

**AUTOMATED INSTRUMENTATION  
FOR AIR INFILTRATION  
MEASUREMENTS IN BUILDINGS**

**David P. Harrie, Charles M. Hunt\*,  
Steven J. Treado\*, Nicholas J. Malik**

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**\* National Bureau of Standards,  
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**The Center for Environmental Studies  
Engineering Quadrangle  
PRINCETON UNIVERSITY  
Princeton, N. J. 08540**

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## TABLE OF CONTENTS

ABSTRACT	1
PREFACE	1
I. INTRODUCTION	3
II. CHOICE OF METHOD FOR AIR INFILTRATION MEASUREMENT	6
III. PRINCIPLES FOR MEASUREMENT OF AIR INFILTRATION	7
IV. CHROMATOGRAPH DESCRIPTION	9
V. AUTOMATION OF MEASUREMENTS	0
VI. INSTRUMENT CALIBRATION	11
VII. CALIBRATION SUMMARY	12
VIII. AIR INFILTRATION FIELD DATA	15
APPENDIX A	21
NATIONAL BUREAU OF STANDARDS	
AUTOMATED AIR INFILTRATION SYSTEM	
APPENDIX B	25
PRINCETON AUTOMATED AIR INFILTRATION UNIT	
REFERENCES	33
TABLES	35
FIGURES	

ABSTRACT

Automated instrumentation using sulfur hexafluoride as a tracer gas in residential housing to determine rates of air infiltration in housing is described. The principles of operation, the necessary calibration procedures and the early field data are discussed in detail. Concentration levels of SF<sub>6</sub> are maintained at the parts per billion level in the buildings and are measured by sensitive electron capture detectors in conjunction with a gas chromatograph.

PREFACE

Developing design criteria for residential, commercial, and industrial structures that minimize energy demands; expending more effort to increase the efficiency of the manufactured energy consuming systems and products; and evaluating the feasibility of energy saving endeavors for existing and newly built structures and systems, are all attempts to optimize energy utilization. Detailed energy usage studies made on energy consuming structures and systems both existing and new are vital to the success of these attempts. Energy usage for space heating in residential buildings, on the average, is more than half of the total energy usage within the residential community. Air infiltration and natural ventilation are phenomena existing in any type of structure and they contribute to an important extent to the energy usage for space heating.

This is the first of the technical reports on air infiltration in residential buildings resulting from studies in new and existing buildings located in a planned unit development at Twin Rivers, N.J., and from a cooperative effort between the National Bureau of Standards and Princeton University's Center for Environmental Studies under the support of the National Science Foundation. The study titled "Energy Conservation in Housing" is presently in its third year. This report focuses on one facet of the study and emphasizes instrumentation for use in air infiltration measurements. The automated units that are described have been field tested in the planned unit development and in a home in Gaithersburg, Maryland. This report describes the principles of operation of the automated air infiltration units, including design details, together with calibration procedures and preliminary data on air infiltration.

Energy losses or gains in buildings are often grouped into three categories. Conduction through ceilings, walls and floors; and the heat transmission through windows are the first two. Both of these losses or gains can be treated in a relatively straightforward manner from a knowledge of material properties and film coefficients, although solar effects and the subsequent influence on window or attic heat transfer can become quite complex. It is the third category of heat transmission, air infiltration, that is the subject of this report. Air infiltration

results from door and window openings, cracks, and the porosity of the walls, ceilings and floors. Measurement of how fast air is exchanged within a building requires sophisticated instrumentation. The parameters that influence the air exchange rate include weather, particularly wind and temperature, the materials that were chosen for the building construction, the door and window seals and the use of doors, windows, and vents by the building occupants.

### INTRODUCTION

The phenomenon of air infiltration is defined\* as the change of air in a structural enclosure without the interference of the inhabitants of that enclosure. The variables, physical and behavioral, that bring about the phenomena of air infiltration and natural ventilation (inhabitant induced air infiltration) are not only numerous but also their influence on the response variable changes with the type of structure. Our concern at this time centers on the two-story townhouse type of structure in trying to understand the influence of these variables. The first question to ask is, how confident can we be at present, in the estimates derived from an empirical model of air infiltration within a residential dwelling? Lacking sufficient confidence, the question to follow is, what sort of experimentation must be conducted to support improved analysis techniques and, ultimately to quantify our theoretical estimates?

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\*ASHRAE Handbook of Fundamentals 1972, pg. 333.

On-site instrumentation at Twin Rivers and at NBS has been used to provide the data and facilitate computations in evaluating the variables and factors that make up the total energy usage. This includes those parameters contributing to air infiltration, and natural ventilation. A thorough statistical analysis will be based on such data to design a model for estimating the amount of air infiltration and natural ventilation under a given situation. The rate of infiltration is normally related to the building volume and expressed as air exchanges per hour.

Air exchange rates may vary throughout a building depending on the location of holes and cracks, the variation in porosity of the structural material and the influence of doors, windows or vents and how they are operated by the occupants. The only difference between infiltration and exfiltration is that the latter is defined as air moving out of the interior of the building, while the former defines air moving inside from the exterior of the building. Under mild wind conditions the air is normally infiltrating on the windward side and exfiltrating on the leeward side of the building.\* Under typical winter conditions (which emphasizes the buoyant effect of the warm internal air) air normally enters near ground level and exfiltrates from upper level rooms in the building. The amount of infiltration, which is dependent on structural conditions plus the amount of natural ventilation, will determine the amount of energy required to maintain internal building temperature. This portion of the energy use for space heating may range from as low as 10% to as high as 50% or more of the total. Keeping in mind, moreover, that the energy use for space heating may be as high as 11% of the total

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\*This movement can be quite complex depending on building orientation and wind intensity (see ref. 15).

energy use in the United States, infiltration may attribute to as much as 5% of this nation's total energy consumption.

Although infiltration is a major factor in estimating home heating requirements it has proven to be a difficult variable to measure accurately\* considering the variety of housing configurations and the effect of local environment. For the sake of comparison, the transmission of heat by conduction and convection across the building shell is subject to theoretical analyses that are sound enough to give confident estimates of the energy consumption compensating for the heat loss due to this phenomenon, given the type and dimensions of wall and window construction, and outside window conditions. The question arises as to how can we estimate the resistance to air leakage through cracks around specific types of windows and through door or vent openings? To complicate the problem still further, how would one quantitatively consider the faults in the construction of a building? What about the porosity of the walls and imperfections in vapor barriers? These questions which pertain to the physical system fail to include resident or occupant behavioral effects which are still more difficult to model. Problems have arisen in trying to explain many of the physical observations, either because they were too complicated to yield to mathematical logic, or simply because not all parameters influencing this phenomenon are subject to measurements. By utilizing experimentation that involves direct measurement of air exchange rates, one can by-pass the estimation difficulties and such an approach should hopefully lead to improved models so that more reasonable estimates of air infiltration are possible.

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\* ASHRAE Handbook of Fundamentals 1972, pg. 346.

These estimates then could be based upon limited direct measurements and variables such as external weather conditions, structural conditions, door openings, etc.

#### CHOICE OF METHOD FOR INFILTRATION MEASUREMENT

The approach chosen to measure air infiltration has been to release and mix a small quantity of tracer gas within a building and then record the concentration decay with time using sensitive detectors. The choice of tracer gas was made by considering candidate gas properties and the necessary gas volumes and concentration required to conduct studies with no occupant safety problems over a period of days. The development of the extremely sensitive electron capture detector by Lovelock<sup>1,2</sup> and the observation that sulfur hexafluoride, SF<sub>6</sub>, can be measured to concentration levels of the order of one part per billion in air by this technique<sup>3</sup>, answered the requirements. Because SF<sub>6</sub> can be measured in minute concentrations, this gas has come into increasing use as a tracer of air movements<sup>4,5,6</sup>. Indoor use for ventilation studies is also common<sup>7,8,9</sup>.

Besides the high sensitivity with which SF<sub>6</sub> gas can be measured, it is stable, inert, and non-flammable. It is not a normal background constituent of air. One of the principal uses of SF<sub>6</sub> is as a dielectric in transformers. The gas is nontoxic in the concentrations used in tracer measurements and not highly toxic even when present as a major constituent in air, thus inadvertent loss of a townhouse-week supply of SF<sub>6</sub> would pose no danger to house occupants (factor of safety ~1000).



There are certain problems which must be considered using SF<sub>6</sub> as a tracer. The detector unit may require frequent calibrations to maintain the desired accuracy. Also, because of the high sensitivity of the measurement, minor leaks in regulators, valves and connections which would go unnoticed in other gas measurement systems are completely unacceptable when SF<sub>6</sub> is used as an indoor tracer. In order to obtain high sensitivity a gas chromatograph is used. This means that measurements are in the form of chromatographic peaks which may require more work to automate and data process than a continuous output. Although SF<sub>6</sub> is not normally present in air, the detector responds to other halogenated compounds such as certain refrigerants and propellants used in aerosol spray cans. These compounds occasionally appear in the indoor background. Finally, electron capture detectors contain radioactive sources and require an AEC license to own and operate.

This report describes the use of SF<sub>6</sub> with an electron capture detector and a gas chromatograph to measure air infiltration in buildings and describes two approaches to an automated air infiltration unit design, one developed at NBS the other at Princeton University. Some of the problems and fundamental sources of error in the method are described.

#### PRINCIPLES FOR MEASUREMENT OF AIR INFILTRATION

In the measurement of air infiltration by the tracer dilution method a tracer gas is distributed in the air of a building, and the decay in concentration measured as a function of time. The

theory of the method may be outlined briefly by considering the equation:

$$\frac{dc_i}{dt} = (c_o - c_i) \frac{\dot{v}(t)}{V} \quad (1)$$

where  $c_o$  and  $c_i$  are respectively the outside and inside concentrations of tracer at time  $t$ .  $\dot{v}(t)$  is the rate at which air enters the building. It is also the rate at which air leaves the building assuming there is no storage capability.  $V$  is the ventilated volume of the building, and  $\dot{v}(t)/V$  is the air infiltration rate per unit time. Since  $\dot{v}(t)$  is usually measured in cfm and  $V$  in  $ft^3$ , infiltration in air changes per hour is  $60 \dot{v}(t)/V$ .

If the outside concentration of tracer is small enough to be neglected, equation 1 may be reduced to:

$$\frac{dc_i}{dt} = - c_i \frac{\dot{v}(t)}{V} \quad (2)$$

Under conditions of perfect mixing equation 2 may be integrated to give:

$$\ln \frac{c_i}{c_{i0}} = - \frac{\dot{v}(t)}{V} t \left[ \frac{\dot{v}(t)}{V} \text{ independent of } t \right] \quad (3)$$

or

$$\frac{d}{dt} \left[ \ln \frac{c_i}{c_{i0}} \right] = - \frac{\dot{v}(t)}{V} \left[ \frac{\dot{v}(t)}{V} \text{ dependent on } t \right] \quad (3a)$$

where  $c_{i0}$  is the initial indoor concentration of tracer, at  $t_0 = 0$ . Equations 2-3a have the familiar form of the radioactive decay law, first order kinetics or the equation of the well-mixed tank. Equations 3 and 3a can be solved directly, but when manual calculation is performed it is common practice to plot  $\ln \frac{c_i}{c_{i0}}$  against

t and calculate the infiltration rate from the slope of the line. It is also to be noted that it is not necessary to know absolute tracer concentrations to calculate infiltration rate provided relative concentration,  $c_i/c_{i0}$  can be determined.

#### CHROMATOGRAPH DESCRIPTION

Chromatography is a method of separation of the components of a mixture as a result of their partition between two immiscible heterogeneous phases, the stationary phase and the mobile phase. Gas chromatography is the chromatographic operation (analysis) where the mobile phase is a gas. The particular analysis in question is the frontal gas chromatographic analysis, which may be termed isothermal-isobaric chromatography, where both the temperature and the flow of the mobile phase are kept constant during the entire operation. The gas chromatographic column is packed with an adsorbent, which is the stationary phase, made up, in our case, of granular, 100-200 mesh aluminum oxide. The gas stream, the so-called carrier gas, (high purity argon) is fed into the column, and flows through the small irregular channels of the stationary phase. The sample, which includes the tracer gas and ambient air is introduced at the head of the column together with the carrier gas that moves it along the column. Each component of the sample at each point along its flow, in the direction of the gas flow, establishes an equilibrium between its fraction retained in the stationary phase and its fraction remaining in the mobile phase. Partition

coefficients of the components are different from each other and with the proper manner of operation, the components will be completely separated and will appear in succession in the emerging carrier gas at the end of the column. This is a consequence of the laws of diffusion mass transfer.

The electron-capture detectors under evaluation employed the pulsed voltage technique with an applied voltage of 70 volts (pulse height), a pulse width of 1  $\mu$ sec. and a pulse period of 50-100  $\mu$ sec. One type unit has a 300 mc tritium ionizing source, while the others each have a 500 mc tritium ionizing source.

#### AUTOMATION OF MEASUREMENTS

Using very similar approaches the responsible groups at the National Bureau of Standards and at Princeton University have developed the automated systems for air infiltration measurement and recording as shown in Figures 1 and 2. Both systems inject  $SF_6$  in carefully controlled amounts into the home heating duct system just upstream of the furnace fan. The concentration level within the home stabilizes in less than 10 minutes. The automated sampling system then proceeds to sample at regular intervals and record the  $SF_6$  concentrations. Records are currently in the form of strip charts<sup>\*\*</sup> as shown in Figure 3 indicating the individual samples of  $SF_6$  concentration. The details of the automated systems are described separately in Appendixes A and B.

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\* This unit is a Panatek Leak Detector 2000, a device no longer available on the market, replaced by the Ion Track Instrument  $SF_6$  B Detector with the 500 mc tritium ionizing source. Other detectors could serve the same purpose.

\*\* Future systems will record digitally on magnetic tape cassettes.

### INSTRUMENT CALIBRATION

It is necessary to calibrate the instruments against known concentrations of SF<sub>6</sub> in air. Calibration mixtures are prepared by leaking SF<sub>6</sub> at a measured rate\* into a wind tunnel operating at a known flow rate. The gas is stored in a compressed air tank for use as needed. Samples stored this way for a month usually agree within experimental error with freshly prepared samples drawn directly from the wind tunnel. For preparing concentrations of less than 10 ppb, dilutions of the primary standard are made with a dilution system consisting of a graduated closed cylinder with a piston and stopcocks.

The calibration of the units determines the response of the electron capture detector (ECD) to small amounts of SF<sub>6</sub> in air at the parts per billion level (5-65 ppb SF<sub>6</sub><sup>\*\*</sup> in air), for each unit at a constant flow rate of the high purity argon. Two standard samples are used, one with ~13.8 ppb SF<sub>6</sub> in air, and the other with ~48.4 ppb SF<sub>6</sub> in air. The calibrated, 10 liter, variable volume chamber is supplied a controlled volume of one of two samples. Successive dilution is easily accomplished by means of a sliding piston, where pure air is drawn in to dilute the mixture, which is maintained at atmospheric pressure. Six readings of the standing current I<sub>0</sub>, and the SF<sub>6</sub> peak current value I are taken for each concentration of the mixture being sampled.

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\* A convenient form of controlled leak for SF<sub>6</sub> can be made from a capillary tube packed with a finely ground pigment. The rate of flow of the leak is determined with a soap bubble meter.<sup>1</sup>

\*\* NBS used somewhat lower concentrations in the calibration procedure.

CALIBRATION SUMMARY

It is evident from the calibration that care must be taken in how to best process field data which relies on laboratory calibrations for quantitative values. Both NBS and Princeton tests have shown that sensitivity changes to SF<sub>6</sub> concentrations do occur. This is especially true in the warm-up period of the detector-chromatograph. Another important conclusion is that while rather simple expressions relating concentration to recorder output apply over a limited range of concentration, i.e., 8 - 25 parts per billion SF<sub>6</sub> in air. Higher concentrations, > 25 ppb, require more complex polynomial expressions.

