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Summary

An integrated exhaust gas analysis system has been designed and installed in the hot-section facility at the Lewis Research Center. The system is designed to operate either manually or automatically and also to be operated from a remote station. The system can measure oxygen, water vapor, total hydrocarbons, carbon monoxide, carbon dioxide, and oxides of nitrogen. Two microprocessors control the system and the analyzers, collect data and process them into engineering units, and present the data to the facility computers and the system operator. Within the design of this unique system there are innovative concepts and procedures that are of general interest and application to other gas analysis tasks.

Introduction

The hot-section facility (HSF) at the Lewis Research Center is a new and unique facility directed toward the testing of components for advanced aircraft turbine engines at high temperature and pressure. The highly automated state-of-the-art instrumentation for the HSF includes a gas analysis system, which is the subject of this report. This gas analysis system is of novel design and features microprocessor control integrated into the assembly.

When examined in the context of the HSF requirements for measurements, conventional gas analysis systems were inadequate. In conventional systems manual operation is the norm. Not only is conventional system operation labor-intensive, but it also requires a great amount of operator skill. In the past, computer use in these systems has usually been limited to processing the output signals of the individual analyzers. The HSF design guidelines for the gas analysis measurements emphasized accuracy, speed, automation, and safety. To achieve these goals, the computer tasks were extended to include system control. The result is an advanced gas analysis system bringing together a variety of dissimilar components, integrating disparate operating modes, and standardizing control methods and output formats.

The detailed system design is so specialized that it is of very limited interest. However, within the overall design, there are innovative concepts and procedures that are adaptable to general gas analysis system usage. It is these concepts and procedures that are the primary focus of this report. Furthermore this report is written on the assumption that the reader is familiar with gas analysis instruments and conventional gas analysis systems.

A detailed discussion of the HSF is well beyond the scope of this report. Therefore reference 1 is suggested as a source of information concerning the HSF, its mission, and its capabilities. However, the HSF cannot be totally dismissed from this report. Many features of this gas analysis system were dictated by the unique nature of the HSF. The overall configuration and function of the gas analysis system were shaped by constraints imposed by the facility. These were not design decisions, but rather *a priori* conditions that were imposed. Therefore a cursory discussion of HSF and its effect on the gas analysis system design is necessary.

Preliminary Design Considerations

Figure 1 was taken from reference 1 to illustrate the constraints placed on the gas analysis system by the HSF. The primary elements in figure 1 that are of interest here are the combustor rig and the control room.

The mission of the HSF gas analysis system is the analysis of the exhaust gases of the combustor rig and the presentation of the results in engineering units and in a format compatible with the facility computers.

The other elements of figure 1 such as the preheater, high-pressure air system, and turbine rig are all essential parts of the overall HSF system but are not germane to the discussion at hand. They are thoroughly discussed in reference 1. It is sufficient to indicate that the operating conditions within the combustor will generate temperatures and pressures in excess of 2200 °C and 4 MPa.

With these conditions personnel are not permitted near the combustor rig during operation. The control room is designed as a safe haven for personnel during facility operation. Any systems requiring operator attention must be located within this area. Figure 1 shows but half of the safe area. Directly below the illustrated control room is a second room, of equal size, called the equipment room. Both rooms share a common environment; they are connected by a circular stairway.

The time frame for delivery of a gas analysis system required the use of off-the-shelf gas analyzers. Lengthy
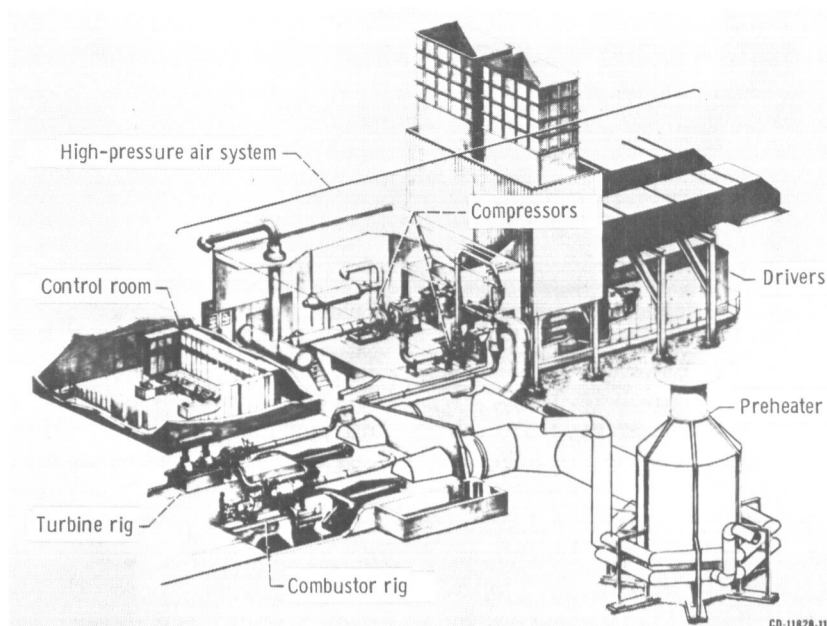
Figure 1.—Perspective view of hot-section facility (HSF).

development programs could not be considered. Such off-the-shelf analyzers are typically "flowthrough" devices: gas is extracted from the test object and conducted to and through the analyzers. Also, past experience indicated that these analyzers cannot operate totally unattended.

From this, it follows that the gas analysis system must be located within the safe environment of the control/equipment room and that the sample gas must be conducted from the combustor rig to the analyzers. Furthermore, space restrictions required that the system be located on the lower level, in the equipment room. The primary facility control point for HPF is the control room. Personnel limitations would not allow an operator to be dedicated to the gas analysis system. Therefore a degree of automation was required along with the capability to remotely monitor system performance.

From these considerations a system configuration evolved that was the starting point for this report. The overall gas analysis system consists of a sample collection and transport system that transports the sample gas from the test object in the combustor rig to the main analysis system console in the equipment room. The sample collection and transport portion of the overall system was arbitrarily separated from the analysis system as a separate design effort and is not a part of the work reported herein. A subsequent section of this report treats the sample collection and transport design so as to establish the interface between the sample line and the analysis system. The main console (fig. 2) is designed to
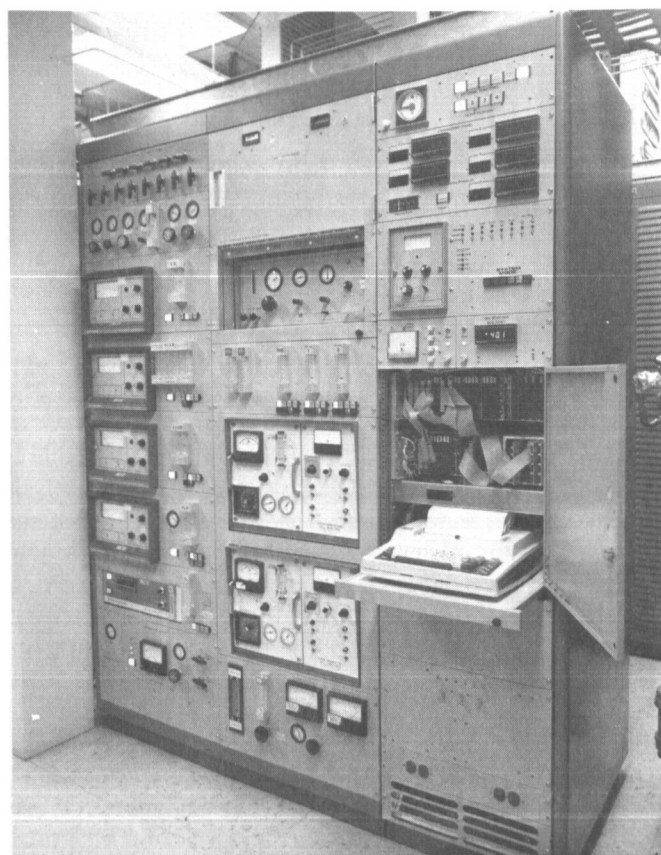

Figure 2.—Exhaust gas analysis system for HSF (main console).

operate under microprocessor control with minimal operator interaction. In the control room a remote control/readout console allows the operator to monitor system performance and to provide system control input. These then are the salient features of the HSF gas analysis system. It is from these preset conditions that this reported design effort began.

Gas Analysis Instruments and Techniques

The design of the HSF exhaust gas analysis system began with the definition of measurement requirements from the research and operation personnel. These requirements included not only a list of measurements and ranges, but also a request that the analysis system interface directly with the facility research computer and that it require a minimum of operator-hours. Along with these factors, safety was paramount.

The design criteria for the HSF gas analysis system required measurements of carbon dioxide (CO_2), carbon monoxide (CO), water (H_2O), oxygen (O_2), total hydrocarbons (THC), and oxides of nitrogen ($NO-NO_x$). To this end, eight gas analyzers are used in the HSF exhaust gas analysis system. Table I summarizes the gas species, concentration ranges, analysis techniques, and analyzer models for this analyzer set.

The $NO-NO_x$ measurement requires two simultaneous measurements: one of nitric oxide (NO) and the other of total oxides (NO_x). For these measurements two identical analyzers are used. Either analyzer can be configured to measure either NO or NO_x. A single analyzer can monitor only one of these at any given time. To measure both, it must be switched back and forth to yield sequential, not simultaneous, measurements. By using two analyzers, both gas species can be continuously monitored. Then for analyzer diagnostic purposes, both may monitor the same gas simultaneously, or the roles of the two analyzers may be reversed.

Four analysis techniques are used among the eight analyzers; nondispersive infrared (NDIR), flame ionization detection (FID), chemiluminescence (CLA), and coulometric oxygen sensing (COS). The instrument set of table I is unique in only one respect, few gas analysis systems contain this number of analyzers. Individually these analyzers are all in general usage.

Standard Analyzer Interfaces

Without dwelling on details certain generalizations can be made concerning the analyzers and their effect on system design. First, as a group, the analyzers are designed for manual control. Without exception, each analyzer requires hands-on input from the operator during operation. All of the analyzers, to varying degrees, exhibit sensitivity and zero offset drift so that periodic checks and adjustments are necessary. Conventionally these adjustments are manual functions. To achieve automatic or remote analyzer operation, each individual manual control or monitoring function had to be examined to determine which would be automated and which would remain as a manual task.

Second, with four different analysis techniques, there arise a variety of special needs that the integrating system

TABLE I.—ANALYZER SET USED IN HSF GAS ANALYSIS SYSTEM

Gas species	Concentration range		Analysis technique	Manufacturer and model number
Carbon dioxide (CO_2)	0-15 percent		NDIR	Beckman 864
Carbon monoxide (CO)	0-100 ppm 0-1000 ppm	} Low CO	NDIR	Beckman 864
	0-1 percent 0-15 percent	} High CO	NDIR	Beckman 865
Water (H_2O)	0-15 percent		NDIR	Beckman 864
Oxygen (O_2)	0-25 percent		COS	Beckman OM-11
Total hydrocarbon (THC)	0-20 ppm 0-200 ppm 0-0.2 percent 0-2.0 percent	}	FID	Beckman 402
Nitric oxide (NO) and higher oxides of nitrogen (NO_x)	0-20 ppm 0-200 ppm 0-0.2 percent 0-2.0 percent	}	CLA	Thermo Electron 10A (two analyzers used for simultaneous measurements)

must provide to the individual analyzers. For example, the NDIR and COS instruments require external means (pumps or pressurized sources) to move the gases through the analyzers. The FID instrument requires a source of fuel and combustion air for the detector. The CLA device requires a source of oxygen. In addition, the special control functions or safety requirements of the individual analyzers must be considered.

In the conventional philosophy of analysis system design the gas analysis instruments are accepted as is and the system is made to conform to the nature of the individual analyzers. The complexity of the integration system increases with each analyzer added to the system. It is also increased by efforts to add remote or automatic features. However, by carefully modifying the individual analyzers, more uniform analyzer interfaces to the system and operator can be achieved. These uniform interfaces, in turn, result in a simpler integrating system. The uniqueness of the various analyzers makes truly standard interfaces impractical. However, to the extent possible, the analyzers were modified to achieve a degree of uniformity.

Inverted Flow Configuration

One of the key factors in the standardization of the HSF gas analysis system was the adoption of a gas flow configuration termed the "inverted flow configuration." This name arose since the basic arrangement of components in the flow path had been reversed. This apparently trivial change significantly simplified the system pneumatics.

The orthodox flow pattern in general usage is shown in figure 3. This is a generalized figure; it has been adapted from reference 2 and other systems in general use. Here, gas is pumped from the sample line through the analyzer

and vented to atmospheric pressure. Atmospheric pressure is commonly used in gas analysis instruments as the reference pressure. Since most gas analyzers respond to the number density of molecules within the analysis chamber, the chamber pressure must be known. The usual practice is to vent the chamber to atmosphere.

Note that in figure 3 there is a flow restriction (the flowmeter) between the analyzer and the atmospheric vent. Therefore the analyzer pressure must be monitored and controlled by manipulating the analyzer gas flow rate. The pressure gauge, along with the flow control, is critical in maintaining the analysis chamber at the required pressure level. Automation of such a system would involve controllers for two flow control valves, plus a gas selector valve and readout capability for two flowmeters and a pressure gauge. Obviously for a system of several analyzers the number of controllers and measurements becomes significant, if not prohibitive.

The inverted flow configuration adopted for the HSF is presented in the conceptual schematic of figure 4. In this configuration the gas to be analyzed is drawn from a gas manifold at atmospheric pressure by a pumping device downstream of the analyzer. Flow restrictions between the analysis chamber and the atmospheric pressure gas sample are minimized so that the chamber pressure may be assumed to be atmospheric.

Whenever possible, venturi pumps are used to draw gases through the analyzers. The venturi pump offers several advantages: low maintenance, small size, no mechanical vibration, and pulsation-free pumping to name a few. When operated from a stable pressurized air source, the venturi pump provides a stable and repeatable gas flow rate through the analyzer if a suitable flow restrictor (R_1) is employed.

