO_2 and O_2 measurement (as well as other gases), and tests have been made on the loss, if any, of less commonly analyzed gases such as ethane, methane and nitrogen. It is known that extremely polar compounds such as acetone and ammonia do readily pass through Nafion membranes, but there are no such compounds in the expected mine atmospheres.

Therefore, additional work with the gas blending system was reduced in priority in favor of more pressing developmental problems. Actually, one of the major reasons membrane drying was selected was because of its known high selectivity for water while maintaining high integrity of the original gas sample composition. Although the intention was not to eliminate sample degradation evaluation from the testing program, the reduced priority and expenditure of funds for more critical elements of the development had that effect. Charlton Technology, Inc., however, is confident this does not compromise the promise of the system.

Tubing Lengths

The tubing was evaluated and measured with respect to the pressure drops and wire resistance in multiples of 1,000 feet, but it was not possible to include the actual bundles in the temperature chamber, although both bundles were taken to Ryan. A 50-foot line served as a heat exchanger to lower the incoming purge air temperature and a power potentiometer simulated the maximum line resistance of one mile.

Recommendations

Although the system performed as expected with the exception of the thermal control for the sample inlet tubing, the development effort experience with the system and the test results point out a number of areas where the system could be simplified or the performance improved.

Sample Input Line

The warm air into the sample line insulation jacket was nominally 26°C, which does not allow enough heat to be supplied to keep the sample line warm from the borehole to the dryer box. The air supply has too much heat removed from it by the heat exchanger. Actually, the inside of the dryer chamber doesn't need the vortex heat because the catalytic heater is supplying adequate heat and that effective catalytic output could be further increased by raising the thermostat control temperature or by providing added heat-storage mass.

There are options to allow more heat into the inlet sample bundle. One simple change would be to use all the vortex air for heating the sample bundle. Further, the vortex air could be preheated in the main chamber. Although the changes would not be difficult, the system would have to be retested in the environmental chamber which would be the bulk of the effort.

Another possible method would be to use air heated by the catalytic heater to keep the inlet tube bundle heated. This option would likely require redesign of the heater to provide a lower level, more constant heat output which is one of the recommendations we make anyway.

Vortex Heater

Since the catalytic heater performs so well, it could be worth considering eliminating the vortex heater and choosing an alternate method to keep the input sample line warm. The vortex is a very low efficiency device and requires a large supply of very dry air, most of which is "wasted" as a cold exhaust. It would result in a simpler, lighter field system and in a considerably smaller dry air supply at the central station. It may not be possible to eliminate the vortex heater, though, unless the system including the catalytic heater could be reconfigured to provide a constant warm air supply to the sample tube bundle.

Catalytic Heater

The catalytic heater used in the system is a commercial unit modified to meet our basic needs without performing extensive redesign.

The redesign that was mandatory at the time involved reduction in the electrical power to operate the heater. This was done by reducing the catalyst pre-heater wire size which also reduced the portion of the catalyst being heated. This results in slower ignition, wasted fuel (because the fuel is being passed over an inactive catalyst and exhausted), and a bulkier than necessary heater. However, design of a smaller catalyst bed and heater structure was beyond the scope of the contractual effort, and it seemed important to first verify the concept before committing to a new heater design.

It would be relatively straight forward to design a scaled-down version of the catalytic heater. A smaller heater could be sized for continuous operation at the lowest ambient temperature of -26°C and would cycle off the progressively longer intervals as the ambient temperature increased.

Alarms

The dryer flow alarms add complexity to the field system and central station that may not be justified. It would be considerably simpler to instrument the central station with alarming flow indicators to indicate a flow blockage in the incoming sample lines. The only sacrifice in fault location would be that a severed sample line would still indicate a flow but the primary concern, that of a blocked flow due to freezing in the sample line, would be detected.

Retention of the temperature and purge flow alarms in the field unit is recommended. The temperature alarm verifies performance of the thermal system and verification that sufficient purge air is getting to the field unit is necessary to assure that all dryers and the catalytic heater can function.

Also, it would still be necessary and desirable to have the propane fuel level reported from the field unit.

Dryers

As the dryers "aged" they seemed to suffer a reduction in drying efficiency. The dryers designed to dry air at 10 liters per minute with about a 20% margin apparently settled out at around 6 liters per minute. The cause is believed to be nesting of the individual membrane tubing with corresponding reduction in sample air to membrane surface contact. This could be corrected by reducing the number of drying tubes, adding small separators during dryer fabrication or a combination of the two.

Another recommendation is to consider a downsized system where only one sample line is needed per borehole and where a smaller sample (on the order of one to three liters per minute) was needed. The result would be a considerably smaller, simpler, lighter, less expensive and inherently more reliable system.

Central Station

The "central station" as defined in this report is the control and analysis facility which would house the sample input manifold, valving, pumps, analyzers, air supply and other necessary field support equipment.

The prototypes as supplied each have a control module housed in a separate chasis. If a complete field system involving multiple borehole capabilities were developed, a simpler, integrated control system would be proposed for handling the various field modules. This is an effort where cost savings and total system simplification could be realized with a modest engineering effort, but should only be considered in the event a complex system were planned.