The changes in detector chromatograph output during the warm-up period are evident for both meter readings and strip recorder chart readings. That differences in meter and chart recorder readings were found should not be surprising since one is attempting to read chromatographic spikes which are of relatively short duration (order of a few seconds overall, less than one second at the peak) and each of these readout methods has associated inertial factors and damping times. This is a factor to be carefully watched, although the tests indicate that reproducible readings may be achieved with either method even though the proportionality constant is different.

Our goal is not to determine the electron-capture coefficient of SF<sub>6</sub> but rather to find a region of applicability of

a "universal" calibration curve within a reasonable range of SF<sub>6</sub> concentration values. The possession of this curve will allow accurate determination of air infiltration within narrow ranges of SF<sub>6</sub> concentration values.

Consider the Beer-Lambert law\* for radiation to the ion detector:  $I/I_0 = e^{-uxc}$ . Here the intensity  $I$  and initial intensity  $I_0$  are related to the absorption coefficient  $u$ , the path length  $x$  and,  $c$ , the concentration of the absorbing substance. Stated in another form where  $u$  and  $x$  are collapsed into a single coefficient,  $k$ , corresponding to the sensor conditions for a particular unit, then we can consider the relationship:

$$-\ln \frac{I}{I_0} = kc$$

In order to adapt this relationship to better follow the calibration data an exponent  $B$  is added to  $c$ , recognizing that  $B$  should be very close to 1.00 in value. See Figure 4 for example.

To check the range of applicability for the relationship  $-\ln \frac{I}{I_0} = kc^B$ , the data for one test series is shown in Table 1 as data points are added for increasing SF<sub>6</sub> concentrations.

The maximum error between 7 and 27 ppb was found to be  $\pm 2\%$  based on  $B = .942$ . A second example, at another standing current level, and  $B = .917$ , errors of  $\pm 1\%$  were found over the 8-28 ppb range as shown in Table 2. These test series were typical of the additional test series summarized in Table 3, and the conclusion is that the proposed model

$$-\ln \frac{I}{I_0} = kc^B$$

is applicable, with errors limited to  $\pm 2\%$ , over a limited con-

\* It should be pointed out that other investigators<sup>2,12</sup> have proposed alternate relationships working with different gases or in other concentration ranges.

centration range, order 8-25 ppb.\* Because the quantity of interest is the air exchange rate it is not necessary to determine  $k$  since this factor cancels as we take ratios of concentrations at various time periods (cf. equation 3a, page 8).

Although the symbols have been previously defined, they are repeated here for the specific instrumentation used.  $I$  is the current reading for the  $SF_6$  concentration present at a given time and is recorded as the lowest point the needle or chart pen reaches when  $SF_6$  is being analyzed (following  $O_2$  analysis in the chromatograph as shown in Fig. 3).  $I_0$  is the standing current, the steady-state reading prior to the  $SF_6$  sample, also shown in Fig. 3.  $c$  is the  $SF_6$  concentration expressed in parts/billion (ppb).  $B$  is the concentration exponent with values between .8 and 1.1. Individual calibration curves are associated with each air infiltration measuring unit due to slight detector variations. Calibrations must be repeated as the units age.

If the error in the  $SF_6$  concentration does not need to be restricted to  $\pm 2\%$  (as in the  $kc^B$  relationship just described) the traditional  $\frac{I}{I_0} = kc$  equation will yield results in the  $\pm 10\%$  error range. Should more accurate values of  $SF_6$  concentration be required, the use of a polynomial fit to the calibration data is recommended. Figure 4 illustrates how the applicable range of  $SF_6$  concentration can be more than doubled by the polynomial fit (above 60 ppb) with errors of the order of  $\pm 1\%$ .

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\* The  $\frac{I}{I_0} = kc^B$  relationship has worked well with the Princeton field studies but the NBS unit calibrations require a somewhat different equation for best fit.



AIR INFILTRATION FIELD DATA

To test the NBS infiltration measurement system use was made of a four-bedroom, ranch-type house near Gaithersburg, Md. The tests covered a ten hour period. During the test  $SF_6$  was introduced automatically into the furnace fan at selected time intervals, and the buildup and decay of tracer in the house was measured. Instrumental response as a function of time is plotted in Figure 5. It is to be noted that a decrease in concentration appears in the figure as an increase in  $I/I_0$ .

Two sampling methods are represented in the figure. In one method air was sampled from the main return duct just ahead of the furnace fan. In the other method, blended samples were drawn from different parts of the house through a network of tubes of equal length extending to a central location in each of the rooms. These tubes converged at a sampling junction connected to a 2 cfm (57 liters/min) diaphragm pump. The automated system sampled in timed sequence from the output of this pump, from the return, and from the standard reference gas system. Sampling from the return is the simplest means of measuring infiltration rates in occupied homes. Network sampling provides an independent check on this procedure.

Infiltration rates calculated from the data in Figure 5 are presented in Table 4. The agreement between the two methods of sampling was within normal experimental error except when the furnace fan was not operated, as was the case during runs 2 and 4. Under these conditions it was not possible to accurately measure

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\* Internal air infiltration volume of the building under test can be estimated from concentration measurements after a known quantity

the infiltration rate in the house by sampling in the return duct. Also measurement through the sampling network showed the effects of poor mixing when the fan was inoperative. Buildings which do not have a central forced air circulation system, present special problems in measurement of air leakage by the tracer dilution method, since each room would likely differ from the next and average values for the structure might require individual room mixing to insure accurate measurements.

From these NBS tests and from subsequent measurements it is concluded that automated operation of the chromatograph itself can go for hours unattended. However the standardization needs further development before the measurement system could be considered fully automated for unattended operation.

The ability to field test for extended periods - for one week unattended - is the design objective of the Princeton Automated Air Infiltration Unit (AAIU). The field testing of the AAIU was begun in November, 1973 with a number of additional week-long infiltration data collections taking place in the Winter, Spring, Summer and Fall of 1974 and Winter of 1975. The data from these tests form the basis of subsequent reports, the first of which will soon be available.

This report will only briefly describe the air infiltration field data as collected with the automated units. Perhaps the easiest way to understand the important contribution of continuous records on air infiltration documentation is to study a typical air infiltration record over a one day period. Figure 6 illustrates

the first air infiltration field data for a 3 bedroom, two-story interior (in contrast with an end unit) townhouse at Twin Rivers, N.J. Air infiltration measurements were based on concentration changes in SF<sub>6</sub> between the three-hour SF<sub>6</sub> injection into the return duct. Samples were taken from the return duct (again three every 15 minutes, Princeton AAIU).

Three parameters in addition to the air infiltration rate have been plotted in Figure 6: wind velocity, differential temperature (the difference between indoor and outdoor temperature), and pressure differential (variation in outside pressure over time). Even these first data revealed that parameters such as wind velocity can be very influential in achieving high infiltration rates. For the 15 mph wind velocity air infiltration is greater than 1.2 air exchanges per hour, exceeding conventional ASRAE estimates\* (order .75). The procedure for obtaining the air infiltration data relied upon 15 minute samples (three individual samples are averaged) as shown in Figure 3 using the automated air infiltration unit as described in Appendix B.

The fact that activities within the home (as previously outlined on page 3) directly influence air infiltration rates is shown in Figure 7. Here door opening times from one of the highly-instrumented townhouses \*\* 13 greatly increased the air infiltration rate, allowing values to exceed two air exchanges per hour.

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\* ASRAE Handbook 1972 page 337 (also see ref. 14).

\*\* 60 channels of energy-related data are available from each townhouse; of interest here are door opening times (minutes/hour), individual window opening times are also available.

The conclusions on AAIU field operation, from an instrument standpoint, have been favorable. Repeated week-long unattended operation has been achieved. Calibration over such periods has changed only slightly (less than 5%). Rather than sample from the standard gas container every three hours on-site recalibration has been substituted at roughly two-week intervals. (The standard sampling time slot has been devoted to basement  $SF_6$  concentration measurements.) Mechanical problems or failures have involved the following items:

- Problems due to the sensitive nature of the seal packing on the sample valve. Too tight an adjustment can result in slow sampling (and resulting errors) or valve sticking, whereas too loose an adjustment results in excessive leakage of the argon. Hence, care must be taken in the adjustment so that the valve will operate between these extremes.

- Noise and sticking of the solenoid which was first used to depress the sample valve. This problem resulted in a redesign making use of a rolling-diaphragm-sealed piston, which is attached to the valve shaft and the valve is depressed by the pressure from a few cubic centimeters of argon. Argon consumption was minimized such that the week-long sampling duration was unaffected. The current design insures quiet, trouble-free operation.

- Failure of the air sampling pump diaphragm plastic back disks. Replacement disks from the manufacturer are now metal and no further problems are anticipated.

- Leakage of  $SF_6$  through the solenoid valve seals. This has been recognized as a problem from the beginning of the development of the AAIU. Careful inspection of the sealing surfaces and

making sure valve seating depends upon O-ring type surfaces has minimized this problem (soft seating such a neoprene).

A total of five automated air infiltration units have been fabricated. Three units have seen extensive service at Twin Rivers and in the Ohio State University energy research in Columbus, Ohio. The latest AAIU is presently at NBS to receive a magnetic tape cassette addition so that the air infiltration data can be recorded in digital form. With this feature the one disturbing feature of the AAIU - extensive time is required for hand data reduction from the recorder chart paper - should be overcome.

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APPENDIX A

NATIONAL BUREAU OF STANDARDS AUTOMATED  
AIR INFILTRATION SYSTEM

A. Sampling and Measurement System

The NBS automated system for operating the chromatograph is shown in Figure A-1. A block diagram and wiring diagram are shown in Figures A-1 and A 2. The system actuates sampling at selected time intervals and records the responses on a strip chart recorder. It also selects the sampling site so that air may be drawn sequentially from more than one location.

Referring to Figures A-1 and A-2, the detailed operation of the sampling and measurement system is as follows: Timer (1)\* is the main control of the system. It is a 2 gang timer with a 30 second cycle. One gang operates stepping switch (2) or stepper as it is sometimes called. Stepper (2) selects the functions in sequence which are to be performed. It is a 40 step switch and is operated in two 20 step cycles. When actuated every 30 seconds it completes a full cycle every ten minutes.

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\* Numbers in parenthesis refer the individual components in the figures.

The other gang actuates solenoid (12) which operates the sample injection valve of the chromatograph (13).

Solenoid valves (3), (4) and (5) when actuated by stepping switch (2) select the sites from which air samples are drawn. Solenoid valve (6) opens when the automatic system for introducing tracer into a building is actuated. It allows the sampling pump to draw air during tracer feed steps. Otherwise the pump would be pulling against a closed system, since all of the other solenoid valves are closed. If it is used to sample tracer free air it also provides a check on leaks in the system.

Relay (7) is normally closed. It controls the operation of auxiliary sampling pump (9). It also must be closed during sampling steps for sample injection solenoid (12) to operate. During non-sampling steps the pump and the solenoid are deactivated. Relay (8) performs two functions. One pole closes during non-sampling steps and shorts out the output from the chromatograph to establish the zero current baseline. The other pole opens during non-sampling steps and stops chart movement.

Small modifications have been made in the system since it was originally designed. For example, stepping switch (2) and sample injection solenoid (12) are operated with rectified current as shown in Figures A-1 and A-2.



This permits use of lower voltage and reduces electrical noise. Other modifications include padding of the plunger of solenoid (12) with sponge rubber to reduce mechanical impact and introducing screens in the sampling lines to keep large particles of dirt out of the sampling solenoids and the pump. Also a 2-port atomizer bulb with check valves was placed in the output of pump (9), because it was found that otherwise samples were contaminated with ambient air at the pump output during the return stroke of the pump.

#### B. Tracer Injection System

The automated system for injecting  $SF_6$  into a building is shown in a block diagram in Figure A-3. A wiring diagram of the timing control of the system is shown in Figure A-4 and the relay valves and pumps which deliver the tracer are shown in Figure A-5.

The operation of the system may be described by referring to Figures A-3, A-4, and A-5. Stepper (15) is actuated once every 10 minutes by stepper (2). The 40 steps are apportioned so that a feed cycle is initiated every 60 or 70 minutes.

Timer (16) is actuated for 30 seconds by stepper (15) at

the beginning of each feed cycle. It is a 2-gang timer, one gang of which is connected so as to take over from the stepper and operate the timer for a single 10 minute cycle. The other gang controls the time of feed. By adjustment of the cam and the electrical connections it is possible to select feed times of a few seconds up to nearly 10 minutes. Manual override switch (17) is also provided to permit feed of SF<sub>6</sub> independently of the automated system.

Air is drawn through the feed lines at all times by one or the other of two 2 liter/minute diaphragm pumps (20) and (22). During a feed cycle tracer from a controlled leak is diluted with air and directed into the ventilating system of the building by automatically opening solenoid valve (21) and turning on pump (22). During most of the time, however, this valve and pump are off, and air is drawn through the lines and exhausted to the outside by means of solenoid (19) and pump (20). This prevents leakage of residual tracer from the line into the building when the feed is off.

Relay (18) is actuated by stepper (15) and alternately operates the feed or the exhaust.

APPENDIX B

PRINCETON AUTOMATED AIR INFILTRATION UNIT

General

The Princeton automated air infiltration unit, AAIU, has been designed to automatically sample the concentration level of the tracer gas, sulfur hexafluoride ( $SF_6$ ), so that the decreasing concentration levels with time can be used to determine the rate of air infiltration in a building under test. To maintain the  $SF_6$  in uniform concentration within the building, the furnace warm air blower circulates the building air continuously during the test period. The AAIU can operate unattended for a period up to one week.

Figure B-1 is a schematic representation of the AAIU. Overall design is based upon the ease of movement of the unit to the basement furnace or central ducting location in the building or home. For this reason a commercial hand cart with stair glides is used as the frame to which are attached the air infiltration subsystems. These subsystems are described in the following paragraphs.

A. Master Timer Control Center

All timing originates from the master timer control center, located behind the handles on the cart. The wiring schematic is shown in Figure B-2; power is 115V AC. The control center is shown in Figure B-3. The aluminum box houses (1) the master timer, a 1/3' RPH motor-driven cam with

12 evenly-spaced detents. Triple microswitches (center, top and lower) are activated by the cam and two switch tripping posts. (1a) Each of the 12 detents activates, for three minutes, the one RPM sample timing motor to provide the required three SF<sub>6</sub> samples at 15 minute intervals.

(1b) One switch tripping post activates the 90 second SF<sub>6</sub> injection valve every three hours, and the other post provides for readings of the SF<sub>6</sub> concentration standard, if desired.

(2) The one RPM sample timing motor drives cams which reproducibly activate the SF<sub>6</sub> concentration sampling detector by sending small amounts of argon to a pneumatic cylinder and piston attached to the sampling valve. The timing motor stops the timing cycle at precisely the same timing orientation to provide reproducibility on succeeding samples.

(3) Two relays (R-1, R-2) are provided to achieve these reproducible timing features, i.e., cam detents on the one RPM subsystem are favored over the necessarily less precise detents on the one-third RPH cam system to reproduce just three full detector timing cycles. (4) The valve to connect the standard SF<sub>6</sub> concentration sample container\* to the detector is also mounted here. Unactivated, this valve normally connects the SF<sub>6</sub> detector to the sample line from the return duct to measure building SF<sub>6</sub> concentrations.