A conventional rotameter (FM_1) gives a visual indication of the analyzer flow rate. However, the
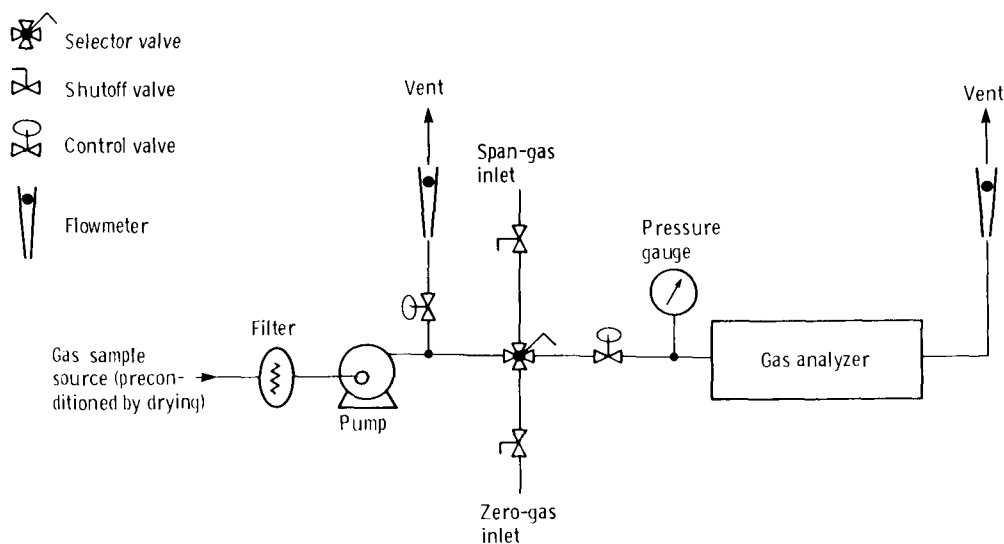

Figure 3.—Typical orthodox gas analysis system—single-analyzer-flow configuration.
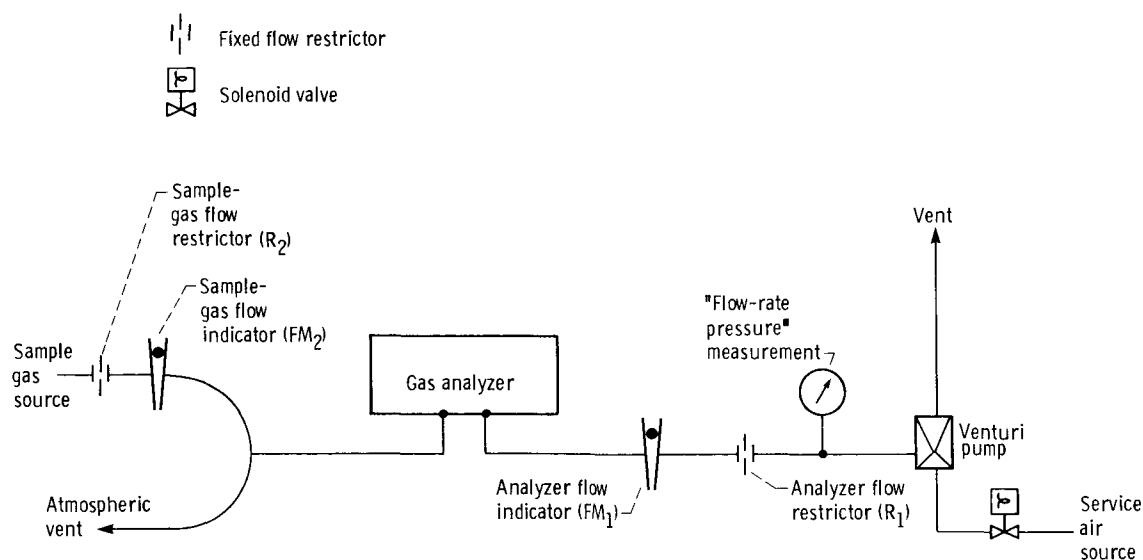
Figure 4.—Conceptual schematic of gas analyzer pneumatics—inverted flow configuration.

inclusion of the fixed analyzer flow restrictor (R_1) provides a second means of flow indication. All of the elements in the flow path from the analyzer inlet to the pump, with the exception of R_1, are of relatively high conductance. Therefore most of the pressure drop from atmosphere to the pump inlet occurs across R_1. This pressure drop is then a direct measure of analyzer flow rate. By monitoring this pressure a "flow-rate pressure" can easily be used as an indicator of analyzer flow rate.

By design the inlet manifold operates at atmospheric pressure. This is achieved by minimizing the flow restrictions between the sample-gas flowmeter (FM_2) and the atmospheric vent. This, in turn, means that if the gas source is stable, the sample-gas flow restrictor (R_2) can be fixed, thus eliminating another manual adjustment. Therefore the only parameter requiring adjustment is the gas source pressure. In the final form of the system this pressure adjustment is done externally to the gas analysis system, at the source, so as to maintain the pressure within preset limits.

For all gas analyzers it is necessary to periodically introduce "zero" and "span" gases into the individual analyzers. These gases are used to monitor, and correct for, the omnipresent drift of analyzer zero offset and sensitivity. In the inverted flow configuration this is accomplished by using dual inlet flow loops: one for the sample gas, and the second for the zero and span gases. This dual flow loop arrangement is shown in figure 5. A solenoid valve (V_1) at the analyzer is used to select the appropriate flow loop. This valve must have high conductance (~ 0.5 or greater) so that pressure effects are minimized. Furthermore the flow rates from the two manifolds should be equal. In figure 5 the same components and parameters are used downstream of V_1 for both manifolds so that the flow variation between the manifolds is minimized.

An important feature of this design is that V_1 operates with all ports at or very near atmospheric pressure. One of the subtle, yet devastating, problems associated with gas analysis system valving is that of slight valve leakage. Low leak rates across a valve can be very difficult to discern in situ. Until a valve is isolated and tested, a critical leak may go undetected. Yet even small leakages can cause gross dilution of the gases. Leak rate is the product of pressure differential and leak size. Here, the pressure differential is reduced to near zero, and hence the potential leak rate is minimized.

Gas source 1 (fig. 5) would typically involve additional components to introduce the span and zero gases to the analyzer inlet. This flow loop and associated components for introduction of span and zero gases is considered in the section System Pneumatics.

Gas source 2 (fig. 5) and the associated flow loop is actually shared by several analyzers. In this case the flow rate through restrictor R_{2b} must be greater than the sum of the flows through the individual analyzers and yet low enough to prevent any discernible manifold pressure above atmospheric. Test data indicate that the range of allowable flow rate is quite broad; flow rate does not become a critical, limiting parameter. However, this range of allowable flow rates will be an important design parameter in the subsequent sections on sample-gas collection, transport, and handling. Further discussion is reserved for these sections.

Sample-Gas Collection and Transport

Before proceeding further into the description of the HSF gas analysis system, it is necessary to describe the sample-gas collection and transport systems within the HSF. Although this report deals primarily with the
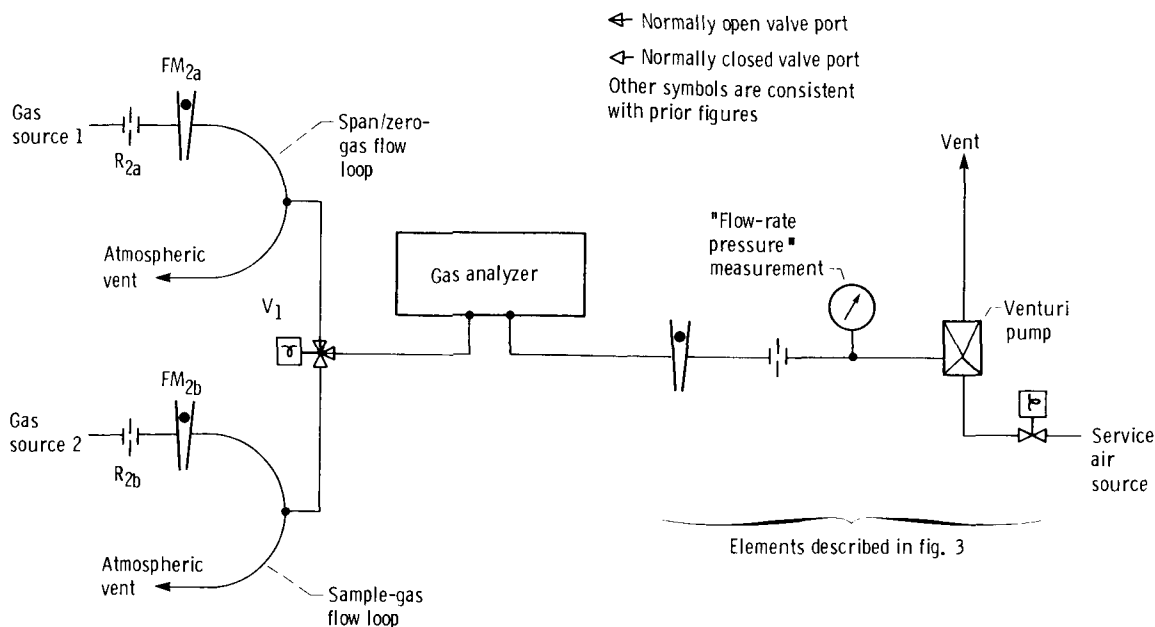
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Figure 5.—Conceptual schematic of gas analyzer pneumatic system.

problems of gas analysis, the factors of sample-gas collection and transport must also be considered. The three functions of collection, transport, and analysis are of equal weight. The following synoptic discussion is intended to lead from the gas collection at the test object to the presentation of the gases at the sample-gas inlet of the gas analysis system.

The primary research tasks within the HSF are directed toward the testing of components for advanced aircraft

turbine engines. A typical test object would be a high-pressure, high-temperature turbine engine combustor. The gas sampling task here is obviously much different from that of sea-level exhaust plume sampling of the total engine.

Figure 6 briefly describes the sample-gas collection and transport functions as implemented in the HSF. The gas collection probes are mounted on a rotating rake assembly within the high-pressure, high-temperature
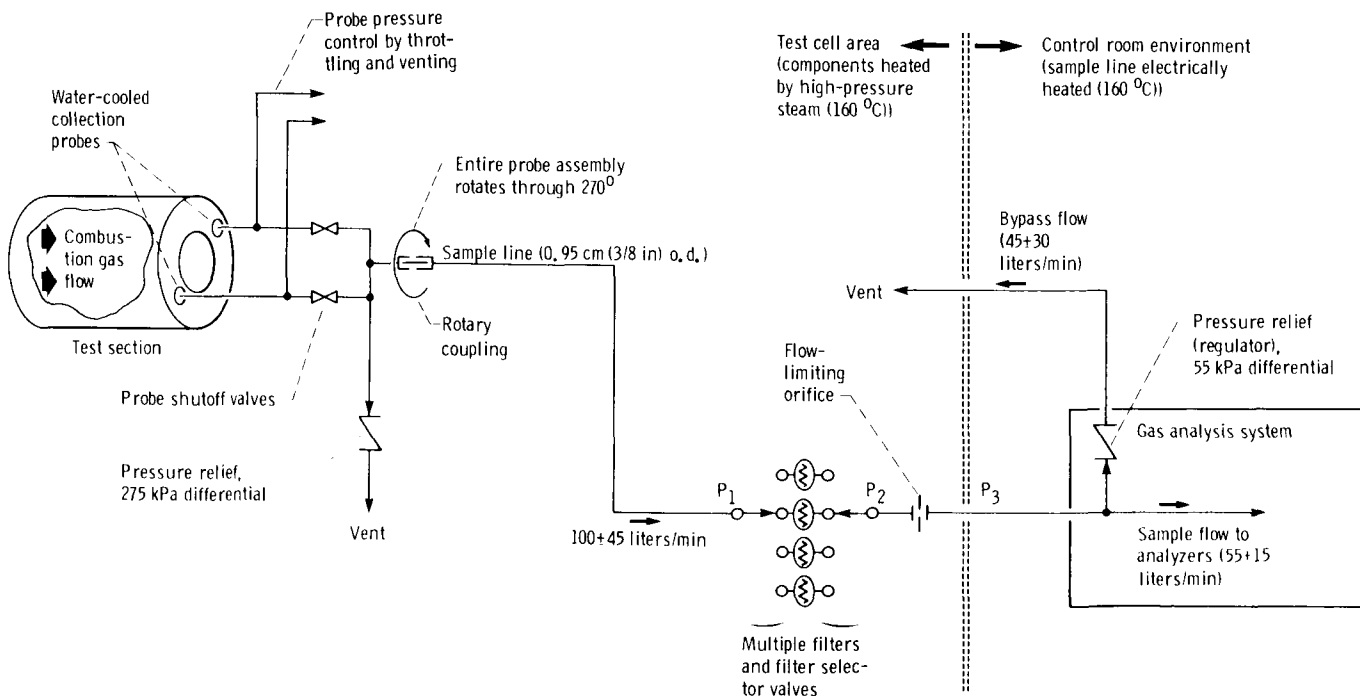

Figure 6.—Schematic of sample collection and transport system.

vessel of the test section. The probes reduce the sample-gas pressure and temperature to about 170 ± 100 kPa gauge (pressure P_1 of fig. 6) and 160 ± 15 °C. Once cooled, the sample gas is then maintained at 160 °C. The transport line and components are all heated by high-pressure steam. For safety reasons the steam heating terminates before the sample line enters the control room area where the analysis system is located. From this point the sample line is electrically heated.

The choice of sample-line pressure and temperature is largely empirical. On one hand, all gas reactions within the sample gas must be eliminated; on the other hand, the gas temperature must be well above the dewpoint of any of the sample components. The choice of 160 °C as the preferred sample temperature is well documented (ref. 2); the pressure is maintained just high enough to ensure acceptable flow through all of the pneumatic elements and flow paths.

