FR-2352-101

FINAL REPORT

SAFETY INSTRUMENTATION PACKAGE

Contract NAS 9-3910

October 31, 1966

Submitted to:

National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas

Beckman INSTRUMENTS, INC.
ADVANCED TECHNOLOGY OPERATIONS
FULLERTON, CALIFORNIA • 92634

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1.0 INTRODUCTION

This contract (NAS 9-3910) requires delivery of fifteen (15) sets of safety instrumentation to be worn by personnel engaged in work inside space simulation chambers. One system may be conveniently divided into two subsystems: the suit equipment called the SIP unit, and the terminal equipment called the Terminal Unit. The SIP unit consists of a nylon net vest, to be worn under the space suit, an electrical harness, and a number of types of sensors and signal conditioners. The harness and signal conditioners are anchored to the vest, while the sensors are located in appropriate regions in the suit or on the body of the person wearing the equipment. With regard to the SIP unit, this contract requires delivery of only the vest, the complete suit electrical harness, the pO_2 and pCO_2 sensors and suit signal conditioners plus interconnecting cables, and a pressure transducer. A number of biomedical sensors and signal conditioners, a Baroswitch, and a suit inlet gas temperature probe are being procured under separate contracts. The Terminal equipment required by this contract consists of two racks (mounting the Terminal units), the Terminal units (mounting power supplies for both SIP and bioinstrumentation, and signal conditioners for pO_2, pCO_2, pressure transducers, and for the suit inlet temperature probe), and two complete sets of calibration and checkout equipment for use with the equipment delivered under this contract.

The purpose of this rather lengthy introduction is to sufficiently outline the scope of the contract to make it clear that much of the equipment is essentially modified off-the-shelf hardware, while a small part of the equipment required new technological developments.

2.0 SUMMARY AND CONCLUSIONS

Each spacesuit is instrumented independently of all others in the chamber. Consequently, a failure in one cannot affect the performance of any other system. Similarly, each safety instrumentation package measures partial pressure of oxygen, partial pressure of CO_2, and suit pressure essentially independently. That is, the only common apparatus involved in the three measurements are the +12VDC and -6VDC power supplies. A failure of either of these supplies, or failure of one channel which effects the output of these supplies, will result in errors in all three measurements. Otherwise, these measurements are made independently, and one may fail without affecting the others.

All final calibrations are performed on the suit equipment, and all terminal equipment is calibrated against a calibration and check-out unit which is in effect a "dummy suit". Therefore, any suit equipment may be connected to any terminal equipment at any time without loss of calibration.

The signal conditioners employed for pCO_2, pO_2, temperature, and pressure approach the limitations of the present state-of-the-art. In general, the errors in total system performance which are contributed by the signal conditioners amount to less than 1/10 of the total tolerance. Thus, the precision of the measurements made depends almost entirely upon the precision with which the measurement could be made by the given sensor under any given set of environmental conditions.

The suit portions of the equipment are essentially flight qualifiable by design. This approach was necessary in order to assure maximum reliability for this critical application.

The terminal equipment design facilitates rapid interchange of the entire terminal units and/or plug-in components. The terminal unit power supplies are all current limited to preclude the possibility of a fire being initiated within a spacesuit. In addition to the active component current limitation, most power leads to the suit are equipped with series voltage-dropping resistors which would limit the current in event of a total failure within the power supply proper. The suit equipment designs included consideration of the effect of these current-limiting resistors and the resistance of long cables (up to 1500 feet) from the terminal equipment to the spacesuit.

It may be anticipated that sensor performance will be improved in the future due to further development. The performance of the signal conditioning equipment is sufficient to take full advantage of approximately a five-fold improvement in sensor performance. Consequently, it is believed that the equipment will be continually upgraded as the sensors are replaced.

3.0 DESIGN APPROACH

3.1 General

The basic approach in design was to utilize off-the-shelf equipment and modified off-the-shelf equipment wherever possible. In some cases this was attempted in early breadboard work without success and new aplifiers were developed. For example, the suit signal conditioners for pCO_2 required new approaches. On the other hand, commercial power supplies were employed in the terminal unit and modified only as necessary to meet the short circuit current limitations. The guide lines followed in new development are detailed in the following paragraphs.

3.1.1 Reliability

Components were selected on the basis of reliability. As soon as preliminary design and breadboard tests were completed, a reliability study was performed. Some reliability data was necessarily arrived at by engineering judgment. In such cases, every effort was made to assure that the reliability estimates were conservative and realistic.

3.1.2 Interchangeability

Preference was given to design approaches which would afford the highest degree of component and subsystem interchangeability. The final design provides complete interchangeability of all suits with all terminal equipment. Final calibration is performed at the suit before closure. All terminal equipment is standardized against the calibration and check-out unit which provides dummy suit signals. The importance of this interchangeability may be realized when the effect upon system reliability of requiring mating of specific suit equipment to specific terminal equipment is considered. The unnecessary complexity of requiring mating of specific items would greatly compromise overall system reliability.

3.1.3 Utilization of Common Components Where Possibl

Once the design of the suit pO_2 and pCO_2 signal conditioners had been established it was found advantageous to utilize the same operational amplifiers throughout the entire system. Consequently, virtually all gain stages are the same op-amp. The cost saving of purchasing a relatively large number (about 150) of operational amplifiers compared to the number required for the suit signal conditioners (about 45) made it advantageous to utilize these components throughout. Similarly, quantity purchases of high-quality differential amplifiers made it feasible to employ the highest quality throughout. A large number of potentiometers were required for trimming zero, etc., in the terminal unit amplifiers. Where possible, all potentiometers have the same value.

3.1.4 Serviceability

Ease of service and maintenance of the equipment was a primary consideration in design. All terminal unit amplifier boards are provided with test points facilitating troubleshooting. The cable from any suit may be quickly disconnected from a terminal unit and connected to another terminal unit. Each terminal unit may be unlocked from the rack and drawn out on rollers for access. The rollers are equipped with positive lock stops which must be released before closure. They are also equipped with disconnects which must be operated before the terminal unit may be completely withdrawn from the rack. Any of these operations may be performed in a matter of several seconds. Both terminal racks are fitted with 8 sets of slides. Since no more than 6 will be in use in each terminal rack at any given time, this means that 2 terminal units may be on standby at all times. A total of 15 terminal units are available leaving one space for mounting one of two calibration and check-out units, utilized to standardize all terminal units. In addition, there are two suit calibrator consoles which include two completely standard terminal units. These terminal units are standardized against either of the two calibration and check-out units, and then utilized in calibration of each set of suit equipment. Each calibration and check-out unit contains a high-quality meter which may be utilized for monitoring the outputs of the terminal unit while calibrating. The suit calibrator console also provides a means of storing pCO_2 sensors in a humid sample, and provides a sample manifold for use in calibration of both O_2 and CO_2 sensors. A flow meter with throttling valve is built in for convenience of use.