Details of adjusting the components just described to perform a standard analysis are as follows. Adjustment of the timing for the .2 detent master cam is made such that the central microswitch on the three switch column is activated

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\* Basement SF<sub>6</sub> concentrations have also been determined in lieu of the standard reading.

for a period of nominally 2-1/2 minutes. This timing is achieved with the adjustment screw on the central micro-switch movement. The 2-1/2 minute setting allows the one RPM timer to continue operation through the full three minute cycle while power is maintained for the final half minute through one of the two relays in the circuit.\* Should more or less than the normal three samples be desired at 15 minute intervals, adjustments can be made by altering the setting of the central switch adjustment screw. The fine adjustment of timing for the SF<sub>6</sub> injection (nominally 90 seconds) or the standard SF<sub>6</sub> concentration sample (again 2-1/2 minutes is used) are made with the lower and upper screw adjustments on the triple microswitch column. One feature that may be added in the future is a line orifice to conserve sample gas usage.

Adjustments on the one RPM timing cams are arranged as follows: The FIRST CAM (closest to the motor) provides for the reproducible reset feature, i.e., power to the motor is initially supplied from the master cam switch when activated by one of the detents, an alternate source of electric power is from the house sample relay -- after the 2-1/2 minutes are completed power continues to the one RPM motor via the relay until this first cam gap is reached, reproducibly stopping the sequence; the SECOND CAM is set to energize the sampling valve on the SF<sub>6</sub> detector -- this is achieved by activating

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\* see explanation under THE FIRST CAM

the argon gas valve that pressurizes the cylinder connected to the SF<sub>6</sub> sampling valve, thus silently depressing the SF<sub>6</sub> sampling valve for a reproducible three seconds duration (shorter times or nonreproducible depression results in sample measurement inaccuracies). The THIRD CAM controls the timing on the standard SF<sub>6</sub> sample (NBS has used 13.8 ppb SF<sub>6</sub> concentrations as this standard).

Under normal operation no adjustments need be made to the one RPM motor driven cams. However, an occasional check that set screws have not loosened from vibration is recommended. Cam setting order is such that cam number one must stop the one RPM unit prior to activation of cam number two (otherwise the unit could lock in the depressed SF<sub>6</sub> sample position). Cam number three is set to open the standard concentration sample valve (only when the post activated switch on the master timer is also depressed) approximately 20 seconds prior to SF<sub>6</sub> sampling (to allow adequate gas travel time for this sample to reach the detector) and shutting off five seconds after sampling -- this limited opening time conserves the supply of the standard SF<sub>6</sub> mixture.

#### B. Sulfur Hexafluoride Storage and Metering Unit

Contained on an entirely separate slide out Plexiglas panel on the front lower section of the AAIU is the SF<sub>6</sub> storage and metering system. \* The entire assembly is designed to maintain zero leakage. Filling of the SF<sub>6</sub> storage bottle to a nominal 25 psig should be done remotely -- not in the build-

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\* Although shown in Figure 2, the panel components are more clearly depicted in Figure B-4 viewed through the transparent plastic.

ing under test. For this reason the slide out panel is completely removed from the AAIU by first electrically disconnecting this panel at the master center, and then by loosening the upper rod connected on the two slide rails to the meter shelf -- tilting the rails forward and removing the panel by the hand grip provided. Remove hyperdermic tubing if there is any danger of damage in the panel removal procedure.

Remote filling of the SF<sub>6</sub> storage bottle is essential if accurate building air infiltration measurements are to be taken. Every three hours only 10 cc's of SF<sub>6</sub> is released in the building heating/cooling ducts -- any loss of SF<sub>6</sub> during filling operation can completely overwhelm sensitive concentration measurements.

Safety design of the SF<sub>6</sub> container is such that should all the SF<sub>6</sub> be released inadvertantly in the small home, 10,000 cu. ft., only one ppm would be present -- a safety factor of 1000.

Containment of the SF<sub>6</sub> is maintained by zero leakage solenoid operated valves. To inject the 10 cubic centimeters of SF<sub>6</sub> required every three hours, the low pressure regulator is set to between 1/2 - 1 psig. Use of 0.020 inch internal diameter hyperdermic tubing to transfer the SF<sub>6</sub> to the furnace ducting limits trapped SF<sub>6</sub> after valve closure to less than .1 cc or <1% of total injected SF<sub>6</sub>. This eliminates problems of SF<sub>6</sub> seepage from the line during the air infiltration test period. The test method to measure SF<sub>6</sub> total injection utilizes soap bubble movement along known diameter transparent tubing.

### C. The SF<sub>6</sub> Sampling Unit and Recorder

The aluminum instrument shelf supports the ITI SF<sub>6</sub> sampling unit and the Rustrak continuous writing strip chart recorder. (See Figures 2 and B-1).

First the SF<sub>6</sub> sampling unit is turned on and adjusted to the SET position so that the argon carrier gas flow is displayed as an approximately mid range reading on the analyzer dial. Pump switch is ON. With each depression of the SF<sub>6</sub> sampling valve, an individual air sample is analyzed. (Continuous sampling is far less sensitive in detecting the small concentration of SF<sub>6</sub> that are being employed in the home, ~ 5 to 40 ppb.). Within the ITI unit a sampling column separated air components of varying molecular weights. Electron capture detection based on a tritium source provides the extremely sensitive detection mechanism (few parts per billion).

A typical record following sample valve depression (see Fig. 3) consists of the ~ 80 meter reading for the ultra high purity argon carrier gas, followed by a ripple at valve depression and a pause (returning to ~ 80) prior to ionized oxygen concentration measurement where the scale reading drops rapidly to zero, indicating complete electron capture (returning to ~80 again) the meter records the concentration -- second pause of the higher molecular weight ionized SF<sub>6</sub>, which depresses the scale reading from ~ 80 to, say, half that amount indicating a degree of SF<sub>6</sub> concentration that has only partially absorbed the electrons. This technique is repeated three times every 15 minutes so that spurious readings



can be eliminated and remaining readings averaged.\*

Recording of the SF<sub>6</sub> concentration data is on a continuous writing Rustrack recorder, operating only when data is being recorded and then at 16 inches per hour. The display level of this 100 millivolt recorder is adjusted by the RANGE.KNOB on the right side of the SF<sub>6</sub> detector unit just described. ADJUST THE PURE ARGON READING TO APPROXIMATELY 80 FOR BEST RESULTS. All concentration levels are clearly shown on the paper roll records. Additional check points are included for the 13.8 ppb SF<sub>6</sub> standard sample when this check feature is desired. Hand reduced data is then fed into a computer program and reduced to air exchanges per hour for air infiltration rate.

#### D. Argon Carrier Gas

The simplest component of the AAIU system is the argon bottle and regulator assembly. Held in place by metal detents on the AAIU base and a seat belt strap to the vertical frame, the 30 standard cubic feet, Ultra High Purity Argon bottle supplies the required carrier gas to the SF<sub>6</sub> sampling unit and activates the piston which depresses the sampling valve on command. The gas regulator is set to the sticker value on the output pressure gauge of the individual AAIU. Characteristics change slightly from unit to unit call for pressure ranging from 10 to 18 psig.

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\* in most cases only small variations occur <<10%

E. On Site Deployment

The following description outlines the steps required to initiate measurements in the field with the AAIU.

1. Load SF<sub>6</sub> Unit REMOTELY.
2. Move AAIU to central duct location normally next to home furnace.
3. Bend tab on return air duct joining strip and insert sample tube and SF<sub>6</sub> hypodermic tube through opening.
4. Load fresh paper roll in Rustrack recorder.
5. Open high purity argon cylinder setting pressure regulator to that noted on pressure gauge of the individual unit.
6. Turn on furnace fan at thermostat - - use TAG if there is danger that the fan may be inadvertently shut off during the test period.
7. Plug in AAIU unit - - SWITCH ON POWER STRIP - - set master timer cam with knurl knob to point initiating SF<sub>6</sub> injection.
8. Record start time on Rustrack chart.

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Table 1 †

Testing of  $-\ln \frac{I}{I_0} = kc^B$

$I_0 = 81.5$

argon pressure = 17.8 psig

No. of Points Considered	$-100 \ln_e \left(\frac{I}{I_0}\right)$	Concentration of Last Point	Correlation Coefficient	Value of B
3	24.95	7.07 ppb	0.9999999	0.943
4	30.80	8.83 "	0.9999999	0.945
5	38.42	11.04 "	0.99995	0.954
6	46.49	13.8 "	0.99987	0.942
7	56.76	17.25 "	0.99984	0.933
8	70.43	21.56 "	0.99989	0.932
9	84.39	26.95 "	0.99982	0.924
10	101.0	33.7 * "	0.99968	0.913

\* beyond range of equation applicability

Table 2 †

Testing of  $-\ln \frac{I}{I_0} = kc^B$

$I_0 = 77.7$

argon pressure = 17.8 psig

No. of Points Considered (for Fitting $-\ln \frac{I}{I_0} = kc^B$ )	$-\ln \frac{I}{I_0} \times 100$	Concentration of Last Point	Correlation Coefficient	Value of B
3	35.46	9.3	0.9999999	0.918
4	43.68	11.6	0.99999	0.923
5	53.07	14.5	0.99996	0.917
6	65.65	18.1	0.99997	0.917
7	79.75	22.7	0.99996	0.913
8	96.84	28.3	0.99994	0.908

Table 1 and Table 2 are represented as test points 1 and 2 in Table 3.

Table 3

General testing of AAIU to test applicability of  $\ln \frac{I}{I_0} = kc^B$   
 Argon pressure = 17.8 psig. Range of concentration approx. 5-3

Test No.	Error Magnitude*	$I_0$	B**	Correlation Coefficient
1	2%	81.5	0.942	0.99987
2	1%	77.7	0.917	0.99996
3	3%	74.0	0.954	0.99900
4	1%	72.0	0.908	0.99997
5	2%	72.0	0.910	0.99979
6	1%	78.0	0.918	0.99990
7	1%	73.0	0.940	0.99900
8	3%	84.0	0.950	0.99910
9	5%	74.0	0.958	0.99860
10	2%	79.0	0.947	0.99999
11	1%	75.5	1.010	0.99980
12	1%	71.5	0.905	0.99996
13	2%	76.5	0.905	0.99996
14	2%	72.0	0.905	0.99999
15	3%	78.0	0.940	0.99999
16	1%	76.0	0.832	0.99990
17	2%	74.0	0.986	0.99870
18	1%	70.0	0.910	0.99991
19	1%	72.5	0.983	0.99983

\* This indicates the worst fitting point for a given test series of typically eight points.

\*\* Chosen on the basis of the median value with best fit see Table 1 as an example.

Table 4

Infiltration Rates Obtained with  
NBS Experimental Automated System

<u>Run No.</u>	Air Changes per hour	
	<u>Network Sampling</u>	<u>Return Sampling</u>
1	0.45	0.46
2	.14*	- - - **
3	.44	.34
4	0*	.76*
5	.27	.23
6	.27	.27
7	.25	.25
8	.26	.26
9	.21	.22

\* House circulating fan not operated during these periods.

\*\* Uninterpretable as an exponential decay process.

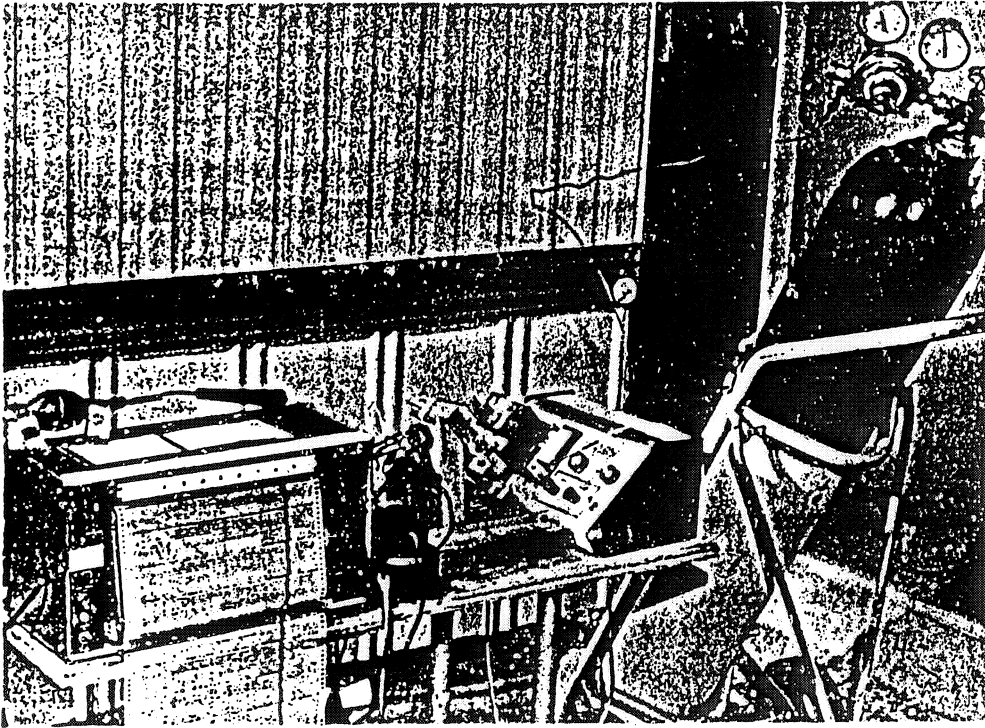


Figure 1. NBS  
Automated Air  
Filtration System

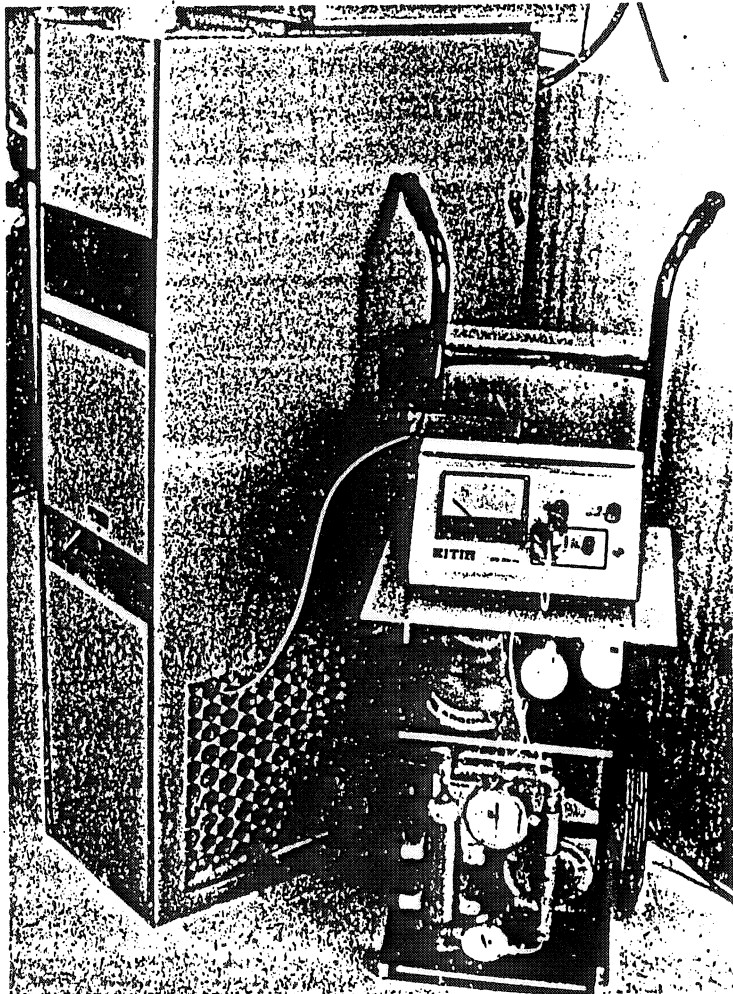


Figure 2. Princeton  
Automated Air  
Filtration Unit



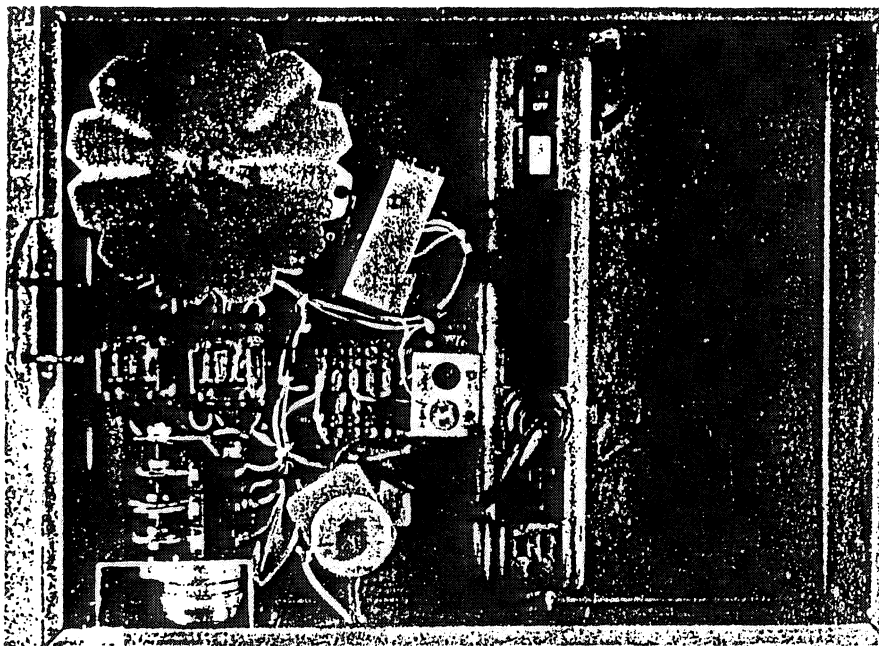


Figure B-3 Master Timer Control Center, main timing cam, switch column, sample selection valve, 3-gang cam switch, relays and wiring.