For safety the sample filters are located outside the control room area since filter canisters are frequent sources of leakage. Since the filter location is not accessible during facility operation, multiple filters and remotely actuated selector valves are used. After filtration an orifice limits the sample-gas flow entering the control room area.

Within the main gas analyzer console about half of the sample gas passes through a pressure relief valve and vents outside the control room. Only a fraction of the total gas flow is used within the gas analyzer console. The pressure relief valve serves as a coarse pressure regulator. This in combination with the upstream orifice provides a reasonably regulated low-pressure (55 kPa gauge) source of sample gas from which the gas analysis pneumatics are operated. The large bypass flow serves to minimize the residence time of the sample gases within the transport system.

The residence time of the gases within the transport system is of interest for several reasons. Obviously the overall response time of the system is directly a function of sample residence time. Long residence within the line allows time for undesirable chemical reactions or interactions between the sample gas and the sample line, as well as unwanted gas mixing or separation.

With the system described previously, the sample-gas parameters within the sample transport line, before filtering, are as follows:

Sample flow rate, liter/min............................100 ± 45
Sample pressure, kPa gauge.........................170 ± 100
Sample temperature, °C...............................160 ± 15

At the inlet to the gas analysis console the flow and temperature parameters are the same; however, the sample pressure is reduced to 55 ± 20 kPa gauge. The parameters are maintained by facility control of conditions at the gas collection probes. There are no controls within the analysis system to modify these

parameters. The gas analysis console is designed to operate satisfactorily over this range of inlet conditions. Of the total sample-gas flow rate, only about 55 liters/min is used within the analyzer console; the remainder is vented through the bypass vent.

System Pneumatics

Sample-Gas Handling

Between the sample-gas collection and transport system and the analyzers lies another subsystem that receives the sample gas from the transport line, conditions it, and distributes it to the various analyzers. Figure 7 shows the pneumatic elements that make up the sample-handling pneumatics within the system console. Those elements that are located within the test cell environment are discussed in the preceding section. The filter (F_s) as shown in figure 7 is schematic; recall that multiple filters and selector valves are actually used.

The HSF sample gas will, on occasion, exhibit water content in excess of 10 vol %. Several of the analyzers, particularly the NDIR instruments, cannot tolerate this moisture level since condensation would occur within the analyzers under normal operating conditions. Therefore a portion of the sample gas must be dried before delivery to the analyzers. Reliable measurements of water content, before and after drying, are also necessary so that suitable volume corrections can be applied to the measured gas concentrations of the dried sample.

Within the system console the dried sample gas is distributed through a gas manifold called the dry-sample flow loop. The drying process for this flow loop has two stages. In the first stage a water-cooled coaxial tube condenser and a water separator reduce the sample-gas water content to approximately 2 percent. In the second stage a dryer device based on the permeable nature of perfluorosulfonic acid polymers is used (ref. 3). This permeation drying technique reduces the water content of the gases to less than 1 percent, which approximates that achieved with conventional ice bath techniques. (The ice bath, as a drying technique, was rejected in this system because of the manual operations involved.)

After the gas is dried, a flow restrictor (R_d of fig. 7) limits the gas flow into the atmospheric pressure manifold. A flowmeter (FM_d) gives an indication of the gross flow of dry-sample gases. This flow loop manifold is electrically heated to 50 °C so that gases flowing into the analyzers are preheated to the nominal operating temperature of the analyzers.

Within the sample-gas pneumatics there is a second flow manifold through which undried sample gas flows. This manifold is called the wet-sample flow loop. If this gas were to be dried, the drying process would modify the level of some of the gas species to be measured,
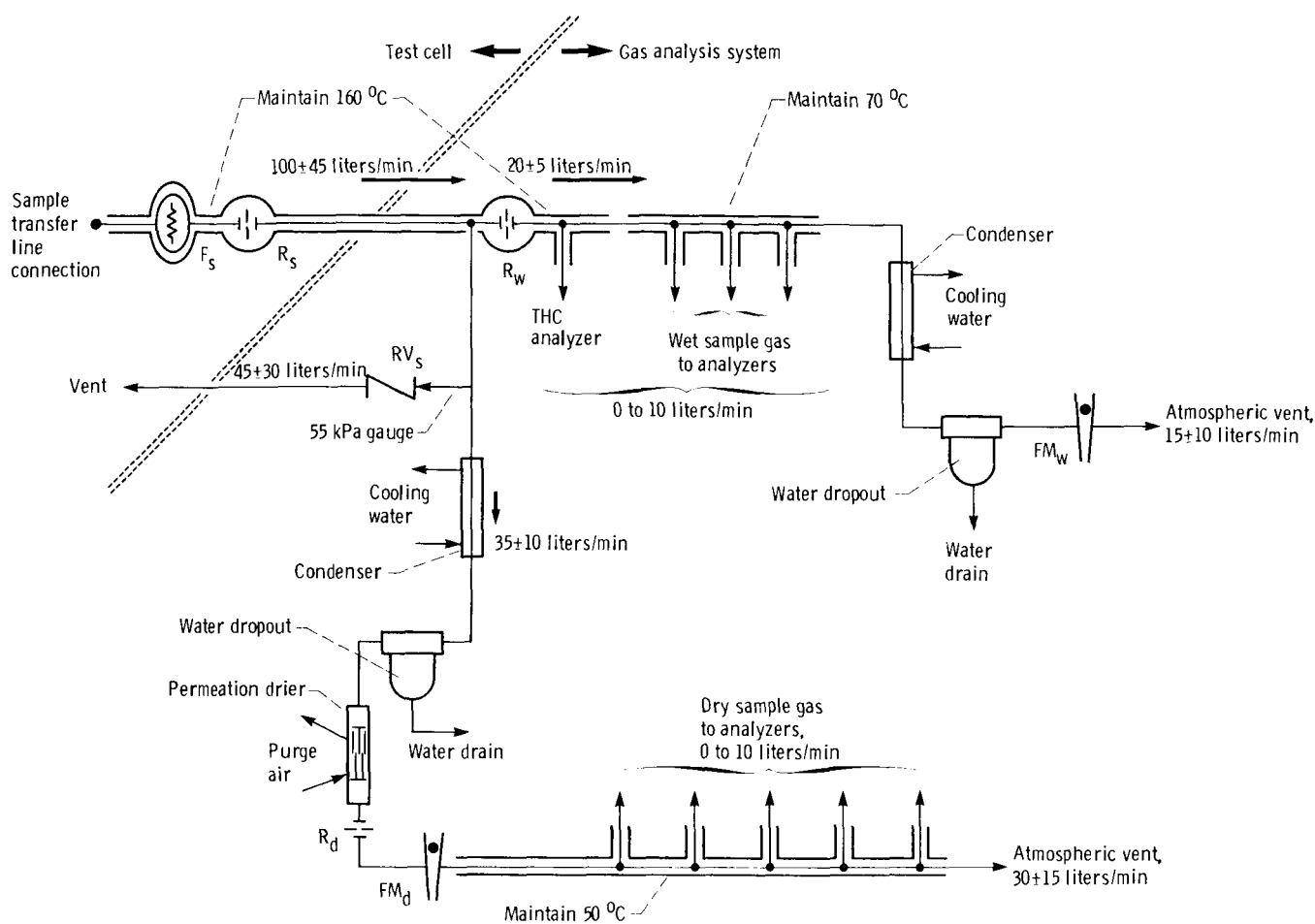
Figure 7.—Schematic of sample-handling pneumatics.

specifically the THC and NO-NO$_x$ species. Therefore these gases must be presented to the respective analyzers without drying. This manifold must also be heated to prevent condensation. For the THC analyzer the wet sample is maintained at 160 °C. However, for the remaining analyzers the manifold temperature is reduced to 70 °C. The higher temperature region ensures that the hydrocarbons remain in the vapor phase. For the remainder of the manifold, water is the only condensable component of concern.

Before the wet sample is vented to atmospheric pressure, the gas is dried sufficiently to prevent condensation within the vent manifold. A water-cooled coaxial tube condenser and water dropout are used for this purpose. A flowmeter (FM$_w$) serves to indicate the net flow of wet sample into the vent line. Gas flow through these components does introduce some slight pressure above atmospheric within the wet-sample flow loop. However, the analyzers serviced by this manifold do not have the pressure sensitivity of the NDIR analyzers. Each of these analyzers incorporates a means of internal pressure control.

Note that in this array of pneumatic components there are no manual adjustments. All components are fixed; all parameters are controlled by adjusting the sample-gas pressure at the collection probes.

Ventilation

Throughout the previous discussion, two concepts frequently arose. First, there was an overriding concern for safety. Then there were several references to using atmospheric vents as a means of establishing known pressure levels. The two concepts significantly affected the design of the ventilation subsystem. From a safety standpoint the system for venting the various gases is critical since several of the gases used are potentially hazardous and require safe disposal methods. From a functional standpoint much of the system accuracy is derived by establishing known pressure levels via venting a manifold to atmospheric pressure. The ventilation subsystem adopted for the HSF gas analysis system is shown in figure 8.

In figure 8 the gases are conducted away from the analysis system by a blower drawing upon a vent stack

approximately 6 cm in diameter. At design pressure the blower develops a throughput in excess of 367 liter/min. The maximum sum of all of the gases generated within the console amounts to about 287 liter/min. This means a makeup flow of air of 80 liter/min from the control room environment is drawn into the vent through the console.

The vent manifold within the console (fig. 8) is divided into two quite different manifolds: the closed-vent leg and the open-vent leg. The two legs of the manifold are separated by two sequential flow restrictors. The closed leg of the manifold operates at a very slight subatmospheric pressure; the open leg remains at the local ambient atmospheric pressure.

The open-vent leg is used to capture the vent flows that are pressure critical. These are the vents from the gas distribution manifolds of figures 4, 5, and 7. The maximum flow of these gases is 81 liter/min. Another group of gas flows, the vents from the venturi pumps, for example, are not as pressure critical. These are connected to the closed leg and amount to 146 liter/min, maximum. Makeup air from the console is then drawn into the open vent to balance the 367 liter/min of blower throughput.

A variety of miscellaneous gas sources within the console are not directly attached to the vent manifold. These contribute a maximum gas flow of 60 liter/min. This leaves a minimum of 80 liter/min of air to be drawn into the console from the control room environment. By design, the analysis console is a closed container. This means that the interior of the console operates at a

pressure slightly less than the control room ambient pressure.

Maintaining the console at a slight negative pressure ensures that gases within the console are ingested into the ventilation subsystem and not allowed to escape into the control room atmosphere. However, this negative pressure also must be considered. The local atmospheric pressure is a significant factor in establishing and maintaining measurement accuracy. Therefore an absolute pressure transducer is dedicated to monitoring the internal console pressure; this pressure is then used as the atmospheric pressure reference.

The closed nature of the console also eliminates convective cooling of internal components. A closed-loop air-conditioning unit is incorporated into the system to provide the necessary cooling.

The purpose of this rather complex design is safe disposal of potentially hazardous gases. Obviously a ventilation failure could lead to an unsafe condition. This leads back to the two flow restrictors that separate the two vent legs. Gas flow from the open-vent leg into the vent stack will cause a pressure drop. This pressure drop is monitored and used as a ventilation failure alarm and also as a permissive for gas introduction into the console.

The ventilation alarm/permissive is derived from two pressure switches, one monitoring each of the two sequential flow restrictors. Proper flow conditions will cause a pressure difference across each restrictor. If either restrictor becomes blocked, the other will not
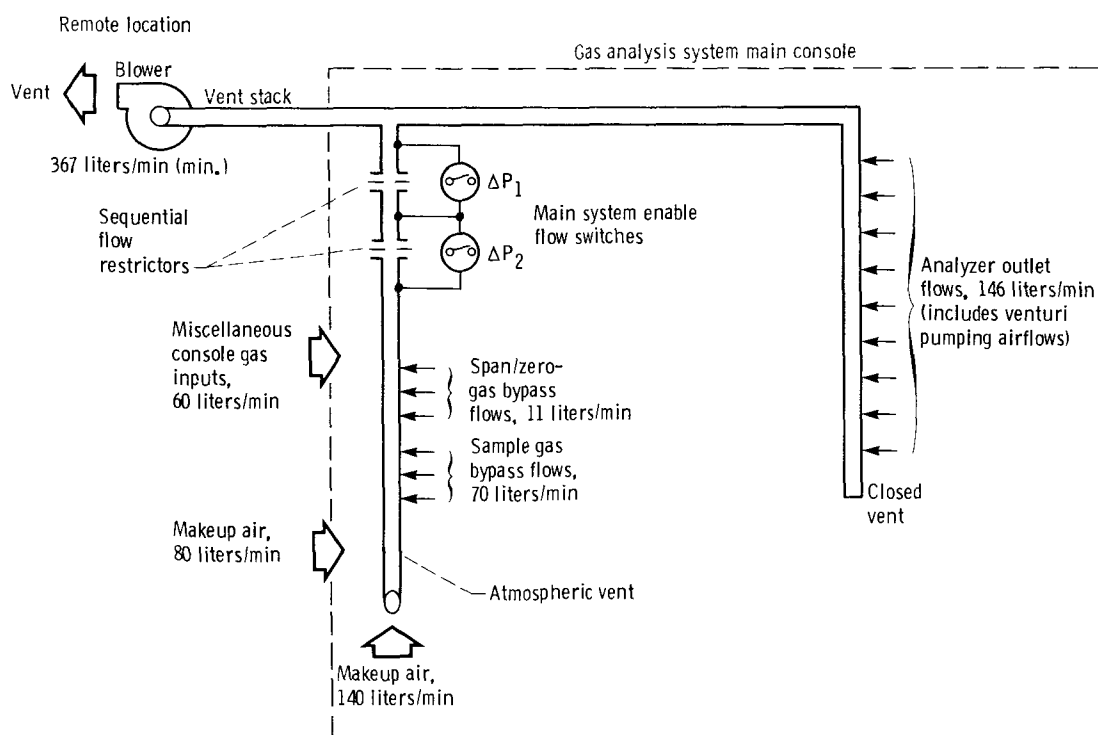

Figure 8.—Schematic of ventilation subsystem.

exhibit the required pressure difference. Unless both restrictors exhibit a preset pressure difference, a vent failure is actuated. Conversely the presence of both pressure differences is used as a permissive signal that allows the introduction of gases into the system console.