3.1.5 Applicability to Other Usage

An attempt was made to select design approaches which provided maximum flexibility of the end product where cost and development time were not affected by such choice. For example, an initial effort was made to eliminate the isolated 20-volt power supplies required for the temperature and pressure signal conditioners. While the results of this investigation were not entirely negative, it became apparent that the freedom from pick-up in long cables and the interchangeability of systems would be compromised by elimination of the isolated power supply. Consequently, the isolated power supply was utilized. The pressure amplifier was tested with a gain providing a 5-volt output for 10-millivolt input. Its performance and lack of dependence on environmental temperature were exceptionally good. The only limitation upon its usefulness arises from the necessity for utilizing an isolated power supply. The same is true of the temperature signal conditioner, but in this case the input voltage is relatively large (0.65 volts). As a further example, the suit pO_2 amplifier is capable of providing a 0 to 5 volt output with high precision. For this application, however, the range resistor selected provides a nominal 0 to 3-volt output. This 3-volt output is attenuated in the terminal unit by the range switching network, and further amplified to a 0 to 5-DC output for all three ranges. For any similar application, requiring a 0 to 5-volt output, the suit amplifier may be modified by changing at most three resistors. Similarly, the pCO_2 amplifier provides a 0 to 5-volt DC output for approximately a 0.1 to 40 mm Hg pCO_2. However, suffic' .t zero control (calibration) is provided to permit operation on a 2 to 200 mm Hg pCO_2 range if desired

3.1.6 Desirable Advances in the State-of-the-Art

The scope of this contract did not justify all-out efforts to advance the state-of-the art. Where reliability was concerned, however, such efforts were justifiable. For example, an effort was made to eliminate the chopper from the pCO_2 amplifier because prior experience indicated that the least reliable component in such a system would be the chopper. Previous contracts had investigated the use of semiconductor choppers, but the high impedance required for a pCO_2 amplifier (10^{11} ohms) made such prior efforts entirely futile. Recent advances in the MOS-FET (metal oxide silicon-field made it advisable to investigate their use as a semiconductor chopper. While results were not totally negative, the contract funding and delivery schedule did not permit pursuit of this investigation. Similarly, an attempt was made to develop a MOS-FET chopperless DC amplifier. Several major problems were not solved, and it became necessary to freeze the design using the conventional mechanical chopper amplifier.

The available pCO_2 sensor at the start of the contract was both too large and too slow for this application. Consequently, a change in scope was made and additional funding was secured for development of a miniaturized electrochemical pCO_2 sensor. These efforts are described in detail in the following section.

4.0 NEW TECHNOLOGY REQUIRED FOR SIP UNIT

4.1 Miniature Electrochemical pCO_2 Sensor

The Beckman pCO_2 sensor has, for several years, been employed for spaceborne pCO_2 determination. Briefly, a glass pH electrode and a Ag/AgCl reference electrode are immersed in an electrolyte, and covered by a gas permeable membrane. Solution of CO_2 results in the formation of carbonic acid, changing the pH of the electrolyte. The reaction is reversible, but response is normally slow (about 2 to 3 minutes for 63 percent response to a step function increase of pCO_2) because of the time required for the CO_2 to diffuse into (or out of) the electrolyte. Furthermore, at the outset of this contract, the smallest available pCO_2 sensor was about 0.62 inches in diameter and about 1.68 inches long. That model weighs about 18 grams. While no other method of measuring pCO_2 was feasible for this application, a decrease in sensor size and an increase in response rate were highly desirable. Prior work at Beckman Instruments, Inc. had demonstrated that both improvements could be made at reasonable cost. Consequently, an improved sensor was developed under this contract.

The new sensor, Figure 4-1, has a maximum diameter of less than 0.50 inches, an installed length of 0.675 inches, and it weighs about 6 grams. It has a screw-base design (identical to that of the Beckman Hypoxia sensor), and must be installed in a receptacle of comparable dimensions.