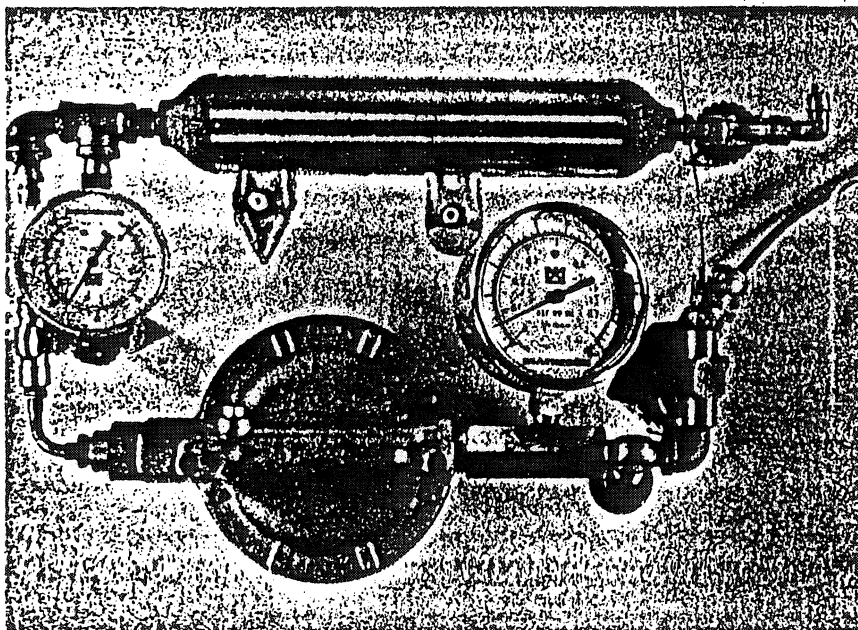
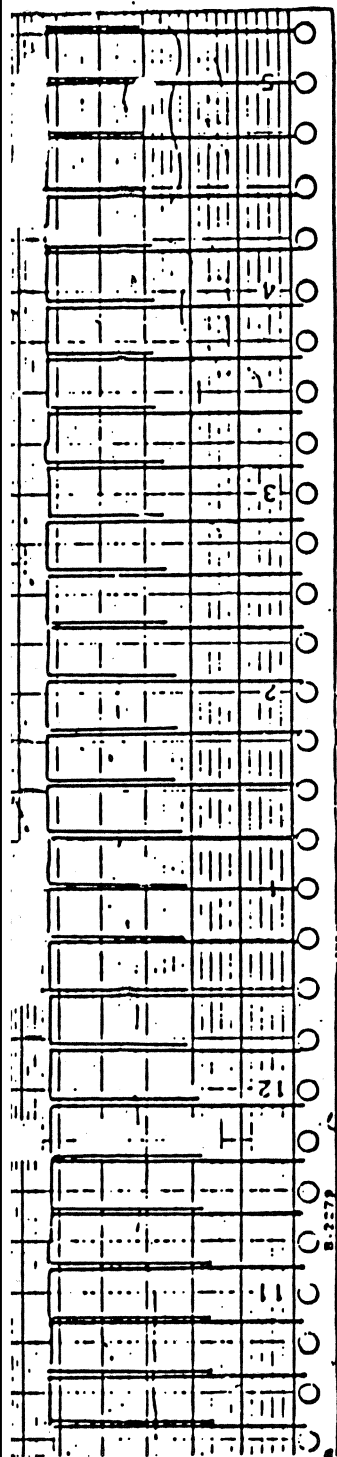
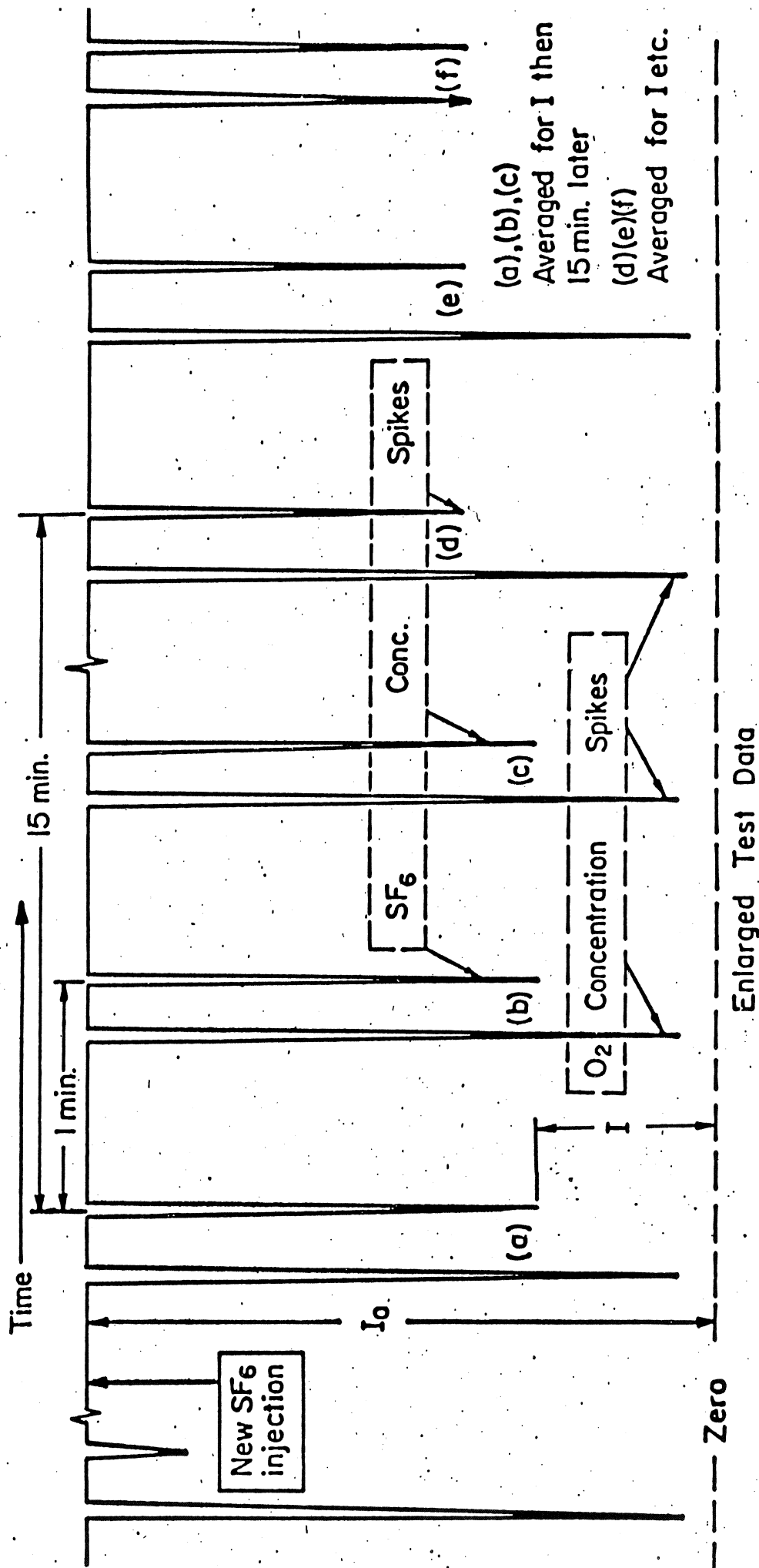


Figure B-4 Slide Out Plexiglas Panel containing 30 cc SF<sub>6</sub> storage bottle, low pressure regulator, gages, injection valve and hypodermic injection tube.



Actual test data



(a),(b),(c)  
Averaged for I then  
15 min. later  
(d)(e)(f)  
Averaged for I etc.

Enlarged Test Data

Actual and Enlarged Chart Record of Air Infiltration Measurement

Figure 3

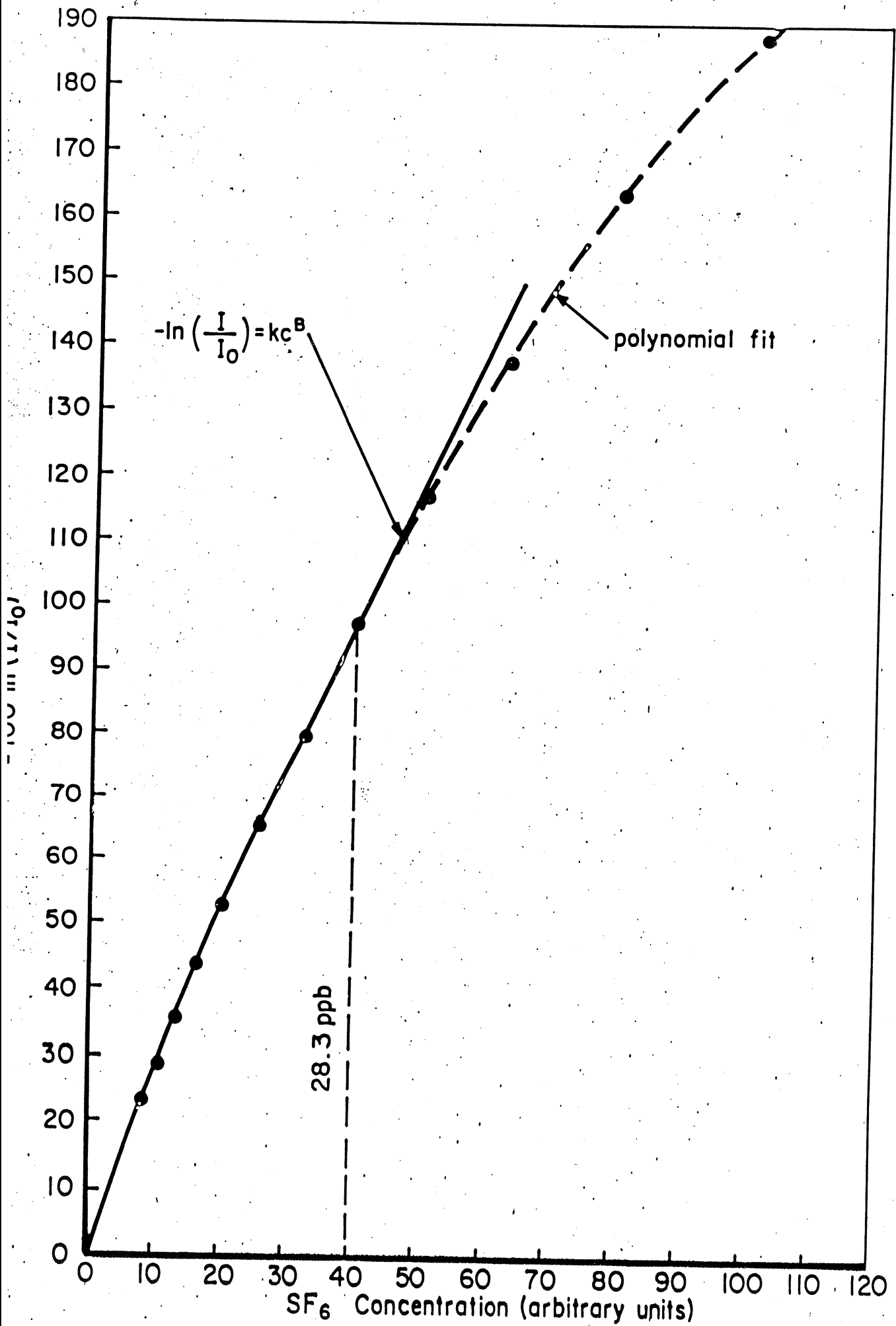
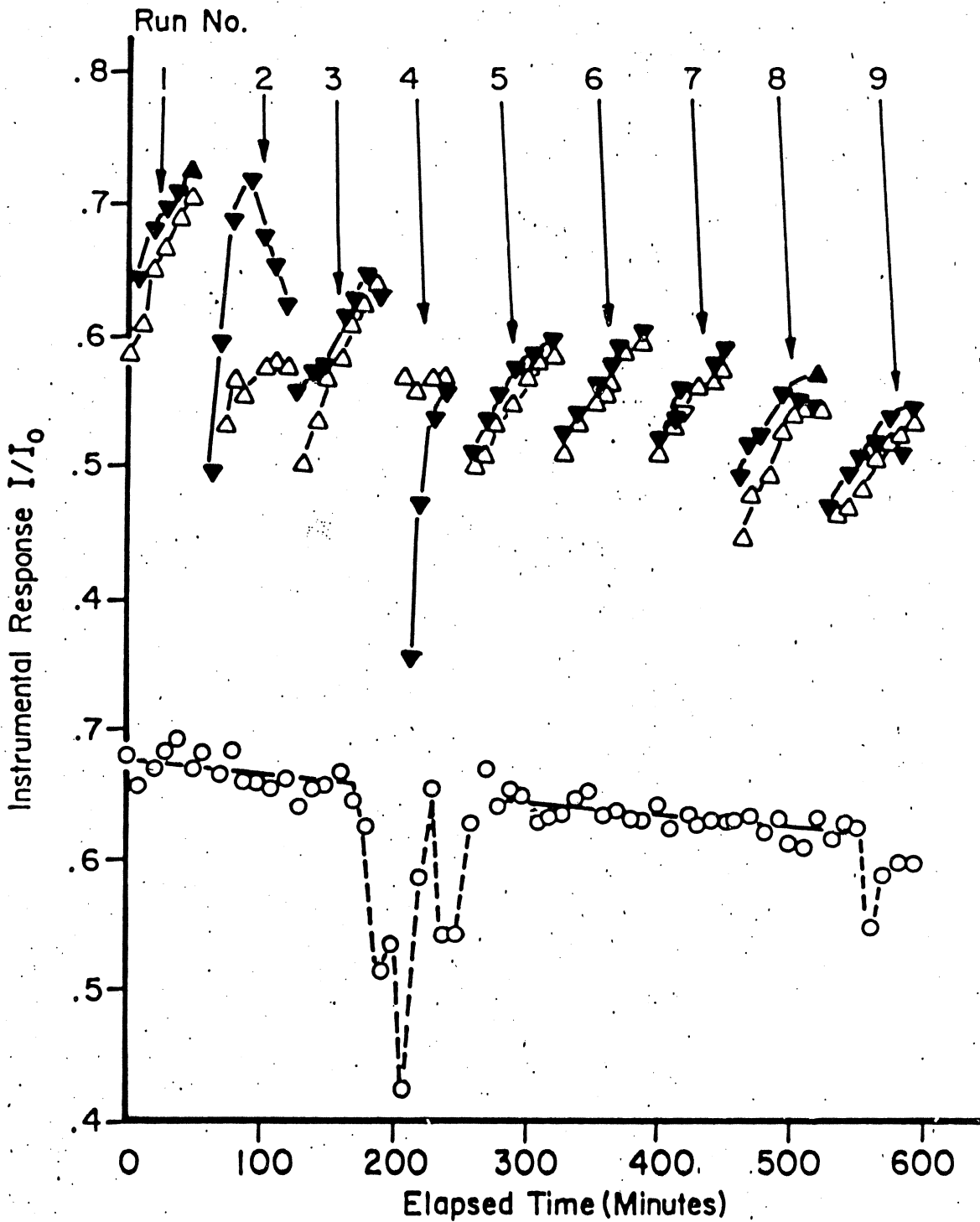