The pressure switches used are reliable with pressure differences as small as 25 Pa (1/10 in of water pressure). Reliable operation of the overall alarm assembly is achieved with the closed-vent leg operating at about 125 Pa (1/2 in of water pressure) below the console internal pressure.

Some gas sources and venting procedures have been omitted from figure 8. For example, the level of vacuum required by the NO-NO$_x$ analyzers precludes the use of venturi pumps; mechanical pumps are required. These necessary mechanical vacuum pumps use a separate dedicated vent line. The gas flow from these pumps contains pressure pulsations due to pump action. These pressure pulsations, if conducted into a common vent, could be coupled back into other analyzers. For large-volume gas flow streams, such as the inlet sample-gas bypass flow, the individual streams are vented by other dedicated lines. The dedicated vents conduct the gases to atmosphere at a remote location for safe disposal via dilution to acceptable concentration levels. With these exceptions, the remainder of the gas disposal task is accomplished by the ventilation subsystem described in figure 8.

Span- and Zero-Gas Pneumatics

The method of handling the zero and span gases within the HSF gas analysis system was developed not only to be compatible with the inverted flow configuration, but also to meet stringent safety requirements. A typical zero/span-gas pneumatics installation is shown in figure 9. The sample-gas flow loop is shown only schematically therein. It should be emphasized that the pneumatics of figure 9 are repeated for each of the analyzers but the sample-gas flow loop is common to several analyzers.

A zero gas, typically gaseous nitrogen (N$_2$), is used for analyzer zeroing. A fixed restrictor (R$_2$) limits N$_2$ flow from the low-pressure source (typically 55 kPa gauge) through valve V$_4$ and flowmeter FM$_2$ to an atmospheric pressure manifold. The flow through this manifold must be greater than the analyzer flow rate so that there is always a net flow of gas toward the manifold's atmospheric vent. If the N$_2$ flow rate is not higher than the analyzer flow rate, the zero gas will be diluted by air ingested from the vent.

The system for introducing span gas is similar yet requires some further comment. In order that the span-gas bottles might have a reasonably controlled
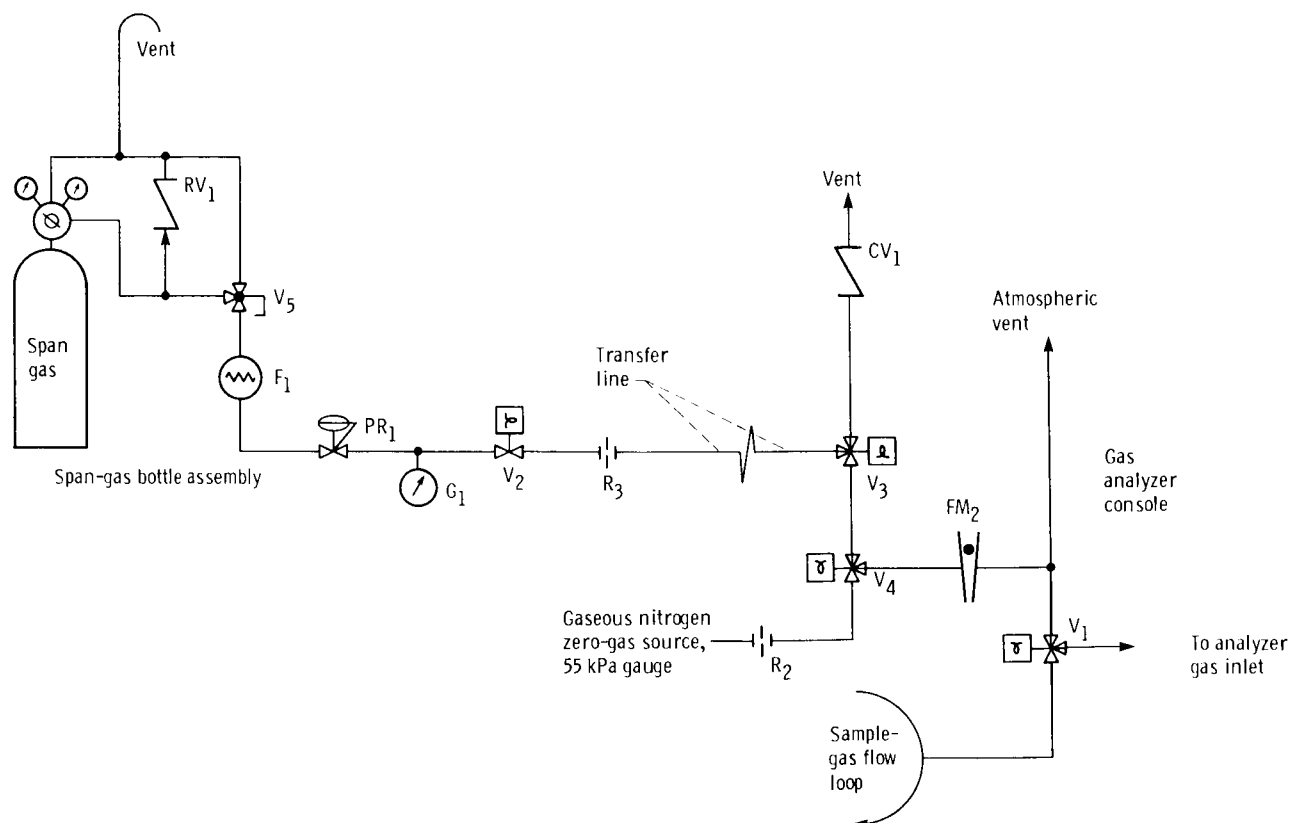

Figure 9.—Schematic of typical span-gas pneumatic system. (Symbols are consistent with prior figures.)

environment, they are located in an area frequented by personnel. To minimize the hazards associated with gas leakage, all bottle regulators are equipped with suitable vents and pressure relief valves. Valve V_5 is a manual valve that allows the bottle or regulator pressure to be released into the vent while all other components are isolated. A second regulator (PR_1) is used to adjust the span-gas working pressure to nominally 55 kPa gauge. When span gas is requested, valves V_2 and V_3 are actuated. Flow restrictor R_3 limits the span-gas flow rate through V_3, V_4, and FM_2 and into the same manifold as is used for the zero gas. As in the zero-gas case the span-gas flow rate must exceed the analyzer flow rate so that there is a net flow into the atmospheric vent.

At the end of the span-gas usage cycle, valves V_2 and V_3 are deactivated. Now the remaining span gas between the valves is vented through the check valve (CV_1). When not in use, the span-gas transfer line is depressurized to atmospheric pressure. The check valve (CV_1) prevents any back diffusion of air into the line. This is considered to be a safe condition without internal pressurization and with minimal gas content. This span-gas handling technique avoids a host of problems concomitant with the usual safety practice of purging gas lines after usage, yet it achieves the same safety goals.

Note the valve logic associated with this system. For sample gas, only valve V_1 is actuated. For zero gas, only valve V_4 is actuated. For span gas, valves V_2 and V_3 are actuated. Obviously, when any of these valves are actuated, the venturi pump that pulls the gases through the analyzer must also be active. With this technique span-gas usage is perhaps 30 percent higher than in conventional gas analysis systems. However, mixed gases such as these have a limited useful life. With time, the accuracy of the gas mixture becomes suspect. The increased usage of the gases can result in a more timely replacement of the gases and hence some slight improvement in measurement accuracy.

Typical Analyzer Flow System

The actual flow system used on several analyzers in the HSF system is obtained by combining the inverted flow configuration of figure 4 with the span- and zero-gas pneumatics of figure 9. This combined flow system is shown in figure 10.

One additional feature is incorporated into figure 10. Frequently there is a need to introduce other gases into the analyzer. This is not part of the routine operation of the system; it occurs during periods of system maintenance or during "off line" calibration of the analyzers. For this purpose, valve V_7 is introduced into the zero-gas line. Valve V_7 is a manual valve used to allow the introduction of gases through an auxiliary gas input. The necessary gas pressure at this auxiliary input is the same as the zero-gas pressure, about 55 kPa gauge.

The pressure measurement at the venturi pump inlet is further defined in figure 10. For an array of analyzers individual pressure measurements are made by a single pressure transducer and a group of multiplexing valves. Valve V_8 is a multiplexing valve that connects the pressure transducer to the venturi pump inlet pressure.

For an array of analyzers a common zero-gas source can be used. This means that there is but one zero-gas pressure adjustment for all of the analyzers, that being the source pressure of 55 kPa gauge. This same comment can be applied to the service air source that powers the individual venturi pumps. Each span-gas source has individual pressure adjustments. However, these pressure adjustments are the only manual operations within the system of figure 10 except for the manual introduction of specialty gases through valve V_7, the auxiliary input. Furthermore these adjustments are not critical since the various flow rates have a wide range of acceptable values. With the exception of these few manual functions all other functions are now compatible with either remote actuation or automatic operation.

Analyzer Specifics

The system concepts previously presented give the designer the tools required to approach the problems of system automation or remote system operation. However, all are based on a flow scheme for analyzer operation. In truth, not all analyzers are adaptable to the inverted flow configuration. These individual analyzers then present special problems of adaptation to the approach just developed. Each of these analyzers and the adaptations used are discussed in this section.

Flow Measurement

The inverted flow configuration is not used for the THC and $NO-NO_x$ measurements inasmuch as these analyzers incorporate all of the necessary components required to accept and exhaust gases at atmospheric pressure. These analyzers can be coupled directly to the sample-gas and vent manifolds. However, a capability lost in not using the inverted flow configuration is that of inferring analyzer flow rate remotely or automatically through the "flow-rate pressure" measurement (figs. 3 and 4 and associated discussion). For reasons discussed in a later section the water analyzer is not adaptable to this flow-rate pressure measurement. Since remote or automatic flow monitoring is desirable, means for measuring flow for these analyzers were added to the system. For these four analyzers an electronic flowmeter and valve manifold was provided to remotely monitor analyzer flow rates. Figure 11 shows this flowmeter addition to the THC analyzer span-gas pneumatics.
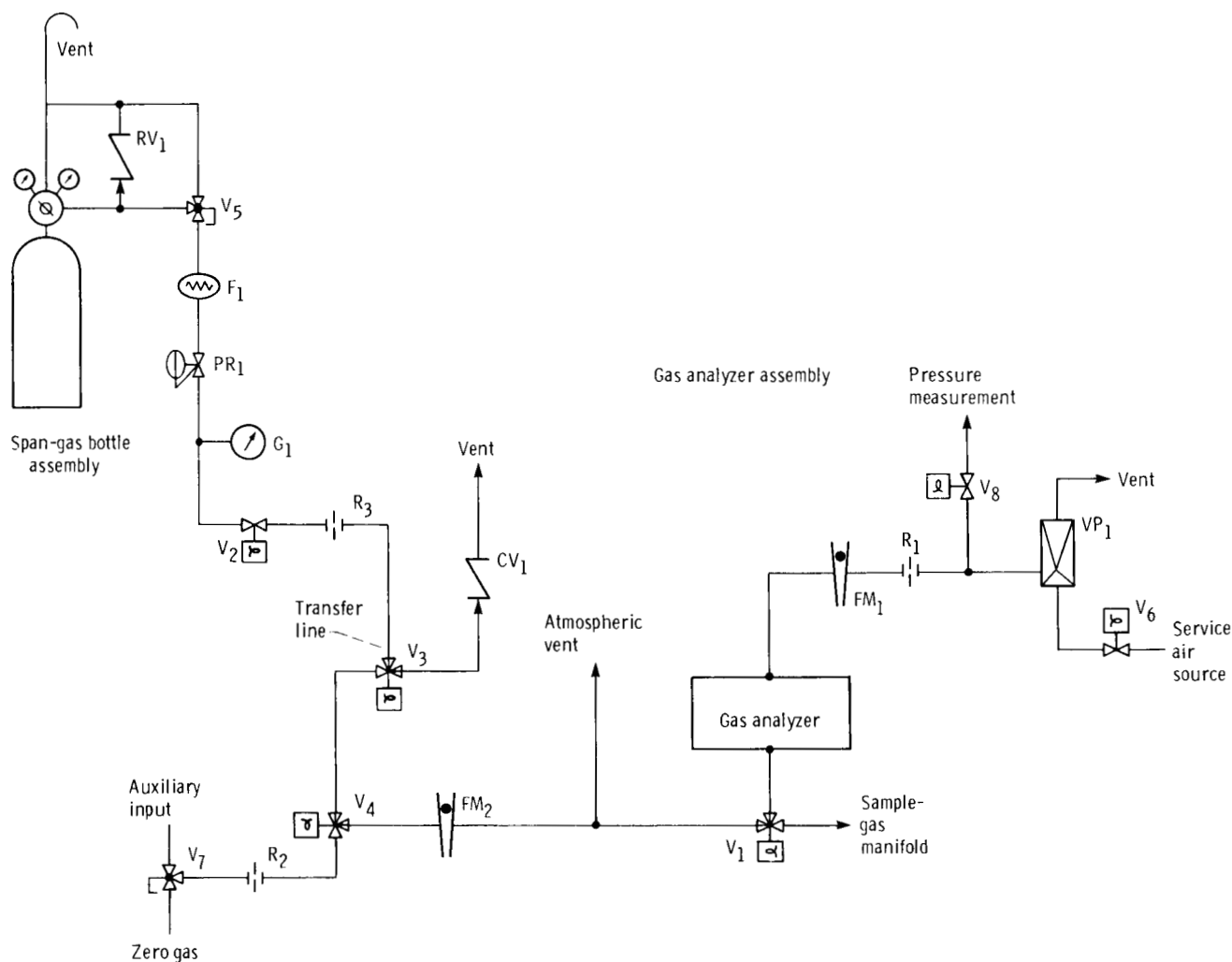
Figure 10.—Schematic of total flow system for CO_2 and low-CO analyzers. (Symbols are consistent with prior figures.)