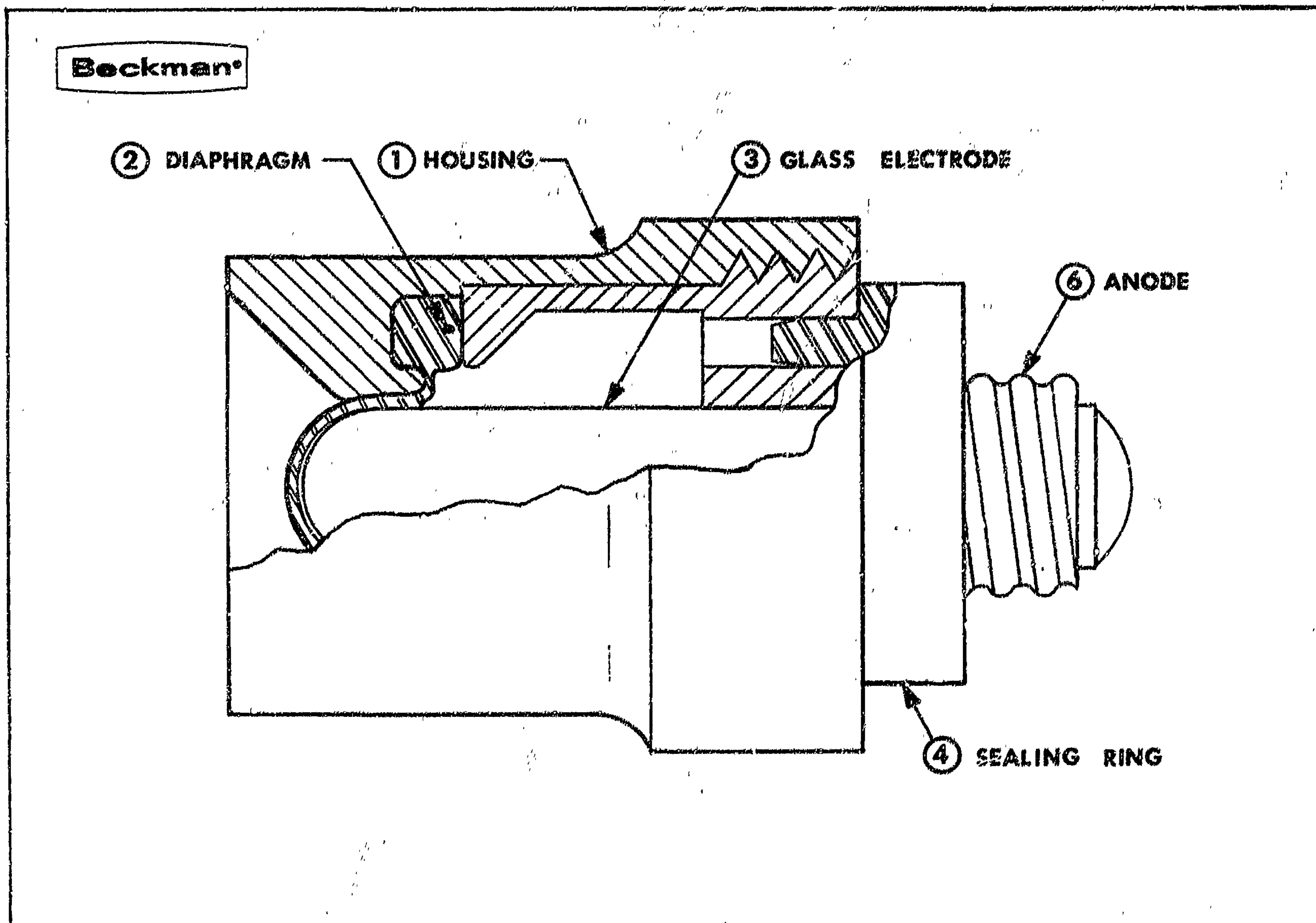

Figure 4-1. Carbon Dioxide Sensor

Initial results with the new pCO_2 sensor indicate that the time constant is well under the design goal of one minute, and is typically as small as 30 seconds. The sensor output is more affected by relative humidity than were previously employed designs as an undesirable consequence of the reduced time constant. Specifically, in order to speed up the response it is necessary to employ a membrane having much greater permeability to gases. Consequently, when exposed to a dry sample, the loss of water by diffusion through the membrane results in a steady-state condition, wherein the electrolyte between the membrane and the glass pH electrode is more concentrated than in the bulk of the electrolyte. On sample gases at 100 percent relative humidity, this concentration gradient would be slightly reversed, but negligible. Preliminary results indicate that a maximum zero shift of 6 percent of scale will occur in a period of time (beginning in about 10 minutes and lasting about 4 hours) after changing the sample relative humidity from zero to 100 percent, or vice versa. The sensors produced under this contract may also suffer a loss of sensitivity when exposed to dry samples. Both effects vary in magnitude from one unit to another, and also are dependent upon the charging technique, as explained in more detail below:

4.1.1 Membrane Design Considerations

The membrane finally developed is approximately 0.0045-inches thick in the critical diffusion areas. It is reinforced with monofilament nylon net about 0.0015-inches thick, and it has five cylindrical protrusions about 0.003 inches high and 0.020 inches in diameter on the surface in contact with the pH sensitive glass bulb. The purpose of these "feet" is to space the membrane away from the glass bulb in a reproducible manner, providing a layer of electrolyte of pre-determined thickness between the membrane and the bulb. The thickness of the electrolyte layer is critical with regard to both the speed of response and the effect of dry samples. In connection with response rate, the system is analogous to a simple capacitance being charged and discharged through a resistor. The capacitance is proportional to the solubility of CO_2 in the electrolyte (including that which hydrolyzes to form HCO_3^- and $CO_3^=$) and to the volume of electrolyte in the critical region. (The volume and solubility constant for CO_2 in the membrane constitute a capacitance which must be partially "charged" before "current" flows into the capacitance of the electrolyte film. This mechanism results in a totally dead lag time between sample change and initial response of the sensor). The resistance is proportional to the permeability of the membrane (product of solubility constant and diffusion constant) and inversely proportional to the thickness of the membrane. Consequently, fast response requires both a thin membrane and a thin layer of electrolyte. Both of these conditions are undesirable with regard to the effect of dry sample gases upon the sensor. The rate of water loss by diffusion of vapor through the membrane is inversely proportional to the membrane thickness. The rate at which water can diffuse from the bulk of the electrolyte into the critical thin film zone is directly proportional to the thickness of the electrolyte film. Consequently, a compromise between response rate and sensor dependence upon sample humidity is necessary.

The initial design was satisfactory from the standpoint of response rate, and initial results indicated that dry-out effects would not cause excessive errors. In subsequent testing, however, several undesirable characteristics were discovered. The following paragraphs detail these specific problems and their solutions.

4.1.1.1 Shifting of the Membrane with Pressure Variations

Using the original molded silicone rubber membrane, the sensor displayed erratic behavior when subjected to the pressure variations required for use in a space suit. The membrane was bulging under vacuum conditions, and binding too tightly when pressurized. These effects were transient in nature, but in extreme cases lasted up to several hours, and occasionally caused errors of up to 50 percent of full scale. As an interim solution a preformed cover of monofilament nylon net, 0.0035 inch thick, was added. With this reinforcement the effect from 0 to 20 psia was made less than ±3 percent of scale. (Dry-out effects, however, continued to present a problem, especially at elevated pressure). The final solution to this aspect of the problem was achieved by molding a monofilament nylon net, about 0.0015-inch thick, into the silicone rubber part. The Type 287-S Ny-Tex nylon was obtained from Western Supply, 2525 Washington Blvd., Los Angeles, California. The nylon reinforced rubber parts were molded by Space Age Elastomers, Inc., 1549 Embassy St., Anaheim, California.

The use of monofilament net is advisable, and the nylon is preferably preformed, but otherwise the process is apparently quite simple.

4.1.1.2 Wetting of the Glass pH Bulb and Silicone Rubber Membrane

As refinements of the sensor were made, the improvements in performance were great enough to permit detection of secondary effects which escaped detection initially. It was found that sensors very often lost up to 20 percent of their normal sensitivity in as little as four hours of operation. Microscopic inspection revealed that the glass pH bulb was dry under some or all of the five silicone rubber "feet" used to maintain spacing between the membrane and the glass bulb. In addition other parts of the bulb were found to be dry on occasion, even though there was an ample supply of electrolyte in the sensor. Observationally, the silicone rubber does not wet, and neither does glass in a reliable manner. Several surfactants were tested and found to be of little benefit.