Figure 4

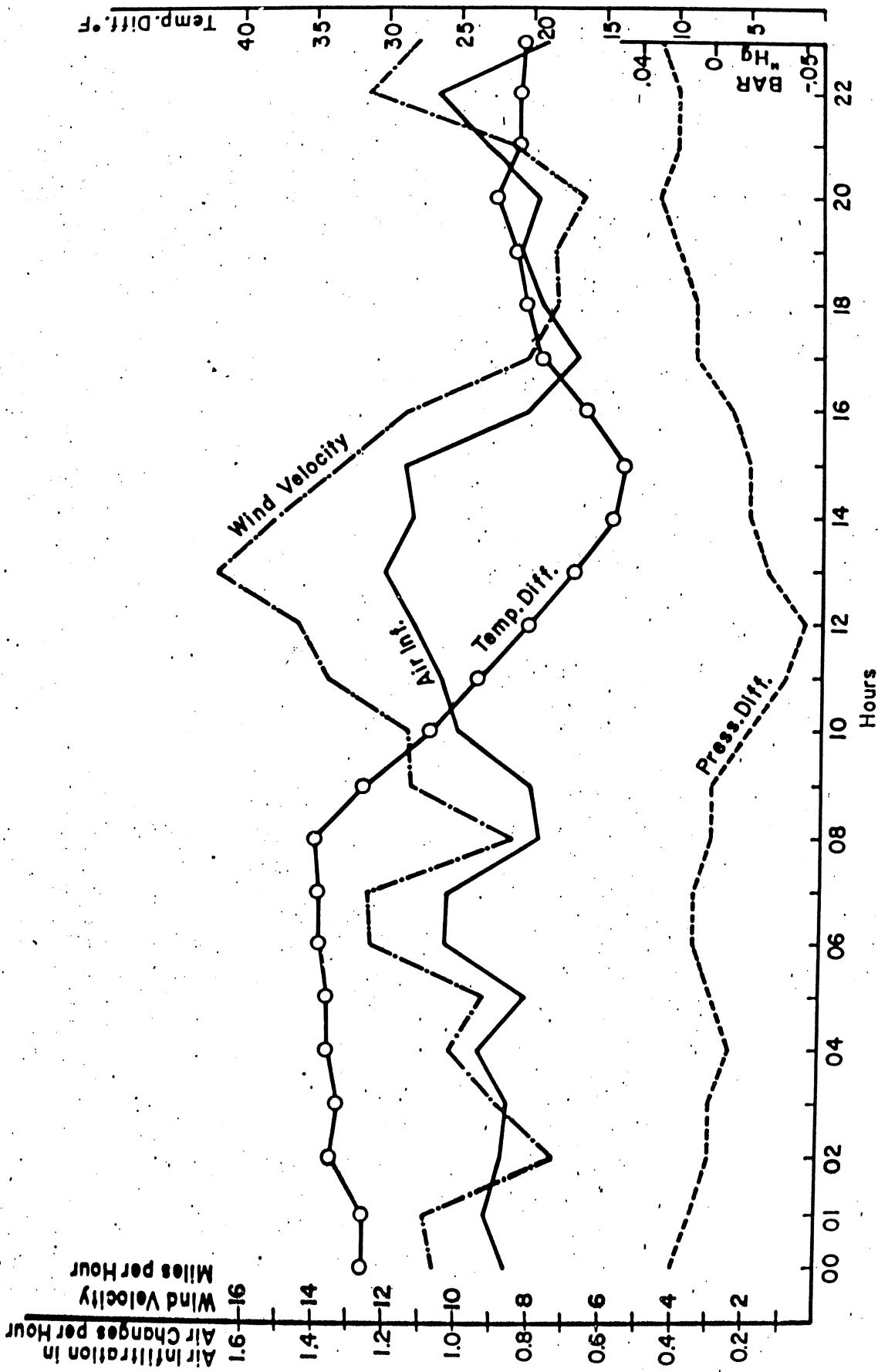


▼ Sample from network, △ Sample from return air, ○ Secondary standard

Test Data NBS Automated Air Infiltration System

Figure 5

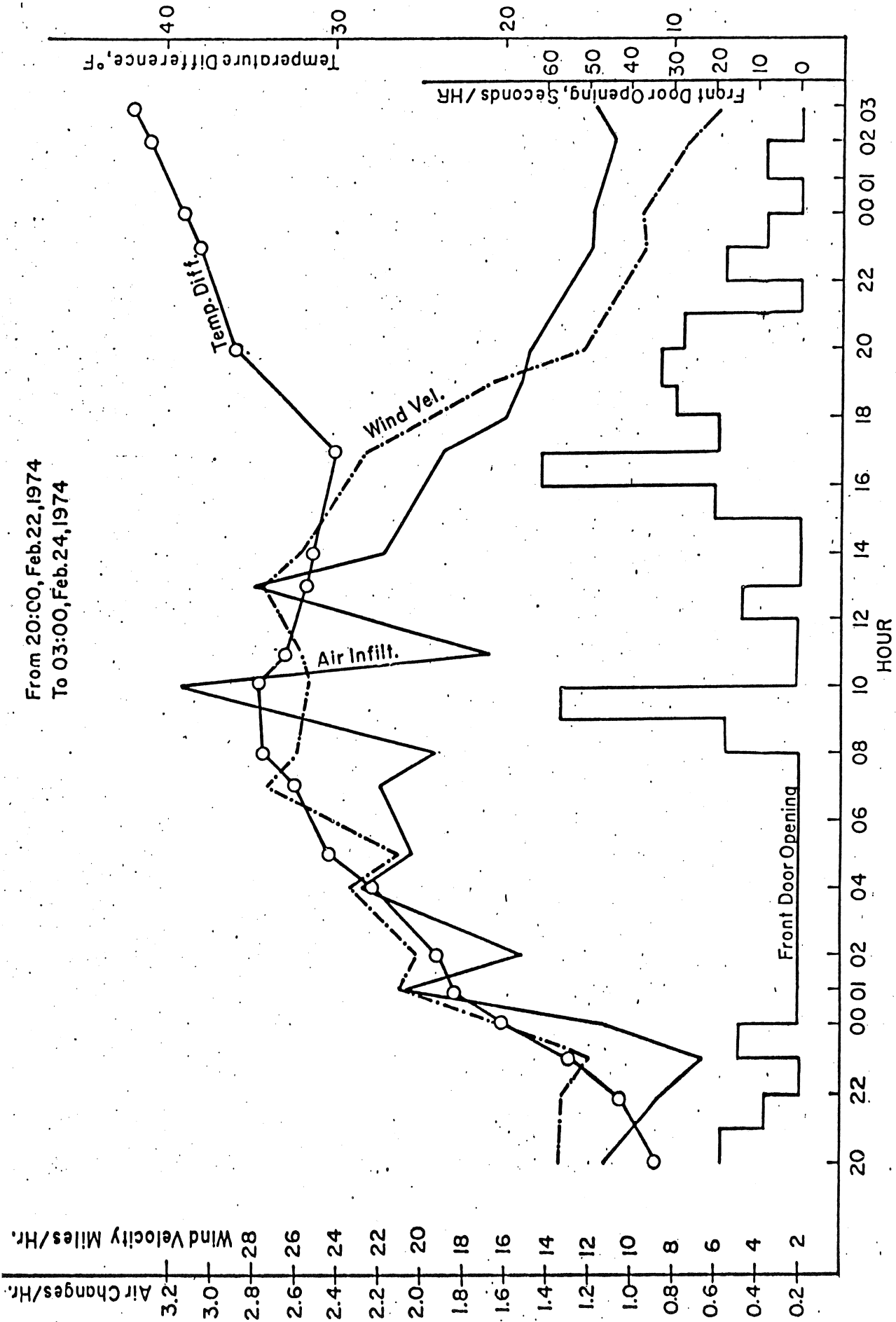
Nov. 30, 1973



First Data Acquisition with Automated Air Infiltration Unit

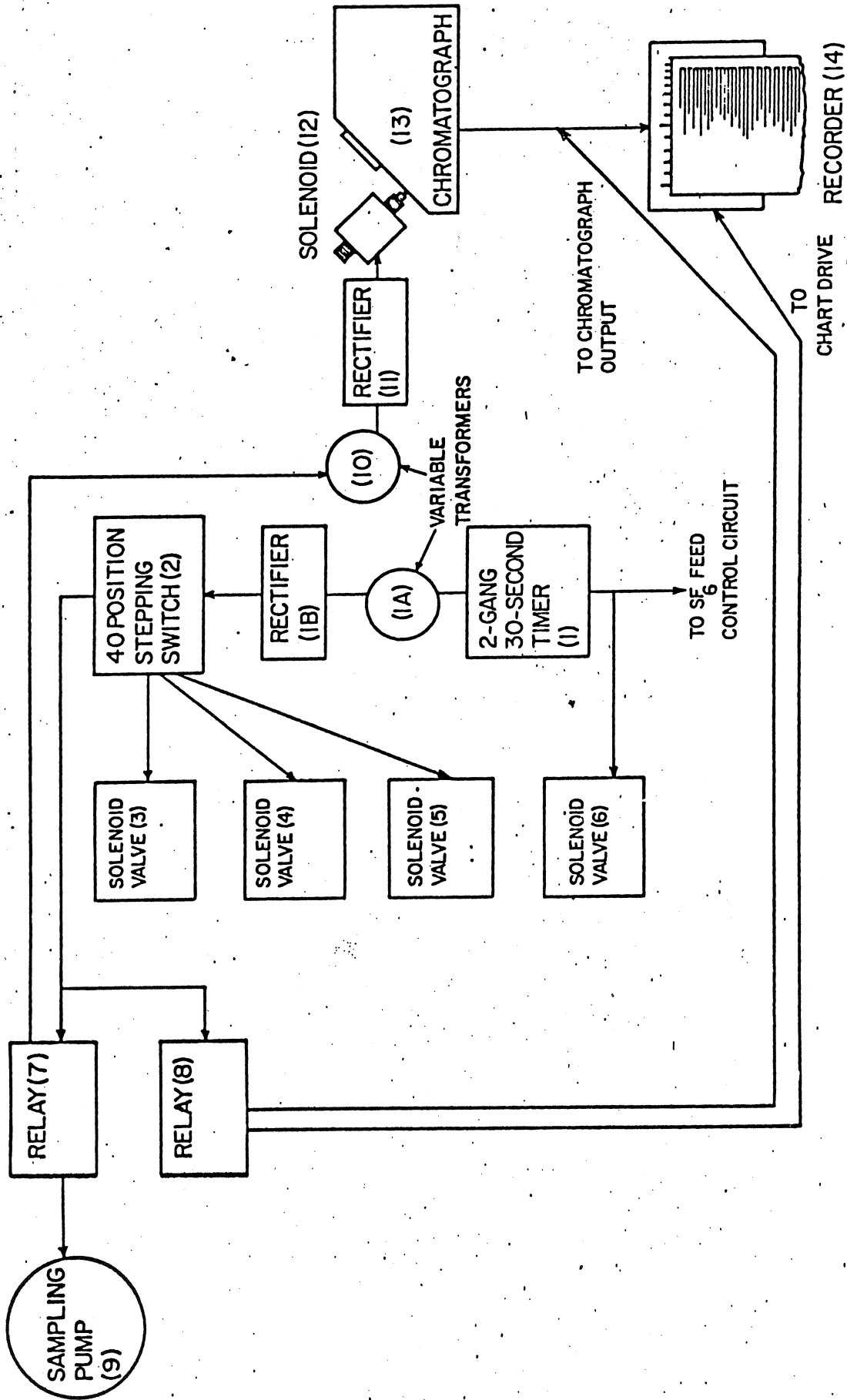
Figure 6

From 20:00, Feb.22,1974  
To 03:00, Feb.24,1974

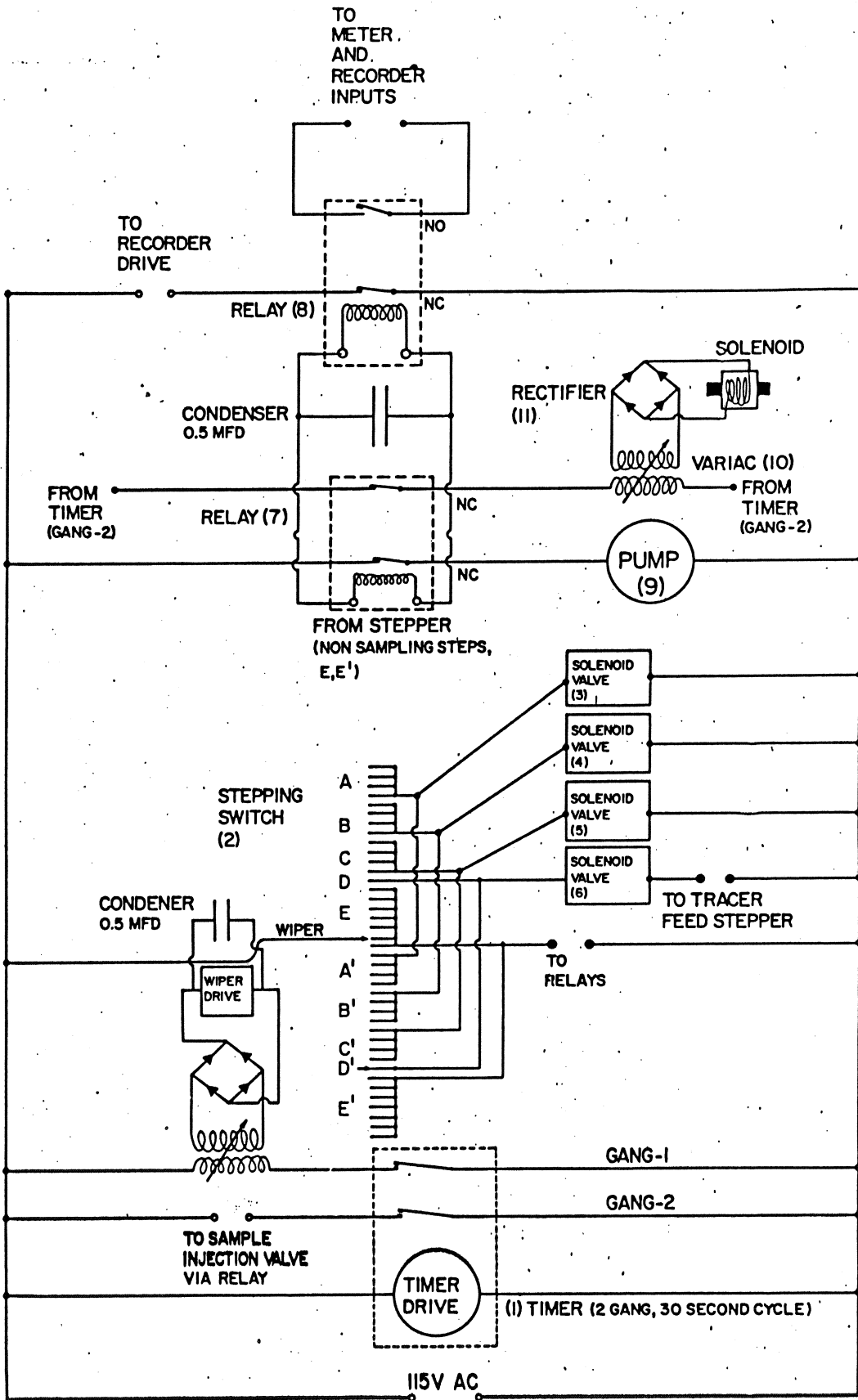


Townhouse Air Infiltration With Door Opening Time