Most of the components in figure 11 have been previously described. The exceptions are valves V_{9a} to V_{9d}, the filter, and the electronic flowmeter. For a THC flow measurement, valve V_{9a} is actuated so that ambient air is drawn in through the filter, the flowmeter, and valves V_{9a} and V_1 by the analyzer. Valves V_{9b}, V_{9c}, and V_{9d} are each associated with one of the three remaining analyzers requiring flow measurement. The placement and function of these valves in their respective analyzer pneumatics parallel that shown for valve V_{9a} in figure 11. These valves then allow the flowmeter to monitor the four analyzer flow rates, one at a time.

There are limitations to this approach to analyzer flow measurement. First, there can only be one analyzer flow-rate measurement at any given time. Furthermore during the measurement the analyzer is subjected to and is analyzing ambient air. Normal gas analysis functions are lost during flow measurement. Therefore suitable valve control and sequencing must be used so that analysis measurements are not inadvertently lost by enabling a flow measurement.

Obviously this approach does not give flow measurements during the process of acquiring analysis data. However, all of the analyzer flow measurements are used to evaluate analyzer and system performance. Flow data are not required as part of the gas analysis task. This scheme is sufficient to evaluate analyzer performance.

Total Hydrocarbon Analyzer

The THC analyzer for the HSF gas analysis system uses the proven technique of flame ionization detection. However, the detector requires a fuel gas (40 percent hydrogen in helium) for its operation. For safety a variation on the span-gas pneumatics of figure 9 was adopted for fuel-gas control. This pneumatic system is shown in figure 12. The THC analyzer is equipped with a flame sensor and a solenoid valve so that in case of detector flameout the fuel-gas flow is shut off. This function is internal to the analyzer and is shown schematically in figure 12. With just this flameout control the fuel-gas line remains pressurized with the
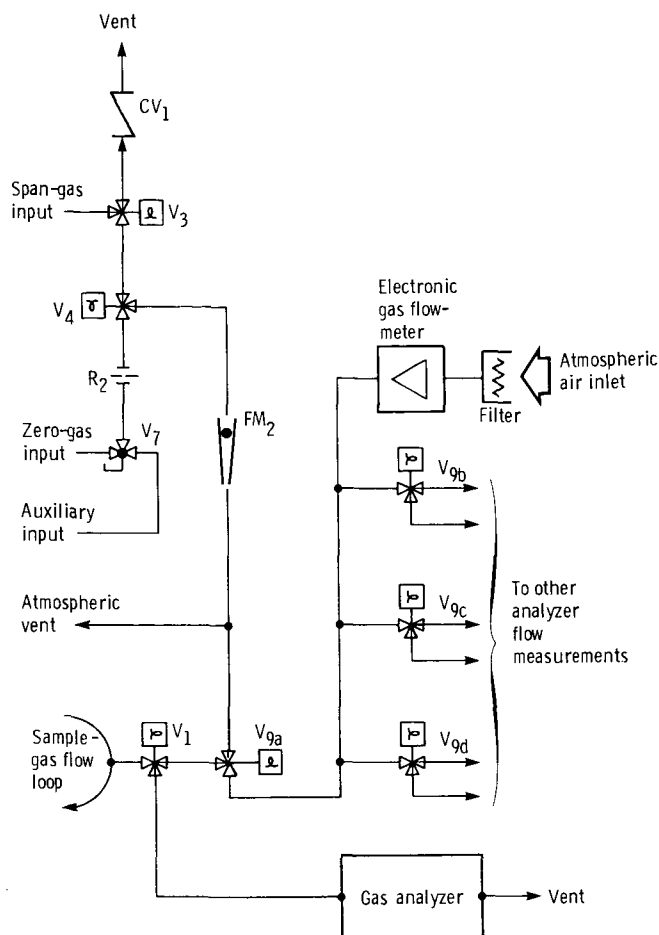
Figure 11.—Schematic of gas analyzer pneumatic system with electronic gas flowmeter—THC analyzer application.

combustible gas. For HSF, safety requires that the line be depressurized when not in use. Also, no fuel line purge is used. Purging adds little to system safety yet greatly complicates detector relighting procedures.

With a purge the purge gas must, in turn, be purged from the line before the burner can be relighted. For this application, valve V_B of figure 12 is electrically connected in parallel with the analyzer fuel shutoff valve (V_A). Note that the fuel gas from the line is vented at the gas bottle and not within the analyzer console. The purpose of restrictor R_B is to limit the maximum fuel flow rate in case of a system failure. The other components of figure 12 are analogous to those found in figure 9.

Water Analyzer

One of the more difficult problems associated with the HSF gas analysis system was the measurement of sample-gas water vapor content. Design guidelines indicated that sample-gas water content would approach 15 vol %. This is a dewpoint in excess of 50 °C at atmospheric pressure. The analyzer of choice, the NDIR, operates at this temperature so that condensation within the analyzer was probable.

The solution to this dilemma involved a divergence from the inverted flow configuration. The water analyzer system was designed to operate at a subatmospheric pressure. With the analysis cell of the analyzer operating at about 65 to 70 kPa absolute, the maximum water concentration yields a dewpoint well below the analyzer operating temperature.

Figure 13 shows the salient points of the water analyzer flow system. The analyzer input valve (V_1) is a five-way
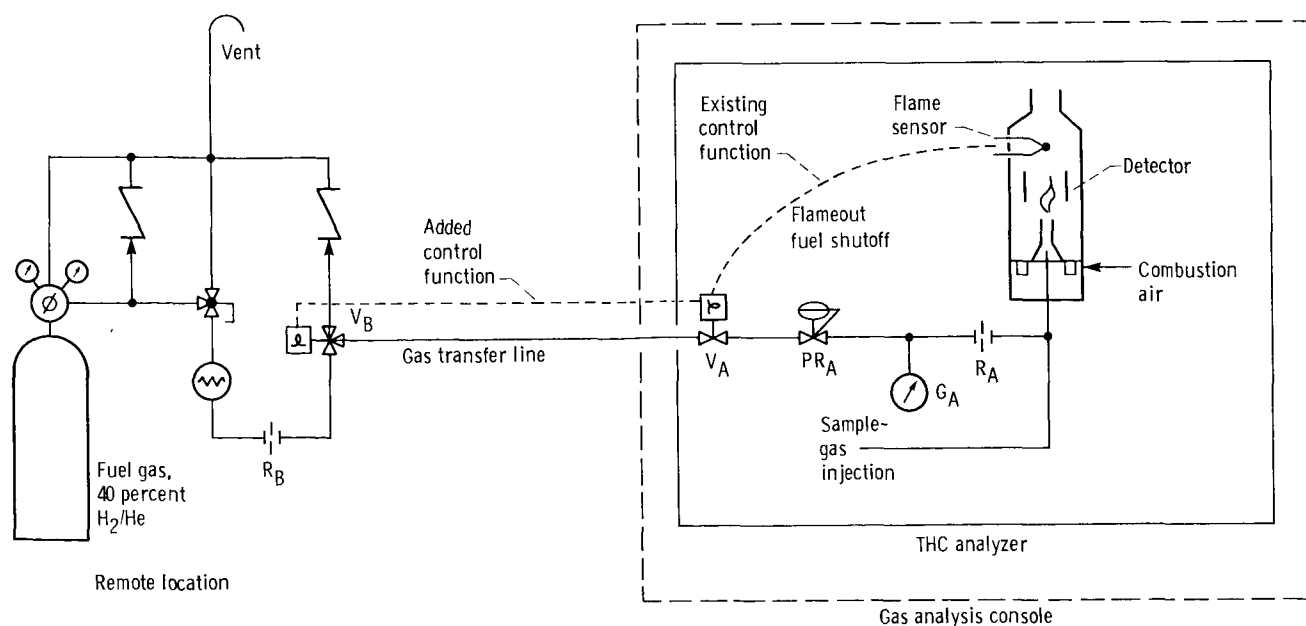

Figure 12.—Schematic of THC analyzer fuel subsystem. (Components with "A" subscript are preexisting analyzer components.)
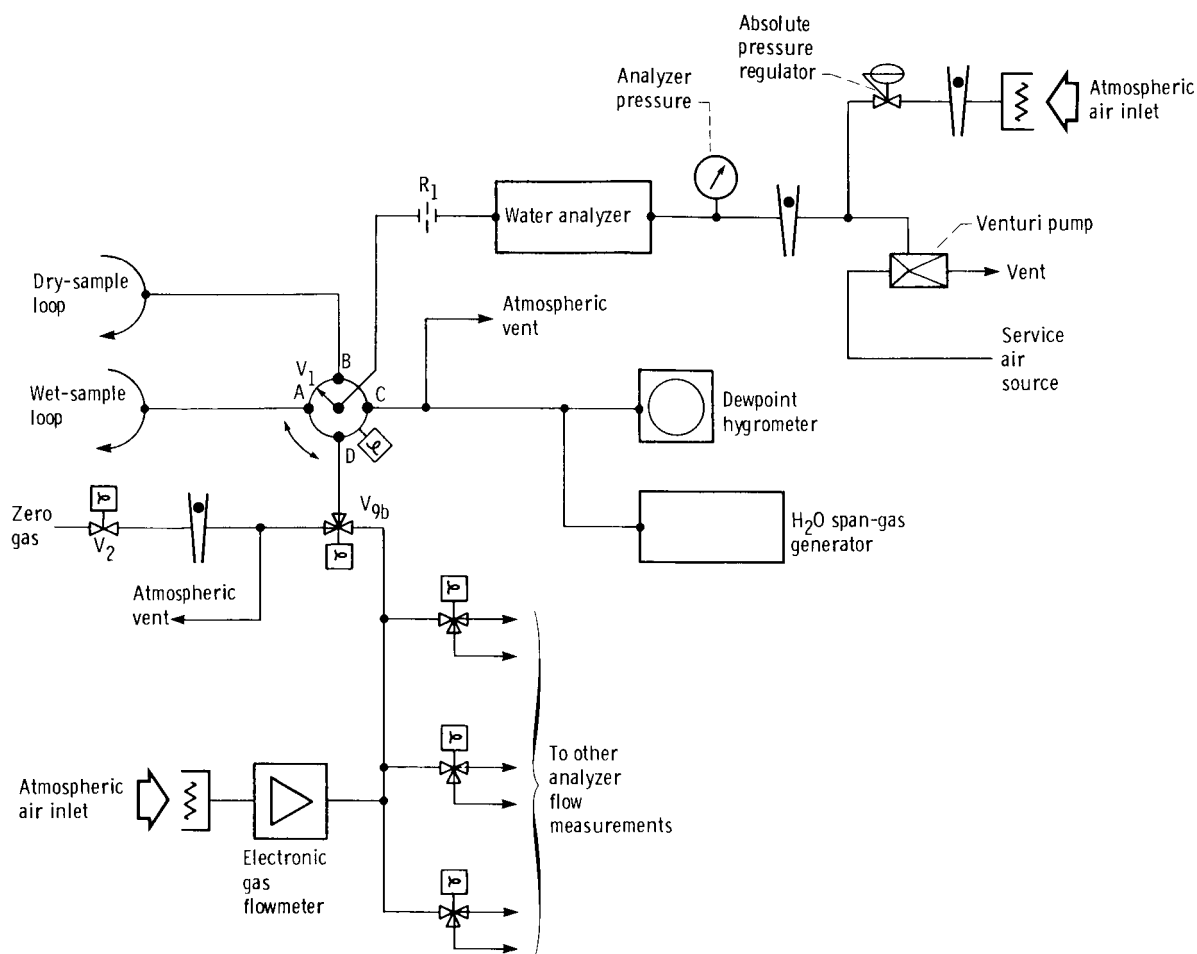
Figure 13.—Schematic of total flow system for H_2O analyzer. (Symbols are consistent with prior figures.)

rotary valve. Two of the four valve positions are used for the two sample gases, wet sample and dry sample. A third valve position is reserved for the necessary span-gas input. The final valve position is then used for zero-gas input and for flow measurement. This input arrangement differs slightly from that of figure 11 for the THC analyzer, in that both sample gases can be sampled (before and after drying). Also, the span gas has direct access to the inlet valve. Restrictor R_1 limits the gas flow rate from the atmospheric pressure gas inlet manifolds into the analyzer. The water analyzer operating pressure is established by the pressure regulator and venturi pump acting in concert. The stability of the water analyzer measurements is directly affected by the stability of this pressure.

The necessary periodic spanning operation for the water analyzer presents its own problems. The required span-gas concentration for this analyzer is 12 to 13 vol %. Such a mixture cannot be prepared, bottled, and stored. The span gas must be generated as it is required. For this application an air bubbler type of generator was used. However, this generator does not lend itself to either accuracy or stability. Separate means are necessary

to measure the true water content of the generated span gas. For this purpose a dewpoint hygrometer of the cooled-mirror type is used. Then from the observed dewpoint and the local atmospheric pressure the percentage of water content is calculated.

Using a hygrometer to calibrate the NDIR analyzer to measure the sample-gas water content seems at first redundant. This is not the case because the hygrometer, although having the necessary accuracy and stability, cannot tolerate the working environment of exhaust gas sampling. Deposition of hydrocarbons on the cooled-mirror surface soon renders the detector of the hygrometer inoperative. On the other hand the NDIR lacks stability but is adaptable to this type of environment.

NO-NO$_x$ Analyzers

These analyzers are totally compatible with the atmospheric-pressure-gas inlet manifolds. However, mechanical vacuum pumps are necessary to achieve the required vacuum pressures within the analyzers. These pumps must be considered with care since the mechanical

vibrations and exhaust pressure pulsations can couple into the other analyzers. For this reason the pumps are resiliently mounted and provided with separate, isolated vent lines.

Another area of concern is the known effect of high CO concentrations on the measurement of NO_x with the chemiluminescent analyzers. This effect has been observed and reported, along with efficacious solutions to the problem, in reference 4. Therefore no further discussion is included herein.