Previous sensors of this type had employed an electrolyte gel thickened with CMC (carboxy methyl cellulose), but the size of the subject sensor made it desirable to employ a liquid electrolyte for convenience of cleaning and recharging. The gelled electrolyte appeared to have an advantage in that, while it did not truly wet the surfaces, it prevented the occurrance of spots which were totally devoid of electrolyte because of its high viscosity. A water soluble, non-ionic, resin, polyvinyl pyrolidone (PVP) was added to the electrolyte (8 percent by weight), to produce a thin but "sticky" solution. This electrolyte appeared to wet the glass, and to almost wet the silicone rubber.

The addition of PVP to the electrolyte made a large improvement in performance, primarily with regard to limiting the loss of sensitivity of the sensors to about 5 percent. Further modifications to the membrane made additional improvements.

4.1.1.3 Roughening of Membrane to Promote Wetting

The membrane mold was sand blasted to produce a roughened surface on the liquid side of the membrane. This modification, coupled with the addition of 8 percent (wt) PVP, greatly reduced the tendency for zero shifts and loss of sensitivity to occur when operating on dry samples. Such effects were observed in acceptance testing of the final sensor, but errors in excess of 5 percent of scale were very rare. It appears that tensioning of the membrane is a critical factor in this regard, and that minor redesign of the membrane and membrane clamping cap would almost eliminate the effects still observed, and make the recharging technique less critical.

4.1.1.4 Preservation of High Impedance Insulation

The insulation resistance between glass pH and silver-silver chloride reference electrodes must exceed 10^{11} ohms in order to meet performance specifications of this contract. This was a problem of the first magnitude. Repeated failures of sensors due to loss of insulation resistance greatly complicated the problem of isolating and solving the difficulties discussed above.

The prototype sensors were fabricated using "black wax," a proprietory Beckman product, which has been in use for 30 years for the purpose of preserving adequate inter-electrode insulation. It developed that while the wax was capable of providing the necessary insulation, it was very difficult to apply, and could not be sealed into the unit against high temperature. Both of these difficulties were a consequence of the very small dimensions of the new unit. A number of alternatives were tried, but none produced sensors which lasted more than one to three weeks, even at room temperature. At present it appears that a new Dow Corning product (Q 96-005, conformal coating) has solved this problem completely. At the time of this writing (October, 1966) approximately forty units have been fabricated using this product to assure preservation of insulation resistance, and there have been no failures in over nine months. The silicone rubber conformal coating is easy to apply, adhers to glass and other substances well, has high electrical resistance properties, and effectively blocks the diffusion of electrolyte.

4.1.1.5 Recommended Changes for Further Refinement

The use of five protrusions of 0.020 inch diameter on the glass electrode side of the membrane (for spacing) leads to loss of sensitivity due to dry-out of the bulb under these regions of relatively high pressure contact. This effect has been observed even when using wet samples, when the tension on the membrane is excessive. Similarly, the molded rubber part does not conform to the shape of the glass bulb. This was done to facilitate machining of the mold, and it caused no difficulty with the initial design, but it requires an undesirable tension in order to make the nylon reinforced parts conform to the shape of the glass. A new mold should be fabricated with many more protrusions of smaller diameter (for example 80 with 0.005 inch diameter), and which would produce parts having an unstrained hemispherical form, rather than with a right circular cylindrical configuration. The glass bulb side should be roughened by sand blasting the mold, as was the present mold.

4.2 pCO_2 Sensor Amplifier

One of the difficulties associated with the measurement of pCO_2 with the Beckman electrochemical pCO_2 sensor has been, and continues to be, due to the inherently high impedance of the glass pH electrode. At 40°F the sensor has an output impedance of 10^9 ohms or higher, and it provides a signal of only about 55 mv per decade change of pCO_2 (logarithmic). For one percent precision, the amplifier must have an input impedance of 10^{11} ohms minimum. Such high impedance is normally achieved by proper feed-back and very high loop gain. At the outset of this contract, it was believed that a chopper stabilized amplifier could be separated into a suit preamplifier consisting of a miniature chopper and the first stage (FET), or two stages, and a terminal unit amplifier consisting of the gain, power, and demodulator stages. It was found that ac pickup in the long (up to 1,500 feet) interconnecting cable was too severe. (Such a system had been used for Project Mercury, but the cable length was only about 12 feet). It was necessary, therefore, to develop a suit amplifier which would provide a 0-5vdc low impedance output.

4.2.1 Final Suit pCO_2 Amplifier

The SIP pCO_2 amplifier is a welded module containing a selected AIRPAX model M-40A chopper, two TO-18, and two low silhouette TO-5 cans. It has an input impedance of about 10^{11} ohms, an open loop gain greater than 10^5, a closed loop gain of 45.5, and an output of 0 to 5vdc at an output impedance of about 20 ohms. The output is clamped at -.6 and +6.2v, and becomes current limited at about 3 milliamperes. It is probably capable of operating in the temperature range of -40°F to +200°F, but it has been tested only in the range of +40°F to +120°F for purposes of this contract.

4.2.1.1 General Knowledge Gained Which Is Potentially Useful in Design of High Input Impedance Amplifiers

The maintenance of high insulation resistance for the input of the pCO_2 amplifier requires that the unit and input connector be dry, and hermetically sealed. Furthermore, the choppers must be selected for extra high insulation resistance because the glass headers are essentially thermistors with a very high resistance. At 100°C the resistance of glass is about two orders of magnitude lower than it is at room temperature. Other materials, such as epoxy, have similar properties. In the SIP application, the sensor and amplifier are both exposed to essentially the same temperature, and hence the output impedance of the glass electrode drops correspondingly as temperature rises. It must be borne in mind that in general applications the amplifier input impedance decreases with amplifier temperature, and that this factor may limit the practical working input impedance in any given application.

The use of feedback to increase the apparent input impedance of an amplifier has a practical limitation, which is not apparent from a simplified circuit analysis. While the effective input impedance, with regard to loading, is the actual impedance multiplied by the loop gain of the amplifier, as a practical matter the zero stability is dependent upon the signal to noise ratio, which is not reduced by loop gain. For example, with a 5000 megohm source impedance, the SIP amplifier may display very small loading effects, indicating an apparent input impedance greater than 10^5 megohms. Yet the zero may shift up to 50 percent of full scale when the source impedance rises from zero to 5000 megohms. This is primarily a consequence of ac pickup, which is introduced into the input from a source impedance which is comparable to that of the signal source. The practical signal source impedance is, therefore, limited by the stray pick-up source impedances.