Figure 7

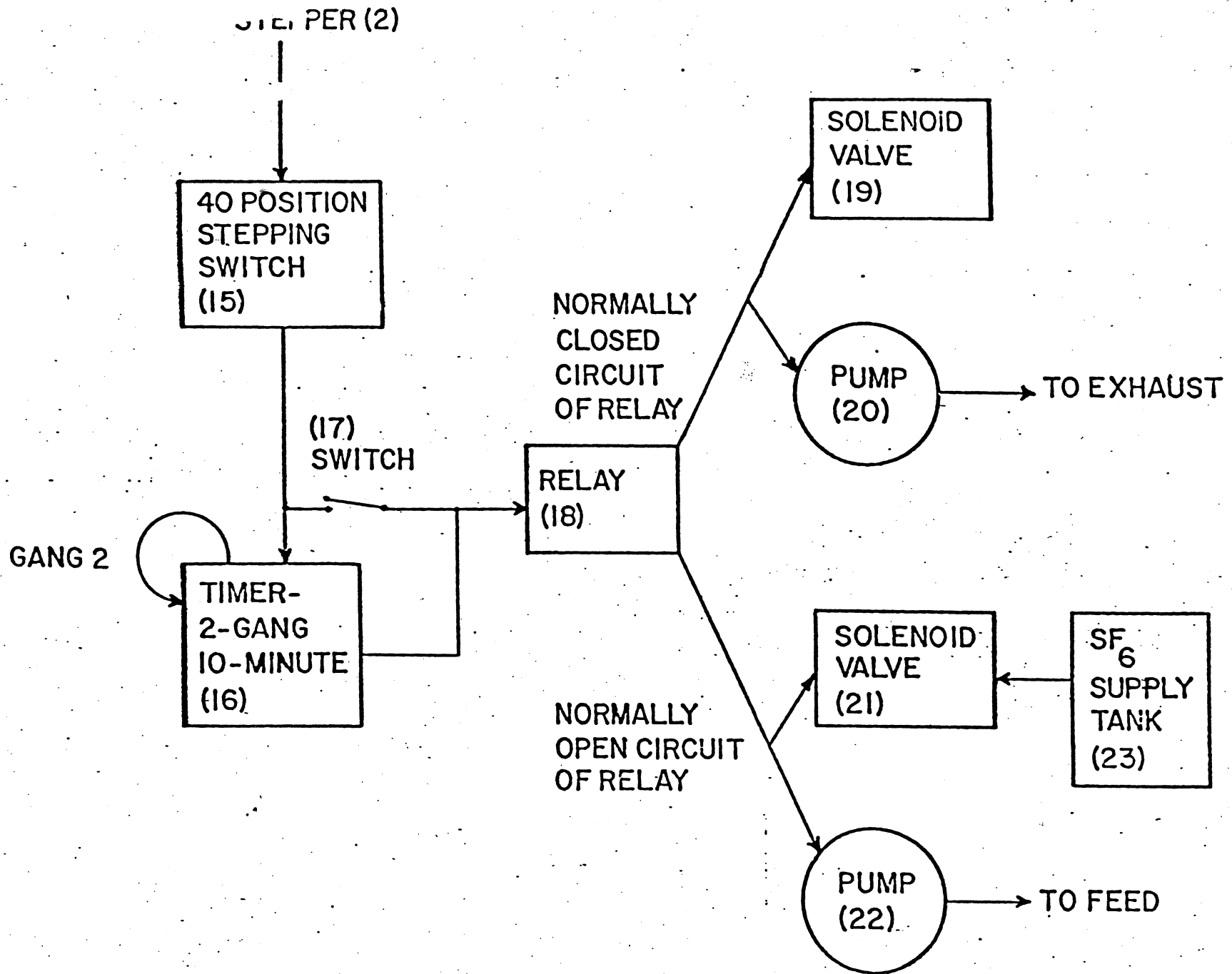


Block Diagram of NBS System for Automated Operation of the Chromatograph

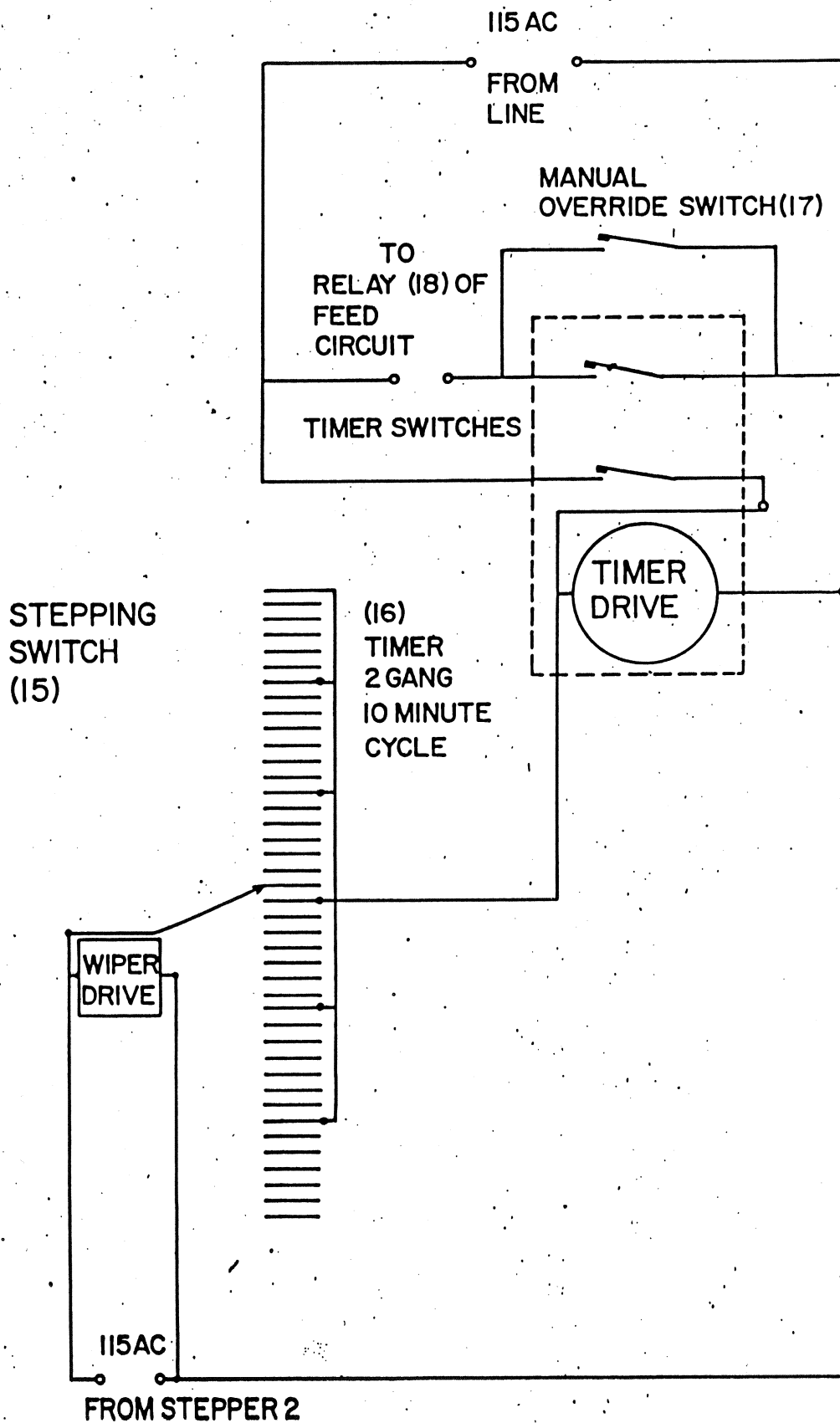


Wiring Diagram of the NBS Automated System

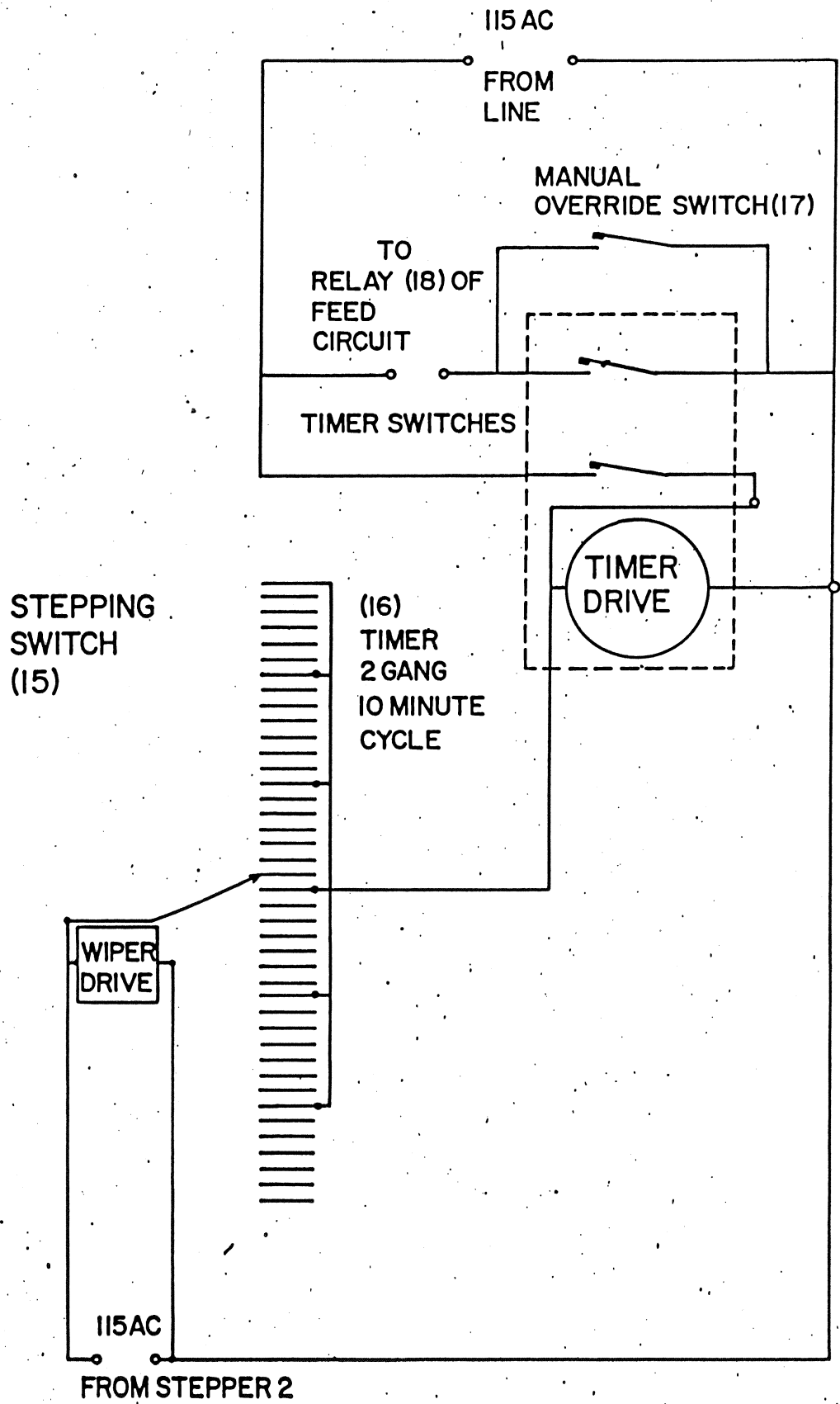




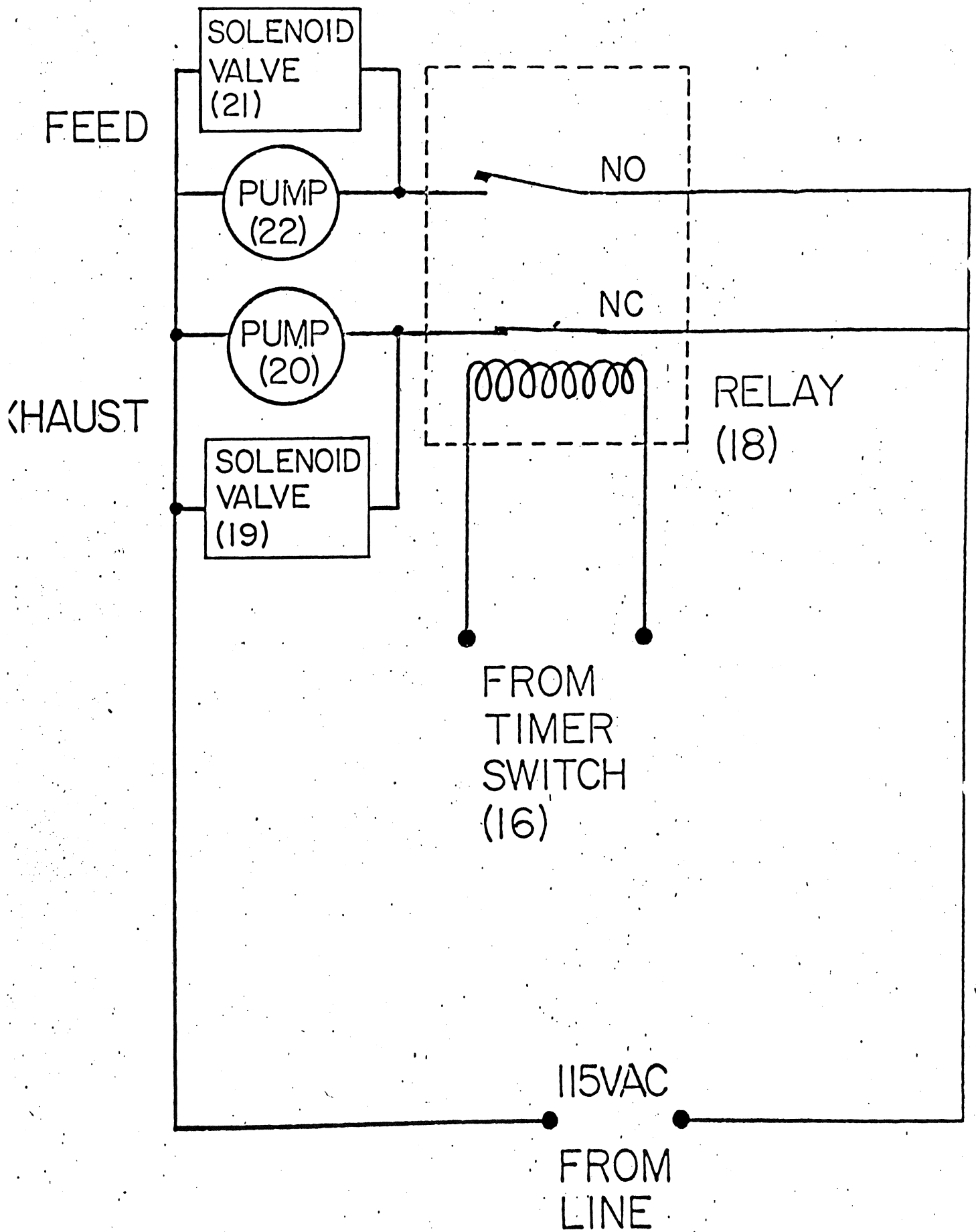
Block Diagram of NBS Tracer Feed Supply



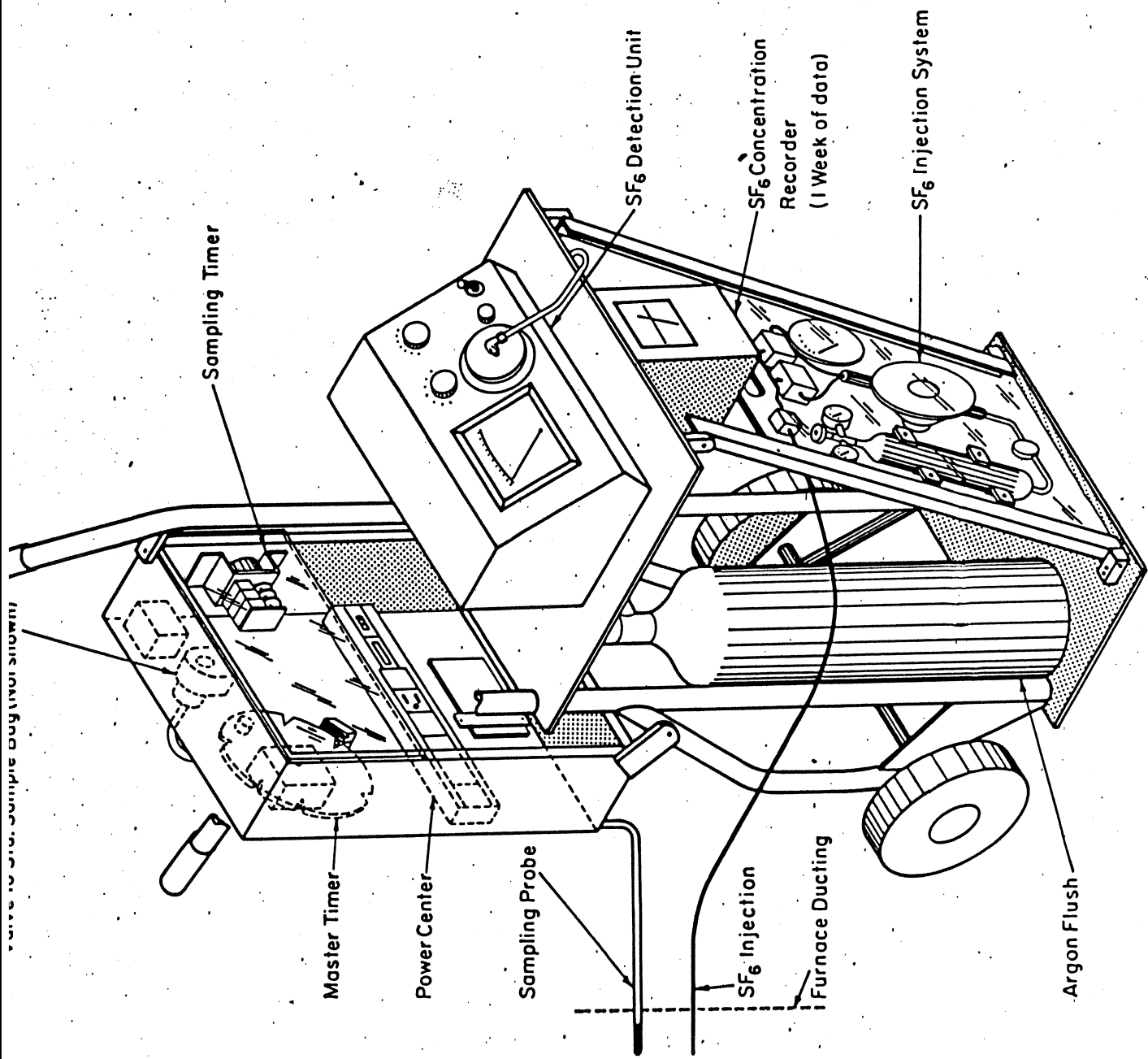
Wiring Diagram for NBS Feed Actuating System



Wiring Diagram for NBS Feed Actuating System