Oxygen Analyzer

The only comment of note for the oxygen analyzer is the use of atmospheric air as the span gas. Since air represents a stable mixture of 20.9 percent O_2 in N_2, it was adopted as a convenient source of span gas. Care must be taken to assure that the air is suitably dry. On humid days the amount of moisture in the air can introduce significant errors.

Analyzer Integration

With the various concepts and approaches described here for system pneumatics, most of the operations external to the analyzer, such as valving and flow control, can be automated. Other internal analyzer functions are usually performed manually. It is to the automation of these functions that this section is directed.

There is one generalization that can be applied to all of the analyzers used in the HSF system. As received, most of the operator manual controls interact with the analyzer electronics and not with the detector. On the whole, the problems of automating or remoting the controls is one of electronic modifications.

There are exceptions. The THC analyzer has manually adjustable fuel and combustion air controls. Some manual pressure controls are also associated with the $NO-NO_x$ analyzers and the water analyzer. But in each case the adjustments of these controls are infrequent and they remain quite stable. No attempt was made to automate these functions. For the HSF gas analysis system this one concession away from total automatic or remote operation simplified the overall design task. The initial system startup routine is performed manually at the system console. Some tasks, such as adjusting the THC analyzer fuel and combustion air pressures, are performed conventionally (manually). These parameters are quite stable once set and can be ignored for the duration of the system operational cycle.

Analyzer States

Earlier the concept of standardized interfaces was introduced. In pursuing this concept the idea of analyzer states evolved. Three specific states of analyzer operation

can be defined: run, zero, and span. To these can be added a fourth nonoperational state called standby. In run the analyzer is continuously analyzing the content of the sample gas for a particular species. In zero the analyzer is monitoring a suitable zero gas. Here by definition the input gas contains none of the sensitive gas species for that analyzer. When in this state the analyzer output is the zero offset of the analyzer. In conventional procedures the operator would at this point adjust the analyzer zero offset to achieve a zero analyzer output. In span the gas being applied to the analyzer contains a predetermined amount of that analyzer's sensitive gas species. For this particular gas the analyzer should show a fixed level of output voltage, depending on the specific analyzer calibration. Any deviation from this output level represents a drift in the analyzer span or sensitivity. Again, in conventional procedures the operator would adjust the analyzer gain to achieve the correct output level. Obviously the span adjustment would be preceded by the zero adjustment. The final state, standby, is any other analyzer configuration that is not one of the other states; this includes "analyzer off."

The sole purpose of the span state is the assurance of reading accuracy when the analyzer is placed into the run state. This is also the primary purpose of the zero state. However, within this gas analysis system there is one other use for the zero state. A variety of measurements on or about the system should not be made when the analyzers are generating gas analysis measurements (recall the "flow-rate measurements" of a previous section). For these the zero state is used as a permissive condition for enabling the measurements.

The four states defined here cover all of the normal operational modes of all of the gas analyzers used in the HSF system. Also, all of the operations involved in going from one state to another are limited to choices of valving or turning pumps on or off. These operations are easily automated. The task of automation is further simplified by the fact that for seven of the eight analyzers the operations for state change involve valves and items external to the analyzer. The exception is the THC analyzer.

As received from the vendor, the THC analyzer has internal manual valving, which provides the choice of state. Also, the hardware involved does not lend itself to easy automation. For the HSF application the internal valving of the analyzer is continuously left in the manual position for sampling. Then external valving is provided so that the THC state functions conform to those found with the other seven analyzers. This allows all eight analyzers to have uniform state functions and be controlled in an identical manner. For the THC analyzer the manual zero and span components have been left intact, although they are not used. This will allow the analyzer to be restored to its original form at a later date if so desired.

When the analyzer support pneumatics are examined in light of the concept of analyzer states, a logical matrix of analyzer functions and valve actuation can be constructed. Figure 14 shows examples of such matrices. These choices are then easily implemented by any of a variety of control logic methods.

Analyzer Ranges

Most gas analyzers are provided with manually controlled multiple ranges. Usually range changes are accomplished by electronic means such as amplifier gain change. An exception to this in the HSF system is the high-range carbon monoxide (high CO) analyzer. Here range changes also involve the choice of analysis cell within the analyzer. For this specific analyzer the choice of range is in part pneumatic and in part electronic. For the HSF system three distinct steps were involved in establishing a compatible range-changing system: (1) elimination of unnecessary range changes, (2) evolution of an electronic system that is applicable to and implementable with all analyzers, and (3) integration of

State	Active valves				
	V_1	V_2/V_3	V_4	V_6	$V_7{}^a$
Standby	--	--	--	--	--
Zero	--	--	X	X	--
Span	--	X	--	X	--
Run	X	--	--	X	--
Auxiliary input[b]	--	--	X	X	X

[a]V_7 is a manual valve.
[b]Auxiliary input is a manual function and operates as a subset of zero state.

(a)

State	Active valves		
	$V_1{}^a$	V_2	$V_9{}^b$
Standby	D	--	--
Zero	D	X	--
Analyzer flow rate[b]	D	--	X
Span	C	--	--
Run[c]:			
Wet sample	A	--	--
Dry sample	B	--	--

[a]Letters refer to the positions of V_1.
[b]Flow rate is a subset of zero state.
[c]In run state the analyzer is in either "wet sample" or "dry sample."

(b)

(a) Typical gas analyzers (fig. 8).
(b) Water analyzer (fig. 11).

Figure 14.--Valve logic for gas and water analyzers.

the necessary pneumatic controls (for the high-CO analyzer) into the electronic control system.

The range-changing task was simplified somewhat by the realization that with most digital data acquisition systems the resolution is at least an order of magnitude beyond the ultimate analyzer accuracy specifications. For most analyzers the number of ranges can be reduced by at least a factor of 2 and resolution within the accuracy specification will still be maintained.

The provision of range control external to the analyzer is not a difficult task. As a rule, all of the necessary functions are available at the analyzer's manual range control switch. The conversion process is primarily one of providing the appropriate switch closures for each range. Most gas analyzers can be purchased with external means of range control. However, there exists no common format or protocol for this control feature. For the HSF analyzer set the required inputs to drive the vendor-supplied external range controls were extremely diverse. Various voltage levels, of different polarities, as well as switch closures would have been required to implement range changes for the total analyzer set. The use of vendor-supplied external range controls would have complicated an otherwise straightforward task.

Therefore the external range control was implemented by starting with manually controlled analyzers. The analyzers were then modified to fit the particular needs of this system. The modifications were designed such that all analyzer control inputs were +5 V dc (to be compatible with standard logic elements). This allowed the use of standard logic devices and techniques. Also, among the various analyzers the resulting interfaces were uniform in format and compatible with the digital processor. The internal analyzer modifications were designed such that the analyzers could be easily restored to their original form. In a system such as this, substitution of analyzers in toto is sometimes necessary; irreversible modifications should, if possible, be avoided.

For the high-CO analyzer the process of implementing a pneumatic range change closely follows the concepts and techniques evolved for state control. In a dual-cell NDIR analyzer the inactive cell is purged with zero gas while the gas to be analyzed passes through the other cell. To effect a pneumatic range change, the roles of the two cells are reversed. For range 1, cell 1 is in run state while cell 2 is in zero state. Then for range 2 the cell states are reversed. For this analyzer, range change involved the use of two run states, one for each analysis cell.

Analyzer Functions

With methods and techniques in place for handling the state and range control, and with a variety of operations classed as manual startup or shutdown procedures, there

remained a few functions still to be controlled. These were classed under the heading of analyzer special functions. Figure 14(b) shows the case of the water analyzer where the flow measurement and the choice of wet or dry sample are treated as special functions.

The two sample-gas manifolds, wet and dry, that are monitored by the water analyzer present a special case of the run state. For this analyzer the wet and dry samples were treated as special functions so that there would be only one run state. These functions have no validity unless the analyzer is in run state; "run" can then be used as a logical enable for the wet-sample and dry-sample functions.

The analyzer flow measurement for the water, THC, and $NO-NO_x$ analyzers is also considered as a special function. It was previously noted that data can be lost if a flow measurement is attempted during run state. For this reason it was determined that zero state would be a logical prerequisite for a flow measurement. Also, since there was but one flow sensor, the four flow measurements were made to be logically mutually exclusive.

The $NO-NO_x$ measurement selection for the two $NO-NO_x$ analyzers is considered to be a special function, along with ozone generation. In the HSF system the operator is given control over the ozone generators within the $NO-NO_x$ analyzers. Past experience has shown that this option is useful in evaluating the analyzer's performance.

Zero and Span Correction

In the preceding sections the discussion was limited to the control of discrete choices of analyzer state, range, and function external to the analyzers. There remains for discussion the compensation for analyzer zero offset and sensitivity drift. Numerous approaches to automating these manual functions were examined. The technique of choice was a mathematical correction of the analyzer output by using the microprocessor within the analysis system.

All analyzers have manual controls that allow for continuous adjustment (as opposed to discrete, switched adjustments) of analyzer zero offset and sensitivity. In conventional practice the operator would introduce known reference gases (zero gas and span gas) into the analyzer and then manually adjust the appropriate control to achieve a specific analyzer output. In conventional practice zero gas and "zeroing" are used to adjust analyzer zero offset, and span gas and "spanning" are used to adjust analyzer sensitivity.

The recommended practice (ref. 2) calls for the use of a zero gas to establish a zero level and then a span gas of known concentration to establish an upscale analyzer output. The recommended practice also requires this to be done on each of the analyzer ranges. The automation of this manual task appears, at first, to be complex. However, the identification and utilization of two factors reduces this task to a manageable level.

The first factor involves the nature of analyzer sensitivity drift. All gas analyzers exhibit some degree of sensitivity drift. However, experience has shown that from range to range the short-term (the order of days) drift is independent of range. Over an extended time the range-to-range sensitivity ratios do change and must be considered. But for normal day-to-day operations a single span adjustment on any given range can be applied to all ranges with no discernible loss of accuracy. For the HSF system the multirange analyzers were provided with a single span gas per analyzer. Then the same span correction factor was applied to all ranges on a given analyzer.

Each analyzer does have range-to-range systematic errors. Therefore an additional set of correction factors is required to compensate for these errors. These range-to-range correction factors are relatively fixed and need to be updated at infrequent intervals, of the order of months.

The second factor in the automation of the span/zero correction task arises from the nature of the adjustments. The actual source of analyzer drift can be anywhere in the analyzer from the detector, through the signal processing, to the analyzer output. However, without exception, all analyzers compensate for drift by varying the gain or zero offset of an amplifier. It then follows that analyzer sensitivity compensation can be interpreted as a multiplication function, whereas zero compensation can be considered as an addition function.

For the HSF system it was decided that the span/zero compensation would be implemented mathematically to achieve the same final result as that with manual controls. With the capabilities of the system's microprocessors the mathematical treatment of zero and span correction is straightforward and easily implemented as a software task. Details about the generation of zero and span corrections are covered in the section Calibration Cycle.

Note that as a part of the system startup procedure the zero and span of each analyzer are manually adjusted in the conventional manner. This is then followed by an automated calibration cycle. Here zero and span correction factors are determined for all analyzers and recorded automatically. This table of correction factors is used on each datum received from each analyzer. Then periodically through the operating cycle of the system the correction factors are redetermined and the table of values updated.

General System Considerations

With the analyzers and gas flow paths defined, it is necessary to consider the overall gas analysis system. Recall that the HSF gas analysis system has three distinct control and readout points. First, there is the main system console, where the operator can interact with the system. Second, the microprocessor integrated into the system has the capability of total system monitoring and control. Third, the remote control/readout console allows the operator to monitor and control the system from a remote location.

For such a system a network of control signals is required so that control can be exercised or handed off from any of the control points and stable system control yet be maintained. For such a system a variety of measurements must be formatted so that any control point can access a given parameter. The processes of control, monitoring, and readout must be considered for each control point. This section addresses these considerations.

Ancillary System Measurements

In earlier discussion, passing reference was frequently made to various measurements that were ancillary to the primary measurement of gas species concentration. Eight analyzers, with eight analog outputs, provided the gas concentration measurements. However, various pressures, temperatures, and gas flows within the system are of critical importance because of their effect on the primary gas measurements. In a conventional, manually operated system, these secondary measurements would be monitored by the operator. Here, remote or automatic operation is required. These secondary measurements of pressure, temperature, and flow must be transduced and integrated, along with the analyzer outputs, into the fabric of system measurements.

Flow measurement.—To the extent possible, direct flow measurements in the HSF system were avoided. As a group, direct flow measurement devices tend to be expensive and bulky, to introduce excessive pressure drop, or to be environmentally sensitive—or have combinations of these characteristics. Whenever possible, flows were inferred by measuring the pressure drop across existing fixed-flow restrictive elements. This ability to infer analyzer flow rate by measuring a pressure drop is one of the attractive features of the inverted flow scheme.

This same pressure drop technique was also applied to the flow of gases within the sample-gas manifolds. Pressure measurements in and around the flow-limiting elements sufficed to infer flow rate. For the most part, these flow rates are not critical parameters. By design,

these gas manifolds are not flow sensitive for a wide latitude of flow rates. Pressure is the critical parameter.

This discussion of flow inference also applies to the system ventilation manifold. Here, as previously described, the vent flow rate is monitored by pressure switches that yield a simple "go/no go" decision and indication. It was also previously noted that four analyzer flow rates required the use of a flow transducer since the concept of a "flow-rate pressure" could not be applied.

Temperature measurement.—Throughout the HSF gas analysis system, there are a variety of temperatures of interest. The gas manifolds that carry the sample gases are heated; these manifold temperatures are monitored. In many of the analyzers temperature, by its influence on gas density, directly affects the measurement accuracy and is also measured. For the HSF system the digital processor was provided with a 20-channel thermocouple scanner with analog output to monitor these and other temperatures of interest. Although the thermocouple scanner is under microprocessor control, the operator can monitor the scanned temperatures via microprocessor commands.