The use of a synchronous demodulator can theoretically completely eliminate the effects of pick-up of second and higher even harmonics, regardless of phase, but in practice a limitation arises when the magnitude of these components exceeds the dynamic range of any stage of the amplifier, which results in blocking of the signal with consequent loss of effective gain. A synchronous demodulator cannot discriminate against pick-up of the fundamental or of odd harmonics, except at one particular phase angle for each. It is essential, therefore, that sources of AC pick-up be minimized to obtain the maximum allowable source impedance. It is also undesirable to increase loop gain beyond the level required to raise the effective input impedance to more than about 100 times the permissable source impedance, as this merely increases the tendency for amplified stray even harmonics to block the effective amplifier gain, resulting in a "motor boating" type of oscillation.

The SIP amplifier chopper drive leads are twisted and shielded from the connector to the chopper driving terminals. The chopper driving terminals are first insulated with high impedance epoxy, then shielded with a conductive epoxy. The input leads are kept as short as possible and, as far as possible, are isolated from all leads carrying AC signals. The AC gain is kept down to about 1000, and the demodulated signal is amplified by about 1000. The net result is an open loop gain (after demodulator losses) of about 2 x 10^5. The actual input impedance is about 200 megohms, determined primarily by inter-electrode capacitance of the chopper and field effect transistor. The closed loop gain is about 45.5 to provide a 0 to 5vdc output for 110 mv input. The loop gain is about 4×10^3, which provides an effective input impedance of about 10^5 megohms. The shielding, isolation, use of minimum lead lengths, and care in preserving high insulation resistance result in a practical source impedance of between zero and 1000 to 5000 megohms, depending upon the condition of the chopper. The principal reasons for variances in chopper performance are considered in detail below.

4.2.1.2 Limitations of Mechanical Choppers for High Source Impedance Applications

Two sources of trouble with mechanical choppers have been noted and studied briefly in the performance of the work required under this contract and under several previous contracts performed for NASA. Since these problems are relatively obscure to those who have not encountered them previously, it appears to be in keeping with the spirit of reporting the development effort to discuss them in some detail here.

As the modulated contact of a chopper traverses from one fixed contact to the other, there is a time period during which the amplifier input is "open," and is determined by sources of stray pick-up. In addition to the ordinary pick-up problems, there is a source of energy due to the fundamental physical fact that all metals have an inherent potential called the "contact potential." If the three contacts are of <u>exactly</u> identical material, then no difference of contact potential exists, and no "spikes" are generated. Every effort is made by manufacturers of such devices to achieve this condition, but the nature of the phenomena is such that only a few surface layers of molecules determine the contact potential, and very minor contamination of the surface of any material employed can change its contact potential significantly. The formation of oxides, nitrides, etc., and even unrelieved stresses in the surface, alter the contact potential.

The contact potential of a metal is equal to its electron "work function." It was first measured by R. A. Millikan by utilizing the fact that the potential between the two open ends of conductors joined at one end is the difference of their respective contact potentials (or work functions). By varying the spacing between parallel plates of a capacitor formed of different materials, a charge was made to flow in the circuit connecting them, in accordance with the equation relating potential, charge, and capacitance (q = cv). This, of course, is exactly what occurs in a mechanical chopper, wherein the capacitance varies from near zero (2 or 3 pfd) to infinity (as the contacts close). If any contact difference of potential exists the charge which flows may be quite large, and the voltage spike generated may also be large, 0.5V being observed in some cases. Furthermore, the stationary contacts are not normally at the same potential in a practical application, and this fact alone is sufficient to cause a current flow as the capacitance approaches infinity (just as the contact closes).

The energy contained in such switching spikes is basically second harmonic in nature, but any assymetry results in a component at the fundamental frequency which is 90° out of phase with respect to the desired signal. When using a properly phased synchronous demodulator the fundamental component which is 90° out of phase is negligible, and even harmonics are canceled regardless of phase.

However, in an extreme case the spikes may block a stage of the amplifier, as discussed in the preceding section, and become troublesome. From this standpoint, it is preferable to integrate the spikes to lower the amplitude. In general, however, this also shifts the phase of any component at the fundamental frequency, and a portion of it passes through the demodulator as signal. Furthermore, the probability exists that a contact difference of potential within the chopper will vary with time, due to variations in the condition of the surfaces.

In view of the above discussion, it should be apparent that the chopper contacts themselves must be viewed as one of the possible sources of stray AC signals, in connection with determining the maximum practical source impedance. (Refer to paragraph 4.2.1.1).

A second major problem area with mechanical choppers for high impedance inputs arises from the fact that the contacts may close mechanically, but fail to close electrically. Any practical design must be a compromise between the ideal of definitely "wiped contacts," and the ideals of very long life and low driving power. If driven hard enough to wipe through surface layers upon each closing of the contacts, the parts will wear and fatigue rapidly. If a large enough voltage is being chopped to break through surface layers of oxides (nitrides, etc.) the chopper performs very satisfactorily. But in the application of interest, the typical signal level (between stationery contacts) is the amplifier error signal, which in this case is only 0.11V divided by the loop gain (10^5), or about 1 microvolt. Since the source impedance may be as high as 2000 megohms, it is apparent that very little can be done by way of assisting the contacts to close until and unless the output drifts off enough to provide a larger error signal. This, of course, is a condition resulting in abnormally high noise. It may occur at any time in the life of a chopper, but experience to date indicates that it most often occurs within the first few hundred hours of operation and that those which operate for several hundred hours will probably continue to perform satisfactorily. It is also possible that the age of the chopper is a factor, since the AIRPAX model M40-A is sealed containing dry N_2, and leaks of atmospheric oxygen into the system could be a source of this type of failure. However, there is no direct evidence that this is the case.

The choppers used in SIP pCO_2 amplifiers were selected for header insulation resistance (10^{12} ohms minimum at room temperature). They were also operated for a minimum of three days in a breadboard circuit to verify that the signal did not become noisy with a 1000 megohm source impedance. It is possible that the failure rate will still exceed 50 percent in the first 200 to 1000 hours of operation. The manufacturer specifies a life of 1000 hours, and has indicated verbally that greater than 2000 hours is fairly rare for the 400 cps model.