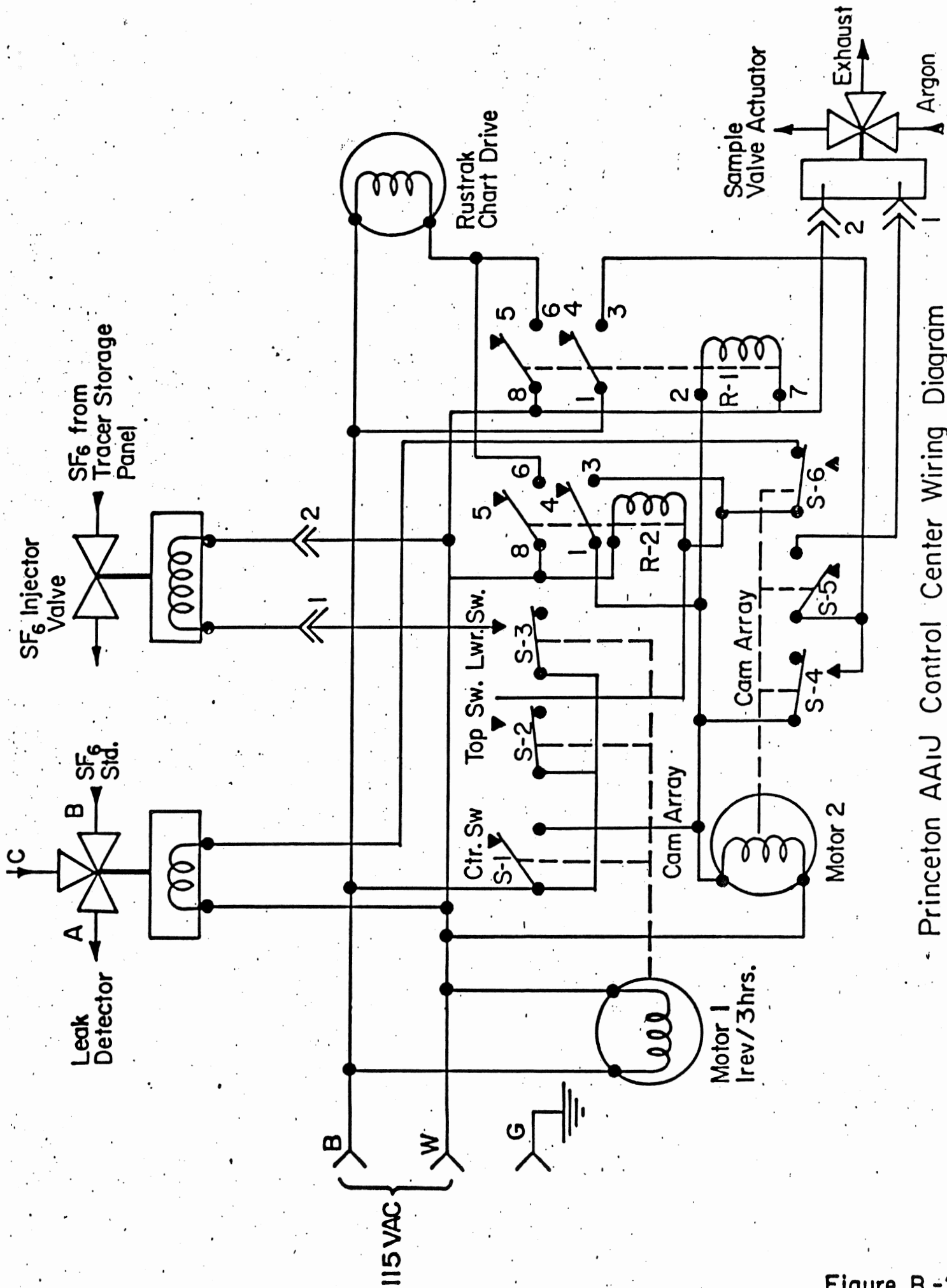


Wiring Diagram of NBS Feed Control System.



AUTOMATED AIR INFILTRATION UNIT

FIGURE B-1



Princeton AAIJ Control Center Wiring Diagram

Figure B-2

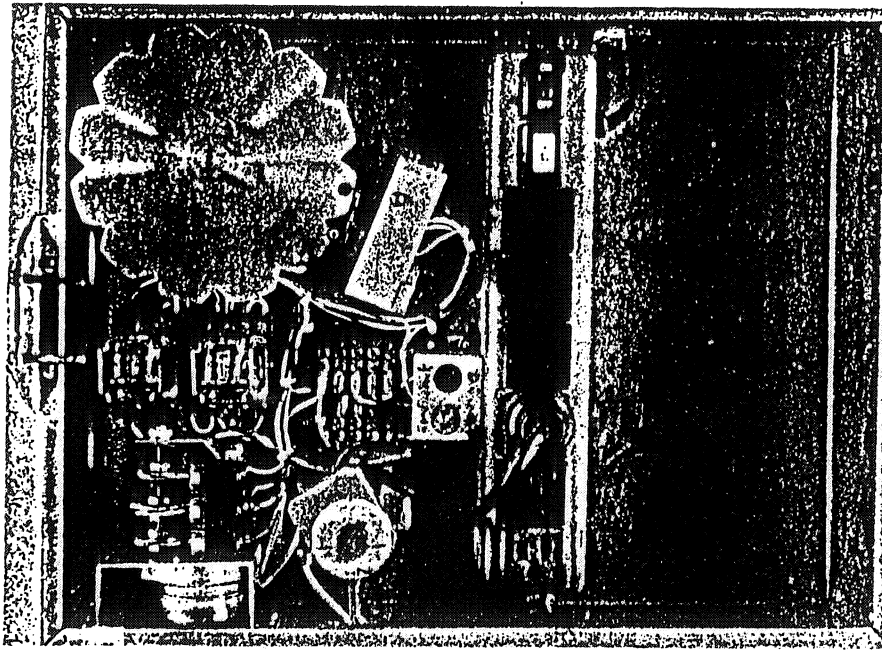


Figure B-3 Master Timer Control Center, main timing cam, switch column, sample selection valve, 3-gang cam switch, relays and wiring.

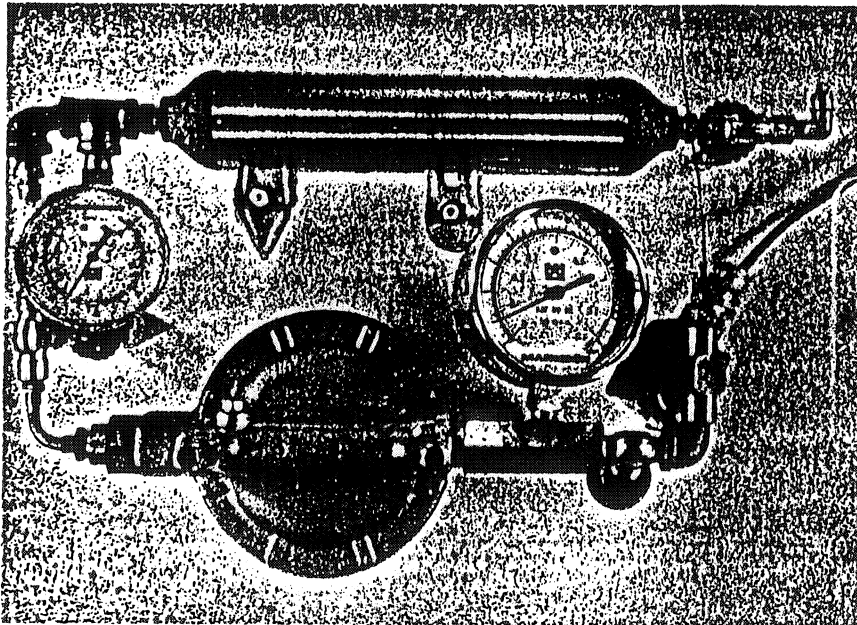
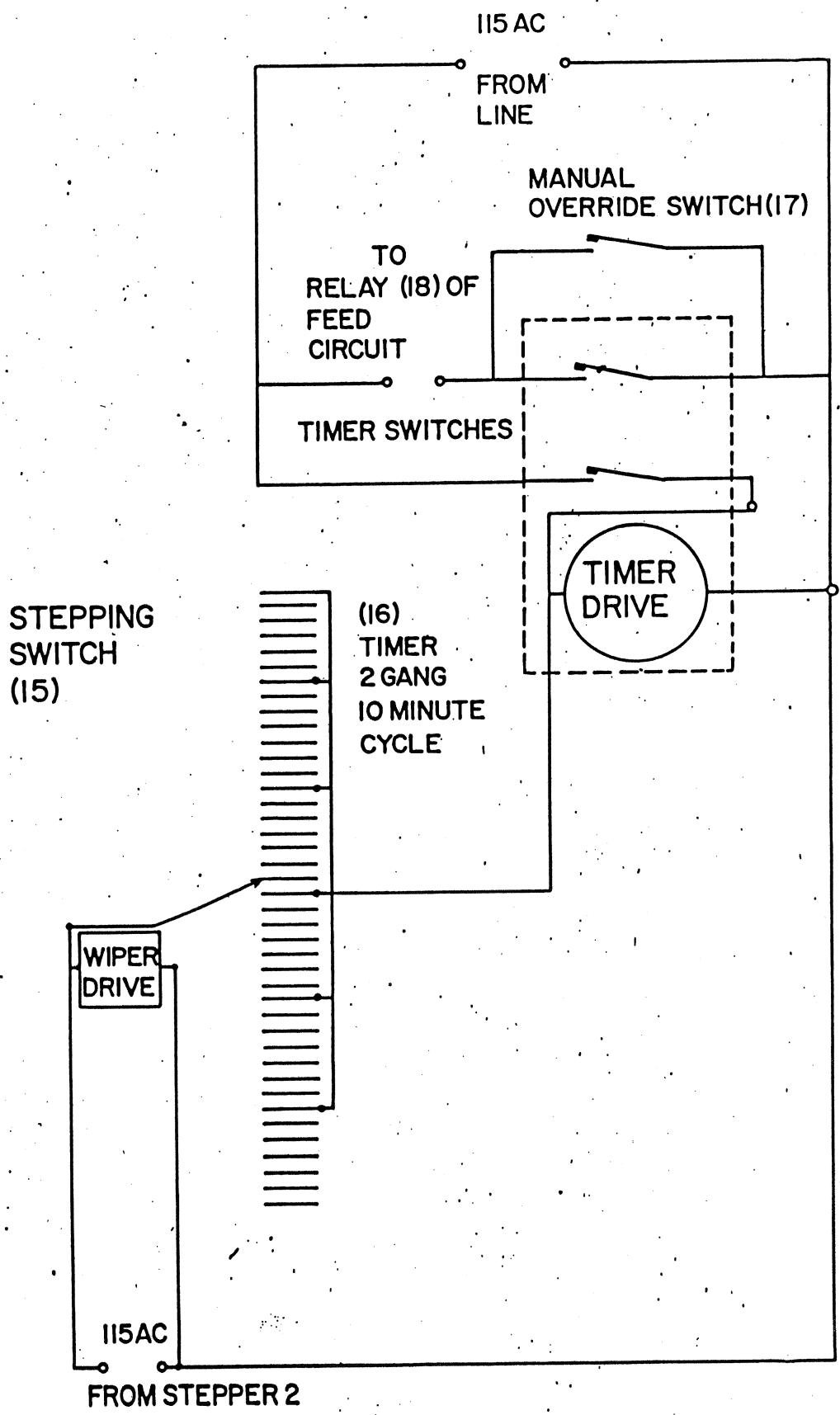
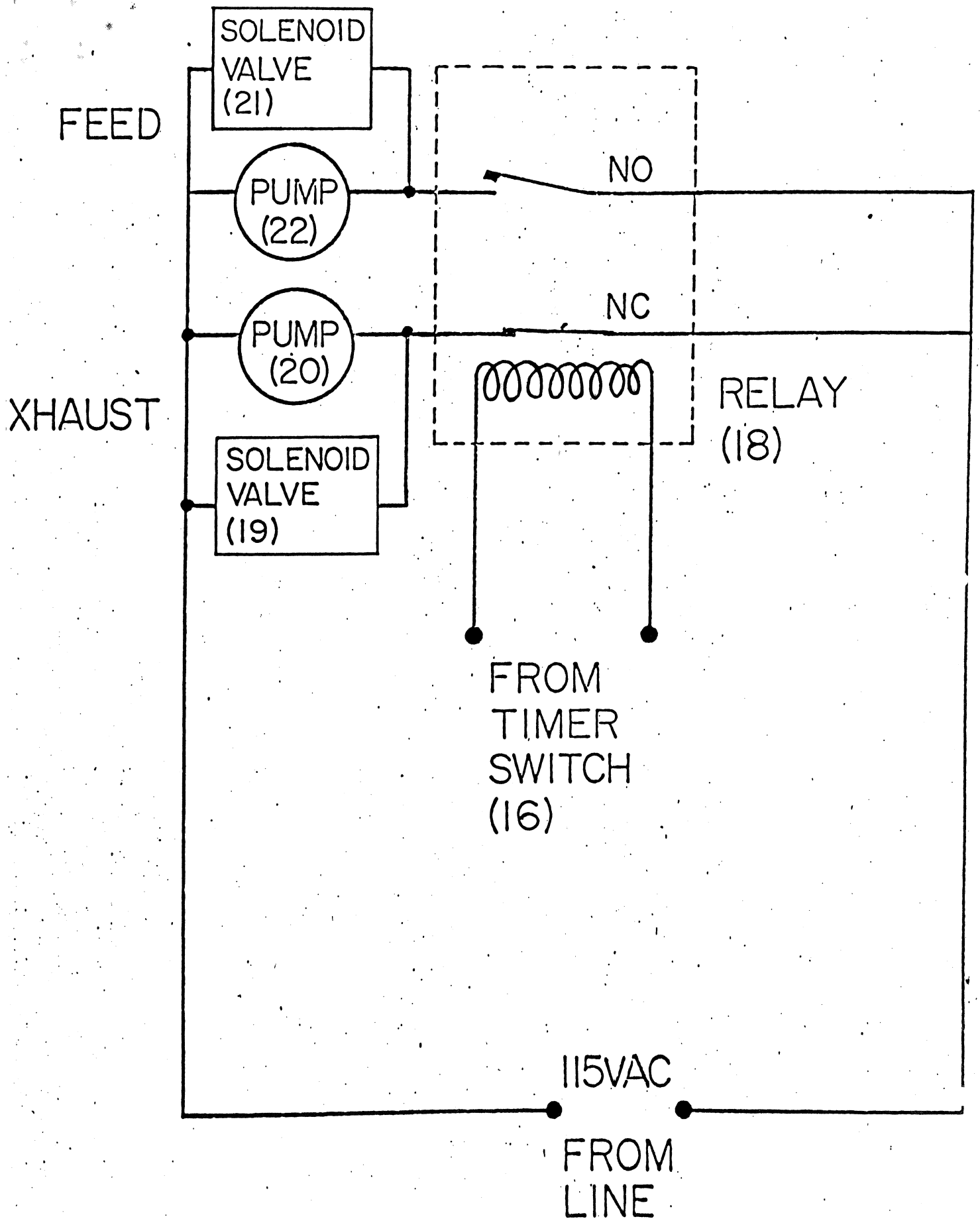