By design choice the microprocessor does not continuously scan the system temperatures during normal operation. The scanner is locked onto the measurement of THC analyzer temperature unless the microprocessor is instructed, by the operator, to read one of the other temperatures. The other system temperatures are considered to be of much lower priority and are typically used only for system diagnostics. These temperatures are periodically scanned. A later discussion of the calibration cycle touches on this scan.

Another independent temperature measurement is an integral part of the water analyzer calibration subsystem. The calibration scheme, previously described, uses a hygrometer. The output of this device is the dewpoint temperature of the generated calibration gas. This is a critical measurement. In combination with the atmospheric pressure this temperature is used to calculate the water span-gas concentration.

Pressure measurement.—In all, five separate pressure transducers are incorporated into the HSF gas analysis system. Three measure discrete pressures; the remaining two transducers, through valve multiplexers, monitor a variety of pressures.

The primary pressure measurement within the system is that of atmospheric pressure. However, the pressure of interest is not the true ambient atmospheric pressure. What is of interest is the ambient pressure within the system enclosure. The gas analysis system, as previously described, is a physically tight enclosure that is maintained at a pressure slightly lower than local ambient by forced ventilation. Furthermore the system is located

in a control room environment that is maintained at a pressure slightly above atmospheric pressure. The system's internal pressure is then removed at least two steps from the true ambient atmospheric pressure. However, for convenience, within this text, the system internal ambient pressure is referred to as atmospheric. Since this is a critical pressure, a dedicated transducer monitors this pressure at all times.

A second transducer is dedicated to the measurement of the pressure within the water analyzer analysis cell. Recall that this analyzer operates with an analyzer pressure of 65 to 70 kPa absolute. With this analyzer the concentration measurement is directly affected by the analysis cell pressure.

The third transducer is assigned to measure THC analyzer sample pressure. This analyzer uses an internal pump to raise the pressure of the inlet gases to about 40 to 50 kPa gauge. A portion of the gas then flows through a capillary tube and into the analyzer's flame ionization detector. Analyzer sensitivity is directly affected by this pressure.

The fourth transducer is used to monitor pressures in and around the sample-line filters and flow-limiting orifice. These pressures are identified in figure 6, where P_1 is the pressure in the sample transport line, P_2 is the pressure after filtration and before the orifice, and P_3 is the analysis system inlet pressure. A single transducer and a valve multiplexer are used to scan these pressures. Multiplexing is under the control of the microprocessor. From these pressures orifice flow rate and filter condition can be inferred.

The final pressure transducer is assigned the task of monitoring the "flow-rate pressures" previously described plus some assorted noncritical analyzer pressures. This transducer uses a valve multiplexer much like that of the fourth transducer; it is also under microprocessor control.

Analog Signals

Within the HSF gas analysis system there are 16 analog voltages of interest. These voltages are the outputs of one thermocouple scanner, one hygrometer, one flowmeter, five pressure transducers, and eight gas analyzers. All of these voltages are conditioned and digitized by the microprocessor-controlled data acquisition module. Within the HSF gas analysis system the primary data path is through the digital processor.

Although there are 16 discrete analog voltages, many of these take on a variety of meanings depending on the configuration of the voltage source. For the gas analyzers the individual instruments could be in any of the four previously defined analyzer states. Also, four of the system transducers (two pressure transducers, one flow

transducer, and the temperature scanner) are multiplexed over a variety of measurements. From these four transducers, 28 flow, pressure, or temperature measurements are obtained. Furthermore many of these must be related to the four states of the eight analyzers. Obviously the processor requires additional information by which the analog voltages may be assigned the proper meaning.

Control Signals

To assign the proper meaning to the 16 analog voltages, a series of digital signals were defined to carry the necessary information throughout the system. These control signals are in the form of parallel, TTL-compatible, binary logic levels. The signals are bused throughout the system and serve multiple purposes. Depending on the usage the control signals may be a control input, a control output, or purely informational. They may be driven or sensed at any of the control points (the console, the remote station, or the digital processor). Furthermore they serve to drive indicators, gas analyzers, valving, and switching elements.

Within the HSF gas analysis system the control signals were distributed in a parallel format, with each signal being generated or detected by discrete logic elements. However, since any number of methods or formats would be equally valid, further detail of the implementation of the control signals is omitted.

The configurations of all of the system elements are controlled and indicated by the control signals. In addition, there are a number of informational or warning signals. These are of three types and are denoted as "alarms," "inhibits," or "flags." Each is described here.

Alarms.—Each of the eight analyzers can generate an alarm signal. This alarm is based on the analyzer meeting any one of a group of conditions that are indicative of analyzer failure, malfunction, or improper configuration. Typical conditions for an alarm might be loss of electrical power, low oven temperature, or an improper switch position.

In addition to these analyzer-related signals, another group of alarms were included that indicate the loss of various services which are necessary to system operation. Separate alarms indicate the loss of the facility services of water, pressurized air, or gaseous nitrogen. In addition, insufficient sample-gas pressure is indicated by its own alarm. The alarm for the analysis system ventilation was previously described; it serves a dual purpose, as an indicator of adequate ventilation and also as a permissive for the introduction of gases into the system.

Inhibits.—In the process of implementing the digital control of the various gas analyzer elements, a method of

recognizing instrument settling time became necessary. This task was fulfilled by the inhibit timers.

Whenever any of the gas analyzers are pneumatically switched from one flow stream to another, there is an interval, of the order of tens of seconds, before steady-state conditions are achieved. For electronic range changes the analyzers also exhibit a similar, but shorter, settling time. With either event the data system must be aware of the unstable condition.

Any change in the analyzer pneumatics or electronics is accompanied by changes in the control signals previously described. The digital processor continuously monitors these signals, looking for a change. When a change occurs, the processor triggers the appropriate one of a group of interval timers, which in turn sets an inhibit signal for a preset time interval. Each analyzer has an associated inhibit. However, some analyzers have both pneumatic and electronic time constants of interest. For these analyzers the outputs of two timers are combined into a single inhibit signal.

The inhibits are displayed at both the analyzer console and at the remote control point. Here they serve as a visual signal to the operator of analyzer settling time. The inhibits are also presented to the system's computers, where they serve the same purpose. Many of the computer functions are timed by these signals. The inhibits are primarily an informational signal. Typically the inhibit is used as an indicator and not a controller.

Flags.—The third signal of interest here is the flag. Each analyzer has a flag signal that is asserted when any one of three conditions is satisfied: (1) an analyzer is not in the run state, (2) an inhibit is asserted, or (3) the individual analyzer zero or span correction is out of preset limits. The primary purpose of the flag is a warning that the data being generated are suspect. The flag signals cover a variety of situations that may require operator intervention.

Through these three indicators, the operator is given a variety of information. The alarm, generated by the system or the analyzers, warns of malfunction or incorrect procedure. The inhibit, triggered by the data system, indicates a need to pause while an analyzer settles after a change in range or state. Finally the flag, generated in the data-processing stage, indicates something has happened that can affect the quality of the reduced data.

Fiducial Calibration

Before discussing the automatic calibration functions of the HSF gas analysis system, it is necessary to turn aside and discuss the nomenclature used with instrument calibrations. Within the arena of gas analysis and gas analysis instruments, two very distinct types of calibrations are performed: the frequent correction of analyzer span and zero, and the less frequent fiducial calibration.

Periodically it is necessary to quantify all of the parameters associated with a given analyzer. Range-to-range systematic errors must be defined. The analyzer must be tested for its sensitivity to interfering gas species. The calibration curve for nonlinear analyzers must be defined. This periodic fiducial calibration function is performed outside the normal day-to-day use cycle of the analyzer and falls outside the routine use of the analyzers and the associated system. It is still a necessary function since it is here that the various constants used to process the analyzer output voltage are generated.

However, gas analyzers do drift. The individual analyzers all show various amounts of zero offset and span drift. Normal usage then requires that at frequent intervals during operation, span and zero gases be passed through the analyzers so that the drift in span or zero can be corrected.

Within the HSF system the span and zero corrections are performed automatically within a system cycle called the calibration cycle. The fiducial calibration is a special procedure that falls outside the context of this report. The two are separate and must not be confused.

Calibration Cycle

Previously the concept of mathematical compensation for analyzer drift as an alternative to manual span and zero adjustment was introduced. This operation has two parts: first, a calibration cycle in which a table of mathematical operators are derived, and second, the application of these operators to each datum.

Within the HSF system an automated zero and span measurement cycle has been adopted wherein all functions are performed and all data collected and processed in a sequence programmed into the digital processing and computing elements of the system. This automated cycle is called the calibration cycle.

In the calibration cycle the system microprocessor is in control of the total system. The analyzers are all placed into zero state and the zero offset is measured on each analyzer range. All analyzers are then placed into span state, on an appropriate range, and the analyzer outputs are measured for a known input. Using these data, the system computer performs a set of mathematical manipulations and generates a set of correction factors that are stored and then applied to the subsequent data. With each calibration cycle the computer updates the stored array of correction factors that cover all of the analyzer-range combinations.

The system computer must know the correct concentration value for the span gases used in the calibrator cycle. An array of thumb-wheel switches are integral to the HSF system for the manual entry of the

span-gas concentrations. These values are relatively constant; however, they do require updating whenever span gases are replaced.

System data.—Along with the zero and span measurements, described previously, the various system pressures, temperatures, and flows are also of interest during the calibration cycle. Any variations in these parameters during the calibration could affect the accuracy of the calibrations. For this reason a block of system measurements that define conditions during the calibration cycle is stored along with the zero and span parameters.

Flow measurement.—At this point the flowmeter data must be considered. The problem of response time for the various gas analysis system components has been raised and discussed. However, of all the instruments, the flowmeter is the slowest.

Automatic scanning of the four flow measurements occurs only during the calibration cycle. Additionally, since the flow measurement sequence lengthens the total calibration cycle by several minutes, the operator can inhibit the flow measurement entirely. The operator has the choice of two calibration cycles: a short cycle, without flow measurement, and a long cycle, with flow measurement. Typically the operator enables the long cycle, with flow measurement, during the initial calibration cycle. Thereafter the short cycle is used. The long calibration cycle is repeated only as the operator deems necessary or prudent. Of course, at any time the operator can manually request a flow measurement on any or all of the four analyzers.

Calibration clock.—With the calibration cycle defined, there remains the question of timing the start of the cycle. For the HSF gas analysis system a "calibration clock" was incorporated into the system. As implemented, the calibration clock is reset and begins running at the end of a calibration cycle. The clock can be manually adjusted by the operator to run for any given time interval. When the clock runs down, a switch closure can begin another calibration cycle. The manner in which this clock can begin a calibration cycle is discussed in the following section.

System Mode Control

To accommodate the several types of operator-system interaction, the concept of system "mode" was developed. There are times when the operator interacts with the system directly. At other times the operator will attend to the system from a remote control point. Finally a degree of automation wherein system operation is controlled by the digital processor is desirable. For each of the various options a system "mode" is defined.

Four modes are defined: local/remote, manual, auto range, and total auto. These along with another function,

"calibrate," are grouped together and are described here. The choices involve the degree of sharing system control and monitoring tasks between the operator and the system computers. Another mode choice is that of the operator's location at the system console or at the remote control panel. The system mode is chosen manually by the operator.

Local/remote.—The local/remote mode provides the choice of operator location. This choice can only be made at the main console. In local, control is limited to the system console although all remote displays remain active. In remote, control of all functions (except local/remote) is handed off to the remote control point. In remote, all local displays remain active.

From this point forward, the discussion of mode control can proceed without reference to the local/remote choice. The next three modes define the division of labor between the operator and the digital processor.

Manual mode.—With the choice of manual mode the operator has complete control over all analyzer functions; the processor's role is primarily one of data collection.

Auto range.—In entering auto range the operator relinquishes control over analyzer range change. State and function decisions still reside with the operator. Now, in addition to the functions performed in the manual mode the processor assumes the task of range control. The processor tests the output of each analyzer and then, as required, sends range change commands to the various analyzers.

Total auto.—For this mode the processor assumes both state and range control over the analyzers. However, the significant addition here is the calibration cycle. In this mode the processor will act according to the condition of the calibration clock. As long as the clock is running, the processor places the system into the condition for analysis of gas samples. When the clock runs down, the processor will proceed with a calibration cycle.

Calibration cycle.—The calibration cycle presents a unique situation that must be considered. During this cycle the digital processor has total control over the analysis system. During this cycle the entire system is totally preoccupied with the calibration process and will ignore any commands or requests until the cycle is complete. It is, at the minimum, sometimes inconvenient to have the gas analysis system become incommunicado for several minutes while a calibration cycle is performed. To avoid this situation, an external control input is provided whereby the facility computer can inhibit the beginning of the calibration process during those times when gas analysis data are being generated. However, once begun, the calibration cycle will continue to completion.

Calibrate.—This final control function, although grouped with the mode controls, is not really a mode function but an operator's request for the processor to perform an immediate calibration cycle. Upon receipt of this command, the processor seizes control of the system mode and proceeds directly into total auto and the calibration cycle. This command is inactive only when the facility inhibit input (described previously) is present. At the end of the cycle the processor releases the system mode and the system returns to its configuration prior to the calibrate request. In the manual or auto range modes the calibrate request is the only method of performing a calibration cycle. This feature also allows the operator to anticipate the beginning of a data run and request a prerun calibration.

Although the choice of mode is an operator choice, safety considerations can override this choice. In the case of a failure in the ventilation of the analysis system the system is forced into the local-manual mode with all analyzers in the standby state.

System Computers

To this point in the text the discussion has centered on the hardware and procedures of gas analysis. Reference to the system computers was limited to brief references to function. Within this section of the report, details of the computers, proper, are developed. By intent, this report section provides only a brief description of the system computers. A more detailed discussion of these computers can be found in reference 5. There are two specific reasons for abbreviating this discussion. First, there are a variety of equally workable methods of implementing these data-handling and control tasks. Second, over the period of time involved in designing and constructing this system the state of the art of digital design has advanced rapidly.