4.2.2 Investigation of a MOS FET Chopper

The MOS FET (metal oxide silicon field effect transistor) has a truly insulated gate, the dc resistance of which exceeds 10^{13} ohms. The units tested were the Fairchild Fi-100, which operates in the enhancement mode. While the results did not justify further work under this contract, the primary reason was that the delivery schedule demanded that the design be frozen before this investigation could be completed. The tests were made using the breadboard model of the mechanical chopper circuit. To avoid unnecessary detail the two choppers are shown in Figure 4-2, with corresponding parts identified. Either chopper may

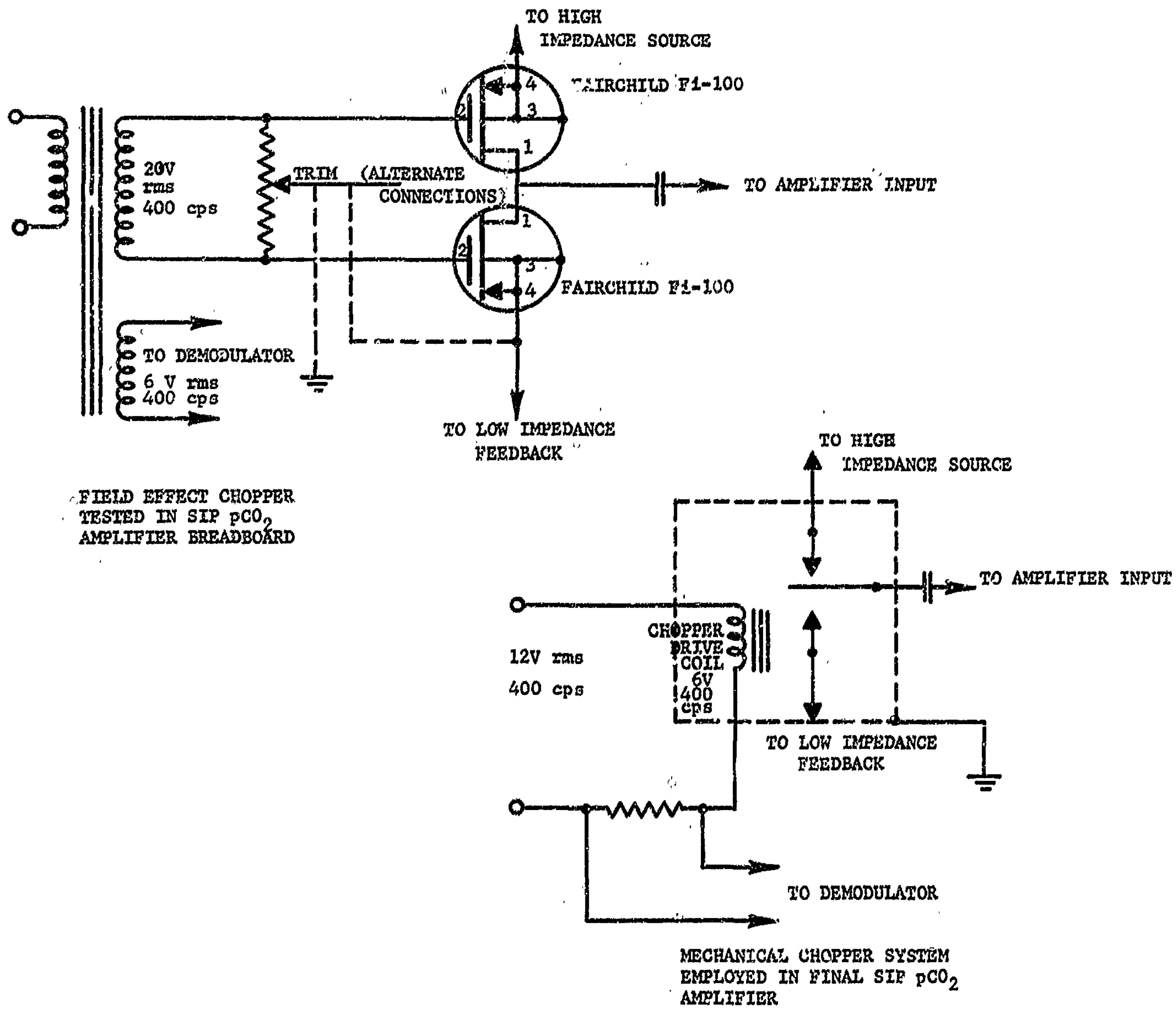

Figure 4-2. Two Choppers

be inserted into the final amplifier, shown schematically in Beckman drawing D-142720.

The investigation of the field effect chopper was hampered by lack of time in which to acquire special transformers, etc. A number of variations of the configuration shown in Figure 4-2 were tried, but no significant improvements were achieved. The alternative connection of the trim pot to the feed-back point appeared to be preferable, but since the test transformer was not properly shielded, no conclusions of this sort are justified. An equivalent transistor having a smaller maximum turn-on voltage was tested, but in order to achieve satisfactory switching a drive of about 20V rms was still required. While the FET's could be connected at their drains rather than their sources, the connection shown is preferred because the transistor housing provides electrostatic shielding for the internal elements.

In order to perform satisfactorily, when in the "off" condition, the FET must reach a source to drain impedance at least equal to that of the signal source, which is 1000 megohms in this case. For this application the impedance when in the "on" condition could be as high as ten megohms, without affecting the performance as a chopper. With the devices tested about 100 kilohms should have been the maximum equivalent resistance when in the "on" condition, and a very large gate drive was required to produce the necessary high "off" resistance.

The gate to source and gate to drain capacitance of the Fi-100 transistor are both about 3 pfd. At 400 cps this capacitance amounts to about 130 megohms as input source impedances from each gate to the input of the amplifier. Since the gates are driven by a 20 v rms signal, a very small imbalance of the gate-to-source impedance produces a large input signal. That is, in this respect the chopper system is a bridge circuit, the output of which is applied to the input of the amplifier. A change in balance of the trim pot, or of the gate to source impedances, of only one part per million will apply a 20 micro-volt signal to the input. The normal maximum error signal being chopped is only fifty microvolts. Consequently the trim adjustment is very critical, and variations in driving amplitude and wave form can cause very large shifts in output.

While all tests were performed without the benefit of adequate shielding for the gate drive winding of the transformer, excellent results were obtained so long as a stable drive voltage was applied, and the laboratory temperature was kept constant. One weekend run with 0-100 mv full scale sensitivity and a 5000 megohm source impedance proved to have ±3 percent stability, which compares favorably with the best results obtainable with the mechanical chopper. It must be remembered, however, that even a change for a few percent in magnitude or frequency of the driving source could produce full scale zero shifts.