Figure B-4 Slide Out Plexiglas Panel containing 30 cc SF<sub>6</sub> storage bottle, low pressure regulator, gages, injection valve and hypodermic injection tube.

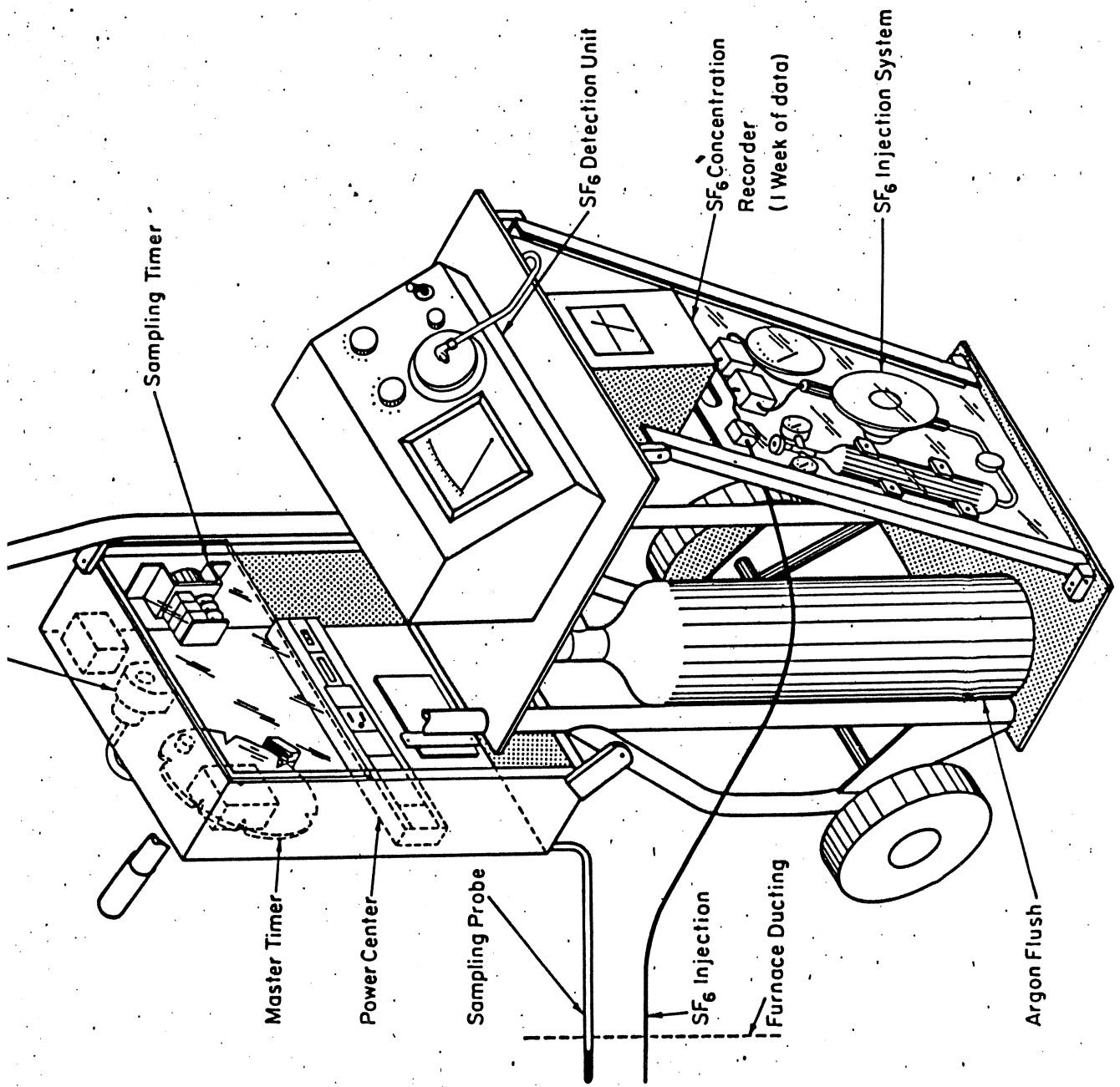


Wiring Diagram for NBS Feed Actuating System





Wiring Diagram of NBS Feed Control System



AUTOMATED AIR INFILTRATION UNIT

FIGURE B-1

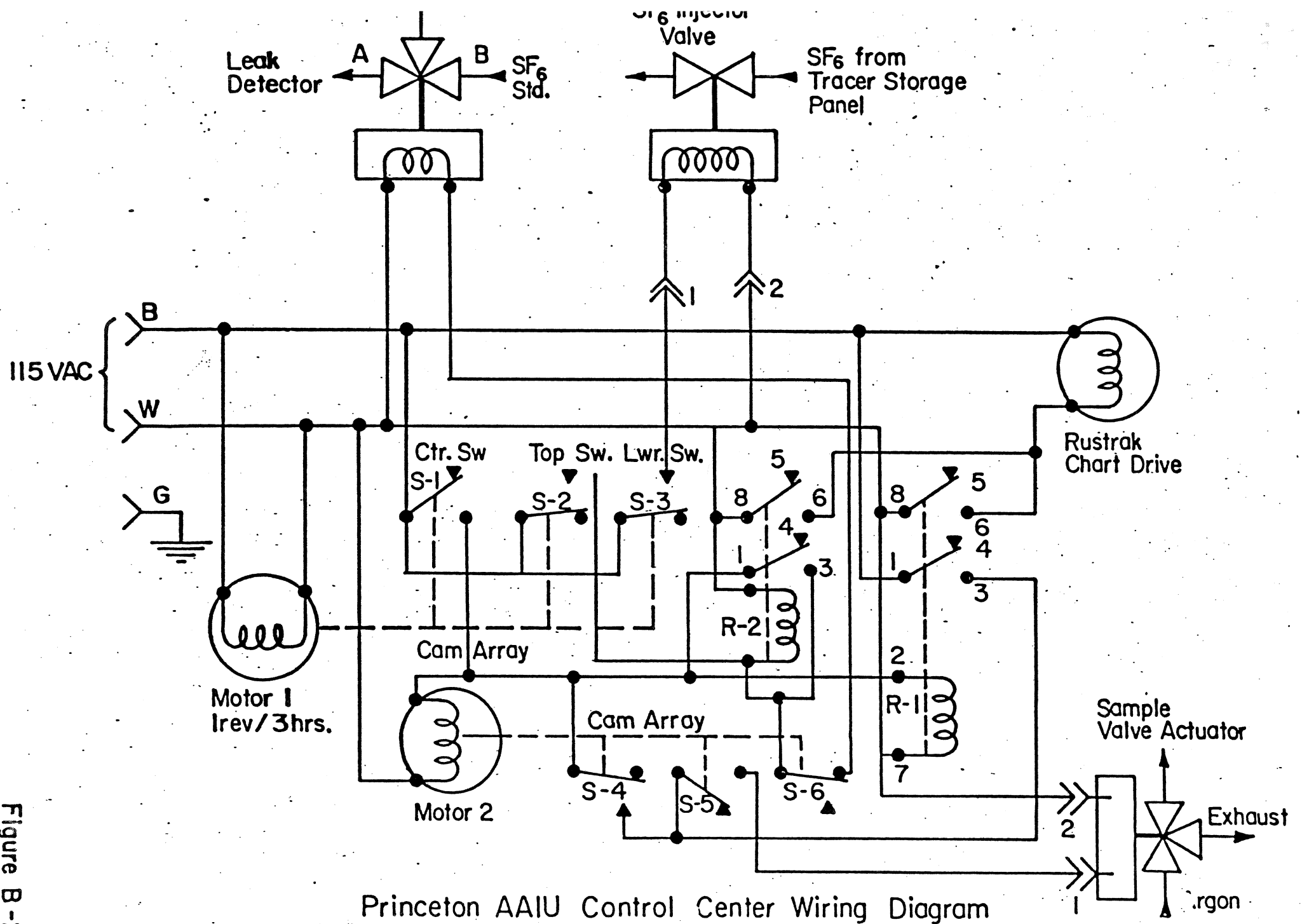


Figure B-2

Princeton AAIU Control Center Wiring Diagram

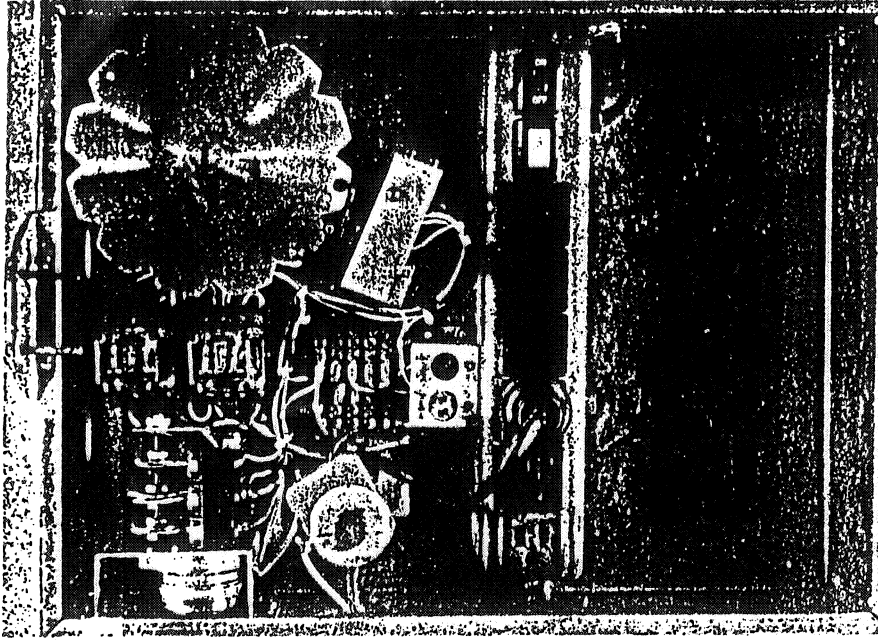


Figure B-3 Master Timer Control Center, main timing cam, switch column, sample selection valve, 3-gang cam switch, relays and wiring.

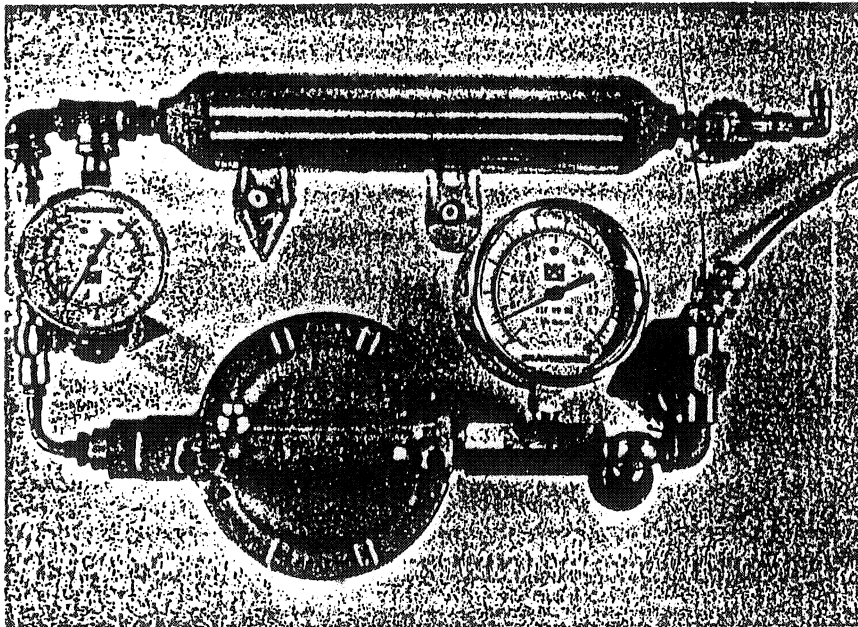


Figure B-4 Slide Out Plexiglas Panel containing 30 cc SF<sub>6</sub> storage bottle, low pressure regulator, gages, injection valve and hypodermic injection tube.