There are two computers in the HSF gas analysis system. One computer, called the data/control computer (previously referred to as the processor) is programmed for data acquisition and control. The job of the data/control computer is to acquire and store system data and to control the system within the definitions of the system mode. The second computer, called the data-processing computer, is programmed to process the data into units of concentration. The task of the data-processing computer is to acquire data from the data/control computer and to generate tables of gas concentration or system parameters. The two computers operate independently except when the data/control computer is transferring data to the data-processing computer. Both computers have segments of their programs devoted to interacting with the operator.

Data/Control Computer

The data/control computer conveys system information to the operator through various indicators and readouts on the system console or remote control panels. The operator has very limited control over the function of this computer. Its actions are based on the input received through the system control signals.

The operator can interact with the data/control computer via the engineering data readout panels, located at both the main system console and the remote control panel. It has been stated previously that the operator can request displays of a variety of analog signal voltages that are present within the gas analysis system. This display function is served by these panels. These panels are discussed in more detail in a later section of this report.

Hardware and software.—The data/control computer is the data flow manager for the gas analysis system. All data output from the gas analysis system flow through this computer. All data received by the data-processing computer pass through the data/control computer. All of the automated functions of the gas analysis system are under the control of the data/control computer.

Signal processing.—As previously noted, there are 16 analog signals within the gas analysis system—eight analyzer outputs and eight system sensor outputs. These 16 signals are all presented to the data/control computer. A modular data acquisition system in the computer digitizes these signals with 12-bit resolution. Each data word stored by the computer is the sum of eight digitized readings taken over 16 ms in order to average the signal and to reduce 60-Hz noise.

The data/control computer maintains a data base of all of the data words, along with sufficient information to determine the data source and other information such as analyzer state/range or system mode. This data base is then continuously updated.

Communications and controls.—In normal operation, communication between the data/control computer and the operator is limited to various pushbutton switches and indicators located on the system control panels and the engineering data readout panel.

Data-Processing Computer

The data-processing computer is the primary interface between the gas analysis system and the HSF facility. It is through this computer that data are transferred to the facility data system. The operator can interact with this computer via a typewriter-terminal to request and receive printouts of various system data, both raw and processed.

Hardware and software.—The hardware for the data-processing computer is based on a commercial single-board microcomputer. The system components include

the computer chassis, a dual floppy disk drive, and a terminal. Of the two floppy disks, one is used for program storage and the other is used for a history file. This history file contains "snapshots" of all of the raw and processed data known to the data-processing computer. Once every 40 s, the main program stores a record, including time and date, on the history file. On a single disk there is room for 450 record sets, or about 5 hr of system running time.

Data-processing computer output.—The primary task of the data-processing computer is to convert the raw data from the gas analysis system into engineering units of gas concentration. The primary output from this computer is a table of gas concentrations in engineering units, along with various ancillary information about the system and measurements. This table of information is updated three times per second. The information is then presented to the facility data system on request.

Normally the research data output values are positive. The data-processing computer uses the zero value and the negative sign to denote the alarm and flag conditions, respectively. These conditions, alarm and flag, have been described previously.

The data-processing computer zeros analyzer data in the output list when an analyzer alarm is asserted. This alarm is sensed by this computer through the data sent from the data/control computer. The data-processing computer negates analyzer data in the output list to indicate a flag condition. This flag may originate with the data received from the data/control computer. However, the data-processing computer can also assert a flag if anomalies in the calibration data are detected.

There is a second form of output available from the data-processing computer. The operator has at his/her disposal a set of single-stroke terminal commands by which he/she may request terminal output of desired data. These outputs fall into two groups: a single line of data from a single analyzer, or an output of a large block of data, either raw or processed.

History file.—In conventional gas analysis systems the task of maintenance and repair is complicated by the lack of a detailed record of events. In the HSF system the history file maintains a comprehensive sampling of data over the prior 5 hr of operation. Since the sampling process covers all data, the source of most problems can be found in a retrospective analysis of the history file. This can be done at the integral system terminal, or the disk may be transferred to another computer for unlimited data massage and manipulation.

Remote Console

The remote console for the HPF exhaust gas analysis system, frequently alluded to, is shown in figure 15. This
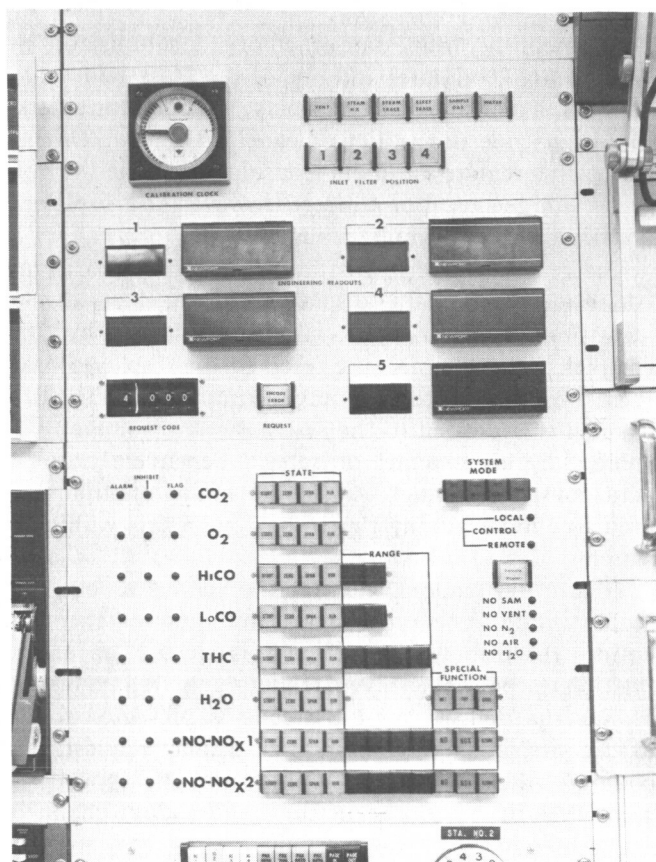

Figure 15.—Remote console.

console consists of three parts, or panels. The top panel contains controls and indicators for the total analysis system. Here are controls and indicators for the calibration clock, the sample-gas inlet and filtering, the ventilation system, service air, service nitrogen, and cooling water. This panel exactly duplicates controls and indicators found on the main system console.

The bottom panel contains the analyzer and system mode controls and indicators. All of these controls and indicators are also found on the main console. However, here the controls and indicators are closely grouped. At the main console the analyzer controls are logically placed with the appropriate analyzer.

On the remote console all switch functions are active only when the system is in remote mode. Conversely the equivalent functions at the main console are active only when the system is in local mode. In addition, as previously described, the analyzer state or range functions at both consoles may be inactive if the system is in the automatic or auto range mode. However, all indicators at both consoles are active at all times.

The central panel shown in figure 15 is the engineering data readout panel. It also exactly duplicates a readout panel found on the main system console. By using these panels, the operator can access and display

simultaneously four data memory locations of the data/control computer and one of the 16 system analog voltages. To enable a given display, the operator enters a four-digit code (lower left of panel). The code entry at either the remote or main console is enabled by the system mode—local or remote. However, the displays at both consoles are simultaneous.

The readout panels provide five channels of display. Alongside each data display, a three-digit display identifies the particular parameter shown by that channel. Four channels are reserved for display of data from the data/control computer memory array. The fifth channel is dedicated to the system analog voltages. The analog display channel operates independently of the data/control computer. A separate analog multiplexer is used to choose among the 16 analog signals within the system.

To use the readout, the operator enters a four-digit request code. The most significant digit of the code defines the display channel. If this is "5," an analog multiplexer presents a given analog signal to data display 5. For the digits 1 to 4 the code is presented to the data/control computer as a data display request. The computer then presents the contents of the appropriate memory location to one of the four readout channels. The remaining three digits of the request code are also displayed alongside the referenced readout so that the displayed data are identified.

By using this readout, the operator has access to 129 system parameters stored within the data/control computer. Some of the data, such as those from the flowmeter or the temperature scanner, are not frequently updated. Special request codes are available to ask the computer to immediately update the data and to display the new readings. Some of these data requests, such as the water analyzer flow rate, might affect the process of system datataking. For such a case, the computer will examine the system control signals to ensure that specific requirements are met before satisfying the request. For an unallowed request code the operator will receive an error indication.

When the 16 analog signals are added to the 129 parameters discussed previously, we find that in total, the readout panels can display 145 discrete system parameters.

Results

A report on a development effort, such as this, does not lend itself to a simple tabular summary of results. Nonetheless, a statement of the result of this effort is necessary. The HSF gas analysis system is in place, in operation, and generating the required gas analysis data. In addition, as a part of the initial installation, performance was rigorously assessed. From the on-line

data and the initial assessment the success of this effort can be gauged.

A variety of flow and pressure parameters were observed during the initial performance evaluation. To generate these data, the sample line inlet pressure, under the control of the facility operators, was varied over the design range of 70 to 270 kPa gauge. Over the entire inlet pressure range the sample-gas manifolds feeding the gas analyzers showed no measurable variation in operating pressure. Furthermore gas species measurements performed at the same time showed no discernible errors that could be attributed to the system pneumatics. The normal random output variations of the analyzers (of the order of $\pm 1/4$ percent of reading) more than masked any effects associated with the flow configuration.

Of all the components within the HSF gas analysis system, the water analyzer and the associated calibration are the least satisfactory. As much time is required to maintain and operate this item as is involved with the rest of the system. Because of these problems the accuracy of measurement with the water analyzer is somewhat degraded. The inaccuracy here appears to be of the order of 7 percent of reading. However, this level of accuracy is still acceptable since the water measurement data are primarily used as a correction factor for those measurements made on the dried sample gas. For example, if the sample gas contained 10 percent water, the corrected data would be in error by about 0.7 percent because of the error in water measurement.

In repeated measurements the overall system can generate data with a random error band approaching $\pm 1/4$ percent of reading, and this error is primarily attributable to the gas analyzers. Individual analyzer calibrations (with the exception of the water analyzer) are all performed with National Bureau of Standards traceable gases. The overall calibration of the analyzers (excepting water) appears to be of the order of ± 3 percent of reading. Of this, 2 percent is attributed to the standard gases.

The final proving of the system occurs when the results of gas analysis are compared with other measurements. Combustion parameters derived from gas analysis can be compared with data from other sources. To date, the gas analysis data have been used to generate combustion efficiency, fuel-air ratio, and combustion temperature. In comparing combustion parameters derived by various techniques, those due to the gas analysis data appear to always be in error by a factor of about + 10 percent. A careful examination of this error leads to error sources outside the analysis system. The bulk of this error is thought to be due to the specific design of the sample collection probes. Although it is not a part of this design effort, the nature of the probes does affect the overall measurement accuracy.

The HSF combustors are of an annular geometry. The gas-sampling probes are intended to collect an averaged

sample across the diameter of the annulus. The particular collection probes used to date seem to weight the collected sample toward the inner, hotter portion of the combustion zone. The net result is to generate gas analysis data biased toward higher temperatures, fuel-air ratios, and efficiencies. This evaluation is, of course, speculative and can be validated only by continued observations with various types of probes. At present the overall system accuracy can only be summarized as having a random error approaching ±1/4 percent of reading, an overall calibration accuracy of about ±3 percent (excepting water), and an upper error limit of <10 percent.

One further observation can be made concerning this system. The degree of automation achieved has significantly reduced the system's operator workload. The quantification of such a reduction is very subjective. However, it is estimated that there has been about a sixfold reduction in the workload.

Concluding Remarks

This concluding section is, in the main, one of retrospection. It is written from the perspective of the question "If the HSF gas analysis system were to be replicated, what changes would be made?"

Obviously this system is so unique and specialized that it will never be duplicated. Yet the subassemblies that make up the whole have the potential for application to other systems. Therefore the answer to the question does have value. Based on hindsight and accumulated experience, there are specific areas that could and would be changed. Of the entire assembly, the technique of generating the calibration mixture for the water analyzer is the least satisfactory. Although the generator does function and does generate an acceptable calibration mixture, further evolution of the technique would be required.

Several areas in the system design have proved their value. These areas deserve some further highlighting. The keystone of this design effort is the inverted flow configuration. Along with this configuration, a number of unique peripheral systems were developed to complete the pneumatic assembly. These elements were evaluated with special care in the testing phase of the system. In both testing and actual facility operation, the pneumatics have met and exceeded all expectations. The inverted flow configuration must be labeled an unqualified success.

The innovative procedures of data handling in the HSF gas analysis system have given the operator an expanded ability to evaluate the system performance. With this system the operator can assess the system performance at many levels. At the lowest level there are the assorted manual readouts on the main console proper. The engineering data readout panels give access to a variety of unprocessed data. The terminal associated with the data-processing computer allows inspection through the computing phase. Finally the history file allows for a retrospective analysis of all data.

As previously stated, the upper bound on system inaccuracy has been placed at ±10 percent. Careful analysis of performance has led to the belief that most of this error resides outside the analysis system proper. The major contribution to the error is thought to be gas sampling and transport. The next major error source appears to be the procedures of analyzer calibration. Present state-of-the-art gas mixtures are accurate to, at best, ±2 percent, with another 1 percent error being contributed by the techniques of calibration.

The conclusion reached from these considerations was that further efforts toward system improvements (excluding that directed toward the water measurement) would be of marginal benefit. The major problems yet to be solved in the task of gas analysis seem to lie elsewhere. The area of sample collection and transport seems the most significant error source. However, the calibration task is also worthy of careful consideration.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, October 30, 1984

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15. Supplementary Notes

16. Abstract

An integrated exhaust gas analysis system has been designed and installed in the hot-section facility at the Lewis Research Center. The system is designed to operate either manually or automatically and also to be operated from a remote station. The system can measure oxygen, water vapor, total hydrocarbons, carbon monoxide, carbon dioxide, and oxides of nitrogen. Two microprocessors control the system and the analyzers, collect data and process them into engineering units, and present the data to the facility computers and the system operator. Within the design of this unique system there are innovative concepts and procedures that are of general interest and application to other gas analysis tasks.

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