Had the work upon this device been continued, the approach would have been to build an inverter into the suit amplifier to avoid cable noise and distortion of the drive signal. The gate drive winding (or separate windings) would have been completely shielded, and the inverter design would have been such as to provide stable amplitude, frequency and wave form. Other modes of driving would have been investigated, since a properly shielded system would have provided more freedom of choice. For example, separate coils connected directly from gate to drain of each transistor (180° out of phase) could be a preferable driving mode.

A final factor to be considered was that of mass and volume of the FET chopper compared to that of the AIRPAX model M-40A. A tentative lay-out, making assumptions with regard to the required size of the transfor er, indicated that very little more mass and volume might be required, but that about twice as much should be tentatively allowed to permit redesign and refinement. There was, of course, no certainty that the system would meet specifications in any event.

4.2.3 Investigation of a MOS FET (Unchopped) DC Amplifier

The desirability of avoiding the use of a chopper stabilized amplifier is obvious, but until the recent improvements in MOS FET technology there appeared to be no hope of accomplishing the necessary stability. The gate-to-drain voltage is larger and is not as well defined as the base-to-emmitter drop of a conventional transistor. Hence the excellent matching of characteristics against variations in temperature, collector current, etc. which can be easily achieved with ordinary transistors is not yet possible with the FET.

The work performed under this contract attempted to utilize recent improvements in product uniformity, which is said to have resulted from imposing a requirement for another order of magnitude upon the purity of the silicon base. While early MOS FETs were prone to acquire a semi-permanent shift in gate voltage of several volts, the Fi-100's investigated did not display an effect of this type greater than about 5 mv (5 percent of scale for the SIP pCO_2 amplifier). In operation, the behavior was as if some source of transient spike signals drove the gate (of one or the other) to a different operating level, from which it recovered in a period of several hours. Two breadboard units were fabricated to assure that no obscure circuit flaw was the source of this error. Each were operated for many days, with the output being recorded continuously. The occurances of such upsets were apparently random, recurring within either hours or days of operation. In every case, a drift of this sort was observed when the power was applied to a unit which had been off for some time. Little effort was actually expended upon means of eliminating this effect, but it is believed that if large transient gate signals are the cause, they could be eliminated by inclusion of RC protection circuitry.

The second problem encountered was that of thermal instability. The two Fi-100's were selected on the basis of equality of source voltage when operated in the self biased mode in a circuit similar to that of Figure 4-3. In initial efforts drain resistors were provided for each FET. The relative magnitude of these components was varied in an attempt to balance the thermal shifts of the two units. It appeared at first that this was an effective means of overcoming this most serious problem, but after several days of investigation, it developed that this was not a reproducible condition.

The contract delivery schedule necessitated freezing of the design before this work could be completed. Overall, the results were quite encouraging, but the lack of certainty of meeting performance specifications made it necessary to select the relatively proven design employing the mechanical chopper.

4.3 DC Signal Conditioners Developed for the SIP

The pO_2, suit pressure, and suit inlet temperature signal conditioners are all

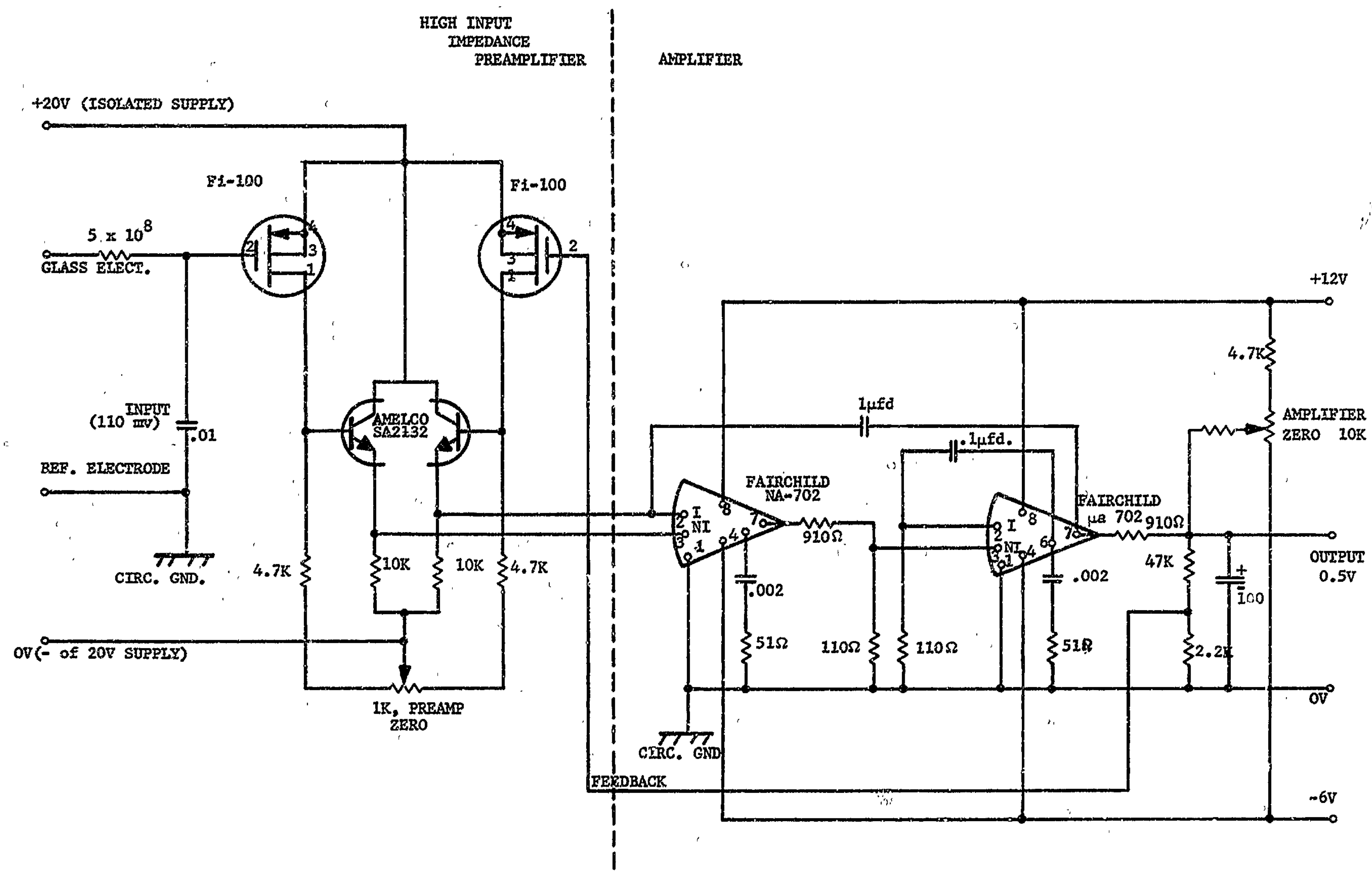

Figure 4-3. Experimental DC Amplifier For pCO_2 Sensors

pure dc amplifiers, and are essentially conventional in design. Several of the operational requirements made it necessary that exceptional freedom from cable noise be achieved, and that the input and output characteristics of the signal conditioners make them completely interchangeable. All of the amplifiers are exceptionally stable thermally and have been rolled off in frequency response to make them almost immune to pickup problems. The outputs are all 0-5vdc at an output impedance of 20 ohms or less (until they become current limited at about 3 ma), and are clamped at -.6v and +6.2 vdc. The outputs are short circuit protected by the current limiting resistor.

4.3.1 Pressure Transducer Signal Conditioner

The pressure transducer is a 500 ohm bridge, designed for operation from a 20vdc supply. The actual bridge voltage is of the order of 2v, the balance of the voltage being dropped in a series resistance network which compensates the transducer sensitivity against temperature variations. The output is 0-100 mv dc (by adjustment) for a pressure range of 0-20 psia, from a 500 ohm source. The series dropping network is split symmetrically to provide about 10V at each bridge output tap.

In order to permit complete interchangability of suit transducers and terminal signal conditioners, the signal conditioner has an input impedance of over 100 kilohms. The input stage is a differential amplifier (Amelco SA 2132) connected as an emmitter follower, operating from the isolated 20 vdc supply which powers the pressure transducer. The isolated, double-ended, output of the preamplifier is applied to a low impedance operational amplifier with an open loop gain of about 10^6 (two Fairchild µC 702A, P/N 9571231, operational amplifiers in cascade). The closed loop gain is made either 200, 100 or 50 for 0-5, 0-10, and 0-20 psia full scale ranges, respectively, by switching the feedback ratio. The feedback to the isolated, double-ended, preamplifier output is so connected that the apparent amplifier input impedance is the actual value multiplied by the loop gain of the amplifier. This would not be possible if the input to the amplifier was not isolated.

The thermal shifts of the two halves of the differential preamplifier are matched by adjustment of one of the base impedances. The preamplifier output is zeroed independently, to assure interchangeability of systems, by adjusting the emitter resistances. The preamplifier is thus made stable to within $\pm$.05 mv for a temperature range of -40°F to +200°F under steady state conditions. Care must be taken to assure absence of thermal gradients across the differential amplifier can, since a gradient of 0.025°C will produce a 0.05 mv offset. During rapid thermal transients errors of 0.25 or even 2.5 mv may occur, depending upon how symmetrically the differential amplifier is coupled to its surroundings.

One of the input resistors of the input operational amplifier is selected to minimize thermal zero shifts, and the amplifier is independently zeroed to avoid apparent zero shifts when the range is switched. In this manner the overall stability of the preamplifier and amplifier is $\pm$.05 mv, referred to the input. Experience to date indicates that all of the adjustments could have been accomplished by selection of one component in place of each potentiometer for greater simplicity and reliability. At the time the design was frozen, it was deemed wise to provide for field adjustment, in the event component characteristics should drift with time.

The preamplifier input is assymmetrical when the pressure transducer is disconnected. This results in a negative output for all range positions in the event of an accidental disconnection.

4.3.2 Temperature Probe Signal Conditioner

Th temperature probe selected was a Yellow Springs Instruments, Inc. Thermilinear thermistor network. These probes require a maximum applied bridge voltage of 4v (ac or dc) from a low impedance source (less than 10 ohms). The balance of the bridge components are specified, and so is the output detector impedance (over 500 kilohms), to assure conformance of the probes to linearity, sensitivity and interchangeability specifications. While the probes were procured under a separate contract, Beckman provided the signal conditioner.

The features of this signal conditioner are similar to those of the pressure signal conditioner detailed above, except that the temperature probe provides a relatively large signal, and careful balancing of components was not required. An isolated 20 vdc supply was employed, using a differential amplifier emitter follower to obtain a low impedance regulated bridge driving supply. The bridge output is applied to a differential amplifier emitter follower for impedance matching, and the feedback to the double-ended, isolated, signal from the preamplifier is such that the amplifier input impedance is multiplied by the l op gain of the amplifier. In this manner a low impedance operational amplifier may be made to provide very high effective input impedance. This is not possible unless the signal source is isolated.

The output is negative (0 vdc=35°F) in the event of an accidental probe disconnection.

4.3.3 pO_2 Signal Conditioner

The pO_2 sensor provides a current output, as if from a very high dc impedance source. Impedance matc ing is achieved by employing two differential amplifiers in Darlington connection, driving an operational amplifier of low input impedance. The feedback loop is closed at the input, to provide an effective low impedance input for the pO_2 sensor current. This approach provides an extremely stable current amplifier for a 0 to 2 microampere input. A brief investigation indicated that excellent stability would be possible with a 0 to 0.2 microampere input, with a 0-5 vdc output. Selection of the resistor connected from reference base to the OV line provides exceptional thermal stability.

The suit pO_2 amplifier provides a 0 to 3 vdc output for 0-8 microamperes input (adjustable), and an output impedance of less than 20 ohms, which is current limited at about 3 milliamperes. This signal is attenuated selectively at the input of the terminal unit pO_2 signal conditioner to provide an output of 0-5vdc for each of the required ranges of 0-5, 0-10, and 0-20 psia pO_2. The terminal amplifier is conventional in all respects, but uses the same Fairchild operational amplifier used in all SIP signal conditioners.

Temperature compensation is accomplished with a thermistor mounted in the sensor receptacle, but connected in the suit amplifier feedback network. After the amplifiers had been fabricated it was discovered that thermal compensation was not optimum. The available improvement is only about 20 percent for the temperature range of interest. Consequently the amplifiers were not modified. It is recommended, however, that any new units, such as spares or new systems, be modified slightly to achieve optimum compensation for any required temperature range.

4.3.4 pCO_2 Inverter and Signal Conditioner

The pCO_2 inverter is conventional in all respects. It is powered from the

20v (isolated) power supply used for the temperature probe and preamplifier. The output to the suit is current limited by series resistors. The 0-5vdc suit pCO_2 amplifier output is passed through the inverter board in order to provide a potentiometer for adjustment of the output applied to the terminal unit meter.